MARINE BIRD ASSEMBLAGES

IN RELATION TO ARMORED AND UNARMORED SITES

IN CENTRAL PUGET SOUND

by

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ABSTRACT

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The Puget Sound nearshore provides critical habitat to overwintering migratory and resident marine birds. Long-term monitoring has shown that populations of many marine bird species are experiencing declines. There has been limited research regarding the factors driving these trends, and more information is needed if adequate management and conservation measures are to be implemented. Coastal population growth in the region has led to extensive use of shoreline armoring to protect development, which has impacted the nearshore environment. Some prey species, including forage fish, are deleteriously affected by shoreline armoring. The impacts of armoring on upper trophic level predators, such as marine birds, are largely unknown. This study examined marine bird assemblages and behavior at paired armored and unarmored sites in central Puget Sound. Surveys of marine birds in the nearshore were conducted from January through March 2015. Findings demonstrated that average abundance and species richness was significantly greater at armored survey sites; however, results varied between individual paired sites. The proportion of marine birds in each foraging guild was dependent on whether or not a site was armored, with piscivorous species comprising a lower percentage of birds at armored sites. Confounding natural and artificial factors could be contributing to these results, emphasizing the difficulty in determining what aspects contribute to habitat use and foraging behavior of marine birds in the nearshore. Further research is warranted to explore the response of marine bird abundance and behavior in response to shoreline modification.

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Chapter 1: Introduction and Literature Review

INTRODUCTION

Humans have been drawn to coastal areas for thousands of years. They benefit from the numerous ecosystem goods and services provided by the nearshore, including flood protection, nutrient cycling, water filtration, and nursery habitat for marine species. Nearshore ecosystems also provide food, cultural value, and opportunities for recreation. Globally, the economic value of these ecosystem services is estimated at 12.3 trillion dollars annually (Hoggart et al., 2015).

While people have long been interested in inhabiting coastal areas, the desire to live near the ocean has come at a cost. Shifting coastlines, rising sea levels, coastal storms, and floods can damage and destroy property and infrastructure. For centuries, people have built coastal infrastructure, such as shoreline armoring, to protect their land and homes from the encroachment of the ocean (Charlier et al., 2005). While coastal floods and erosion are natural phenomena, extensive coastal urbanization has resulted in viewing these occurrences as urgent problems. This has led to increasing use of shoreline armoring to protect development and human interests (Nicholls et al., 2015). At present, more than 40% of the world's population currently lives within 100 km of the coast, and armoring is used worldwide to protect development in coastal areas (Wilson et al., 2015). Human populations and associated development pressures in many coastal areas are growing, and the use of armoring is expected to increase to shield waterfront properties from waves, floods, and rising sea levels (Nordstrom, 2014). As with many anthropogenic alterations of the environment, the construction of these armoring structures is not without consequence, both for coastal ecosystems and the ecosystem goods and services upon which humans depend. The Puget Sound region in the northwestern United States is one coastal area that has experienced dramatic growth in human population and coastal development.

Puget Sound is a fjordal estuary located along the coast of the northwestern United States and comprised of dynamic marine and terrestrial ecosystems framed by the Olympic Peninsula and the Cascade Mountains in Washington State (Shipman, 2010). The Puget Sound Basin has been identified as a hot spot for biodiversity in the United States and is home to approximately 7,000 terrestrial and marine species (Quinn, 2009). The ecosystems of Puget Sound have been degraded due to anthropogenic activity, including industrial and residential development, agriculture, and overexploitation of natural resources such as salmon and old growth forests (Fresh et al., 2011; Quinn, 2009). Regional and national attention has been focused on the declines of ecosystem function and the urgent need for restoration and conservation efforts in the marine, coastal, and terrestrial environments (Quinn, 2009).

While the Puget Sound region has been inhabited by Native Americans for thousands of years, the arrival of Europeans in the late 18th century and subsequent colonization dramatically altered the coastal landscape (Quinn, 2009). Approximately 4 million people now inhabit the Puget Sound region, and the population is growing by 1.5 percent each year (Fresh et al., 2011). Nearly 30 percent of the Puget Sound coastline is now armored, and the amount of armoring is increasing, particularly in residential areas (Puget Sound Partnership, 2013; Shipman, 2010). Along with the goal of protecting anthropogenic interests such as development, there is growing interest in conserving the nearshore habitat and associated species. However, the issue of armoring is controversial and involved numerous stakeholders with conflicting interests. When considering the removal or replacement of armoring, the rights of private property owners must be considered along with the public responsibility to protect the Puget Sound and the natural resources that sustain the economy and human population.

Despite its extensive use both regionally and globally, research into the impacts of armoring has only recently begun (Davis, 2008). Shoreline armoring affects the physical and ecological processes of the nearshore environment and can alter macroinvertebrate density and species composition and reduce spawning habitat for forage fish and salmonids (Rice, 2010). The effects on fauna higher in the food chain, such as marine birds, have been less studied. This research seeks to contribute to this understudied topic by examining the impact of armoring on seabirds in the Puget Sound.

Puget Sound is a vital migratory stopover on the Pacific Flyway and critical overwintering ground for many seabirds, which are often chosen as indicators of the health of marine ecosystems (Bower, 2009; Piatt et al., 2007). Studies suggest that many seabird species that overwinter in the Puget Sound have experienced significant population declines in the past few decades (Anderson et al., 2009; Bower, 2009). The factors driving these population declines are copious, multifaceted, and potentially interact with each other, magnifying the effects. Seabirds face threats from habitat modification, fishing, oil spills, introduced species, pollutants, direct exploitation, and climate change (Boersma et al., 2002; Bower, 2009). However, the specific causes of the population declines of Puget Sound marine bird species are largely unknown.

Three chapters comprise this thesis. The first chapter is a literature review which describes the Puget Sound nearshore environment, a history of shoreline armoring, the use of armoring in the Puget Sound, and the population trends of marine birds that overwinter in the Puget Sound. The second chapter describes this research and has been formatted as a manuscript for publication in a journal of ornithology. It contains an abstract, introduction, methods section, and a description of the results and discussion of this study. The third chapter reiterates the findings of this study, along with an interdisciplinary consideration of shoreline management with regards to permitting and restoration opportunities for and alternatives to armored shorelines.

LITERATURE REVIEW

THE PUGET SOUND NEARSHORE

Puget Sound is a fjordal estuary bordering the coast of western Washington and encompassing more than 8,000 km^2 of marine and estuary waters, with nearshore ecosystems spanning 4,000 km of Puget Sound coastline (Fresh et al., 2011). Puget Sound is ranked as a hotspot for biodiversity in the United States by the Center for Biological Diversity, with more than 200 species of fish, 100 species of birds, and 10 species of marine mammals inhabiting the region (Lipsky & Ryan, 2011; Quinn, 2009). Numerous avian and mammalian species are dependent on both marine and terrestrial ecosystems, emphasizing the importance of conservation efforts for both biomes (Gaydos & Pearson, 2011). The Puget Sound region is home to species with both cultural and economic value, including five species of salmon, top-level predators such as orcas, and numerous species of marine birds (Sobocinski et al., 2010). Anthropogenic activity has dramatically impacted the health of the Puget Sound, leading to degraded ecosystems, reduced biodiversity, and species endangerment (Fresh et al., 2011; Quinn, 2009). Concern about the health of the Puget Sound led to the formation of numerous governmental and non-governmental organizations focused on restoration and conservation.

Puget Sound is located in the southern Salish Sea, an inland sea that is 16,925 km^2. The landscape of Puget Sound and the greater Salish Sea was shaped by several glaciations, most recently the Vashon glaciation, which occurred 15,000-20,000 years ago (Shipman, 2010). The modern shoreline was established as sea level rise slowed at the beginning of the late Holocene period, approximately 5,000 years ago (Quinn, 2009). The coastline continues to be shaped from the deposition of sediment carried by rivers to the coast and through wave action, which causes erosion and transports sediment (Shipman, 2010).

The nearshore environment is vital to the health of Puget Sound and significant in providing numerous ecosystem goods and services upon which humans depend (Beck et al., 2003). Concurrently, it is subject to numerous anthropogenic modifications and impacts and particularly vulnerable to such disturbances (Fresh et al., 2011). A healthy nearshore provides shoreline protection, water filtration, and nutrient cycling (Beck et al., 2003). It also serves as habitat for invertebrates, fish, and shellfish and is important to human activities such as commercial fisheries and recreation, including beach walking, kayaking, and clamming (Beck et al., 2003; Fresh et al., 2011). The nearshore zone has been defined in numerous ways. For the purpose of this research concerning marine shorelines, it begins in the upland at coastal bluffs or the marine riparian zone and extends to the lower limit of the benthic photic zone, at which point sunlight cannot sustain seagrasses or algae (Williams & Thom, 2001). The photic zone ranges from 10 to 30 meters beyond the Mean Lower Low Water in Puget Sound and is dependent on water clarity (Williams & Thom, 2001).

Coastal landforms and processes

The glacial history of Puget Sound formed a diverse landscape. The Puget Sound nearshore is an aggregate of four principal geomorphic systems: beaches, rocky coasts, embayments, and river deltas (Fresh et al., 2011; Shipman, 2008). These systems are in turn made up of distinct landforms, which are the result of coastal processes, historic changes in sea level, and the topography of the shoreline (Shipman, 2008). Barrier beaches and bluff-backed beaches constitute the majority of the shoreline (Shipman, 2008). Bluffs develop when the shoreline retreats inland, while barrier beaches are established when sediment accumulates seaward from the shoreline (Shipman, 2008). Coastal bluffs, composed of glacial till and other sediment deposited during glaciation, are vital to the nearshore. The erosion from coastal bluffs contributes sediment to the nearshore, giving them the alternative name of feeder bluffs (Fresh et al., 2011). The prevalence of coastal bluffs along the Puget Sound shoreline can be attributed to wave action and gravity eroding glacial sediment over thousands of years (Fresh et al., 2011; Shipman, 2008). Marine and land-based processes trigger bluff erosion, as do anthropogenic activities, which supplies beaches with their dominant substrate types: gravel, sand, and mud (Dethier, 2010; Johannessen & MacLennan, 2007).

The main geomorphic process that drives the formation and maintenance of beaches is erosion, transport, and deposition of sediment by wave action (Shipman, 2008). Cross-shore transport moves sediment perpendicular to the shore, forming the shape of the beach profile. Longshore transport moves sediment parallel to the shore over great distances to form other landforms, such as spits and barrier beaches (Shipman, 2008). This sediment transport occurs in semi-independent sections of shoreline which are known as littoral, drift, or net shore-drift cells (Johannessen, 2010). There are three components to a littoral cell: a place of origin and sediment supply, a transport area, and an area where sediment is deposited (Johannessen, 2010). In Puget Sound, 860 littoral cells have been identified, as well as more than 200 areas where this net shore drift does not occur (Envirovision et al., 2010). These cells have unique sediment sources and sinks, and the direction of sediment transport can be identified for each cell. There may be overlap of sediment sources and sinks between cells (Shipman, MacLennan, & Johannessen, 2014). The sediment that bluffs supply to littoral cells is significant to the health of the nearshore (Johannessen, 2010).

Ecology of the nearshore

The nearshore bridges the terrestrial and marine ecosystems, and its ecology is driven by both. It plays many important ecological roles, including functioning as nurseries for fish and shellfish and foraging habitat for marine birds and other predators (Beck et al., 2003). The nearshore can be broken down into several different areas, including the marine riparian zone, intertidal zone, and subtidal zone (PSNERP, 2014). The supratidal, or supralittoral, zone is the area above mean higher high water (MHHW) in the intertidal zone. Decomposition of marine wrack in the supratidal zone adds nutrients that nourish the upland terrestrial environment, while terrestrial leaf litter and insects and sediment from eroding bluffs contribute to the beach and marine environment. Supratidal habitat in Puget Sound is influenced by several physical factors, such as tidal regime, drift cell dynamics, and sediment size. Forage fish, marine crustaceans, and other invertebrates rely on the supratidal zone for various life stages (Sobocinski et al., 2010). The success of these lower trophic levels impacts the availability of prey for marine birds and other predators.

The substrate type and depth of the photic zone influence the types of marine vegetation, composed of seagrasses and macroalgae, in the Puget Sound nearshore. Eelgrass is an important species of the nearshore, providing many important functions, including buffering wave energy, nutrient processing and habitat for diverse invertebrate communities, and serving as a food source for marine birds (Williams & Thom, 2001) Eelgrass thrives in "mixed-fines" substrate, a combination of sand and mud. Native eelgrass (*Zostera marina*) grows in the shallow subtidal zone and the intertidal zone (Dethier, 2010). Dwarf eelgrass (*Zostera japonica*) has a greater vertical reach in the intertidal zone than the native species. Both species stabilize the substrate and provide foraging and refuge habitat for many species in the nearshore, as well as spawning habitat for herring (Dethier, 2010). Even in death, marine vegetation contributes to the success of the nearshore environment. The detritus from eelgrass beds and other marine vegetation is one of the primary drivers of a successful nearshore environment (Williams & Thom, 2001).

The nearshore is particularly susceptible to anthropogenic disturbance due to several characteristics (Fresh et al., 2011). The nearshore is considered an ecotone, or transitional zone, between the terrestrial and marine systems, containing elements of both environments as well as organisms unique to the nearshore (Graves & Wang, 2011). Due to many factors, including an abundance of natural resources, the nearshore attracts residential development and agricultural, commercial, and industrial use. There have been considerable anthropogenic influences on the nearshore over the past 150 years, including modifications to the upland environment, nearshore fill, and roads and railroads built on or near the shoreline. The construction of shoreline armoring is prevalent throughout the Puget Sound nearshore, although its use varies between sub-basins and on a local scale (Fresh et al., 2011).

A HISTORY OF COASTAL ARMORING

Over the course of history, people have settled along coasts to live near and conduct trade via the ocean. In order to protect harbors and coastal communities, people have been constructing physical defenses against the ocean for thousands of years. Mediterranean countries such as Greece and Egypt were early adopters of coastal engineering, due to the need to protect their harbors, from which they conducted trade overseas (Charlier et al., 2005; Dugan et al., 2011). Around 1800 BCE, Minoans built the first known harbor in Alexandria, Egypt. Breakwaters, which are structures built parallel to the shore to reduce wave energy, were constructed of rocks 5 m in length to protect this seaport and the ships that docked there (Coastal and Hydraulics Laboratory: US Army Corps of Engineers, n.d.; Franco, 1996). The Phoenicians, Carthagians, Greeks, and Estrucans also employed innovative techniques, including modifying existing landforms, utilizing submarine construction, and employing rocks and rubble to create breakwaters, artificial basins, and canals that allowed for safer passage and docking of ships. In 530 BCE, a breakwater at Samos, a Greek Island, was constructed in water up to 35 m deep. Materials as diverse as melted lead, hydraulic cement (sometimes made from volcanic ash), broken pottery, and sand were used as mortar (Franco, 1996).

The Romans created intricate artificial harbors and other achievements in coastal engineering throughout their empire. In Great Britain, historic shoreline defense structures were built during the Roman occupation, 43-410 CE, that endured through the 17th century (Palmer & Tritton Limited, 1996). In the 6th to 17th centuries in Italy, shoreline protection was often achieved with groins and revetments devised of timber fences alternating with rock and rubble. These structures were frequently damaged by storms, and repairs occasionally included sinking barges packed with sediment and rocks. In the mid-18th century, following many experimental designs by various experts, a more durable seawall was constructed with huge stone blocks mortared with volcanic cement. This seawall still stands today in Venice, albeit with repairs and reinforcements made over the past two centuries (Franco, 1996).

Coastal defense structures were common in Europe by the Middle Ages (Dugan et al., 2011). In Great Britain, the Church was responsible for the construction of many coastal defense structures until the monasteries were disbanded in the 1530s (Palmer & Tritton Limited, 1996). In medieval times, seawalls were constructed with clay and eventually stone (Charlier et al., 2005). In the Netherlands, stone was not readily available until the 1800s, so in ancient times, clay, peat, and even kelp was used to build seawalls (Bijker, 1996). Other methods used when constructing coastal defenses included sinking old ships that were then covered in dirt and using dried seagrasses as a protective layer. Over time, structures built to armor the coast became more complex and more numerous (Charlier et al., 2005). Around the 19th century, advances in engineering allowed people to develop coastal areas historically considered inaccessible or dangerous (Sørensen et al., 1996).

Over the past 150 years, governments began to focus even more on coastal protection, and armoring was used extensively in Europe, Asia, Australia, and North America (Charlier et al., 2005; Dugan et al., 2011). Local municipalities in Great Britain alleviated unemployment by employing people to build numerous seawalls during the late 19th and early 20th centuries, which served to protect coastal areas from flooding and helped to shape some towns as tourist destinations (Palmer & Tritton Limited, 1996). Despite the proliferation of shoreline armoring and other modifications, the European coastline is actively retreating. Concrete and asphalt cover 22,000 km^2 of coastal areas in Europe. Concrete structures are in place on over 50 percent of Mediterranean coasts, much of which has been built for harbors and ports (Dugan et al., 2011).

