NATIONAL WILDLIFE FEDERATION

Sea-level Rise and Coastal Habitats in the Pacific Northwest

An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon

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July 2007

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Acknowledgements
This report is the culmination of the efforts of numerous individuals at the National Wildlife Federation. Special thanks to Dr. Amanda Staudt, James Schroeder, Joelle Robinson, and Tim Warman for shepherding this report through its final edits and coordinating its release. We also sincerely thank Dr. Doug Canning of the School of Marine Affairs and Climate Impacts Group at the University of Washington and Dr. Dick Park of Eco Modeling in Diamondhead, Mississippi, for providing invaluable conceptual and technical guidance throughout this project. Thank you, as well, to Dr. Mary Ruckelshaus, research biologist with the National Oceanic and Atmospheric Administration's (NOAA) Northwest Fisheries Science Center, for reviewing this report. Finally, we are enormously grateful to King County Executive Ron Sims, Elizabeth Willmott, and the King County Executive Action Group on Climate Change for contributing the foreword remarks.

Cover photo: Bald eagle at Padilla Bay (NOAA)

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FOREWORD

Global climate change is a reality. Human emissions are driving unprecedented and dangerous climate change, with coastal regions on the front lines of its effects. If we allow climate change to continue unabated, it will have significant effects across the world. Here in the Pacific Northwest, it will jeopardize the health of our most valued natural companions: shellfish, salmon, shorebirds, and waterfowl. As this important report shows, it will also fundamentally alter the way our human community lives on this beautiful coastline, how we get our food, how we interact with nature, and how we live as neighbors to Puget Sound.

We can and must change this forecast through aggressive greenhouse gas emissions reductions, while at the same time preparing for its effects on our region. We must set policies that are based on science and data, such as those outlined in the 2007 King County Climate Plan, instead of wishful thinking. We must embed climate change assumptions into our natural resource management plans and strategies to enable the most effective environmental restoration and protection possible.

Accounting for climate change projections in these plans is important from both a cost perspective and a natural resource perspective, especially for our future generations. As a public official making decisions that impact not only our community today, but also millions of future Puget Sound's residents and their natural environment, I refuse to let future generations pay for the consequences of our current lifestyles. By taking steps today to limit climate change, we can save money, natural resources and the quality of life we all value for our region's future residents tomorrow. This is an imperative.

With this report, the National Wildlife Federation reinforces its position of leadership on the most pressing issue facing our human and natural communities today: global climate change. Although the scenarios described in this report may sound gloomy, I am inspired by this honest presentation of one possible future of the Pacific Northwest. Only with such sound science and reason clearly illuminating the problem can we as community leaders and citizens be motivated, empowered and wise enough to cope with and limit the negative consequences of climate change to our beloved coastline. This report advances our collective understanding of that shared future, and I encourage you to read it with that same sense of purpose.

— RON SIMS, King County Executive

EXECUTIVE SUMMARY

The Pacific Northwest is blessed with an amazing diversity of coastal habitats, from rocky bluffs and sandy beaches along the Pacific Coast to the tidal flats, marshes, mixed sediment beaches, and eelgrass beds of Puget Sound. Together, these habitats support thousands of species of fish and wildlife, and they are a linchpin for the regional economy, culture, and quality of life.

Despite its pristine image, however, the region's coastal habitats and the ecological systems they support face serious problems due to human activities, which have prompted numerous local and regional restoration and protection efforts. Whether our significant conservation investments will endure for the future depends on how well the region is able to promote more sustainable use of its coastal resources in the face of continued population growth, pressures for development, and now, the very real threat of global warming.

Climate Change and Sea-level Rise

Scientists have widely and conclusively determined that global warming is happening and that burning fossil fuels is largely to blame. Global warming is disrupting the planet's climate system, and it is already having an impact on the Pacific Northwest. Left unchecked, the region will face higher average air and water temperatures, shifts in precipitation patterns, and a significant decline in average snowpack, all of which will put coastal habitats and the fish and wildlife that depend on them at great risk.

In addition, global warming is contributing to a significant increase in the rate of sea-level rise due to the thermal expansion of ocean waters and melting of glaciers and ice fields. Given the vast expanse of coastline along the Pacific Ocean and in Puget Sound and the critical role that vulnerable coastal habitats such as marshes, tidal flats, and beaches play in the region's ecology and economy, sea-level rise is likely to have a profound impact on the Pacific Northwest.

Of particular concern is the fact that most of the region's important coastal habitats have already been damaged or destroyed by extensive dredging, coastal modifications, pollution, and other development. Not only does this make remaining habitat all the more important for fish and wildlife, but coastal modifications such as dikes and seawalls have significantly reduced the ability for habitats to migrate inland to accommodate for sea-level rise. Any further losses or changes in habitat composition will have devastating consequences for the region's overall ecological and economic health.

Sea-level Rise and Pacific Northwest Coastal Habitats

This study investigates the potential impact of sea-level rise on key coastal habitats in the Pacific Northwest. In addition to raising awareness of the threat, the results of the study will assist coastal managers and other relevant decision-makers identify and implement strategies to minimize the risks. We used the Sea Level Affecting Marshes Model (SLAMM), which simulates the dominant processes involved in wetland conversions and shoreline modifications during long-term sea-level rise. This model was applied to 11 different sites in Puget Sound and along the Pacific Coast in southwestern Washington and northwestern Oregon.

Our analysis looked at a range of Intergovernmental Panel on Climate Change (IPCC) sea-level rise scenarios, from a 0.08 meter (3.0 inch) rise in global average sea level by 2025 to a 0.69 meter (27.3 inch) rise by 2100. We also modeled a rise of up to 2 meters (78.7 inches) by 2100 to accommodate for recent studies that suggest sea-level rise will occur much more rapidly during this century than the IPCC models have projected. Results for each study site are based on relative sea-level rise for the given region, taking into consideration regional changes in land elevation due to geological factors, such as subsidence and uplift, and ecological factors such as sedimentation and marsh accretion. Full model results are available from the National Wildlife Federation.

Projected Habitat Changes

Model results vary considerably by site (see Table 1), but overall the region is likely to face a dramatic shift in the extent and diversity of its coastal marshes, swamps, beaches, and other habitats due to sea-level rise. For example, if global average sea level increases by 0.69 meters (27.3 inches), the following impacts are predicted by 2100 for the sites investigated:

- Estuarine beaches will undergo inundation and erosion to the tune of a 65 percent loss.
- As much as 44 percent of tidal flat will disappear.
- 13 percent of inland fresh marsh and 25 percent of tidal fresh marsh will be lost.
- 11 percent of inland swamp will be inundated with salt water, while 61 percent of tidal swamp will be lost.
- 52 percent of brackish marsh will convert to tidal flats, transitional marsh and saltmarsh.
- 2 percent of undeveloped land will be inundated or eroded to other categories across all study areas.