In comparison, coastal development similar to that in Europe is a more recent phenomenon in the United States. In the 1800s, most coastal defense structures were associated with harbors, where armoring is used to maintain shipping channels (Wiegel & Saville, 1996). Other uses of the shoreline, such as the recreational use of beaches began after the Civil War, primarily in New Jersey. Many coastal areas were not easily accessible until the early 1900s, when the advent of the automobile and highway systems made it possible for inland populations to vacation at the beach (Wiegel & Saville, 1996). Armoring was erected to stabilize beaches and increase the value of coastal land for recreational purposes. In the 1930s, there was increasing awareness that jetties and breakwaters influenced adjacent shorelines and contributed to accretion and erosion of sediment; however, this budding knowledge does not appear to have slowed the use of armoring (Wiegel & Saville, 1996).

Early on, it is likely that many private citizens built their own coastal defenses in the United States. Following World War II, the federal and state governments became more involved in coastal armoring as a method to control erosion (Charlier et al., 2005). In the late 20th century, armoring became very common in the United States, and the use of it continues to expand today. Currently, about 12 percent of the California coast is armored, with shoreline modification generally concentrated in urban areas. Some cities in southern California, including Long Beach and San Clemente, have armoring along more than 70 percent of their shores (Dugan et al., 2011).

Oftentimes, a catastrophic weather event has spurred massive increases in armoring (Dugan et al., 2011). In 1900, a hurricane and resulting storm surge caused the deaths of more than 6,000 people and the destruction of 3,600 buildings on Galveston Island, Texas. In response, the city of Galveston commissioned an extensive project, incorporating both seawalls and grade raising, designed to protect the city from hurricanes and flooding (Wiegel & Saville, 1996). The grade of the entire city was raised 2.4 to 5 m. A seawall was erected to protect the city that was 4.8 km in length and 5.1 m high (Hansen, 2007). Once coastal defense structures have been erected, there can be increased development a coastal area, even after catastrophic weather events, due to a misplaced sense of security (Dugan et al., 2011).

Currently, shoreline armoring is built to protect coastal development from erosion, floods, and storm damage. It can take many forms, with the most common being seawalls and rock revetments (Melius & Caldwell, 2015). Seawalls are vertical or steeply curved and are often constructed from concrete, steel, or timber. Rock revetments, also known as riprap, are sloped retaining walls comprised of large boulders, rocks, or chunks of concrete, giving them a larger structural footprint than vertical seawalls (Dugan et al., 2011; Melius & Caldwell, 2015). Other examples of armoring include breakwaters, jetties, bulkheads, and groins. Construction materials vary, though stone, concrete, steel, wood, and geotextiles (permeable fabrics) are frequently used (Dugan et al., 2011).

Armoring can be costly to build and maintain. Due to coastline dynamics such as wave activity, armoring structures always require monitoring and maintenance and can fail due to waves, scour, or storms. Governments are often responsible for constructing, repairing, and replacing armoring on publicly owned shorelines so inevitably, these costs are born by the general public (Dugan et al., 2011). During the 20th and 21st centuries, armoring has been employed extensively to protect coastal development and combat erosion. The use of armoring is predicted to increase due to growing populations and the location of densely inhabited cities along the coast. Protection will also be sought from impacts of climate change, such as sea level rise and extreme weather events (Dugan et al., 2011). Such trends are seen in the Puget Sound region, where the prevalence of shoreline armoring has sparked concern over shoreline management.

Prior to European colonization, the Puget Sound area was home to about 50,000 native people (Fresh et al., 2011). The Coast Salish people relied on the abundant natural resources of the region, including salmon, herring, and shellfish (Quinn, 2009). European explorers first arrived by sea in 1792, with the first colonial settlement established in 1846 near Tumwater, Washington. Entrepreneurs and others were drawn to Washington state and, in particular, the Puget Sound region (Quinn, 2009). By the end of the 19th century, Europeans were undertaking massive extractions of the Sound's natural resources via sea otter and beaver trapping, logging, and salmon fishing (Quinn, 2009). The population of the Puget Sound area has rapidly increased to 3.5 million people, approximately 70 percent of the state's population, leading to considerable shoreline development and intensive harvesting of natural resources (Fresh et al., 2011; Morley et al., 2012). The population of Puget Sound is growing by 50,000 people, or 1.5 percent, each year. By 2020, it is estimated that Puget Sound will be home to 5.33 million residents (Fresh et al., 2011).

Globally, a variety of anthropogenic activities threatens the biodiversity and impairs the resilience of coastal environments, and the Puget Sound has been no exception. Population growth and the extensive subsequent development in Puget Sound have taken a toll on the region (Fresh et al., 2011). Development and transportation infrastructure, including railways and ports, impact coastal systems. Overexploitation has impacted species populations and overall biodiversity. Pollution from copious sources persist in coastal ecosystems, including agricultural pesticides, heavy metals, and oil spills (Hoggart et al., 2015). Historical industries have left the sediments of Puget

Sound contaminated, while runoff from transportation and chemicals from residential and business properties channel new contaminants into the water (Quinn, 2009).

Residential, industrial, and commercial development have also contributed to the significant alteration of the coasts of Puget Sound. The accompanying geomorphological and ecological impacts of this development have impacted the nearshore ecosystems (Parks et al., 2013). There are anthropogenic modifications to approximately one third, 1,136 km, of the Puget Sound shoreline (Dugan et al., 2011). The use of armoring is pervasive on the eastern shoreline of Puget Sound, where the cities of Everett, Seattle, and Tacoma are located (Shipman, 2010). In the greater Seattle area, over 70 percent is modified, with structures including piers, ports, seawalls, and revetments (Sobocinski et al., 2010).

During the 19th and early 20th centuries, armoring in the Puget Sound was used mainly to protect industrial development, railroads and roads near the shore, and agricultural operations located near river deltas (Shipman, 2010). Currently, residential development is the main impetus for the construction of new armoring and the replacement of aging structures (Shipman, 2010). Waterfront properties are increasing in value, and residential homes are being built on lots that were previously considered too hazardous for development, due to risk of landslides or because of challenging terrain (Small & Carman, 2005). As landowners upgrade cabins and vacation homes to larger buildings intended for year-round use, they are employing seawalls to secure their properties against erosion (Quinn, 2009).

IMPACTS OF ARMORING

Despite increases in regulation, the use of shoreline armoring continues to rise (Carman et al., 2010). Meanwhile, there is growing concern about the environmental impacts of armoring, concurrent with increasing knowledge of the importance of marine riparian and nearshore ecosystems (Shipman, 2010). Shoreline armoring has numerous impacts, some of which are easily identified and others that are complex and require further study (Griggs, 2010). Quantifying the impacts of armoring is challenging due to the heterogeneity of the nearshore and of armoring structures. The shorelines of Puget Sound are dynamic and diverse in regards to substrate, geomorphology, and exposure. Armoring varies in terms of construction materials, age, and placement in the nearshore; furthermore, its use is often accompanied by other habitat modifications or anthropogenic disturbances (Rice, 2010). In addition, the bulk of research related to the impacts of shoreline armoring has been conducted in areas with sandy beaches (Griggs, 2004), which are dissimilar to the shorelines of Puget Sound. There will always be an aesthetic impact from the construction of coastal armoring (Griggs, 2010). However, the impacts of armoring are more than superficial, as this construction influences coastal and ecological processes.

Physical impacts and effects on coastal processes

Shoreline armoring results in a loss of connectivity between terrestrial and marine ecosystems (Rice, 2006). It also disrupts the natural processes of the nearshore environment, altering the wave regime and sediment dynamics, contributes to passive and active erosion, and prevents the deposition of marine wrack and large woody debris

(Dugan et al., 2011; Griggs, 2010; Sobocinski et al., 2010). The associated removal of riparian vegetation, often done in concert with armoring, can alter the moisture and temperature regimes of the beach (Griggs, 2010). In addition, riparian vegetation contributes detritus and insects onto the shore, which serve as food for amphipods and juvenile salmon, respectively (Dethier, 2010). Armoring can also prevent the deposition of marine wrack and large woody debris (LWD) (Heerhartz et al., 2013). Large woody debris is typically transported to the backshores of beaches during high tides and aids in stabilizing the shoreline and serves as habitat for roosting, foraging, and nesting. The moisture and nutrients from LWD benefit dune and marsh plants (Williams & Thom, 2001).

Inevitably, the construction of armoring also results in placement loss, which is the loss of beach due to the footprint of a structure (Melius & Caldwell, 2015). The amount of beach lost depends on the length of the structure and how far seaward it is built. While a vertical seawall might not be very wide, concrete seawalls, riprap, and revetments extend significantly farther onto a beach. Revetments can be 30 to 50 feet wide; in some cases, such as that of a beach in Santa Cruz, California, this eradicates the entire beach (Griggs, 2010). The natural substrate is replaced by these construction materials, with the resulting structure having a hard and vertical surface (Sobocinski et al., 2010). Armoring can reduce vertical and lateral access to a beach, with access loss worsening in winter months and increasing over time due to erosion and impoundment (Melius & Caldwell, 2015). Although stairways can be built into or over armoring structures, these are also subject to wave damage (Griggs, 2010).

Armoring can also cause impoundment loss due to sediment accumulating behind the structure, rather than contributing to the beach. Impoundment loss can cause erosion of the shoreline down-drift of the structure (Melius & Caldwell, 2015). Coastal bluffs provide the majority of sediment to beaches in the Puget Sound. Armoring impedes bluff erosion by blocking wave energy and sediment transport, causing significant alterations to the stability and characteristics of a beach. In addition, cross-shore structures obstruct longshore sediment transport (Johannessen & MacLennan, 2007). When armoring alters the sediment processes in one area, it may impact the nearshore elsewhere in a littoral cell (Shipman, 2010).

Although armoring is put in place to combat erosion, it can contribute to passive and active erosion of a beach (Griggs, 2010). Two types of coastal erosion occur naturally. Erosion occurs on a seasonal basis, particularly due to high energy waves that accompany winter storms. The erosion and sediment accretion that occur seasonally are variable. If the inputs and outputs of sediment are generally in equilibrium, then these changes ultimately balance out. By contrast, there is also landward migration of the shoreline, which is not reversible (Griggs, 2004). The rate of shoreline retreat in Puget Sound is generally 2.5-5 cm per year, while some areas average over 15 cm per year (Macdonald et al., 1994). Passive erosion occurs when the shoreline moves inward on either side of an armoring structure. This eventually narrows or eliminates the beach in front of the structure and subjects the armoring to increased wave activity, which may undermine the integrity of the structure (Griggs, 2010; Shipman, 2010).

Armoring affects the local hydrodynamics of the nearshore (Hoggart et al., 2015; Martin et al., 2005). Structures built parallel to the shore will reduce current flow in the terrestrial system but reflect wave energy back to the seaward side of the structure (Macdonald et al., 1994; Martin et al., 2005). The increased wave energy can alter longshore sediment transport and cause sediment starvation, in which there is a long-term deficit in the sediment supply to a littoral cell (Macdonald et al., 1994; Shipman, 2010). Hydrodynamics influences sediment distribution and the benthic organisms associated with the sediment (Martin et al., 2005). The cumulative impacts of armoring are understudied. They may be linear, increasing with the amount of new armoring, or there may be a critical threshold at which the addition of new armoring significantly impairs or ceases to cause alterations to the nearshore (Macdonald et al., 1994).

Ecological Impacts

In turn, ecological processes and organisms throughout the nearshore trophic web are affected by shoreline armoring. Armoring structures can encourage the spread of non-native species (Chapman & Underwood, 2011). Armoring structures differ from natural coastal habitats in terms of substrate and surface topography. They provide less complex habitat and reduce the overall habitat available (Hoggart et al., 2015). This decreased habitat complexity can lessen the recruitment and survival of intertidal species (Chapman & Blockley, 2009). Mobile species are rarer on armoring than natural intertidal habitats, possibly due to homogeneity of the structure and lack of microhabitats (Hoggart et al., 2015; Pister, 2009). Thus, the biodiversity of the nearshore environment suffers, impacting not just the health the individual species but also the entire ecosystem, with ramifications for recreation, fisheries, and other anthropogenic activities.

Habitat loss resulting from shoreline modification is associated with the declines of salmonids and other animals (Johannessen, 2010). By restricting the transport of eroding sediment from bluffs and increasing wave energy, armoring can cause sediment starvation and coarsening of beach substrate. The altered substrate, including clay, cobble, and gravel, provides an inhospitable environment for native Olympia oysters in Puget Sound, whose numbers are now too low to allow for recreational or commercial harvest (Fresh et al., 2011). An examination of the Duwamish River estuary, located in Seattle, showed variation in species richness and abundance of insects, amphipods, and isopods between armored and unarmored sites. The density of epibenthic invertebrates on unarmored shorelines was more than ten times greater than on armored sites. Taxa richness of epibenthic invertebrates and neuston invertebrates was greater on unarmored sites (Morley et al., 2012).

Shoreline armoring may be the greatest threat to continued spawning by species of forage fish, the most abundant fish in Puget Sound (Fresh et al., 2011). These mid-level consumers are highly productive planktivores that are prey to many species, including salmonids and marine birds (Greene et al., 2015; Rice, 2006). While there are at least seven species of forage fish native to the Puget Sound, the most recognized species of forage fish in the Puget Sound are Pacific herring (*Clupea pallasii pallasii*), sand lance (*Ammodytes hexapterus*), and surf smelt (*Hypomesus pretiosus*) (Greene et al., 2015; Rice, 2010). Forage fish in the Puget Sound face many anthropogenic pressures, and their populations have experienced shifts in abundance and composition over the past 40 years (Greene et al., 2015). Historically, there was commercial harvest of herring and surf smelt, and there is still recreational and commercial use of these species. Harvest of sand lance has been banned due to conservation concerns (Penttila, 2007). Forage fish populations may also be impacted by climate change, hypoxia, competition with and predation by jellyfish, pollutants, and anthropogenic impacts on their preferred prey, zooplankton (Greene et al., 2015).

Human population density is positively correlated with declines in forage fish, and areas that are densely populated tend to have higher percentages of armored shorelines, which have detrimental effects on forage fish spawning (Fresh et al., 2011; Greene et al., 2015). Herring spawn on marine vegetation in intertidal and sub-tidal zones, while surf smelt and sand lance spawn on beaches with fine-grained sediment (Fresh et al., 2011). Armoring that is constructed in the intertidal zone can eliminate spawning habitat for surf smelt and sand lance completely. This is particularly troubling, as these species may be site-specific spawners that return to the same location repeatedly to breed (Fresh et al., 2011). The coarsened substrate of armored beaches is not amenable to the spawning of surf smelt and sand lance, which depend on a mix of finer sand and gravel sediment (Penttila, 2007). The construction of shoreline armoring is often accompanied by the removal of marine riparian vegetation, which alters the temperature and moisture thresholds of a beach. Research found that forage fish spawning on these exposed beaches resulted in fewer live embryos and lower egg density than at natural shorelines (Rice, 2006). Numerous species of marine birds and other predators, including salmon, rely on forage fish, herring eggs, and macroinvertebrates in the nearshore (Fresh et al., 2011).

Policy and regulation of the nearshore

The challenge of protecting and restoring the nearshore is complicated by social, political, legal, and natural factors. The human population of Washington State is concentrated in Puget Sound, just as populations tend to congregate in urban coastal areas throughout the world. Waterfront property in the Puget Sound is particularly valuable due to beachfront access and aesthetic appeal, yet development on such properties is still subject to the natural processes that create a dynamic shoreline (Johannessen & MacLennan, 2007). In Washington State, efforts to restore and regulate the nearshore are complicated by the extensive amount of shoreline that is privately owned and the accompanying interests of property owners and developers to retain the right to modify shoreline property as they see fit. Furthermore, due to the heterogeneous nature of Puget Sound shorelines, attempts at conservation and restoration must take into account the varying geomorphic processes, nearshore ecosystems, and environmental stressors (Shipman, 2010).

There are currently local, state, and national policies in place regarding the protection of and development in coastal areas. Many of these policies recognize that nearshore ecosystems are imperiled by development and inadequate regulation and yet acknowledge that the nature of some development requires shoreline access, such as military bases, fisheries, and ports. On a national level, the Coastal Zone Management Act (CZMA) was enacted in 1972 to protect, develop, and in some cases, restore, natural resources in coastal areas. It asserts that coastal states should develop and implement programs whereby coastal development should be managed "to minimize the loss of life and property caused by improper development in flood-prone, storm surge, geological hazard, and erosion-prone areas and in areas likely to be affected by or vulnerable to sea level rise, land subsidence, and saltwater intrusion, and by the destruction of natural protective features such as beaches, dunes, wetlands, and barrier islands" (16 U.S.C. 1451). Other legislation is aimed specifically at protecting habitat and natural resources. Conservation of critical habitat areas in the nearshore can be employed under Executive Order 13158, concerning the creation of marine protected areas (MPAs), although the level of protection varies. MPAs and marine reserves can be implemented by various jurisdictions, from the local to federal level, in order to protect natural and cultural resources in the marine environment (NOAA, 2014).

Many states have taken steps to reduce or eliminate shoreline armoring, recognizing that its construction can alter coastal processes and result in the loss of beach and intertidal areas. Maine, North Carolina, South Carolina, Rhode Island, and Texas have greatly restricted armoring and in some cases, banned it altogether (Mohan et al., 2003). Massachusetts prohibits armoring in areas where landforms, such as coastal dunes and bluffs, contribute sediment to the nearshore (O'Connell, 2010). Nineteen states and United States territories have identified no-build areas along their coasts, where new development is prohibited. Washington State is one of eight states with coastal access or Great Lakes shoreline that have not implemented no-build areas, but it does require vegetative buffers and structural setbacks in some cases. Structural setbacks require development to be located inland a minimum distance from a reference feature, such as mean high tide, or natural resource area, such as a bluff (NOAA, 2012).

In Washington, limited knowledge of nearshore ecology and salmon life cycles resulted in insufficient regulation of shoreline development for many decades.

Washington State enacted the Hydraulic Code, one of the state's first environmental laws, in 1949. The law required that any project that would influence river flow or sediment to include protection for fish in their planning and receive approval from the Departments of Fisheries and Game. At this time, the importance of the nearshore to salmonids was unknown, and the Hydraulic Code was not applied to marine environments until the 1970's (Small & Carman, 2005). In 2014, WDFW proposed changes to the Hydraulic Code to provide additional protection for forage fish spawning grounds. These changes will go into effect in July 2015 and require "no net loss" of forage fish spawning habitat (Envirovision et al., 2010).

The Shoreline Management Act (SMA) was enacted in 1971 in Washington, albeit with considerably different regulation regarding shoreline armoring from the current standards. Historically, it was believed that sloped armoring, such as rock revetments, might provide habitat for juvenile salmonids than vertical seawalls. With increasing understanding of salmonid and forage fish behavior and use of the nearshore, guidelines were updated to take this knowledge into account (Small & Carman, 2005). Currently, the SMA recognizes that single-family homes are the most prevalent type of development on Washington's shorelines but can also cause significant damage to the nearshore as a result of armoring and other habitat modifications. It dictates that Shoreline Master Programs (SMPs), which implement the SMA at the local level, must contain policies and guidelines that ensure "no net loss of shoreline ecological functions" due to residential development and the use of shoreline armoring (*WAC 173-26-241*, 1971).

While many government agencies and non-governmental organizations recognize the declining health of Puget Sound, efforts at conservation and restoration have been fragmented. Recognizing the need for urgent, coordinated action, the Puget Sound Partnership was established in 2007 with the passage of Engrossed Substitute House Bill 5372. This effort brings together local, state, federal, and tribal governments (Kershner et al., 2011). It requires scientifically-based action agendas and measurable goals in order to restore the health of Puget Sound by the year 2020 (*Engrossed Substitute Senate Bill 5372*, 2007).

The Puget Sound Nearshore Restoration Project (PSNERP) was established in 2001 as a partnership between Washington Department of Fish and Wildlife (WDFW) and the U.S. Army Corps of Engineers. It was established in 2001 to evaluate degraded areas in Puget Sound, assess potential solutions, and propose restoration based projects in specific locations (PSNERP, 2014). The Puget Sound Nearshore Restoration Project recognizes that the shoreline provides a vital area of confluence between the marine, terrestrial, and freshwater systems, but that most Puget Sound shorelines have been subjected to anthropogenic stresses. The project aims to restore nearshore habitat in order to ameliorate conditions for wildlife and improve commercial, aesthetic, and recreational value. Eleven sites in central Puget Sound have been suggested for restoration, which would restore approximately 5,300 acres of the nearshore. Completion of this restoration is vital to the Puget Sound Action Agenda, a state and national plan (PSNERP, 2012). The research and restoration efforts put forth by PSNERP are now incorporated into planning by the Puget Sound Partnership.

South Central Puget Sound sub-basin

The survey sites for this research were located in South Central Puget Sound. The economic activity of South Central Puget Sound drives the economy of the region and even Washington state (Puget Sound Partnership, 2014). Major ports in Seattle and Tacoma support international trade, the cruise industry, and fisheries, while urban estuaries support local and regional industries, such as ship building (Puget Sound Partnership, 2014). The marine and nearshore ecosystems provide natural resources for a variety of industries and recreational activities, and the health of those systems is vital to the health of the human population and economy in Puget Sound.

Evaluation of historical (1850-1880) and relatively recent conditions (2000-2006) demonstrates that there have been considerable changes to this region of Puget Sound (Fresh et al., 2011). In comparison to the other sub-basins in Puget Sound, the South Central region lost the most length of bluff-backed and barrier beaches (a decline of 16.6% and 24.8%, respectively). With 62.8% of beaches being armored, it is also the sub-basin with the greatest amount of armored shoreline (Fresh et al., 2011).

Puget Sound Partnership established key threats to ecosystems and strategies and actions to address such threats, specific to each of seven action areas they delineated in Puget Sound (Puget Sound Partnership, 2014). Puget Sound Partnership identifies shoreline alteration as one of the priority issues in the South Central Puget Sound, along with two strategies to address it. On the policy side, the Shoreline Management Act can be changed so that regulations are stricter in regard to shoreline armoring. In addition, local governments or non-governmental organizations can encourage the replacement of armoring with more environmentally friendly alternatives (Puget Sound Partnership, 2014).

Climate change and the nearshore

Global climate change will impact the physical and chemical processes of the marine environment through sea level rise, increased ocean temperature, and ocean acidification (Huppert et al., 2009). The impacts of climate change on the Puget Sound nearshore will require coastal management to take a long-term view in order to protect the environment and human development (Johannessen & MacLennan, 2007). Each region will respond to climate change differently, depending on substrate, the slope of cliffs, and the landforms comprising the shoreline; however, there will be several chief impacts on coastal areas (Huppert et al., 2009).

Rising sea levels, a combination of factors such as eustatic sea level rise and increased glacial melt, will cause the shoreline to advance inland (Huppert et al., 2009; Johannessen & MacLennan, 2007). Along unmodified shorelines, shoreline advancement generally maintains the beach profiles, as increased sediment contribution keeps pace with the advancing water line (Johannessen & MacLennan, 2007). Sea level rise can also increase coastal flood events by amplifying the impacts of storms (Huppert et al., 2009). Erosion of bluffs and beaches is episodic and is often triggered by storm events. Increases in the strength and frequency of coastal storms, along with increased winter precipitation, will expedite landslides and other erosion events (Huppert et al., 2009). The beaches on the Washington coast are already experiencing erosion from higher waves and changes in storm tracks (Huppert et al., 2009). Shoreline armoring will impede the self-regulation of the beach in the face of sea level rise, while deeper water and increased wave energy will damage seawalls (Johannessen & MacLennan, 2007).

MARINE BIRD POPULATION TRENDS IN PUGET SOUND

Climatic shifts and anthropogenic pressures are taking an unprecedented toll on marine ecosystems. Historically, marine populations have experienced cyclical patterns while they are now demonstrating linear changes (Ainley & Hyrenbach, 2010). Anthropogenic impacts on biodiversity and individual species are intense and will continue to increase due to population growth and expanding development (Monastersky, 2014). Globally, marine bird populations have declined over several centuries (Bower, 2009). Of 337 seabird species worldwide, the World Conservation Union has designated 101 as "threatened," meaning they are critically endangered, endangered, or vulnerable (Croxall et al., 2012; Dietrich et al., 2009). In comparison to other groups of birds, marine birds are more threatened and their populations are declining at a faster rate (Croxall et al., 2012; Žydelis et al., 2013).

The characteristics of marine birds that make them well suited for their environment also make them susceptible to endangerment and extinction. Marine birds gather in colonies during the breeding season, returning to the same habitat regardless of whether it has been degraded. They nest in coastal areas and on islands; both of these habitat types have been extensively developed, with nesting sites being degraded and destroyed (Boersma et al., 2002). Marine birds have long life spans and deferred maturity, with some birds not reproducing until 10 years of age. They have small clutch sizes and rear chicks for extended periods, sometimes up to six months (Schrieber & Burger, 2002). These demographic characteristics contribute to a distinct vulnerability, in comparison to other birds (Croxall et al., 2012)

Marine birds face numerous and complex anthropogenic threats in the marine and terrestrial environment that are contributing to direct mortality and population declines (Bower, 2009). They are affected both by bottom up and top down processes, and there is also the potential for factors driving marine bird population declines to be interactive and synergistic (Ainley & Hyrenbach, 2010; Boersma et al., 2002). Habitat modification has been identified as the predominant reason species become endangered, and marine birds are no exception (Boersma et al., 2002). They also face increasing predation from bald eagles, whose populations have rebounded with listing under the Endangered Species Act (ESA), and increasing competition from species who have similarly benefited from legal protection, such as baleen whales (Ainley & Hyrenbach, 2010; Blight et al., 2015; Parrish et al., 2001).

Commercial fisheries have direct and indirect impacts on marine bird populations. Worldwide, marine birds experience injury and mortality from longline and gillnet fisheries (Croxall et al., 2012; Dietrich et al., 2009; Žydelis et al., 2013). Research in north and central Puget Sound found that Common Murres (*Uria aalge*) and Rhinoceros Auklets (*Cerorhinca monocereta*) were the species most commonly entangled in gillnets (Thompson et al., 1998). Besides causing direct mortality, fisheries have indirect impacts on marine birds and other upper trophic predators by decreasing prey populations. Global demand has increased the fishing of lower trophic level species, including forage fish. Reproductive success and adult survival of marine birds are at risk in times of chronic food scarcity, leading to the suggestion of maintaining one third of forage fish populations for marine birds and upper trophic level predators (Cury et al., 2011).

Pollution in marine and nearshore ecosystems can cause poor health, mortality, and decreased reproductive success in seabirds. Ingestion of plastics and other garbage and high levels of contaminants contribute to seabird mortality and poor reproductive health (Pierce et al., 2004; Votier et al., 2011). Marine birds can also become entangled in plastic debris, sometimes after using it as nesting material (Votier et al., 2011). On land, marine birds and their eggs are threatened by invasive predators, such as cats, mice, and rats (Croxall et al., 2012). Terrestrial stressors also include habitat degradation, such as loss of nesting habitat due to island development (Boersma et al., 2002). Finally, seabirds face direct exploitation through hunting both on land and at sea (Croxall et al., 2012).

There have been relatively few studies regarding the populations of seabirds in the Puget Sound area. Early accounts were largely anecdotal instead of systematic. The Christmas Bird Count (CBC) was established in 1900, but survey sites in the Salish Sea were not established until the 1960s. Several studies have since been conducted that examine trends in seabird populations in the Salish Sea. While caution must be exercised due to differences in geographic locations and methodology between studies, the data collected of the last several decades has shown significant population trends, with several species exhibiting significant declines (Anderson et al., 2009; Bower, 2009; Vilchis et al., 2014).

The Marine Ecosystems Analysis (MESA) Puget Sound Project conducted a systematic study of marine birds in 13 regions from 1978-1979. Study locations were not in Puget Sound itself but in the southern section of the Strait of Georgia. Population counts from shore, transect surveys conducted via ferry and boat, and aerial surveys resulted in more than 7,000 counts over the two years of the study. A variety of habitats were considered, both terrestrial and marine (Bower, 2009). From 1992-1999, the Puget Sound Ambient Monitoring Program (PSAMP) repeated 54 of the aerial transects first done by MESA. While PSAMP was significant because it allowed researchers to evaluate long-term trends, several drawbacks must be considered. The transects flown during PSAMP took place on one day during the winter, whereas the MESA study was conducted during all months from 1978-1979. The locations and habitat evaluated in the transects were not the same, as MESA surveys considered a wider variety of habitats and PSAMP flights over coastal areas were only conducted over straight coastlines (Bower, 2009). Bower (2009) conducted a study of marine bird populations from September to May of 2003-2004 and 2004-2005 with the help of undergraduate and graduate students from Western Washington University. The data from this study, combined with the results of the PSAMP/MESA comparison and CBC data from 11 Salish Sea locations, was used to evaluate trends in marine bird populations and abundance.

Since the 1970s, populations of some species of marine birds in the Salish Sea have declined, while others have increased (Anderson et al., 2009; Bower, 2009; Vilchis et al., 2014). Of the 37 most common seabirds that overwinter in the Salish Sea, 14 have experienced significant population declines. The populations of 11 species declined more than 50 percent (with a mean of 67.1 % +/- 18.9% SD). Populations of Western Grebes

(*Aechmophorus occidentalis*) and Brandt's Cormorants (*Phalacrocorax penicillatus*) declined over 80 percent, while Canvasbacks (*Aythya valisineria*) declined by 98.4 percent and Common Murre (*U. aalge*) declined by 92.4 percent (Bower, 2009). Declines occurred in species from all foraging guilds, although significant declines were not seen amongst herbivorous species, such as the Green-winged Teal (*Anas crecca*) and the Mallard (*Anas platyrhynchos*). Significant population increases were seen in one herbivore species, the Canada Goose (*Branta Canadensis*), and four piscivorous species (Bower, 2009). Research focused on Padilla Bay, a site in Puget Sound used by many overwintering marine birds, found similar results. Populations declined in species from every foraging guild. Maximum densities of Western Grebe (*Aechmophorus occidentalis*) declined by 98 percent (Anderson et al., 2009).

Vilchis et al. (2014) identified several characteristics of marine birds in the Salish Sea that were correlated with population declines. These factors concerned foraging strategy, diet, and breeding location. Species that breed elsewhere were three times more likely to decline than species that breed locally in the Salish Sea, indicating that management implemented only at local or regional levels will not adequately address species that inhabit multiple states and countries throughout their lifecycle. Diving birds, such as grebes and loons, exhibited declines at a rate of about 11 times that of birds that forage on the surface. Out of the diving species, alcids, such as Marbled Murrelets (*Brachyramphus marmoratus*) and Common Murres (*U. aalge*), most frequently exhibited declines.

Specialization appeared to affect the success of certain species. Species that preyed on forage fish were approximately eight times more likely to experience population declines than those that do not prey on forage fish. Piscivorous marine birds that have more generalized diets that include both demersal and forage fish are less likely decline than species that prey on forage fish alone, such as Rhinoceros Auklets (*C. monocereta*) (Vilchis et al., 2014). A generalist diet may allow birds to adapt more readily to changes in prey composition or abundance.

Surveys of marine bird populations were not conducted regularly in the Puget Sound until the 1970s. Since that time, data has been collected by the CBC, WDFW, MESA, PSAMP, and WWU. While there are inconsistencies between these studies in regard to their survey techniques, frequency of surveying, habitats monitored, and locations observed, the compilation of data spanning decades shows definite population trends. Several species of marine birds in the Salish Sea have exhibited significant population declines (Anderson et al., 2009; Bower, 2009; Vilchis et al., 2014). Despite these trends, only two species of marine birds that spend some or all of their life in Washington have been listed under the Endangered Species Act: the Short-tailed Albatross (*Phoebastria albatros*) and the Marbled Murrelet (*B. marmoratus*) (US Fish & Wildlife, 2015). Several other species are considered by Washington State to be endangered with others designated as State Candidate species for listing, including the Common Murre (*Uria aalge*), Horned Grebe (*Podiceps auritus*), and Western Grebe (*Aechmophorus occidentalis*) (WDFW, 2015).

While there is ongoing monitoring of marine bird populations by Washington Department of Fish and Wildlife and other organizations, there is limited research regarding the factors that are driving the success and declines of marine bird species. Rice (2007) found that marine bird species composition varied in conjunction with the amount of urbanization. Opportunistic species such as gulls were more frequently observed in urban areas, while the amount of dabbling ducks and diving ducks decreased as the amount of shoreline urbanization increased. Further research must be done to establish the possible causes of these declines if any attempts are to be made to mitigate the loss of marine birds. Monitoring of populations should be conducted at local and regional scales to determine the factors influencing population trends and identify critical habitat areas.

Marine birds as indicators

Marine birds are useful indicators due in part to their long life span and the fact that they are upper trophic level predators (Vilchis et al., 2014). They are also highly visible and easily observed, in comparison to many other marine species which live underwater (Piatt et al., 2007). Most seabird species are colonial, making it easy to quantify and even sample to their breeding grounds (Piatt et al., 2007). Seabird population trends have been linked in parallel to the success of primary producers, and this sensitivity to fluctuations in food supply adds to their usefulness as indicator species (Frederiksen et al., 2007).

In the Puget Sound, marine bird abundance is intermediate in the winter and peaks in the fall and spring months. This is indicative of the reliance of marine bird species on the Puget Sound as migrating and overwintering habitat (Gaydos & Pearson, 2011). The Washington Department of Fish and Wildlife, along with Puget Sound Partnership, has designated certain marine bird species as indicators that can reflect the status of marine bird species that rely on the Puget Sound. During the spring and summer months, at-sea density trends of Pigeon Guillemots (*Cepphus columba*), Rhinoceros Auklets (*Cerorhinka monocerata*), and Marbled Murrelets (*Brachyramphus marmoratus*) are recommended as indicators. These three species breed locally in the Puget Sound. Rhinocerous Auklets and Marbled Murrelets feed primarily on schooling pelagic fish, while Pigeon Guillemots rely more on benthic fish and fish species in the nearshore. Scoters, including the Black Scoter (*Melanitta americana*), Surf Scoter (*Melanitta perspicillata*), and White-winged Scoter (*Melanitta fusca*), are recommended as indicators of the over-wintering marine bird community. Scoters are dependent on herring spawn, eelgrass beds, and benthic habitats. These six species are highly reliant on the marine waters and marine derived resources of the Puget Sound and are charismatic fauna that can be used to illustrate trends in marine bird communities (Pearson & Hamel, 2013).