Table 1. Summary of Results With a 27.3-inch Global Sea-level Rise by 2100	
	Changes to Coastal Habitats (Percentage Changes are Relative to Totals for Each Site)
Site 1: Nooksack Delta, Lummi Bay, and Bellingham Bay	Due to the presence of dikes at this site and relatively high dry land elevations, the majority of effects occur in wetlands southwest of Marietta (Nooksack River Delta), where areas of dry land, swamp, and fresh marsh are likely to transition to saltmarsh. Changes include a 22-percent loss of swamp (including tidal swamp), a 22-percent loss of brackish marsh, and a 42-percent loss of estuarine beach.
Site 2: Padilla Bay, Skagit Bay, and Port Susan Bay	Much of the dry land for this site is protected by dikes and is not subject to inundation. This means that brackish marshes and beaches that are trapped against seawalls may be especially subject to loss, largely through conversion to saltmarsh or tidal flat. By 2100, brackish marsh is projected to decline by 77 percent, and estuarine beach by 91 percent.
Site 3: Whidbey Island, Port Townsend, and Admiralty Inlet	74 percent of brackish marsh, 29 percent of inland fresh marsh, and a small portion of low-lying dry lands at this site are predicted to be inundated with salt water and converted to saltmarsh and tidal flat. A combination of inundation and erosion is predicted to have significant effects on beaches, especially on western Whidbey Island. This site as a whole is projected to see a 72-percent loss of estuarine beach by 2050 and 80-percent loss by 2100.
Site 4: Snohomish Estuary and Everett	Assuming that the extensive dikes in this area are able to withstand the predicted increases in sea-level rise, the most significant change is the inundation of brackish marsh (47-percent loss) and inland fresh marsh (15-percent loss) north of Smith Island and west of Marysville. The region also faces a 74-percent loss of tidal swamp and a 96-percent loss of estuarine beach.
Site 5: Ediz Hook near Port Angeles through Dungeness Spit and Sequim Bay	Tidal flats at this site are extremely vulnerable, as is Dungeness Spit itself, especially to higher sea-level rise scenarios in which complete loss of the spit is predicted. Additionally, over 58 percent of area beaches (estuarine and ocean together) are predicted to be lost by 2100 under all scenarios.
Site 6: Dyes Inlet, Sinclair Inlet, and Bainbridge Island	Most dry land in this portion of Puget Sound is of sufficient elevation to escape conversion even in the more aggressive sea-level rise scenarios. Over half of beach land is predicted to be lost, however, primarily converted to tidal flats. Saltmarsh and transitional marsh increase, primarily due to loss of dry land.
Site 7: Elliott Bay and the Duwamish Estuary	Limited effects are predicted for the Seattle area due to a higher density of development and high land elevations overall. However, 300-400 hectares (741-988 acres) of dry land are predicted to be at risk of being converted to transitional marsh, saltmarsh, and tidal flats. In addition, 55 percent of estuarine beach at this site could be lost by 2100 under this scenario.

Table 1. (Continued)	
	Changes to Coastal Habitats (Percentage Changes are Relative to Totals for Each Site)
Site 8: Annas Bay and Skokomish Estuary	High land elevations for dry land and swamp make this site less likely to be influenced by sea-level rise than many of the other sites studied. Even beaches are predicted to have fewer effects than at other sites with roughly one-third lost under all scenarios.
Site 9: Commencement Bay, Tacoma, and Gig Harbor	The Tacoma area is well protected by dikes around the Puyallup River, so results of sea-level rise are limited near that river. Three to four percent of undeveloped land is predicted to be lost at this site overall, though, converting to transitional marsh and saltmarsh. Over two-thirds of area beaches are predicted to be lost by 2100 due to erosion and inundation.
Site 10: Olympia, Budd Inlet, and Nisqually Delta	The largest predicted changes for this site pertain to the loss of estuarine beach and the inundation of some dry lands. Estuarine beach, in particular, declines by 81 percent. As with the other sites, all developed lands (including Olympia) are assumed to remain protected.
Site 11: Willapa Bay, Columbia River, and Tillamook Bay	This region is predicted to lose at least 5,000 hectares (12,355 acres) of dry land. There is also likely to be extensive loss of tidal flat and area beaches, especially at higher rates of sea-level rise. Inland and tidal fresh marsh are fairly vulnerable at this site to salt-water inundation. By 2100, the site could lose 32 percent of brackish marsh, 31 percent of tidal swamp, 47 percent of estuarine beach, and 63 percent of tidal flats.

Impacts on Fish and Wildlife

Given the complexity of the Pacific Northwest's coastal and marine systems and the multitude of factors affecting them, it is impossible to know exactly what sea-level rise will mean for the region's fish and wildlife in the decades to come. However, there is no question that these projected changes would fundamentally alter the region's coastal habitats and the species they support. Some species may be able to respond to changes by finding alternative habitats or food sources, but others will not. Furthermore, the larger the changes and rate of change, the harder it will be for most fish and wildlife species to adapt to the impacts of global warming (Inkley, 2004).

For example, a significant reduction in the area of estuarine beaches would affect important spawning habitat for forage fish, which make up a critical part of the marine food web. Unless species are able to find alternative spawning areas, their populations could decline. Inundation of tidal flats in some areas would reduce stopover and wintering habitat for migratory shorebirds. It could also have a major impact on the region's economically-important shellfish industry. Loss of coastal marshes would affect habitat for thousands of wintering waterfowl that visit the region each year. And changes in the composition of tidal wetlands could significantly diminish the capacity for those habitats to support salmonids, especially juvenile Chinook and chum salmon.

Box 1. Examples of Species at Risk	
Salmonids:	Chinook salmon, chum salmon, coho salmon, pink salmon, cutthroat trout, bull trout
Forage Fish/Other Finfish:	Pacific herring, surf smelt, sand lance/Pacific cod, walleye pollock, Pacific hake, lingcod, English sole, rock sole, black rockfish, brown rockfish, copper rockfish, quillback rockfish, starry flounder
Shellfish:	Littleneck clams, geoduck clams, butter clams, Olympia oysters, Dungeness crabs
Waterfowl/Seabirds:	Canvasbacks, greater and lesser scaup, goldeneyes, buffle-head, gadwalls, American wigeon, mallards, northern pintails, green-winged teal, snow geese, brant/surf scoters, common murres, pigeon guillemots, marbled murrelets, Caspian terns, rhinoceros auklets, brown pelicans
Shorebirds:	Dunlin, least sandpipers, western sandpipers, western snowy plovers, black-bellied plovers, killdeer, short– and long-billed dowitchers, red knots, sanderlings, greater yellowlegs, whimbrels, and black turnstones
Marine Mammals:	Harbor seals, Stellar sea lions, sea otters, orcas

Additional Climate and Non-climate Stressors

Sea-level rise is just one of the ways in which global warming will affect the region's coastal ecosystems. Other changes associated with global warming – including heavier rainfall events, lower average snowpack, and higher water temperatures – also will have a considerable impact on the region's coastal habitats. For example, changes in freshwater flows into coastal waters are likely to alter salinity, water clarity, stratification, and oxygen levels. In addition, higher water temperatures in Puget Sound and the Pacific Ocean could exacerbate the impact of excess nutrient runoff into coastal waters, enhancing harmful algal blooms and hypoxia events.