CONCLUSION

Despite the associated costs and hazards of coastal living, populations continue to increase in Puget Sound and other coastal areas. Residential development drives most new shoreline armoring in Puget Sound, where approximately 30% of the shoreline is armored. Shoreline armoring concerns the public because it reduces the aesthetic value of beaches, along with vertical and lateral access to them, limiting recreational opportunities. The extent of a beach is diminished when structures are built on them or at the base of cliffs and bluffs. Furthermore, armoring alters the physical processes, such as hydrodynamics and sediment dynamics, that take place in coastal areas. Species that depend on the nearshore, especially forage fish, which are important prey species for upper trophic levels, are negatively impacted by armoring. Since the ecological impacts of coastal armoring have not been well studied, they have not been included in policy and engineering decisions (Dugan et al., 2011; Griggs, 2010).

Many environmental issues have occurred because people take action in an attempt to slow or halt natural process. These actions have led to unexpected ecological impacts and often have not adequately protected properties anyway. More research needs to be done into the ecological effects of armoring, particularly in regard to upper trophic level predators, in order to make sound management decisions in the future. Research into factors such as habitat modification that are contributing to declines in marine bird species can advance scientifically-based conservation measures.

CHAPTER 2: ARTICLE MANUSCRIPT

Marine Bird Assemblages in Relation to Armored and Unarmored Sites in Central Puget Sound

ABSTRACT

The Puget Sound is an important overwintering habitat for many migratory and resident marine bird species. Population trends show a steady decline of many species overwintering in the Puget Sound and greater Salish Sea. The decreased abundance of many species of marine birds that overwinter in the Puget Sound is cause for concern. Research has been focused on monitoring abundance without a deeper exploration of the natural and anthropogenic causes behind these declines, which remain largely understudied and poorly understood.

The Puget Sound region is a hotspot of biodiversity and the extensive ecosystem goods and services have attracted and sustained a large human population, but at a cost to the natural environment. One ongoing debate is the role that shoreline armoring, used extensively in Puget Sound to protect development, has on ecosystem degradation. On a local scale, the use of armoring alters the physical and ecological processes of the nearshore and affects invertebrates, forage fish, and juvenile salmonids that depend on the nearshore. It is less understood how the consequences of many small modifications translate to a wider scale and impact higher trophic levels, such as the marine birds that depend on the nearshore during the winter season.

This research explored the relationship between marine bird abundance and foraging behavior and natural and modified shorelines, specifically armoring. Surveys for marine bird abundance and behavior were conducted at six paired sites in South Central Puget Sound from January to March, 2015. This study found the average abundance and average species richness of marine birds were greater at armored sites than at unarmored sites; however, results were not similar across all paired survey sites. Analysis of each individual site determined that at three survey locations, there was not a significant difference in average abundance or species richness between paired sites. At the remaining three locations, there was significantly greater average abundance, average species richness, or both, at the armored survey sites. The proportion of birds in each foraging guild depended on whether or not shorelines were armored, with piscivorous species comprising a smaller percentage of all birds at armored sites. Further research is warranted to determine to what extent shoreline modification impacts marine birds.

INTRODUCTION

Puget Sound in Washington State lies within the southern portion of the Salish Sea and is the second largest estuary in the United States (Fresh et al., 2011). Puget Sound's complex and productive ecosystems are home to a vast array of marine and terrestrial species, making it a hotspot of biodiversity (Quinn, 2009). The health and resilience of humans, native species, ecosystems, and Puget Sound itself are intimately linked. Ever-increasing human population and accompanying anthropogenic impacts have drastically altered the landscapes and ecosystems of the Sound (Fresh et al., 2011; Quinn, 2009).

Puget Sound is home to ~4 million people, and this is projected to increase to 5.33 million by 2020, which will put additional pressures on the region's natural resources (Fresh et al., 2011). Due to many anthropogenic influences, the health of the Puget Sound is imperiled (Fresh et al., 2011; Quinn, 2009). Puget Sound ecosystems are degraded and species are threatened and endangered as a result of habitat modification, pollution, introduction of invasive species, and overexploitation of resources (Quinn, 2009). Concern over the degradation of this region led to the passing of legislation in Washington State, which created the Puget Sound Partnership and tasked it with restoring the health of Puget Sound by 2020. The nearshore environment, which is vital to the health of the Puget Sound, marine species, and humans, was identified by the Partnership as a priority for increased study and protection (Pearson & Hamel, 2013).

The condition and productivity of Puget Sound are intimately linked to the state of the nearshore, which bridges bridge the terrestrial, freshwater, and marine environments (Fresh et al., 2011). The nearshore is defined as the area from the top of coastal bluffs to the deepest part of the photic zone (Johannessen et al., 2014). The nearshore provides many valuable ecosystem goods and services, including nutrient cycling, water filtration, shoreline protection, and fisheries (Beck et al., 2003). It also functions as habitat for many species that are important to the marine system and have cultural and economic value, including eelgrass, forage fish, salmonids, and marine birds (Rice, 2010).

The unique landscape and geology of Puget Sound were shaped by the Vashon glaciation and subsequent Holocene period and its associated processes. The shoreline of Puget Sound is varied and dynamic. It is composed of rocky coasts, beaches, estuaries, lagoons, and river deltas (Shipman, 2008). Bluff-backed beaches are the most common nearshore landform, with the bluffs sometimes reaching more than 100 m in elevation (Johannessen & MacLennan, 2007). These bluffs are often referred to as feeder bluffs, due to the sediment they contribute to beaches through erosion (Shipman, 2010). Bluff erosion is not constant but occurs periodically and is a vital process that maintains an equilibrium of the nearshore sediment (Shipman, 2010).

The colonization of the Puget Sound by Europeans led to dramatic alterations of the Puget Sound shoreline (Fresh et al., 2011). One of the most prevalent and visible modifications has been the use of shoreline armoring to protect residential, commercial, and public property from the perceived risk of erosion and flooding. Armoring encompasses a range of structures, some of which are parallel to the shore, such as bulkheads and rip rap or rock revetments, and some that are cross-shore, including groins and jetties (Johannessen & MacLennan, 2007). In the 19th and early 20th centuries, armoring was constructed to protect agriculture, industry, and transportation along the coast, namely roads and railroads. In the mid-20th century, the bulk of coastal development and accompanying shoreline modification switched to residential properties (Shipman, 2010). Urban areas are highly developed and correspondingly, have high rates of shoreline modification. Armoring is prevalent in South Central Puget Sound, from Everett to Tacoma (Shipman et al., 2010; Simenstad et al., 2011). Currently, nearly 30 percent of Puget Sound's shoreline is armored, and there is growing concern over local and cumulative impacts from its extensive use (Shipman et al., 2010).

Comparable to many anthropogenic modifications to the environment, shoreline armoring has unexpected consequences on the environment. By separating the terrestrial and marine environments, armoring disrupts the movement of organisms and material between the marine and terrestrial ecosystems (Shipman, 2010). The footprint of armoring results in placement loss by reducing the intertidal area on beaches, and in some cases, eliminating it altogether (Griggs, 2010). The physical processes of the nearshore can be disrupted by the construction of armoring (Shipman et al., 2010). Armoring prevents sediment from eroding bluffs from reaching the nearshore, disrupts sediment transport, and increases wave energy, all of which contribute to sediment starvation. (Dugan et al., 2011; Shipman, 2010). Armoring can decrease or prevent the accumulation of marine wrack and large woody debris and contribute to passive and active erosion (Griggs, 2010; Sobocinski et al., 2010).

The disruption of coastal processes has ecological and biological consequences. Armoring decreases habitat complexity, which can affect the success of intertidal species and influence the spread of non-native and invasive species (Chapman & Blockley, 2009; Chapman & Underwood, 2011). Studies of modified and natural shorelines have shown a lower abundance and diversity of macroinvertebrates in nearshore marine environments at armored sites (Sobocinski et al., 2010). Sediment starvation caused by armoring can make beach conditions unfavorable to the reproductive cycles of forage fish, which play a large role in the trophic web as prey for salmonids, marine birds, and mammals (Fresh et al., 2011). Two species of forage fish, surf smelt and sand lance, both spawn in the upper intertidal zone and depend on a fine substrate, sand and gravel (Penttila, 2007). The coarsening of beach substrate that results from shoreline armoring creates an inhospitable environment for forage fish spawning. In some cases, the spawning environment is eliminated altogether when a structure takes up a significant portion of the beach (Fresh et al., 2011). Installation of shoreline armoring often is accompanied by the removal of marine riparian vegetation, which leads to increased temperature and moisture thresholds, resulting in embryo mortality and decreased success of forage fish eggs (Rice, 2006). While many armoring structures are small in scale, there is the potential for cumulative impacts on landscape or regional level due to their prevalent use (Rice, 2010).

There is growing concern regarding the consequences of shoreline armoring, but the use of it continues. In fact, it is likely that construction of armoring will increase in the coming years, due to climate change, sea level rise, and a stubborn aspiration to coastal living (Shipman et al., 2010). Policy has not been stringent enough to discourage the use of armoring and motivate property owners to implement more environmentally friendly shoreline modifications. The Washington Hydraulic Code was established to protect fish from in-water construction and has been updated to require that development causes "no net loss" of spawning habitat for forage fish (Carman et al., 2010; Envirovision et al., 2010). Another regulatory effort regarding shoreline armoring is the

Shoreline Management Act (SMA) of 1971, which focused on encouraging water-dependent use of the shoreline, as infrastructure and industry such as piers, aquaculture, and marinas must, by definition, be located next to the water. The SMA was also implemented to protect natural resources and encourage public access to publicly owned shorelines (Carman et al., 2010). Despite the goal of Puget Sound Partnership to reduce armoring by 2020, the construction of new armoring is outpacing the removal of established structures (Puget Sound Partnership, 2014). This issue is complicated by the need to protect natural resources for the good of the public while not infringing on the rights of private property owners.

Puget Sound is a vital overwintering ground for resident and migratory marine birds (Vilchis et al., 2014). Several species of marine birds have experienced population declines in the Puget Sound and the greater Salish Sea over the last few decades (Anderson et al., 2009; Bower, 2009). Significant declines have been seen in 14 of the most common seabird species in the Salish Sea, with 11 of those species declining more than 50 percent (Bower, 2009; see Appendix). The exact causes of these declines are unknown, but marine birds face numerous anthropogenic pressures in marine and terrestrial environments. Commercial fisheries, the ingestion of plastics and other contaminants, hunting, invasive predators, and development have had a deleterious impact on seabird numbers (Bower, 2009; Croxall et al., 2012). Increased urbanization has been correlated with lower abundance and altered composition of marine birds along Puget Sound's shoreline (Rice, 2007).

Marine ecosystems are threatened on a global scale, with many marine species facing endangerment and extinction due to anthropogenic pressures. Seabirds can serve as indicators of marine ecosystem integrity due to being long-lived, migratory between breeding and nonbreeding areas, and components of upper trophic levels (Vilchis et al., 2014). Similar to commercial fisheries and marine mammals, marine birds are highly dependent on secondary production, and their reproductive success has been linked to crashes in fish populations (Piatt & Sydeman, 2006). There is often a relationship between seabird diets and prey abundance and distributions (Gaydos & Pearson, 2011). Therefore, bird populations and assemblages can reflect changes in productivity and prey abundance in marine environments (Vilchis et al., 2014). In the Puget Sound, the following six species of marine birds are recognized as indicator species, and their presence and status reflects the overall health of the marine environment: Surf Scoters, White-winged Scoters, Black Scoters, Pigeon Guillemots, Rhinoceros Auklets, and Marbled Murrelets (Pearson & Hamel, 2013). Further research into the causes of declines of Puget Sound seabird populations can inform conservation measures or policy regarding modification of the nearshore.

Despite the dramatic declines in populations of several marine bird species, there has been limited research conducted regarding the potential natural and anthropogenic factors that could be driving population changes. Research has been focused largely on abundance of individual species and taxonomic groups (Rice, 2007). Due to the importance of marine birds as indicator species and because of their intrinsic value, it behooves us to understand as much as possible about their biology and habitat use, explore factors that may be contributing to their decline, and invest in corresponding conservation measures. Shoreline armoring has been shown to have deleterious effects on populations of salmonids, forage fish, and invertebrates (Sobocinski et al., 2010), which comprise a large component of the winter diets of many marine bird species. Shoreline armoring has been suggested as a potential factor in environmental declines of avifauna, (Rice, 2007; Williams & Thom, 2001), but there has been limited research regarding the effects of shoreline armoring on marine birds and other upper trophic level predators. My research is a pilot study to assess if shoreline armoring impacts marine bird habitat use and behavior in the South Central Puget Sound.

METHODS

Six paired sites with armored and unarmored sections of shoreline were selected for this study. Armored and unarmored segments were adjacent to one another, with the exception of one survey site. The survey sites are located in the South Central Puget Sound Sub-Basin (see Figure 1), the region of the Puget Sound that is most highly developed (Simenstad et al., 2011). Sites were located from Seattle to Tacoma, Washington. The marine bird community of Puget Sound is most diverse in the winter, and many species of birds present in winter are assembled largely in the nearshore (Pearson & Hamel, 2013).

Surveys were conducted from January through March, 2015. The number of surveys varied between sites due to availability of observers; however, most sites were surveyed 10 times, and all paired sites were surveyed the same number of times. The Lincoln Park, Beaconsfield, and Marine View Park/ Des Moines Beach Park sites were surveyed for 10 weeks, while the Poverty Bay, Point Defiance Park, and Titlow Park sites were surveyed between seven and nine weeks. Each location was surveyed for 20 minutes between 08:20 hr to 12:30 hr. Tides were not taken into account regarding the choice of survey day and times; however, later statistical analysis excluded the possibility that tides were influencing marine bird abundance (see Results section). An observation point was designated near the mid-point of each beach. All individual birds seen on the water within a 150 m radius of the observer were surveyed for abundance, distance from shore, behavior, and identification to species and gender when possible. Distance from the observer was recorded with a Nikon Monarch Gold Laser1200 Rangefinder. The distance of individual birds from shore was categorized within one of three bins of 0-50 m, 51-100 m, and 101-150 m from shore. Surveys of armored and unarmored sites were conducted one immediately following the other. The first site to be surveyed was determined randomly.

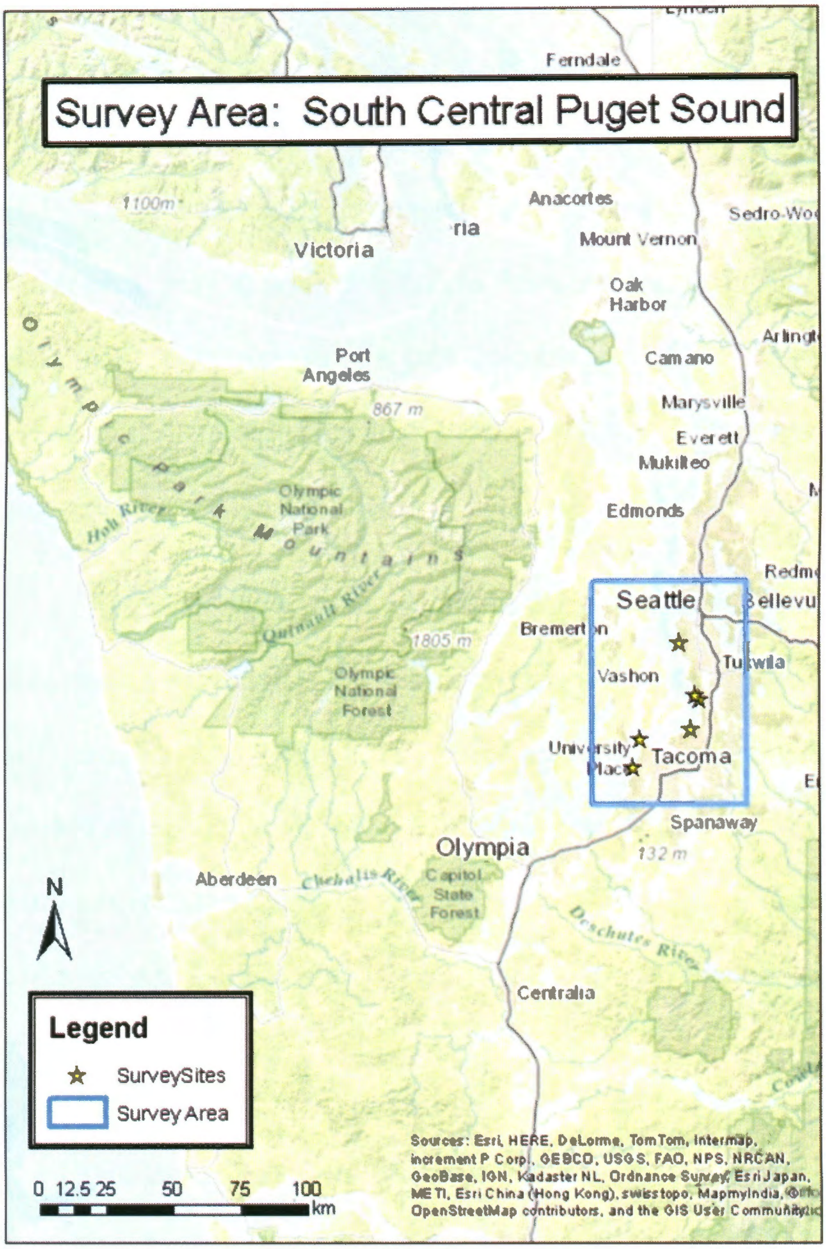


Figure 1. Survey sites located in South Central Puget Sound.

Site Descriptions

Lincoln Park

Lincoln Park is an urban park located inside the city limits of Seattle. In 1922, Seattle obtained 130 acres at Williams Point and opened the park to the public 3 years later. In an effort to protect the park from the wave regime, a seawall was built in 1936. The seawall spanned the length of the park and was constructed from cobblestone and mortar (Macdonald et al., 1994).

Avian surveys were conducted in the northwest section of Lincoln Park, which is more protected from storms and erosion than the south section of the park. The unarmored section is south of residential properties, which are protected with seawalls. There is riprap in this section, but it is above the Mean High Water, and large woody debris has accumulated in front of the riprap. The armored section is without large woody debris. Both sites are separated from riparian vegetation by a walking path.

Beaconsfield

The Beaconsfield site is part of the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) and is targeted for restoration. The Beaconsfield Feeder Bluff is a 1,000 foot long, 5.5-acre section of shoreline in south Normandy Park. There are 26 shoreline property parcels in Beaconsfield. The City of Normandy Park owns 16 of these parcels, comprising 3.33 acres. Approximately 80 percent of the shoreline is armored, with a combination of a concrete bulkhead and rock revetment. The PSNERP plan includes acquiring more of the privately owned parcels and removing 660 feet of armoring, leaving one portion in place to protect a privately owned house (PSNERP, 2012; United States Army Corps of Engineers, n.d.). This restoration is expected to create better spawning conditions for forage fish, encourage kelp and eelgrass growth, and improve habitat for Chinook salmon (*Oncorhynchus tshawytscha*) and bull trout (*Salvelinus confluentus*), both of which are listed under the Endangered Species Act (USFWS, 2015).

The Beaconsfield beaches are composed of sand and gravel. The unarmored section has large woody debris above the mean high water mark. Riparian vegetation is comprised of native and non-native species, including English Ivy (*Hedera helix*), Indian plum (*Oemleria cerasiformis*), and madrone (*Arbutus menziesii*). A small stream runs from the residential area down the bluffs and into the Sound. There is considerably less large woody debris at the armored section. The survey site is of mixed construction, with both a concrete seawall and rock revetment. The riparian vegetation has not been removed from behind the armoring, although much of it is comprised of non-native species, including Scotch broom (*Cytisus scoparius*), Himalayan blackberry (*Rubus armeniacus*), and English ivy (*Hedera helix*).

Marine View Park/ Des Moines Beach Park

Marine View Park is a 27.37-acre park in Normandy Park, composed of steep wooded bluffs and a large ravine. The beach is unarmored, with large woody debris above the mean high water mark, backed by steep bluffs and riparian vegetation. Red alder (*Alnus rubra*) and Indian plum (*O. cerasiformis*), as well as invasive species such as English ivy, characterize this site. The beach substrate consists of sand and gravel.

Des Moines Beach Park is a 19.6-acre park in Des Moines. It is situated next to the Des Moines Marina, and Des Moines Creek empties into the survey area between armored sections of shoreline. The armoring consists of rock revetment. To the north, there are residential properties, most of which are fronted by concrete seawalls. For ease of analysis, these paired sites are identified as Des Moines in the statistical analysis and results.

Poverty Bay

The Poverty Bay site is located north of Poverty Bay Park in Federal Way. The development along Poverty Bay is residential, much of which is armored with concrete seawalls. The armored section has a short, unarmored public access point, bordered to the north and south by private properties with seawalls approximately one meter high. The armored sections are without riparian vegetation, as the residential properties have developed yards of mostly grass. The unarmored section is characterized by a steep embankment and riparian vegetation consisting of species such as red alder (*A. rubra*) and sword fern (*Polystichum munitum*).

Titlow Park

Titlow Park is an 83 acre park in Tacoma, made up of grassy flat land, forest, wetland, an estuary lagoon, streams, and beach. Land was purchased in 1926 and 1928 for the creation of a city park (Woodards et al., 2010). The park is used recreationally for bird watching, walking, picnicking, and scuba diving (Woodards et al., 2010). Metro Parks is interested in maintaining and restoring wildlife habitat at Titlow Park in conjunction with providing cultural, educational, and recreational resources and commercial opportunities that could generate revenue for the location.

Despite its urban location, Titlow Park provides habitat for many native species, including salmon, forage fish, bald eagles, purple martins, and pileated woodpeckers. There is documented surf smelt (*H. pretiosus*) spawning areas at Titlow and potential spawning areas for surf smelt and sand lance (family *Ammodytidae*). Washington Department of Fish and Wildlife designated a portion of the shoreline at Titlow Park as a Marine Preserve Area in 1994 (Woodards et al., 2010). There are restrictions on recreational and commercial fishing in the Titlow Beach Marine Preserve Area (Washington Department of Fish and Wildlife, 2015). Salmon were raised in the lagoon at Titlow Park in the 1980s (Woodards et al., 2010). In 2008, a state grant was awarded to Metro Parks to be used to determine whether restoration of the shoreline and estuary lagoon could establish habitat for Chinook (*O. tshawytscha*) and chum (*O.* keta) salmon (Woodards et al., 2010).

The armored section of the park, South Beach, is located at the southern-most portion of the park in a small inlet and is backed by a rock revetment. There is additional development, including pilings in the water from a historic pier and ferry dock. There is limited riparian vegetation above the revetment, including Scotch Broom (*C. scoparius*) and Himalayan blackberry (*R. armeniacus*). An asphalt walking path is located next to this section of beach, along with a railway that was constructed in 1913 and remains in use in the present day. Two 40-inch pipes located at the north end of South Beach allow for the flow of water between the Puget Sound and the lagoon (Woodards et al., 2010). The unarmored section of Titlow Park, Hidden Beach, is a sand and gravel beach, backed by steep bluffs with riparian vegetation. The riparian vegetation is a mixture of native and non-native species, including Pacific madrone (*A. menziesii*) and Douglas fir (*Pseudotsuga menziesii*).

Point Defiance Park

Point Defiance Park is a 765 acre park in Tacoma. President Andrew Johnson intended this area to be a military reservation, but it was never used for military operations. In 1888, President Glover Cleveland authorized the city of Tacoma to create a public park instead. Pt. Defiance Park is now utilized by over 3 million people per year, who visit the park for the zoo, botanical garden, marina, off-leash dog park, and natural areas (Metro Parks Tacoma, 2015).

The armored section of the park is adjacent to the marina. A concrete seawall approximately 1.6 m high is backed by a concrete walking path. The seawall takes up much of the intertidal zone, and the beach is a mixture of sand and cobble. Riparian vegetation located behind the walking path includes Bigleaf maple (*Acer macrophyllum*), Douglas fir (*P. menziesii*), sword fern (*P. munitum*), and huckleberry. The unarmored section is a sandy beach with large woody debris backed by a steep embankment. The cliffs abutting the shoreline are over 75 m high in some areas of the park. Riparian vegetation is largely native species, such as red alder (*A. rubra*), bigleaf maple (*A. macrophyllum*), and sword fern (*P. munitum*).

Statistical Analysis

Statistical analysis of the data was conducted in JMP and Excel to determine potential differences in seabird abundance, species richness, and foraging behavior at armored and unarmored sites. Tests were run on individual sites and on all sites combined. Because the number of site visits varied between sites, abundance data was standardized by effort.

Using Excel, resampling for Monte Carlo was used to test for correlation between armored and unarmored sites and average marine bird abundance, average species richness, average species evenness, and the average proportion of birds foraging (1000 iterations; DIF and p-value reported). Species evenness was obtained by calculating the Shannon-Weaver Information Function and then using the following formula: $E = e^D/s$ (in which e is a constant, 2.7, D is the value of the Shannon-Weaver Information Function, and s is the number of species in the sample) (Center for Earth and Environmental Science, 2013).

Contingency tables were run in JMP 12 to determine if there was a relationship between distance from shore and the percentage of birds in each foraging guild (see Bower, 2009; with $\chi 2$, degrees of freedom, and p-value reported). Contingency tables were also used to determine if there was a relationship between armoring and the percentage of birds in each foraging guild (with $\chi 2$, degrees of freedom, and p-value reported). A bivariate fit of analysis was run in JMP was used to determine whether tides were correlated with marine bird abundance.

RESULTS

From January to March, 2015, 1,379 individual birds were observed at six paired sites (see Table 1). The total abundance at armored sites was 951, while 428 birds were observed at unarmored sites. Nineteen species of marine birds were seen overall, and the species composition varied between sites (see Figure 2). The highest species richness was seen at Titlow Park and Poverty Bay, with 14 species observed at each site. The species richness varied between nine and 13 species observed at the remaining sites.

Table 1. Total seabird abundance observed by site in South Central Puget Sound, Washington, January-March 2015

Species	Lincoln Park	Beaconsfield	Des Moines	Poverty Bay	Point Defiance Park	Titlow Park
American Wigeon	--	--	61	4	--	4
Barrow's Goldeneye	16	31	55	2	1	2
Bufflehead	17	36	37	86	4	36
Canada Goose	1	--	--	2	--	3
Common Goldeneye	53	6	114	12	22	55
Common Loon	1	1	--	1	--	--
Common Merganser	--	10	3	1	--	--
Double-crested Cormorant	4	2	4	2	4	10
Greater Scaup	--	--	--	--	--	1
All Gulls*	13	13	100	20	5	9
Harlequin Duck	11	--	--	--	--	--
Hooded Merganser	--	--	--	--	--	10
Horned Grebe	75	33	17	19	6	22
Lesser Scaup	--	--	--	1	--	--
Mallard	--	--	11	13	9	2
Pelagic Cormorant	1	--	--	--	--	--
Pigeon Guillemot	2	2	1	--	1	4
Red-breasted Merganser	32	2	14	2	5	13
Surf Scoter	6	30	117	34	--	20
Total abundance	232	166	534	199	57	191

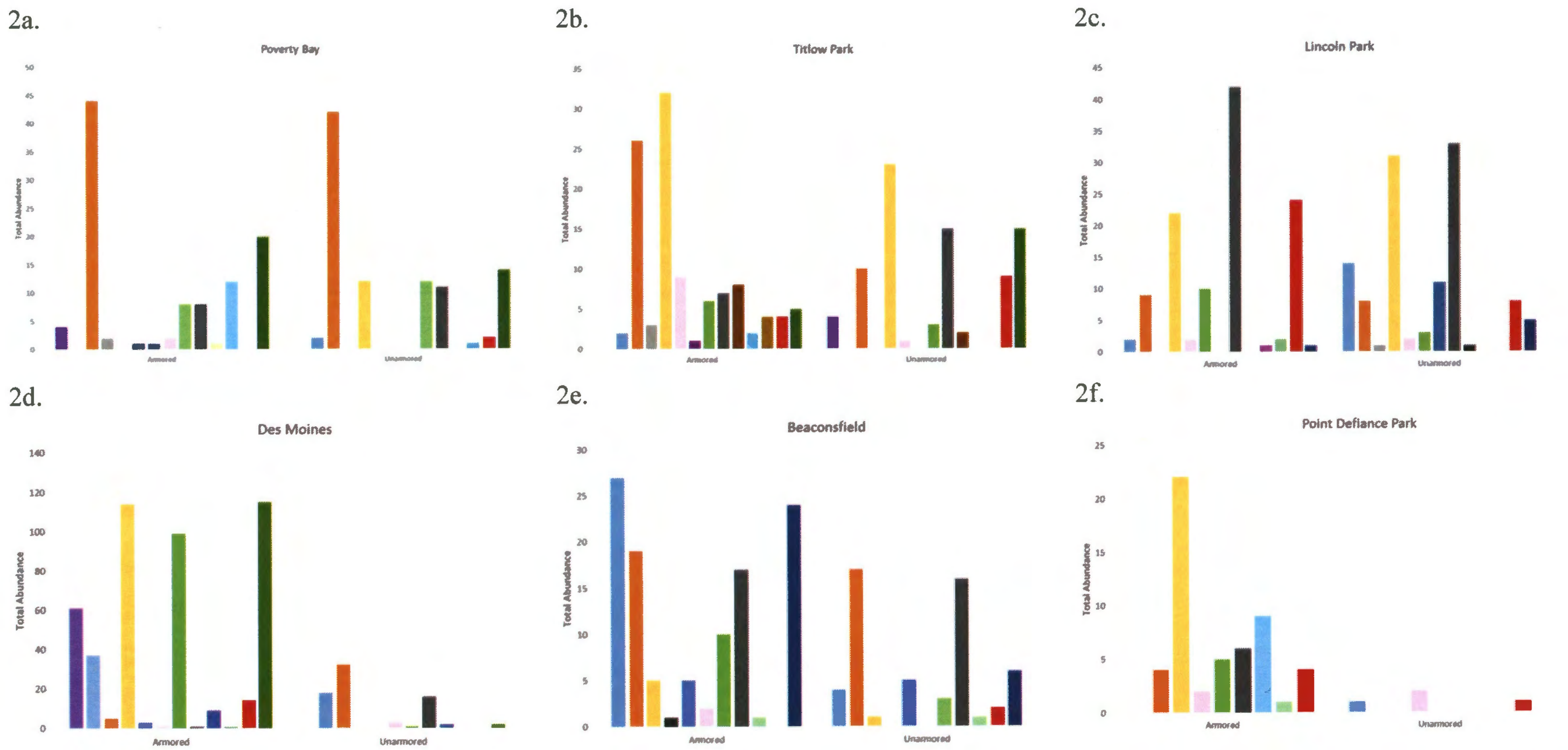
*Gull species, glaucous-winged gulls and glaucous-winged hybrids, were combined

Overall, the most abundant species were Common Goldeneye, Bufflehead, and Surf Scoter (n=262, n=216, n=207 respectively; see Table 2). The most abundant species at armored sites were Common Goldeneye, Surf Scoter, and gulls, while the most abundant species at unarmored sites were Bufflehead, Horned Grebe, and Common Goldeneye (see Table 2). A majority, 65%, of marine birds surveyed were diving ducks.

Table 2. Species table: Number of individuals observed at armored and unarmored sites

Common Name	Scientific Name	Species Code	Sites		Total Record
			Armored	Unarmored	
Common Goldeneye	*Bucephala clangula*	COGO	195	67	262
Bufflehead	*Bucephala albeola*	BUFF	107	109	216
Surf Scoter	*Melanitta perspicillata*	SUSC	165	42	207
Horned Grebe	*Podiceps auritus*	HOGR	81	91	172
All gulls	*Larus* spp.	GULL SP	138	22	160
Barrow's Goldeneye	*Bucephala islandica*	BAGO	68	39	107
American Wigeon	*Anas americana*	AMWI	65	4	69
Red-breasted Merganser	*Mergus serrator*	RBME	46	22	68
Mallard	*Anas platyrhynchos*	MALL	32	3	35
Double-crested Cormorant	*Phalacrocorax auritus*	DCCO	18	8	26
Common Merganser	*Mergus merganser*	COME	9	5	14
Harlequin Duck	*Histrionicus histrionicus*	HADU	0	11	11
Hooded Merganser	*Lophodytes cucullatus*	HOME	8	2	10
Pigeon Guillemot	*Cepphus columba*	PIGU	9	1	10
Canada Goose	*Branta canadensis*	CAGO	5	1	6
Common Loon	*Gavia immer*	COLO	2	1	3
Greater Scaup	*Aythya marila*	GRSC	1	0	1
Lesser Scaup	*Aythya affinis*	LESC	1	0	1
Pelagic Cormorant	*Phalacrocorax pelagicus*	PECO	1	0	1
Total			951	428	1379

Figure 2a-f. Species composition by survey site.



Legend (species by 4-letter code):

AMWI BAGO BUFF CANG COGO COLO COME DCCO GULL SP.