Moreover, these impacts will fall on top of the numerous other stressors that threaten the region's coastal resources as the human population grows. If our conservation goal is to restore and protect the ecological health of Puget Sound and coastal Washington and Oregon now and for the future, then we must take these potentially devastating problems associated with global warming into consideration in our conservation plans.

Ducks over Puget Sound (iStock)

Implications for Coastal Management and Restoration

The most important action the region and nation must take to prevent the possibly overwhelming loss of fish and wildlife due to unmitigated global warming is to reduce greenhouse gas emissions. However, there will be some more warming in the next century that we cannot avoid, and this warming will have a significant impact on local species and habitats. Thus, we must also develop adaptation strategies to help fish and wildlife cope with the expected changes to their habitats, including some sea-level rise, as we build in the flexibility to deal with unforeseen impacts.

Coastal managers must consider a multitude of factors in their planning efforts, including local ecology and geography, pollution inputs, climate variability and change, population growth, and development trends. By examining the intersection of two important pieces of the coastal management puzzle – sea-level rise and critical coastal habitats – it is our hope that this study will provide coastal resource managers and other relevant decision-makers with much-needed information about local impacts of sea-level rise on the wildlife of the Pacific Northwest. The results of this study, along with information about other critical stressors on coastal resources, can help decision-makers assess the risks to specific localities and identify reasonable steps to manage these risks.

The potential for significant shifts in critical habitat due to sea-level rise illustrated in this report, as well as other likely global warming impacts on fish and wildlife, make it prudent to consider global warming in planning future use of coastal resources. This should include the following:

1. ***Account for global warming in habitat restoration efforts.*** Many efforts are already underway to restore and protect coastal habitats in the Pacific Northwest. Addressing non-climate stressors will help wildlife survive global warming, but explicit consideration of sea-level rise and other climate change impacts will be necessary to ensure that potentially devastating long-term threats do not become a foregone conclusion. There are several strategies that restoration managers should consider, including prioritizing projects based on ecological importance and vulnerability to sea-level rise; expanding the area of restoration to accommodate for habitat migration; restoring a diverse array of habitat types; and addressing upstream stressors that affect sedimentation and other factors that affect how estuarine habitats will respond to sea-level rise.

2. ***Explicitly consider climate uncertainties***. Projections of future climate will always be accompanied by some degree of uncertainty, but this should not be used as an excuse for inaction. In fact, the risk of irreversible damages due to global warming necessitates a precautionary approach to action, much like that applied to anticipating flood hazards.

3. ***Incorporate sea-level rise in coastal development plans.*** Sea-level rise and its impacts on habitats and coastal communities should be a major consideration in future development plans. Many steps can be taken to anticipate sea-level rise, including discouraging development in coastal hazard areas, moving or abandoning shoreline infrastructure, preserving ecological buffers to allow inland habitat migration, and enhancing shoreline protection recognizing the negative consequences for shoreline habitat.

Ultimately, coastal management decisions must be made in a coordinated, collaborative way at both the local and regional levels. By taking a longer-term, more comprehensive approach to managing and protecting the coastal resources of the Pacific Northwest, we have a real opportunity to prevent the worst-case scenarios from occurring and ensure that the region's treasured natural heritage will endure for generations to come.

INTRODUCTION

The Pacific Northwest is a place rich in history, culture, and natural beauty. Its mere mention evokes images of snow-capped mountains, stately evergreens, scenic rivers, and rugged coasts. The region is also blessed with an amazing diversity of coastal habitats, from rocky bluffs and sandy beaches along the Pacific Coast to the tidal flats, marshes, mixed sediment beaches, and eelgrass beds of Puget Sound. Together, these habitats support thousands of species of fish and wildlife, and they are important for the regional economy and quality of life.

Some of the region's most important and productive habitats are in its low-lying river deltas and estuaries – the places where rivers and streams meet the sea. Numerous species of shorebirds and migratory waterfowl rely on the shallow waters, tidal flats, and coastal fresh marsh and saltmarshes of estuaries to feed and rest. Estuarine beaches provide vital spawning areas for forage fish, including surf smelt and sand lance, which in turn provide food for birds, marine mammals, salmon, and other fish and wildlife. Thousands of invertebrates, including commercially important oysters and clams, thrive in the mud flats and gravel beds. In addition, estuaries provide critical habitat for juvenile salmon, which spend time there as they acclimate to ocean water.

Unfortunately, the majority of the region's coastal wetlands and other estuarine and nearshore habitats have been damaged or destroyed by human activities. According to the Washington State Department of Natural Resources (WADNR), 70 percent of tidally-influenced wetlands in Puget Sound have been damaged or destroyed by urbanization, port development, industrial and agricultural activities, dredging and filling (WADNR, 1998). In addition, an estimated one-third of Puget Sound's shoreline has been modified by seawalls, bulkheads, and other structures.

Seawall at Alki Beach in Seattle (Chas Redmond, Flickr.com)

Similar problems have affected Pacific Coast estuaries in both Washington and Oregon. Habitats of the Columbia River estuary, in particular, have been significantly altered since the mid-1800s due to extensive dredging, construction of dikes, and other development (Independent Scientific Advisory Board, 2000). Furthermore, in many of these areas, upstream activities such as flood control and installation of dams for hydroelectric power have dramatically disrupted the natural flow of river sediments into deltas. And the loss of pollutant-filtering coastal wetlands has contributed to a considerable decline in regional water quality, especially in parts of Puget Sound.

In recent years, growing signs that the ecological health of the region is in serious decline have bolstered numerous efforts to better protect and restore these important coastal habitats and the fish and wildlife that depend on them, including localized community- and tribal-based projects as well as broad, collaborative government- and stakeholder-driven strategies. Increased investments in land acquisition and habitat restoration, improved watershed planning, and stronger shoreline management have offered considerable hope that, at least in some places, the situation may be turning around (Puget Sound Action Team, 2007).