HADU HOGR HOME LESC MALL PECO PIGU RBME SUSC

Abundance

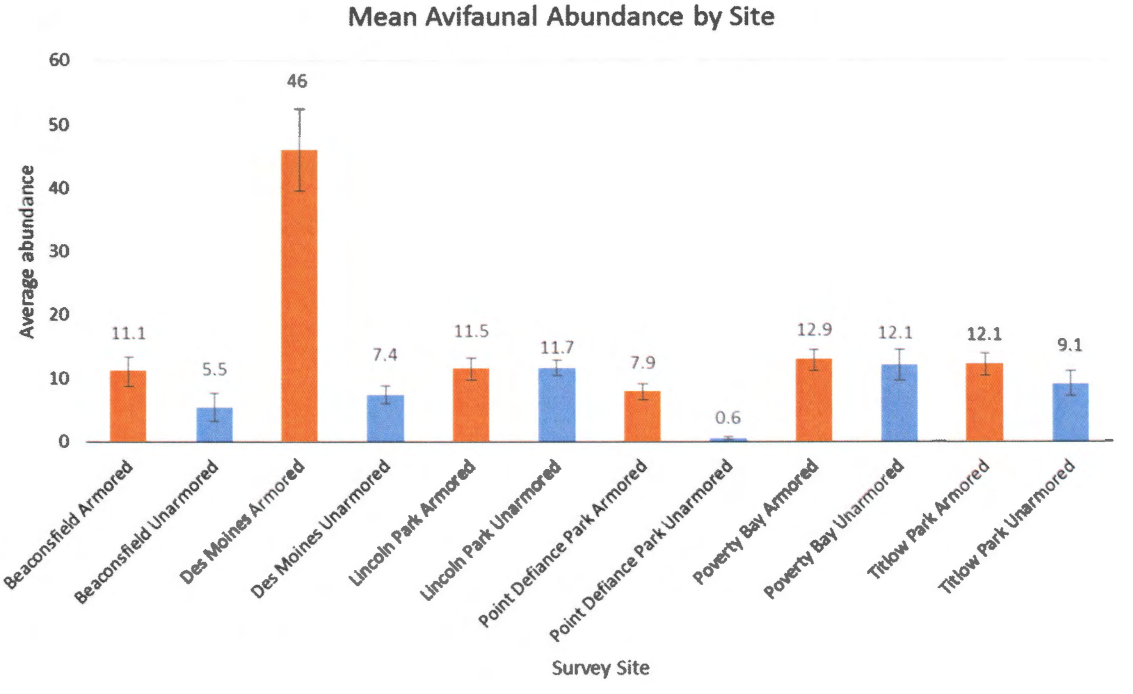


Figure 3. Mean avifaunal abundance by paired survey sites with a standard error of 1 from the mean

The average abundance of marine birds at armored sites (n=17.6 ± 2.4) was significantly greater than at unarmored sites (n=7.9 ± 1.1; DIF=9.7; $p<0.001$).

Although tides were not taken into account when survey dates were chosen, there was no significant relationship between tide and abundance ($R^2=0.008$, $F_{(1, 106)}=0.9$, $p<0.3458$).

Species richness

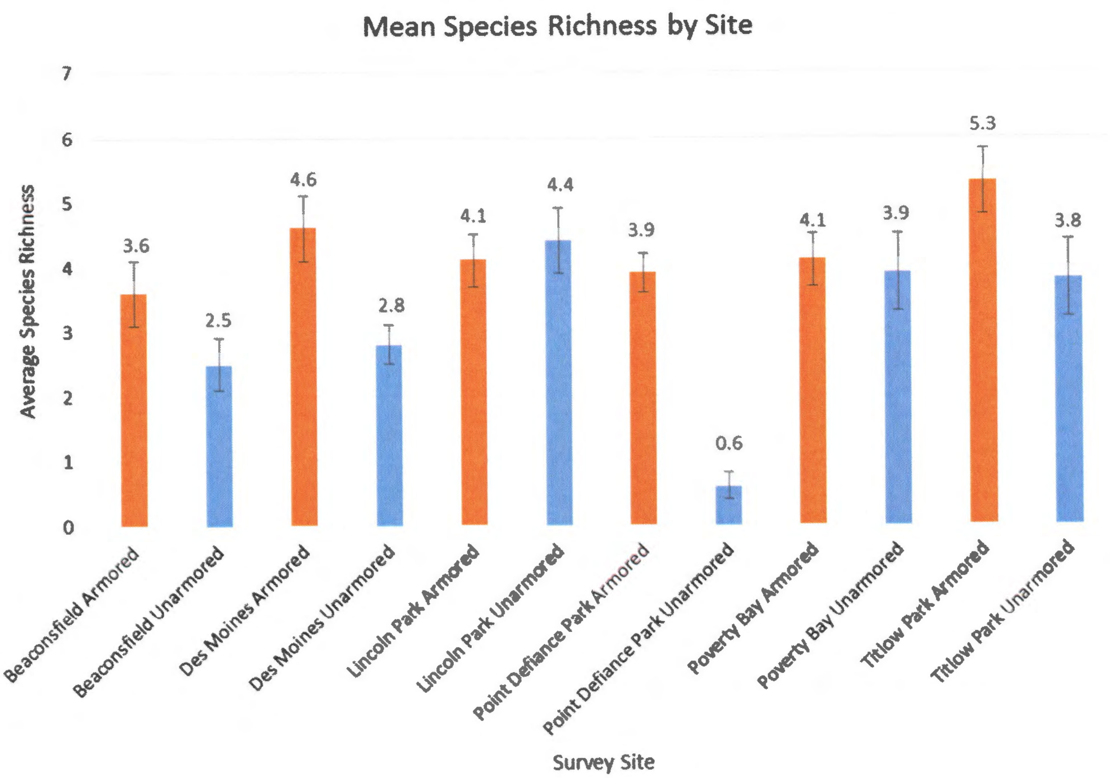


Figure 4. Mean species richness by survey site, with a standard error of 1 from the mean.

The average species richness at armored sites (n=4.3 ± 0.6) was significantly greater than the average species richness at unarmored sites (n=3.1 ± 0.4; DIF=1.2; $p<0.001$).

Species evenness

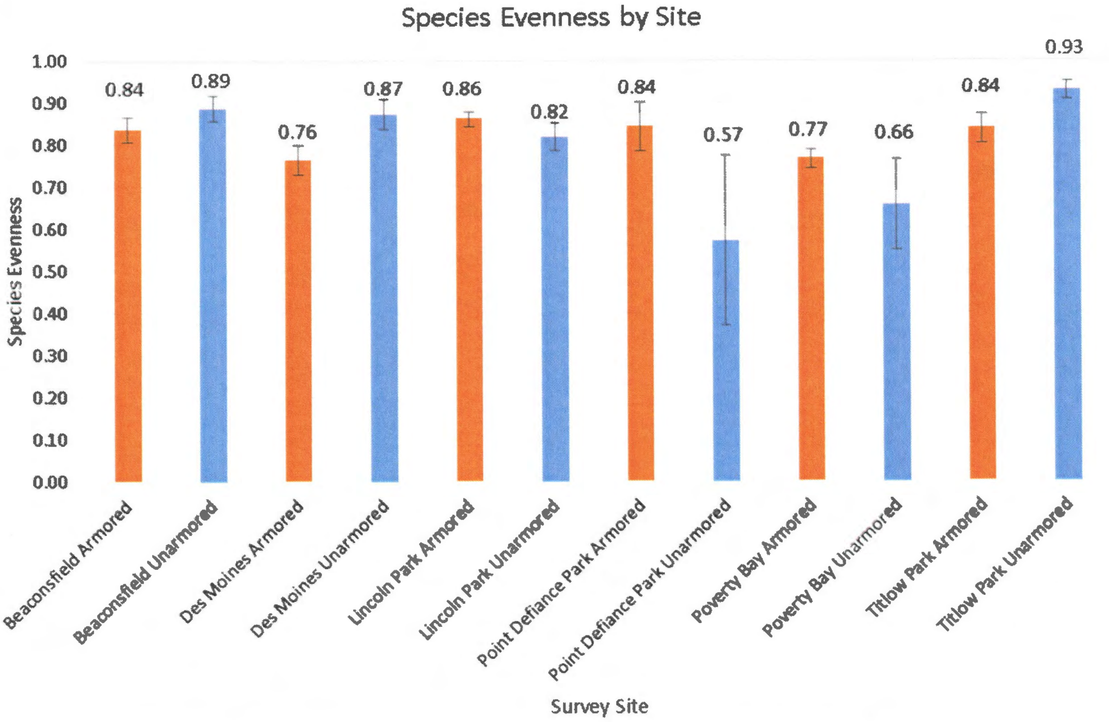


Figure 5. Species evenness by site, with a standard error of 1 from the mean.

The average species evenness at armored sites (n=0.94±0.03) was not significantly different from the species evenness at unarmored sites (n=0.96±0.07; DIF=0.0, p<1.0).

Foraging behavior

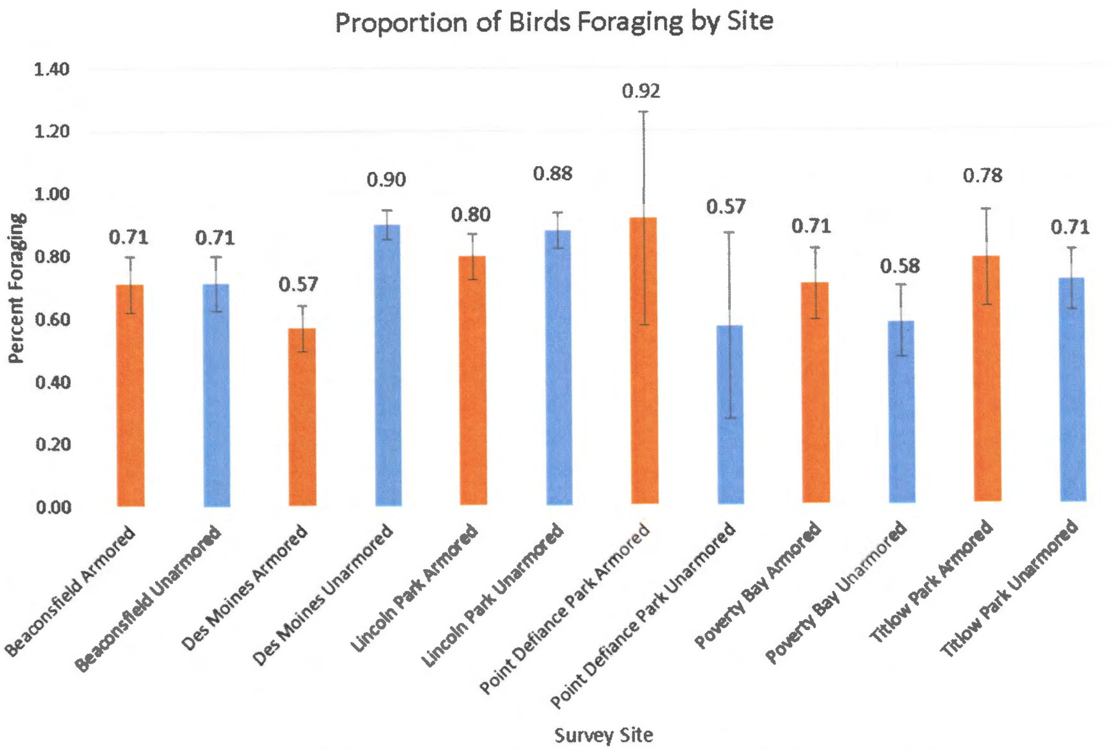
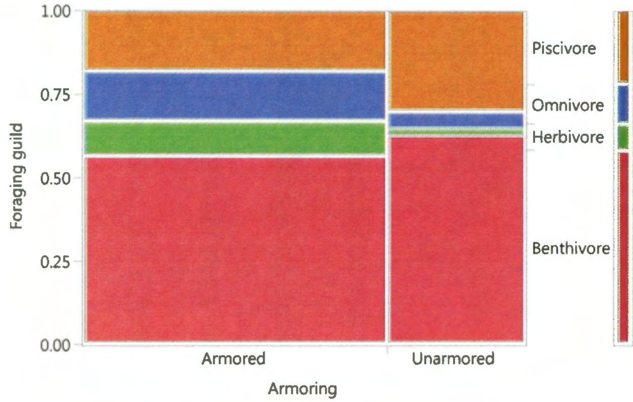


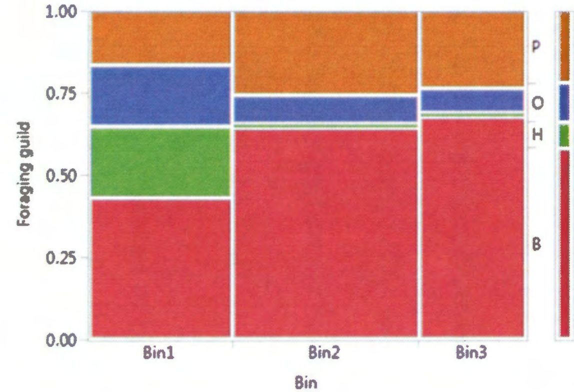
Figure 6. Proportion of birds foraging, with a standard error of 1 from the mean.

The proportion of birds foraging at armored sites (n=0.75±0.14) was not significantly different between armored and unarmored sites (n=0.73±0.12; DIF=0.002, p<0.985).

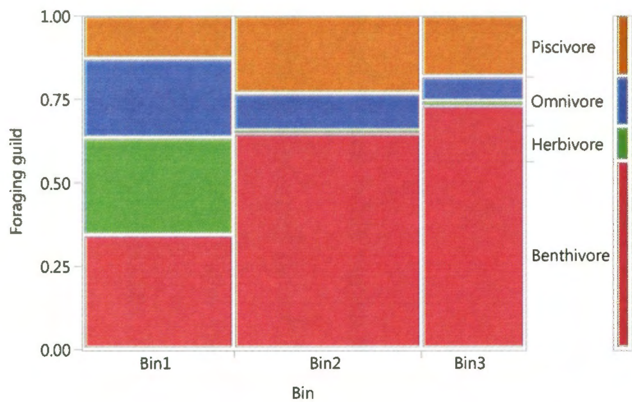
7a. Chi-square Analysis of Foraging Guild by Armoring



7b. Chi-square Analysis of Foraging Guild by Bin



7c. Chi-square analysis of Foraging Guild by Bin: Armored Sites



7d. Chi-square analysis of Foraging Guild by Bin: Unarmored Sites

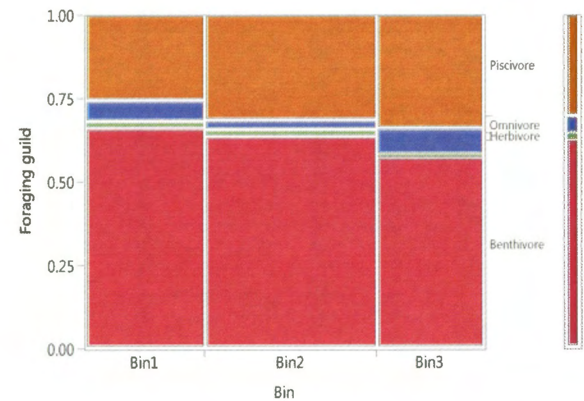


Figure 7. Analysis of abundance in each foraging guild (B: benthivores; H: herbivores; O: omnivores; P: piscivores) in relation to armored and unarmored sites (7a) and according to distance from shore (Bin 1: 0-50 m; Bin 2: 51-100 m; Bin 3: 101-150m) at all sites (7b), armored sites (7c), and unarmored sites (7d).

Approximately 74% of marine birds surveyed were foraging at all survey sites. Although there was no significant difference in the proportion of marine birds foraging at armored and unarmored sites, the percentage of birds in each foraging guild depended on whether or not there was armoring ($\chi 2 = 73.7$, df=3, $p<0.0001$). At armored sites, 56.3% of birds observed were benthivores, 10.7% were herbivores, and 14.7% were omnivores, and 18.3% were piscivores (see Figure 7a). At unarmored sites, 62.6% of birds observed were benthivores, 1.9% were herbivores, and 5.1% were omnivores (see Figure 7a). There were significantly more piscivorous birds at unarmored sites (30.4%) than at armored sites (18.3%).

The percentage of birds in each foraging guild was also dependent on the distance from shore ($\chi 2 = 218.1$, df=6, $p<0.001$; see Figure 7b). There were more birds observed in the second distance bin, 51-100 m from shore, than in the other two bins. Across all bins, benthivores were the most abundant birds observed at both armored and unarmored sites. A higher proportion of herbivores and omnivores were observed at the armored survey sites, where they were most frequently located in the first nearshore bin, ≤50 m from shore.

Individual Sites

The abundance and species richness of marine birds varied between each paired survey site. The average abundance at armored Des Moines Beach Park (46±6.4) was significantly greater than the average abundance at Marine View Park (7.4±1.4), its paired unarmored site (DIF=38.6, $p<0.001$). The average species richness at Des Moines Beach Park (4.6±0.5) was also significantly greater than the average species richness at

Marine View Park (2.8±0.3; DIF=1.8, $p<0.01$). The average abundance was significantly greater at the armored section of Point Defiance Park than at the unarmored section (DIF=7.29, $p<0.001$). The average species richness at the armored section of Point Defiance Park was significantly greater than at the unarmored section (DIF=3.29, $p<0.001$).

Table 3. Monte Carlo resampling of average abundance between armored and unarmored sections at each paired survey site. Reported as mean abundance (+/- SE). An asterisk indicates statistical significance ($p<0.05$).