For the region as a whole, however, there are still many indicators of a continuing decline in the health of its coastal and marine systems, which underscores the need for a more concerted conservation strategy. In particular, success will strongly depend on how well the region is able to promote more-sustainable use of its coastal resources in the face of continued population growth, pressures for development and now, the very real threat of global warming.

CLIMATE CHANGE AND SEA-LEVEL RISE

Human-enhanced global warming poses a serious threat to the world's natural systems, including those in the Pacific Northwest. According to the IPCC, there is irrefutable evidence that human activities, particularly the burning of fossil fuels and destruction of the world's forests, have been causing excessive amounts of carbon dioxide (CO_2) and other greenhouse gases to build up in the atmosphere (IPCC, 2007a). As a result, the earth's average surface temperature is rapidly increasing, and the IPCC projects that it will rise by another 1.1.-6.4 degrees Celsius (2-11.5 degrees Fahrenheit) before the end of this century if the nation and world continue to depend extensively on fossil fuels to meet our energy needs. This warming is disrupting the planet's entire climate system. Average water temperatures are becoming warmer, precipitation patterns are changing, and extreme weather events such as droughts, floods, storms, and heat waves are becoming more frequent and severe.

Rocky shoreline along Puget Sound (iStock)

Like many regions, the Pacific Northwest is already beginning to feel the effects of global warming. According to a recent report prepared by the Climate Impacts Group at the University of Washington, the Puget Sound region warmed 1.3 degrees Celsius (2.3 degrees Fahrenheit) during the 20th century, a rate "substantially greater than the global warming trend" (Snover, et al., 2005, p. 13).

In addition, the dates of peak snow accumulation and snowmelt-derived streamflow across the West have shifted by 10-30 days earlier over the past century, and average snowpack has declined significantly (Steward, Cayan and Dettinger, 2004). The Cascades, for example, have seen a 30-percent decline in springtime snow water equivalent (the amount of water contained within snowpack) since 1945 (Mote, et al., 2005). Without a significant reduction in the pollution that is contributing to global warming, the Pacific Northwest could face even less winter snow accumulation, earlier peak spring streamflows, lower summer streamflows, and elevated water temperatures.

In addition to disrupting the planet's climate system, global warming is causing sea levels around the world to rise due to a combination of thermal expansion of the oceans and rapidly melting glaciers and polar ice sheets. The global average sea level has already risen about 0.17 meters (6.7 inches) over the past century, which is about 10-times faster than the rate of sea-level rise over the last 3,000 years (IPCC, 2007a). The rate of sea-level rise is expected to accelerate during this century. Projections vary, but the most recent projections from the IPCC report show an additional 0.18-0.59-meter (7-23-inch) rise in global average sea level by 2090-2099 relative to 1980-1999 (IPCC, 2007a).

At the localized level, the relative amount of sea-level rise depends on a number of factors that contribute to vertical land movements, including tectonic processes (subsidence and uplift) as well as sedimentation and marsh accretion (discussed in the following section) (Park, Lee, and Canning, 1993). Uplift, deposition of sediments, and marsh accretion lessen the amount of localized sea-level rise, while subsidence exacerbates the amount of localized sea-level rise. Studies of vertical land movement based on changes in tide gage records show the Puget Sound basin subsiding at rates up to 2.0 millimeters (0.08 inches) per year, while the Pacific Ocean coast along the upper Olympic Peninsula in Washington is uplifting at rates up to 2.5 millimeters (0.1 inches) per year (Canning, 2006).

There are also apparent differences in vertical land movement within Puget Sound, with more subsidence occurring in southern Puget Sound than further north. For example, at Friday Harbor in the San Juan Islands, vertical land movement is close to zero, which means that the rate of sea-level rise at this site (from 1935 to present) has been equal to the global average. In Seattle, on the other hand, land has been subsiding at a rate of about 1.4 millimeters (0.06 inches) per year, which makes the rate of sea-level rise for the area roughly double the global average.

It should be noted that there is currently some question about whether the local geological subsidence and uplift rates are linear in space and time (i.e., whether they will continue on the current trend into the foreseeable future) (Canning, 2007). These new findings have emerged subsequent to our modeling effort, so this project includes the historic rates of vertical land movement in the relative sea-level rise scenarios. For most areas, however, the changes are small, so this factor will not likely have a significant impact on the overall implications of sea-level rise on coastal habitats and infrastructure over the longer-term, particularly under the more aggressive sea-level rise scenarios.

In fact, scientists are becoming increasingly concerned that the rate of global sea-level rise in the future could actually be considerably greater than current projections. The latest literature indicates that the global rise in sea levels is progressing more rapidly than was previously assumed, perhaps due to the dynamic changes in ice flow ignored in the latest IPCC report's calculations. Several studies suggest that the rate of ice-sheet decline in Greenland and Antarctica has been accelerating in recent years and that the amount of sea-level rise will be even more pronounced in the future (Chen, Wilson, and Tapley, 2006; Otto-Bliesner, et al., 2006; Overpeck, et al., 2006; Rignot and Kanagaratnam, 2006). A paper in the journal *Science* suggests that, taking into account possible model error, a feasible range by 2100 might be 0.51-1.4 meters (20-56 inches) under a 5 degree Celsius (9 degree Fahrenheit) warming relative to 1990 levels, which is within the range of projected warming during this century (Rahmstorf, 2007).

Indeed, sea-level rise of this magnitude would have enormous global consequences. With a large portion of the world's population living in low-lying coastal areas, millions of people will be displaced by sea-level rise before the end of this century. One study, for example, projects that as many as 80 million people will be at risk from coastal flooding (compared to 14 million in the absence of climate change) by 2080 with a 3.3 degrees Celsius (6 degrees Fahrenheit) global warming (Parry, et al., 2001; Nicholls, 2004). This is likely to be particularly devastating for poor countries, the consequences of which should be of utmost concern; but there are also considerable risks closer to home.

Sea stars (iStock)

SEA-LEVEL RISE AND PACIFIC NORTHWEST COASTAL HABITATS

Sea-level rise poses a significant threat to Puget Sound and the Pacific Coast given the sheer extent of the region's shoreline mileage and the fact that some of the most important habitats for fish and wildlife are concentrated in the region's low-lying, tidally-influenced shores and estuaries. According to the 2005 report *Regional Nearshore and Marine Aspects of Salmon Recovery*, many factors determine the distribution pattern and composition of the region's coastal wetlands, tidal flats, seagrass beds, and other nearshore habitats, including their elevation relative to average sea level, inundation, dessication, wave scour, substrate type, and light penetration (Redman, Myers, and Averill, 2005). Sea-level rise will affect most of these factors, both directly and indirectly.