Site	Armored Average	Unarmored Average	DIF	P value
Lincoln Park	11.5±1.7	11.7±1.2	0.2	p<0.872
Beaconsfield	11.1±2.3	5.5±2.2	5.6	p<0.43
Des Moines	46±6.4	7.4±1.4	38.6	p<0.001*
Poverty Bay	12.9±1.6	12.1±2.4	0.75	p<0.829
Point Defiance	7.9±1.2	0.6±0.2	7.285714	p<0.001*
Titlow	12.1±1.7	9.1±2.0	3	p<0.276

Table 4. Monte Carlo resampling of average species richness between armored and unarmored sections at each paired survey site. Reported as mean species richness (+/- SE). An asterisk indicates statistical significance ($p<0.05$).

Site	Armored Average	Unarmored Average	DIF	P value
Lincoln Park	4.1±0.4	4.4±0.5	0.3	p<0.763
Beaconsfield	3.6±0.5	2.5±0.4	1.1	p<0.1
Des Moines	4.6±0.5	2.8±0.3	1.8	p<0.01*
Poverty Bay	4.1±0.4	3.9±0.6	0.25	p<0.893
Point Defiance	3.9±0.3	0.6±0.2	3.285714	p<0.001*
Titlow	5.3±0.5	3.8±0.6	1.55556	p<0.047*

The species richness was significantly greater at the armored section (5.3±0.5) of Titlow Park in comparison to the corresponding unarmored section (3.8±0.6; DIF=1.56, $p<0.047$). For the remaining three sites, Lincoln Park, Beaconsfield, and Poverty Bay, there was no significant difference in abundance or species richness between the armored and unarmored sections.

DISCUSSION

Comparison of combined armored sites to unarmored sites showed that there was significantly greater average abundance and average species richness of seabirds at armored sites. When each paired site was analyzed individually, the three sites that were not adjacent to a marina or other highly developed area did not demonstrate a significant difference in abundance or species richness.

Importance of the nearshore as foraging habitat

Foraging theory posits that predator behavior and movement aims to optimize energy intake; hence, it would be expected that marine birds will be located in areas with sufficient prey populations (Kirk et al., 2008). The results of this research demonstrated that marine birds are utilizing the nearshore in South Central Puget Sound to forage during the winter months. Overall, 74% of birds surveyed were foraging, and 76% of birds surveyed were located in the first two bins, up to 100 m from shore. This emphasizes the importance of the nearshore environment as foraging habitat to marine birds that overwinter in the Puget Sound. Despite the negative correlation between armoring and abundance and reproductive success of some prey populations reported in other studies (Morley et al., 2012; Penttila, 2007; Rice, 2006; Sobocinski et al., 2010), there was not a significant difference in the percentage of marine birds foraging at armored and unarmored sites.

When exploring the composition of birds according to foraging guilds as categorized by Bower (2009), guild varied by armoring and by distance from shore. While more individual birds of certain species were observed at armored sites, the composition of species when combined into foraging guilds varied between armored and unarmored shorelines. Benthivores, including Barrow's Goldeneye, Bufflehead, Common Goldeneye, and Surf Scoter, were the most abundant birds and dominated all binned distance from shore categories at both armored and unarmored sites. Herbivores, including American Wigeon and Mallard, and omnivores were more frequently observed at armored sites in the nearshore bin. The omnivores observed were almost entirely Glaucous-winged Gulls and Glaucous-winged Hybrid Gulls. In this study, piscivorous birds were more frequently observed at unarmored sites than at armored sites. The most abundant piscivores observed were Horned Grebe and Red-breasted Merganser. Other piscivorous species, including Double-crested Cormorant, Common Merganser, Hooded Merganser, Pigeon Guillemot, Common Loon, and Pelagic Cormorant were less commonly or rarely observed during the survey period (n=26; n=14; n=10; n=10; n=3; n=1, respectively).

Research has shown that armoring is detrimental to the spawning success of sand land and surf smelt, which are important prey species to some marine birds (Penttila, 2007). Herring eggs also compose part of the diet for several species surveyed, including Surf Scoters and Buffleheads (Gauthier, 2014; Lok et al., 2012). Eelgrass meadows provide critical habitat for juvenile salmon, invertebrates, and other organisms and also serve as spawning habitat for herring (Envirovision et al., 2010). The health and productivity of eelgrass beds can be detrimentally affected by shoreline armoring and other anthropogenic activities, such as shellfish aquaculture (Envirovision et al., 2010). Marine birds that depend largely on fish, and particularly forage fish, as primary prey items, may be less likely to reside or forage in nearshore environments in which the shoreline is armored, as was observed in this study, but further research is warranted.

Confounding factors

There were several artificial and natural factors that may have influenced the abundance and behavior of marine birds at the survey sites, beyond the armoring itself. Areas that are armored, particularly in cases of industrial or commercial properties, are sometimes highly developed. This introduces additional anthropogenic variables into the nearshore, and it may be difficult to isolate the impacts of armoring from the other alterations to the environment. The abundance and species richness of marine birds at Des Moines Beach Park and the armored section of Point Defiance Park were significantly greater than at the corresponding unarmored sites. These two sites are located next to marinas and are highly developed (see Figure 8a,b). At Titlow Park, there are pilings in and next to the armored section from a historic ferry terminal (see Figure 8c). The anthropogenic additions to the nearshore, including pilings and docks, could be providing habitat for prey species such as bivalves and crustaceans. Fifty-eight percent of birds surveyed were diving ducks that rely primarily on invertebrates and mollusks as prey, so highly developed areas may provide some benefit to these marine birds.

8a. Pier at the Des Moines Marina, adjacent to Des Moines Beach Park

8b. The Point Defiance Marina, adjacent to the armored section of Point Defiance Park

8c. Pilings from an abandoned ferry terminal, in the nearshore habitat of the armored section of Titlow Park

Figure 8. Photos of additional development in the nearshore habitat at, and adjacent to, three survey sites.

It is possible that marine birds are able to exploit novel prey populations that have established themselves in highly developed areas, due to vertical zonation providing habitat for barnacles and limpets and shade or hiding areas for fish. Overwater structures include docks, piers, and ferry terminals (WDFW, 2006). Research examining fish distribution near Seattle shorelines found that crabs, sculpins, and surfperch were the only groups located under overwater structures and near pilings (Toft et al., 2007). However, shading from overwater structures can negatively impact marine vegetation used as spawning habitat by herring. Herring sometimes spawn on pilings but in greater densities and higher elevations than when spawning on vegetation; these spawning events result in wide-ranging mortality of the eggs due to chemical contamination, smothering, and exposure during low tide (Penttila, 2007).

The most abundant birds at Des Moines Beach Park were Surf Scoters, Common Goldeneyes, and gulls, which were grouped together and consisted of Glaucous-winged gulls and Glaucous-winged hybrids. Surf Scoters are benthivores which rely heavily on clams and mussels in the winter (Kirk et al., 2008). The diet of Common Goldeneyes during the winter consists primarily of crustaceans and mollusks, while gulls are opportunistic and will eat a wide variety of items, including garbage, bivalves, gastropods, crabs, and forage fish (Eadie et al., 1995; Hayward & Verbeek, 2008). The most abundant species at the armored Titlow site were Buffleheads and Common Goldeneyes. Bufflehead largely rely on crustaceans and mollusks, although they also prey upon fish and herring eggs (Gauthier, 2014). Pelagic and Double-crested Cormorants also utilize the pilings at Titlow Park to roost and dry their wings.

Due to the potential habitat at the armored sites for bivalves and crustaceans, it is possible that highly developed beaches could benefit some species of marine birds with generalist diets. The marine birds surveyed at all sites were largely omnivores and carnivores with a varied diet, including bivalves, crustaceans, and macroinvertebrates. Marine birds sometimes favor food items that are easier to obtain yet provide less caloric value. Surf scoters prey on both clams, which are more difficult to obtain, and mussels, which are more accessible but provide a lower energetic gain (Kirk et al., 2008). Low-quality food in the form of anthropogenic garbage may decrease clutch size and egg volume in Glaucous-winged Gulls (Blight et al., 2015).

Des Moines Beach Park was unique among the survey sites due to its significantly higher total abundance of birds observed (n=460). Des Moines Creek empties into Puget Sound at this site. American Wigeons were primarily observed at armored Des Moines Beach Park, with limited detections at other survey sites. Sixty four individuals were observed at Des Moines Beach Park, zero individuals at its paired unarmored site, and four individuals each at Poverty Pay and Titlow Park. The input of freshwater may provide better foraging habitat for these herbivores, as well as being a source of nutrients and sediment to the nearshore. The salinity in Puget Sound is generally lower in front of river mouths, which may reduce salt stress for marine birds that are foraging for invertebrates in the nearshore (Dethier, 2010; Esler et al., 2000). In addition to being observed in the nearshore, Mallards and merganser species were also observed in the creek, which could provide food sources to some birds, such as terrestrial insects.

Disturbances were not included in the statistical analysis, but appeared to affect the abundance of birds on some survey dates. Bald eagles were frequently observed at Beaconsfield, Marine View Park, and Titlow Park. It is possible that fewer marine birds were observed at these three sites due to presence of this raptor and perhaps a greater risk of predation (Buehler, 2000). Marine crafts, including boats and kayaks, sometimes disrupted marine bird activity at the survey sites. Off-leash dogs were also in the water of the nearshore at Marine View Park and Beaconsfield, which could affect bird counts.

Future considerations

The factors influencing marine bird habitat use and population trends are complex, and this research highlights the need for further research in this area. Time and resource constraints limited the number of survey sites in this study and the extent of variables that could be studied. Sample sites were not randomly selected (but anthropogenic modifications to the shoreline are not randomly distributed either) and were based partly on logistics but also due to access of potential sites. Access to armored shoreline is often limited, as much of it is privately owned, and property owners may feel they have a vested interest in preserving armoring structures. The survey sites for this study were located in urbanized areas of Puget Sound; therefore, no comparison could be made between natural and urbanized locations regarding avifaunal abundance and species composition. Future research may benefit from expanding survey sites to other sub-basins in Puget Sound.

There were limitations to assessing temporal and spatial variability in marine bird abundance and behavior in this study. The effects of armoring are likely not localized, as they can impact the transport of sediment throughout a littoral cell. Therefore, differences in marine bird composition and abundance may not be detectable at a local scale due to how habitat modification affects availability of prey. A larger spatial scale and a longer temporal scale may be necessary to assess these differences. The armored and unarmored sites surveyed in this study were adjacent to one another and encompassed relatively short areas of shoreline. Unarmored sites were often flanked by armored shoreline on either side. It is possible that armoring is affecting the sediment transport, substrate, and composition of benthic species of the nearshore on contiguous unarmored shorelines. Historic data is not available for marine bird distribution in the Puget Sound, so limited comparison of marine bird use of the nearshore can be made with the present day. However, Rice (2007) demonstrated that marine birds are less abundant in nearshore habitats that are highly urbanized. Using this larger spatial scale, shoreline modification is negatively correlated with marine bird abundance.

This study was solely focused on whether there was a correlation between marine bird assemblages and armoring. Many natural and artificial factors affect the ecology of the nearshore and could be influencing marine birds' use of this habitat. Future research could integrate two additional factors when exploring the assemblages and behavior of birds utilizing the nearshore. The possibility that marine birds in urbanized areas may be benefiting from marinas should be explored further. Anthropogenic activity and development rarely provide quality habitat for native species; yet, in this study, the abundance of marine birds was greatest at sites adjacent to marinas or with other structures in the nearshore. It is possible that this development is providing novel habitat for prey populations that marine birds are able to exploit. Future research could explore whether marinas or other structures could be providing habitat that benefits some species of marine birds, by placing underwater cameras on pilings or conducting surveys of prey availability via scuba diving or small ROV devices.

In future studies, survey sites could also be chosen by nearshore substrate type, as this influences the amount and type of primary producers in the nearshore. The assemblages of anemones, bivalves, crustaceans, fish, and shorebirds in the nearshore also vary between substrate types (Dethier, 2010). The foraging behavior of some marine birds, such as Surf Scoters, differs between substrate types (Kirk et al., 2008). The abundance of Barrow's Goldeneyes has been found to vary between habitats with different substrates, potentially because mussels are easier to remove in mixed substrate than from rocky nearshore environments (Esler et al., 2000). Shoreline armoring is the primary cause of changes in nearshore substrate, but other forms of habitat modification also affect the sediment. Pilings, used in the construction of piers and other overwater structures, alter the substrate by decreasing wave energy which results in fine-grained sediment dropping out of the water column. Species that colonize on pilings further contribute to changes in the sediment (Envirovision et al., 2010). Future research should be focused on these aspects of habitat use and on identifying critical habitats at local scales, so that conservation measures regarding marine birds can be focused on these areas.

CONCLUSION

The Puget Sound provides critical overwintering habitat for resident and migratory marine bird species, many of which depend primarily on the nearshore environment during the winter season (Pearson & Hamel, 2013). Marine bird survey data spanning the last several decades points to significant declines in marine bird populations in the Puget Sound (Bower, 2009; Nysewander et al., 2005). Despite these concerning trends, little is known about the causes of the declines or to what extent habitat modification is affecting marine bird populations. This research is one of the first studies to assess marine bird assemblages and foraging behavior in relation to armored and unarmored shorelines in Central Puget Sound.

The findings of this research suggest that at these surveyed locations, marine bird abundance, species richness, and foraging behavior are similar at armored and unarmored sites, with greater abundance and species richness at some armored sites. The composition of marine birds by foraging guild varied in response to armoring, with a smaller proportion of piscivores observed at armored sites. These findings underscore the challenges of analyzing marine bird populations in urbanized landscapes, where numerous natural and artificial factors are influencing the nearshore and prey availability. In order to make sound management decisions regarding marine birds and other animals while also satisfying property owners and protecting private and public assets, it is imperative that the local and cumulative impacts of armoring are fully understood. While the results of this study did not suggest that armoring has a detrimental effect on marine birds, confounding factors such as overwater structures and freshwater input may have influenced the results. The multitude of factors potentially affecting marine bird abundance and space use highlights the need for additional research in this area. Further research is warranted regarding the possible interactions between armoring and marine birds and other upper trophic level predators. Future studies could encompass greater spatial and temporal scales. Further exploration of marinas and other development is merited as well as selection of survey sites by substrate. Identifying critical habitats for marine birds in Puget Sound whose populations are in decline can lead to implementing conservation measures, such as restrictions on hunting and boating and protection of prey species.

Given the importance of marine birds as indicators of marine health and the evidence that populations of several marine bird species are declining, future research should be focused on determining factors that are driving population declines. It is likely that these declines are due to a confluence of factors and will require a holistic view regarding management and conservation planning. Marine birds have no regard for political boundaries; therefore, conservation measures must be embraced by all countries that are home to certain species as part of their life cycle or migration patterns.

Concern over the degraded state of Puget Sound has led to restoration and conservation efforts, many of which are focused on the nearshore. Shoreline alteration has been identified as a primary stressor on the nearshore environment, and the removal of armoring on residential properties is considered a priority in restoring the health of

Puget Sound (Puget Sound Partnership, 2014). The updated Shoreline Management Act requires that local governments give priority to more natural shoreline modifications over armoring, yet the construction and repair of armoring still outpace its removal (Puget Sound Partnership, 2014). Several factors, including the political climate in Washington and the numerous jurisdictions involved in shoreline regulation make an explicit ban on armoring unlikely. Clearly, policy and regulation have limited effectiveness in driving change. Coastal homeowners must be provided with attractive, attainable alternatives to armoring and incentives to use such solutions.

CHAPTER 3: Summary, Restoration, & Policy

Marine bird population trends are likely driven by many factors, including coastal processes and development. These complex interactions make this a challenging yet pertinent topic and one that should be explored further if marine birds are to receive adequate protection. This research focused solely on marine bird assemblages in relation to armored and unarmored shorelines; however, other natural and anthropogenic factors are influencing the nearshore environment and prey populations located therein.

Table 5. Key findings from Chapter 2.

Key Findings	• Species composition varied between survey sites and paired shoreline segments • Overall, mean abundance and mean species richness were significantly greater at armored than unarmored shorelines • Overall, mean species evenness and percentage of birds foraging were similar at armored and unarmored shorelines • When analyzed individually, there was variation among paired sites in regards to average abundance and average species richness between armored and unarmored segments • The proportion of birds by foraging guild depended on whether or not the shoreline was armored, with piscivores making up a higher percentage of total abundance at unarmored sites • A majority of marine birds observed were foraging in the nearshore
Conclusions	• There are many natural and anthropogenic factors contributing to the composition of marine bird assemblages in the nearshore • Quantifying the effects of armoring on marine bird assemblages is challenging due to variation in construction materials, age, and placement of structures • Effects of armoring may not be localized, and despite the small scale of residential projects, cumulative impacts may have ramifications for marine birds and other species in the nearshore • Some shorelines may be providing beneficial foraging habitat for marine birds despite, or even because of, development in the nearshore
Future considerations	• Monitoring of sites before and after construction of armoring to establish baseline data regarding species use of the nearshore • Integration of other forms of development and habitat modification as variables when surveying for marine birds • Choose future survey sites by substrate type • Identify critical habitat areas at the local level that are utilized by marine bird species whose populations are experiencing declines so that these areas can be protected

Habitat enhancement and restoration

The importance of the Puget Sound nearshore cannot be overstated, both as habitat for native marine and intertidal species and because of the ecosystem goods and services it provides. A lack of knowledge regarding the requirements of nearshore dependent species, combined with inadequate regulation, has resulted in substantially modified shorelines along much of Puget Sound (Carman et al., 2010). Despite documented adverse effects of shoreline armoring, the use of shoreline armoring continues to increase. Although this research did not find a correlation between shoreline armoring and marine bird abundance, there is compelling evidence that armoring has numerous consequences, including reducing the capacity of coastal systems to adapt to disturbances, thereby decreasing ecosystem resilience, intensifying the vulnerability of coastal communities, and reducing habitat complexity (Chapman & Blockley, 2009; Kittinger & Ayers, 2010). Degradation of the nearshore jeopardizes ecosystem goods and services upon which humans depend, and threatens species that have cultural, financial, and recreational value, including forage fish and salmonids (Kittinger & Ayers, 2010; Rice, 2006). Restoration of the Puget Sound nearshore will require an interdisciplinary approach, taking into account diverse groups of stakeholders as well as an understanding of the ecological and coastal processes of the nearshore ecosystems (Lipsky & Ryan, 2011).

Puget Sound Partnership, along with other agencies and non-profit organizations, has focused considerable restoration efforts on the nearshore environment (Puget Sound Partnership, 2014). Much of the shoreline of Puget Sound has been developed with both residential and industrial properties bordering the coast, and it may be impossible or undesirable to return the shoreline to historic conditions (Shipman et al., 2010). Habitat enhancement and restoration can be used to create more natural conditions, reestablish physical processes, enhance biodiversity, and restore ecosystem services and functions (Fresh et al., 2011). Erosion must be viewed not just in an anthropocentric context, in which it is a threat to property and development. It must also be recognized as a vital geomorphic process that maintains beaches and contributes to healthy nearshore habitat. A focus on restoration of coastal processes will create ecosystems that will be resilient in the face of climate change and future conditions.

There is growing interest in alternatives to shoreline armoring, including hybrid systems that utilize native vegetation or large woody debris to stabilize shorelines and prevent erosion (Shipman, 2010). Siting houses and other buildings far enough back from the shoreline to account for erosion and future sea level rise is vital to protecting coastal development and promoting resilience of the nearshore (Envirovision et al., 2010). Coastal property owners must also consider planned retreat or managed realignment, in which coastal buildings are abandoned or relocated to allow wetlands and intertidal areas to naturally retreat inland (O'Connell, 2010). In high energy environments, even shoreline armoring will likely be inadequate protection in the face of sea level rise and storm surges in the future. Griggs (2004) suggests that oceanfront property may have a finite half-life, due to erosion and future sea level rise.

The complete removal of armoring allows what might be considered the most natural restoration, in which the shoreline can self-regulate without the impediment of any infrastructure (Chapman & Underwood, 2011). Several habitat enhancement projects that involve the removal of armoring are being planned or have been implemented in urban parks in Puget Sound. The Olympic Sculpture Park, located in Seattle, is used by juvenile salmonids, including Chinook salmon (*Oncorhynchus tshawytscha*) and chum salmon (*Oncorhynchus keta*). These two species use nearshore habitat more than other salmonid species, and the former is listed as threatened under the Endangered Species Act. Soft engineering was used to restore the shoreline of Olympic Sculpture Park, which was armored with a seawall and a riprap boulder field. The rip rap was replaced with a pocket beach, and a habitat bench was constructed in front of the seawall to mimic a natural shallow water environment. Riparian vegetation, comprised of native plants, was planted in the supratidal uplands. Monitoring was conducted 1 and 3 years following the restoration project. Taxa richness of epibenthic invertebrates, density of larval fish, and abundance of chinook and chum salmon increased in the years following the enhancement (Toft et al., 2013). While the scope of this project prevented replication, the results are encouraging in that even small-scale restoration projects may increase complexity of the nearshore habitat and encourage species richness.

Policy

Restoring overall ecosystem function and coastal processes in Puget Sound will require a holistic and regional, not simply local, assessment of armoring and land use practices. Analysis of policy concerning shoreline armoring in North Carolina and Hawaii demonstrates an unambiguous ban on shoreline armoring, in comparison to allowing homeowners to apply for variances or permits, is more effective at conserving nearshore habitats and coastal developments (Kittinger & Ayers, 2010). Under this type of regulation, the property owner bears the risk of erosion and damage to development when deciding to build close to the shoreline. Over the long-term, stringent regulation that prohibits shoreline armoring discourages risky coastal development, allows for a dynamic shoreline to self-maintain, and preserves the ecosystem goods and services of the nearshore (Kittinger & Ayers, 2010). However, policy banning armoring outright seems unlikely to be implemented in the Puget Sound area due to widespread private ownership of shorelines and regulation at the local level where policy makers may be unwilling to estrange constituents over this issue. Moreover, regulating armoring structures on an individual basis does not account for the potential cumulative impacts of many kilometers of armored shorelines (Lipsky & Ryan, 2011).

In Washington State, local city and county governments are typically responsible for managing the shoreline, making broad intervention at the state or federal level a challenge (Lipsky & Ryan, 2011). Local governments are required to comply with the Shoreline Management Act (SMA) and Shoreline Master Program (SMP) Guidelines when drafting their local Shoreline Master Programs (DOE, 2015). The SMP guidelines were amended in 2003 to require that more than 260 cities, towns, and counties update their SMPs, some of which have not been altered in over 30 years (DOE, 2015). These updates were supposed to be made between 2005 and 2014, with only 124 updated SMPs currently completed. While the design of SMPs is intended to protect human interests, they also require that "no net loss of ecological function associated with the shoreline" will occur (WAC 173-26-241). This often puts environmental goals at odds with land use practices.

The majority (73%) of the Puget Sound nearshore is privately owned, while the rest is controlled by city, county, tribal, state, and federal governments (Lipsky & Ryan, 2011). While local governments should lead the way in protection and restoration of publicly owned shorelines, due to the high proportion of private ownership, it is imperative that a combination of policy and incentives are used to encourage ecologically friendly development and restoration of privately owned shorelines. Local governments are required to give priority to "soft" shoreline modifications over "hard" modifications such as concrete seawalls in their SMPs. The use of soft modifications aims to stabilize shorelines and reduce erosion while causing the least amount of harm to an ecosystem. Methods that are encouraged due to being more ecologically friendly than armoring include vegetation enhancement, upland drainage control, and beach nourishment (City of Tacoma, 2013). However, many local jurisdictions provide an exemption in their SMPs for permitting of "normal protective bulkheads" on residential properties. Armoring is considered a normal protective bulkhead when placed at or near the Ordinary High Water (OHW) mark and is for the purpose of protecting existing structures from erosion (City of Tacoma, 2013; Seattle City Ordinance 124105). The lack of stringent permitting requirements can encourage irresponsible coastal development, in which the desire to build and protect high value properties in close proximity to the beach take precedence over environmental concerns and the greater public good.

The implementation of SMPS alone is not enough to alter the use of armoring. In Puget Sound, 2.4 km of new armoring is built and 4 km of armoring is replaced annually; in comparison, only 3-4 bulkheads are removed each year (Barnard, 2010). Programs that incentivize responsible shoreline development can be used in conjunction with policy. Local governments in Washington and British Columbia partnered with non-profit institutions to come up with a Green Shores for Homes program to encourage the creation of ecologically friendly freshwater and marine shorelines. Incentives to participate in the programs include property tax reductions and low interest loans to finance the removal of armoring and more natural development (Puget Sound Partnership, 2014). If this model proves successful, it could be targeted towards counties with the highest rates of new construction, including Mason, Island, and Kitsap Counties.

In addition to financial incentives, property owners may be driven to restore armored shorelines if public recognition of their efforts is included in these models. Washington Department of Fish and Wildlife initiated their Backyard Wildlife Sanctuary Program in 1986. Citizens who create wildlife friendly habitat in their own yards can apply for this designation and receive a certificate, a free newsletter subscription, and a sign placed in their yard advertising their participation in the program (WDFW, 2015). Similar programs with various incentives are used in other parts of the country or offered by national non-profit organizations, including the National Wildlife Federation. This type of program gives agency to private citizens by introducing the concept that a homeowner is also a wildlife manager, and that the actions citizens take in regard to their own property impacts habitat for wildlife (WDFW, 2015). A similar program could be enacted for homeowners who maintain or restore their shorelines in a way that will encourage natural coastal processes, with stringent requirements to ensure that shoreline plans are environmentally friendly. Grant funding could be used to train volunteers to assess residential shorelines before awarding this designation. When citizens are able to advertise ecologically healthy shorelines, it will increase awareness of alternatives to armoring.

The need for urgent action to restore the health of Puget Sound is widely recognized; there is less consensus among stakeholders on how this goal should be achieved. Nearshore biomes are linked social-ecological systems, and the success of restoration efforts will depend on political concerns, economics, and social values, in addition to an understanding of ecological processes (Lipsky & Ryan, 2011). Restoration is complicated by numerous issues, including private ownership of Puget Sound shorelines, multiple jurisdictions with varying levels of regulation, a diverse group of stakeholders, and the fact that human development is considered more valuable than the habitat, biota, and natural resources that are displaced and degraded by the use of armoring (Kittinger & Ayers, 2010; Nordstrom, 2014). When considering changes to policy and regulation, the rights of homeowners must be balanced with the need for healthy nearshore ecosystems in the Puget Sound in order to sustain human and wildlife populations.

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Appendix

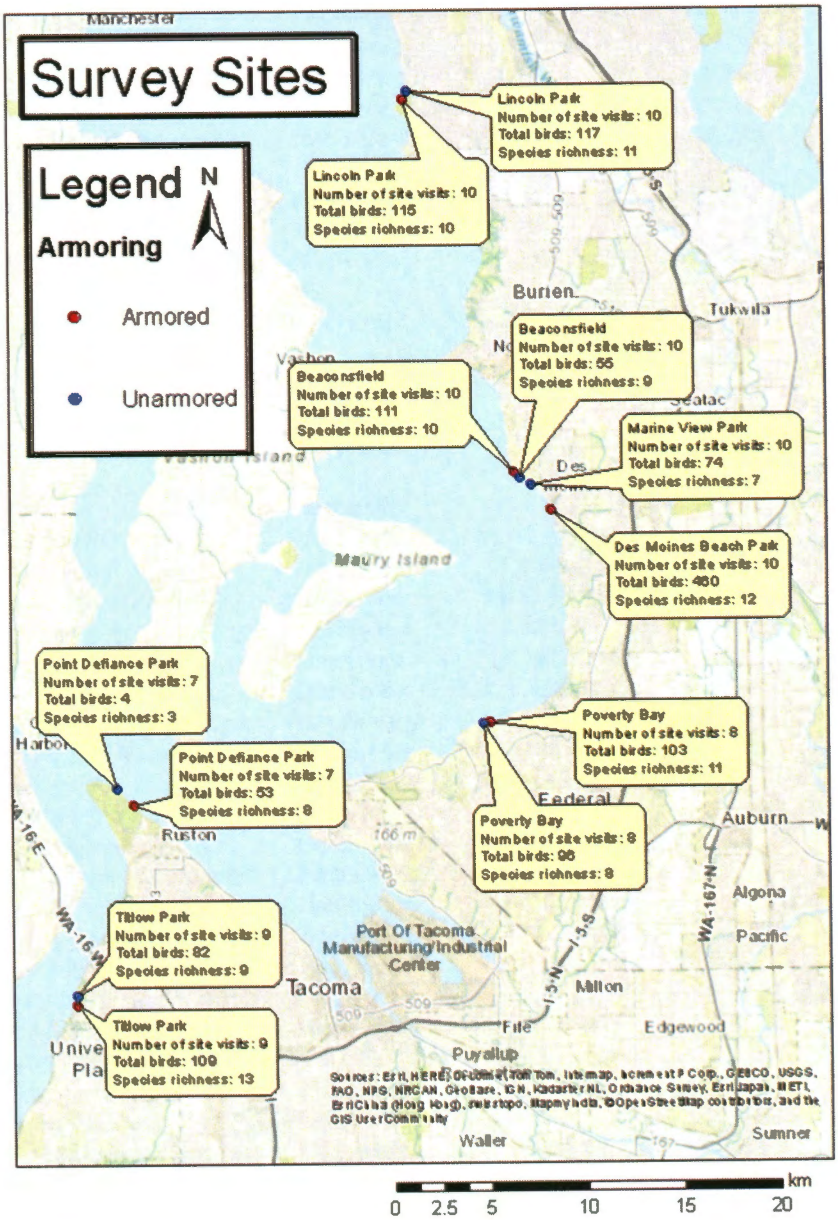

Figure 9. Map of survey sites with number of site visits (n), total abundance, and total species richness.

Table 5. Data collected and reported by Bower (2009) regarding marine bird population trends in the Salish Sea.

Species	Feeding Guild	MESA Surveys (1978-1980)	WWU Surveys (2003-2005)	Change (%)
All birds		1235.2±357.0	878.0±272.8	-28.9*
Red-throated Loon *Gavia stellata*	Piscivore	2.4±0.7	0.6±0.3	-73.9*
Pacific Loon *Gavia pacifica*	Piscivore	16.3±8.8	8.7±2.6	-47
Common Loon *Gavia immer*	Piscivore	2.7±0.8	4.0±1.0	+48.8*
Red-necked Grebe *Podiceps grisegena*	Piscivore	4.0±0.9	2.2±0.5	-45.9*
Horned Grebe *Podiceps auritus*	Piscivore	9.7±2.1	2.8±0.7	-71.6*
Western Grebe *Aechmophorous occidentalis*	Piscivore	97.3±40.5	18.2±8.3	-81.3*
Double-crested Cormorant *Phalacrocorax auritus*	Piscivore	7.8±2.5	15.4±4.7	+97.7*
Pelagic Cormorant *Phalacrocorax pelagicus*	Piscivore	2.2±0.5	4.2±0.7	+87.7*
Brandt's Cormorant *Phalacrocorax penicillatus*	Piscivore	14.4±11.6	1.5±0.5	-89.6
Great Blue Heron *Ardea herodias*		3.1±1.1	4.7±1.6	50.7
Canada Goose *Branta canadensis*	Herbivore	0.0±0.0	3.8±1.2	+10,801.9*
Brant *Branta bernicla*	Herbivore	148.6±97.2	39.9±16.7	-73.2
Mallard *Anas platyrhynchos*	Herbivore	21.2±9.1	10.2±3.9	-52.1
Northern Pintail *Anas acuta*	Herbivore	41.4±18.3	81.8±44.7	97.7
American Widgeon *Anas americana*	Herbivore	86.9±39.9	115.0±69.6	32.3
Green-winged Teal *Anas crecca*	Herbivore	7.0±3.7	5.5±2.9	-21.6
Canvasback *Aythya valisineria*	Omnivore	2.2±1.4	0.0±0.0	-98.4*
All scaup *Aythya* spp.	Omnivore	121.3±45.8	42.7±19.2	-64.8*
Harlequin Duck *Histrionicus histrionicus*	Benthivore	1.3±0.4	1.6±0.4	19.8
Long-tailed Duck *Clangula hyemalis*	Benthivore	3.2±0.8	1.8±0.4	-44
Surf Scoter *Melanitta perspicillata*	Benthivore	141.2±54.9	56.8±16.6	-59.8
Black Scoter *Melanitta nigra*	Benthivore	1.8±0.7	0.6±0.3	-65.7*
White-winged Scoter *Melanitta fusca*	Benthivore	13.8±4.8	19.5±8.7	41.3
Common Goldeneye *Bucephala clangula*	Benthivore	6.7±1.9	3.5±1.0	-47.8*
Barrow's Goldeneye *Bucephala islandica*	Benthivore	1.2±0.8	0.9±0.4	-23.1
Bufflehead *Bucephala albeola*	Benthivore	41.4±12.0	36.9±11.7	-10.8
Common Merganser *Mergus merganser*	Piscivore	1.0±0.6	1.8±0.9	80.7
Red-breasted Merganser *Mergus serrator*	Piscivore	5.5±1.3	5.2±1.3	-6.6
Ruddy Duck *Oxyura jamaicensis*	Benthivore	16.8±11.2	6.8±6.4	-59.7*
Bald Eagle *Haliaeetus leucocephalus*		0.4±0.1	1.1±0.3	+187.0*
Bonaparte's Gull *Larus philadelphia*	Planktivore	32.0±10.5	8.9±3.2	-72.3*
Mew Gull *Larus canus*	Omnivore	28.7±8.5	20.2±5.8	-29.5
Glaucous-winged Gull *Larus glaucescens*	Omnivore	59.2±11.0	44.6±12.4	-24.8*
Common Murre *Uria aalge*	Piscivore	22.6±6.9	1.7±0.7	-92.4*
Pigeon Guillemot *Cepphus columba*	Piscivore	2.3±0.4	4.9±1.3	+108.9*
Ancient Murrelet *Synthliboramphus antiquis*	Planktivore	0.6±0.3	0.2±0.1	-69.1*
Marbled Murrelet *Brachyramphus marmoratus*	Piscivore	2.6±0.7	0.8±0.3	-71.0*