One of the primary ways in which sea-level rise will affect the region's coastal habitats is through sea-water inundation, which can increase the salinity of the surface and groundwater. Many coastal plant and animal species are adapted to a certain level of salinity, so prolonged changes can make habitats more favorable for some species, less for others. Sea-level rise will also contribute to the expansion of open water in some areas – not just along the coasts but also inland, where dry land can become saturated by an increase in the height of the water table. Furthermore, sea-level rise will lead to significant beach erosion and make coastal areas more susceptible to storm surges.

Coastal habitats to at least some extent may be able to accommodate moderate changes in sea level by migrating inland. However, the opportunity for inland migration throughout much of the region has been considerably reduced given the accelerating pace of sea-level rise and the fact that much of the region's coasts have been modified by dikes, seawalls, and other armoring. Coastal armoring can also alter the extent of beach erosion associated with wave action. This may be beneficial in terms of protecting coastal property, but it also limits natural beach replenishment. Similarly, for the region's river deltas, natural deposition of river sediments may enable at least some habitats to keep pace with sea-level rise. However, modifications such as dams and levees upstream in many of the region's river basins have significantly limited this sedimentation (Redman, Myers, and Averill, 2005). Site–specific studies are necessary to supplement the findings of this study to help determine how changes in sedimentation rates associated with upstream activities might affect the localized impacts of sea-level rise.

In terms of tidal marsh accretion, a study by Thom, et al. (2001) found that most marshes in the Pacific Northwest are generally keeping pace with the current rate of sea-level rise, although again, rates vary by location and the extent of coastal modifications such as diking, which can significantly limit the natural sedimentation and accretion processes. Site-specific factors such as soil types, vegetation types, and the amount of tidal influence are important in determining the potential for submergence of coastal wetlands. As with sedimentation, additional research on changes in accretion rates at the localized level will be important to inform on-the-ground management decisions to address the risks from sea-level rise (Cahoon, et al., 2006). It is also important to consider the likelihood that an accelerating rate of sea-level rise due to global warming will significantly limit the ability for marsh accretion in many areas to continue to keep pace with sea-level rise during this century (Morris, et al., 2002).

Damage associated with higher sea level and storm-generated waves during El Niño events illustrates the vulnerability of coastal habitats and property, as seen here on the coast of Oregon near Tillamook Bay. The image above is from October 1997, before storm damage. The image below is the same location on April 1998, after storm damage. (U.S. Geological Survey)

Shoreline and dune erosion

Projected Habitat Changes

This study provides the most comprehensive and detailed analysis to date of the potential impacts of sea-level rise on coastal habitats in the Pacific Northwest. We modeled how ten areas in Puget Sound, as well as the Pacific Coast from northeastern Oregon to southwestern Washington would respond to a variety of different sea-level rise scenarios. The model used for this study is called Sea Level Affecting Marshes Model, Version 5.0 (SLAMM 5.0), which was designed to simulate the dominant processes involved in wetland conversion and shoreline modification under long-term sea-level rise (Clough and Park, 2007). This model looks beyond the impacts based on coastal topography alone and assesses how sea-water inundation contributes to the conversion of one habitat type to another. It can also assess how much erosion may occur due to changes in wave action. For these reasons, it is an excellent tool for considering how sea-level rise will affect habitats important for the fish, birds, and other wildlife in the region.

The section of this report beginning on page 22 includes a more-detailed discussion of the model and sea-level rise scenarios used in this analysis, as well as maps and tables illustrating how each of the 11 study sites is affected under several of the scenarios: an increase of global average sea level of 0.28 meters (11.2 inches) by 2050, 0.69 meters (27.3 inches) by 2100, and 1.5 meters (59.1 inches) by 2100. Model results for the additional scenarios considered in this study are available from the National Wildlife Federation. The projections for habitat changes at each of the study sites incorporate differences in the relative sea-level rise for the given region by taking into consideration regional changes in land elevation due to geological factors, such as subsidence and uplift, and ecological factors, such as sedimentation and marsh accretion (see the Appendix). For some of the less developed sites with extensive dikes protecting agricultural and other dry lands, the model was also run without the dikes in place to help inform decisions about removing dikes, which is already happening in some areas as part of coastal restoration efforts.

Nearshore habitats in the region are likely to face a dramatic shift in their composition due to sea-level rise (see Table 2). Although there is considerable variability among different sites, the region's coastal landscape is projected to change in significant ways as some habitat types are lost and others expand. Many freshwater marshes and swamps will be converted to saltmarshes or to transitional marshes that experience frequent saltwater inundation. At the same time, significant losses in estuarine beaches, tidal flats, and ocean beach are expected across all scenarios.

Furthermore, because all coastal habitats are biologically, chemically, and physically linked, problems that affect even one habitat type is likely to affect the entire coastal system (Restore America's Estuaries, 2002). For example, estuaries and bays that experience a net loss in coastal marsh habitat are more likely to face declining water quality because marshes play a critical role in regulating nutrients and filtering pollutants. Algal blooms and other problems associated with excess runoff of nutrients such as nitrogen and phosphorus in coastal waters can cause significant harm to seagrass beds and contribute to hypoxia (low oxygen) events. These and other ecosystem shifts will have major impacts on the overall food web and on individual species, such as Chinook salmon, in ways that are not yet completely understood.

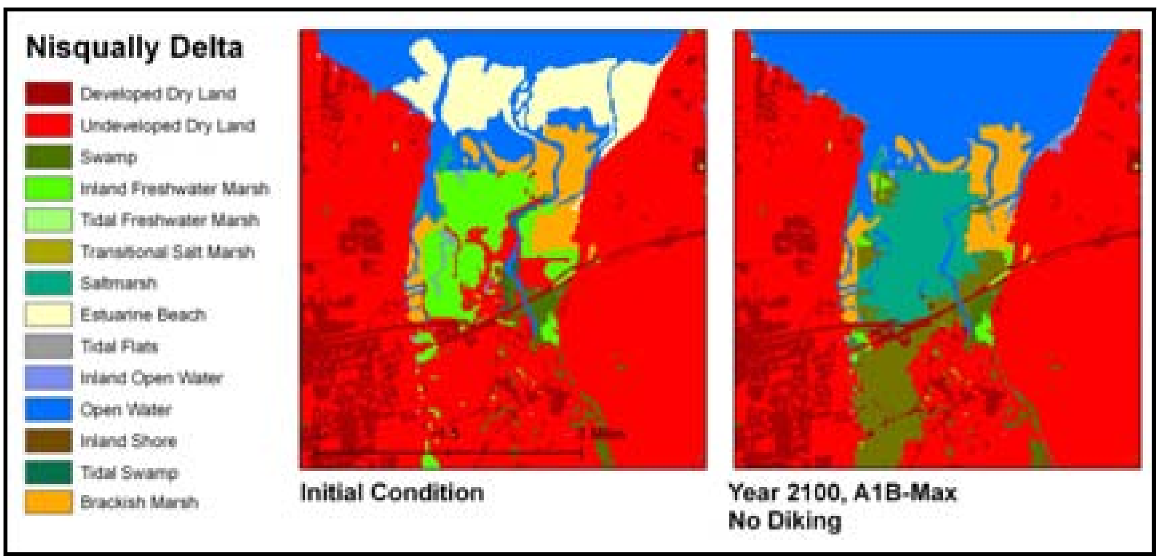
Inundation of Freshwater Ecosystems with Saltwater

As sea level rises, freshwater ecosystems will increasingly be vulnerable to saltwater intrusion and eventual conversion to saltwater ecosystems. Saltmarsh habitats are predicted to increase overall under all scenarios run, due to the conversion of dry land and fresh marsh to saltmarsh. For a 27.3-inch increase in sea level, the area of swamp, and inland and tidal fresh marsh will decrease by over 4500 hectares (over 11,200 acres) across all the study sites. At the same time, the area of saltmarsh will increase by over 3600 hectares (over 9800 acres). Transitional marsh, which is shrub marsh that is now regularly inundated but has not yet converted fully into saltmarsh, will also expand by over 7100 hectares (over 19,500 acres).

Most coastal plant and animal species are adapted to different levels of salinity, so prolonged changes in salinity can make habitats more favorable for some species, less for others. Even those species that may not be directly sensitive to salinity may be affected if their food mainstays are affected. Because the various coastal habitats are all connected in one way or another, changes in their composition will no doubt have consequences for the coastal ecosystems of which they are a part.

The Nisqually delta region, home to the Nisqually National Wildlife Refuge, is one place that is especially susceptible to saltwater inundation, especially if the existing dike structures – some of which are protecting freshwater marsh habitat – are removed (see Figure 1). It is difficult to predict how this salt water intrusion would affect the salmon and other species that are important to the region. As dikes are already being removed to aid salmon recovery, it will be important to consider how the likely results of sea-level rise will affect these sorts of restoration and conservation efforts.

Figure 1



Loss of Beaches and Tidal Flats

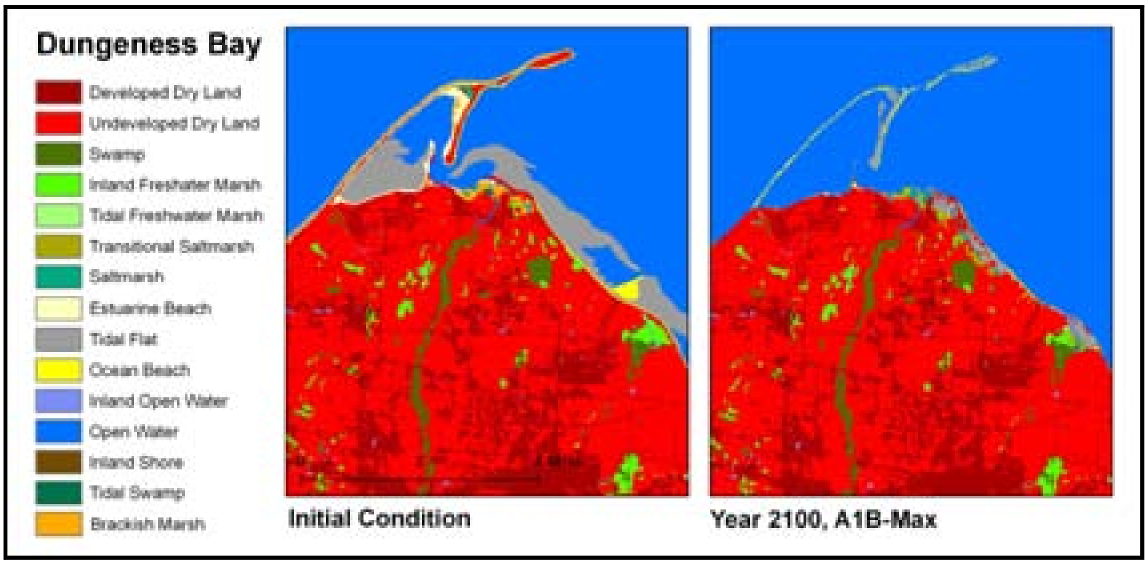
The beaches and tidal flats of the Pacific Northwest are especially vulnerable to rising sea-level over the next century. Under the 27.3-inch global average sea-level rise scenario, about 65 percent of estuarine beaches and 44 percent of tidal flats are lost across all study sites by 2100. In some locations, this will cause significant changes in the coastal landscape. For example, Dungeness Spit is predicted to be subject to inundation, erosion, and overwash due to storm events, leading to major losses of beach and tidal flat habitats (see Figure 2).

Table 2. Projections of Habitat Changes for All Sites Combined							
	Area of Habitat Type in Hectares (Acres)				Percentage Change (Relative to Totals Across All Sites)		
	Initial Condition	**2050 (+0.28 meters/11.2 inches)**	**2100 (+0.69 meters/27.3 inches)**	**2100 (+ 1.5 meters/ 59.1 inches)**	**2050 (+0.28 meters/11.2 inches)**	**2100 (+0.69 meters/27.3 inches)**	**2100 (+1.5 meters/59.1 inches)**
Undeveloped Dry Land	601,102 (1,485,355)	589,245 (1,456,056)	587,588 (1,456,056)	585,724 (1,447,356)	2% loss	2% loss	3% loss
Developed	89,717 (221,696)	89,717 (221,696)	89,717 (221,696)	89,717 (221,696)	No change	No change	No change
Swamp	18,518 (45,759)	17,786 (43,950)	16,511 (40,800)	15,418 (38,099)	4% loss	11% loss	17% loss
Inland Fresh Marsh	18,381 (45,420)	17,300 (42,749)	15,967 (39,455)	14,976 (37,007)	6% loss	13% loss	19% loss
Tidal Fresh Marsh	468 (1156)	383 (946)	352 (870)	329 (813)	18% loss	25% loss	30% loss
Transitional Marsh	56 (138)	5,020 (12,405)	7,181 (17,745)	3,874 (9,573)	8,940% expansion	12,832% expansion	6,878% expansion
Saltmarsh	6,701 (16,559)	13,655 (33,742)	10,324 (25,511)	11,470 (28,343)	104% expansion	52% expansion	71% expansion
Estuarine Beach	16,071 (39,712)	8,357 (20,651)	5,625 (13,900)	2,160 (5,337)	48% loss	65% loss	87% loss
Tidal Flat	24,369 (60,217)	20,227 (49,982)	13,548 (33,478)	14,408 (35,603)	17% loss	44% loss	41% loss
Ocean Beach	3,297 (8,147)	3,520 (8,698)	3,088 (7,631)	60 (148)	7% expansion	6% loss	98% loss
Inland Open Water	6,466 (15,978)	5,770 (14,258)	5,653 (13,969)	5,543 (13,697)	11% loss	13% loss	14% loss
Estuarine Open Water	220,767 (545,527)	232,941 (575,610)	245,728 (607,207)	254,304 (628,399)	6% expansion	11% expansion	15% expansion
Open Ocean	203,191 (502,096)	207,224 (512,062)	210,350 (519,786)	214,687 (530,503)	2% expansion	4% expansion	6% expansion
Brackish Marsh	3,030 (7,487)	1,801 (4,450)	1,443 (3,566)	576 (1,423)	41% loss	52% loss	81% loss
Inland Shore	123 (304)	120 (297)	120 (297)	118 (292)	3% loss	3% loss	4% loss
Tidal Swamp	748 (1,848)	346 (855)	292 (722)	186 (460)	54% loss	61% loss	75% loss
Rocky Intertidal	76 (188)	65 (161)	50 (124)	23 (57)	13% loss	34% loss	70% loss
Riverine Tidal	1,059 (2,617)	664 (1,641)	604 (1,493)	566 (1,399)	37% loss	43% loss	47% loss

Estuarine beaches are also critical spawning habitat for forage fish, including surf smelt and sand lance, which play a significant role in the entire marine food web. Adult salmon and other commercially important fish depend on these smaller fish as an important food source, as do numerous species of seabirds and other wildlife. In addition, many of these beaches provide important habitat for clams, mussels, and other shellfish, which are important to the region's ecology and economy.

Inundation of tidal flats will have a significant impact on the region as well. Thousands of shorebirds rely on tidal flats during their winter migration, drawing hundreds of birdwatchers to the coasts each year. In addition, tidal flats support numerous species of invertebrates, including clams, introduced oysters, snails, and crabs (Sound Science, 2007). While some areas could see an expansion of tidal flats under sea-level rise, regions where tidal flats currently play a critical role in the coastal ecosystem, such as the northern shore of the Olympic Peninsula in Puget Sound and Willapa Bay on the Pacific Coast, could face dramatic declines in the coming decades.

Figure 2

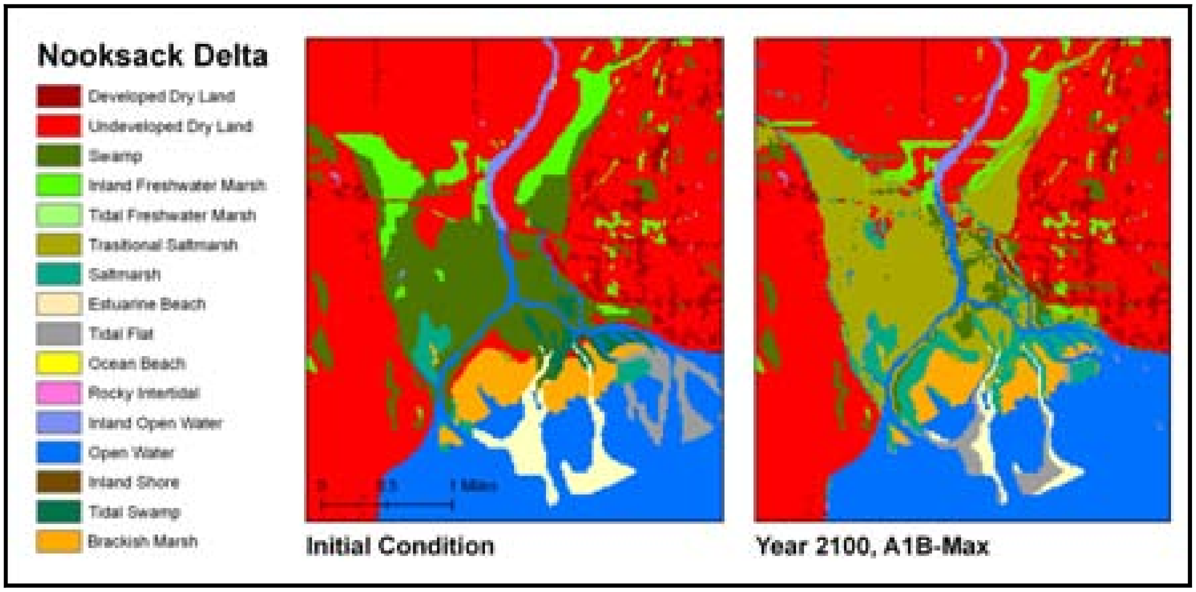


Impacts on the Regional Marine Food Web

Sea-level rise most critically affects the narrow nearshore region along the Pacific Northwest coasts. This nearshore region supports a wide diversity of wildlife, including species that spend their entire lives in the region and those that visit the region during certain times of the year to take advantage of the rich variety of food sources. Thus, the coastal habitats most-directly impacted by sea-level rise play an important role in the overall food web of the Pacific Northwest region more broadly.

Shifts in coastal habitats may even affect some of the large marine mammals that frequent the Pacific Northwest coasts. For example, Northern Puget Sound, including in particular the Nooksack Delta, supports a summer-time population of orcas. Yet this area is projected to undergo major changes in coastal habitats, with significant loss of beach and tidal flats along with large shifts from fresh-water to salt-water ecosystems (see Figure 3). If these changes lead to a loss in habitat for forage fish, which spawn on beaches, then there could be fewer food sources for salmon. With less salmon available to feed on, it is possible that orcas will prefer other locations where they can find more to eat. Of course, much more research is needed to fully understand the interplay among different species in the region today before we can begin to confidently predict such impacts.

Figure 3



As coastal managers and other relevant decision makers consider future steps to maintain and restore coastal habitats in the Pacific Northwest, it will be crucial that they take into account the potential effects of sea-level rise along with other human activities that might compromise the coastal ecology. This study investigates a number of scenarios for sea-level rise that might impact key coastal habitats in the Pacific Northwest, thereby providing important information for identifying and implementing strategies to minimize the risks.

Fish and Wildlife Species at Risk

Changes in the Pacific Northwest's coastal habitats due to sea-level rise will no doubt have a significant impact on the fish and wildlife species they support, although considerably more research is needed in the region to better understand the specific effects of climate change and sea-level rise on estuarine habitats, ecosystems, and species.

Translating the potential habitat changes into impacts on specific species is difficult, as there are many combined factors at play. However, it is reasonable to develop a general sense of those species that are particularly vulnerable given their relative dependence on the most-threatened habitats. The following overview of species at risk is by no means comprehensive, nor is it a "prediction" of what is to come; but it does signify the extent to which sea-level rise could affect the region's ecology.

Salmonids

One of the biggest concerns is how sea-level rise might affect the region's already-beleaguered salmonids. Nearshore ecosystems play a critical role in the life cycle of anadromous fish, many of which use coastal marshes and riparian areas for feeding and refuge as they transition between their freshwater and ocean life stages (see Table 3).

Historical loss of nearshore marine and estuarine habitats throughout Puget Sound and the Pacific Northwest Coast has already contributed to the significant decline in salmonid populations during the past century (Williams and Thom, 2001). It is likely that further declines and/or changes in the composition of coastal marshes and other habitats will make it much more difficult for the region to meet important salmon conservation goals. At particular risk are juvenile chum and Chinook salmon, which are considered to be the most estuarine-dependent species. For example, a recent analysis of sea-level rise in the Skagit Delta estimates that rearing capacity in marshes for threatened juvenile Chinook salmon would decline by

Table 3. Nearshore Marine and Estuarine Habitat Use by Salmonid Species in Pacific Northwest

	Nearshore Marine and Estuary Use		
Species	**Adult Residence**	**Adult and Juvenile Migration**	**Juvenile Rearing**
Chinook Salmon	**Extensive Use**	**Extensive Use**	**Extensive Use**
Chum Salmon	Little or Unknown	**Extensive Use**	**Extensive Use**
Coho Salmon	Some Use	**Extensive Use**	Some Use
Sockeye Salmon	Little or Unknown	**Extensive Use**	Little or Unknown
Pink Salmon	Little or Unknown	**Extensive Use**	**Extensive Use**
Cutthroat Trout	**Extensive Use**	**Extensive Use**	**Extensive Use**
Steelhead	Little or Unknown	**Extensive Use**	Some Use
Bull Trout	**Extensive Use**	**Extensive Use**	**Extensive Use**

Source: Williams, G.D. and R.M. Thom. 2001. *Marine and Estuarine Shoreline Modification Issues* (Sequim, WA: Battelle Marine Sciences Laboratory/Pacific Northwest National Laboratory), p. 14.

Chinook salmon fry (National Park Service)

211,000 and 530,000 fish, respectively, for a 45- and 80-centimeters (18- and 32-inch) sea-level rise (Hood, 2005). The projected changes are also likely to affect coho salmon, pink salmon, cutthroat trout, and bull trout, which depend on coastal marshes and other habitats for part of their life cycle (Williams and Thom, 2001).

Forage Fish and Other Finfish

Estuarine and ocean beaches are critical spawning habitat for forage fish, including Pacific herring, surf smelt, and sand lance, which play a major role in the entire marine food web. Adult salmon and other commercially important fish depend on these smaller fish for food, as do numerous species of seabirds and marine mammals. Across the study sites, estuarine beach is projected to decline by 65 percent by 2100 under the 0.69-meter (27.3-inch sea-level) rise scenario, and estuarine and ocean beaches decline by 87 and 98 percent, respectively, if sea-level rise reaches 1.5 meters (59.1 inches). If forage fish species unable to adapt to these changes by finding alternative spawning sites, the loss of these beaches could have a devastating impact on forage fish populations in the region, which would send ripple effects throughout marine ecosystem.

A number of other fish species are vulnerable to the loss of coastal marshes, seagrass beds, and tidal flats due to sea-level rise. Many groundfish species, including Pacific cod, walleye pollock, Pacific hake, lingcod, English sole, rock sole, black rockfish, brown rockfish, copper rockfish, quillback rockfish, and starry flounder, use nearshore marine habitats for residence and juvenile rearing (Williams and Thom, 2001).

Shellfish

The Pacific Northwest's coasts are home to a highly diverse array of native shellfish, including crabs, clams, oysters, mussels, shrimp, and abalone, which are important to the region's economy and ecology (Dethier, 2006). Shellfish rely on a number of different coastal habitat types throughout the region, particularly in the low- and mid-intertidal zone protected bays and estuaries. Direct loss of beaches and tidal flats in some areas will likely have a significant impact on intertidal species such as littleneck clams, geoduck clams, butter clams, and Olympia oysters. Changes in habitat composition in the region's estuaries may also contribute to a reduction in populations of Dungeness crabs, which depend on estuaries as nurseries.

Waterfowl/Seabirds

Changes in the extent and composition of marshes, beaches, and other estuarine and nearshore habitats are likely to have a significant impact on the region's wintering waterfowl populations. The Pacific Northwest's coasts support hundreds of thousands of migrating and wintering ducks, geese, and swans. According to the U.S. Fish & Wildlife Service (FWS), Tillamook Bay alone supports almost 25 percent of the northern- and central-coast wintering waterfowl population in Oregon (FWS, 2007). This area is projected to lose up to 500 hectares (1,235 acres) of inland fresh marsh and more than 4,100 hectares (10,131 acres) of estuarine beach by 2100 under the 0.69-meter (27.3-inch) sea-level rise scenario. The region's diving ducks, including canvasbacks, greater and lesser scaup, goldeneyes, and bufflehead, are considered to be especially vulnerable to reductions in habitat quality due to sea-level rise and other global warming impacts (Inkley, et al., 2004).

Loss of tidal flats in some areas would also affect dabbling ducks and geese that use those habitats, including gadwalls, American wigeon, mallards, northern pintails, green-winged teal, snow geese, and brant (Buchanan, 2006). In addition, reductions in forage fish and other food sources in the region due to sea-level rise could have a major impact on many seabirds, including surf scoters, common murres, pigeon guillemots, marbled murrelets, Caspian terns, rhinoceros auklets, and brown pelicans.

Shorebirds

Inundation of tidal flats, sand beaches, and rocky shoreline could cause a dramatic decline in populations of shorebirds that rely on these areas during their winter migration. While some areas are expected to see an expansion of tidal flats under sea-level rise, areas where tidal flats currently play a critical role in the coastal ecosystem, such as the northern shore of the Olympic Peninsula, Skagit Bay, Port Susan, and Padilla Bay in Puget Sound, and Willapa Bay and the Columbia River estuary on the Pacific Coast, are projected to face a significant reduction in important shorebird habitat in the coming decades (Drut and Buchanan, 2000). Some shorebird species at risk include dunlin, least sandpipers, western sandpipers, western snowy plovers, black-bellied plovers, killdeer, short– and long-billed dowitchers, red knots, sanderlings, greater yellowlegs, whimbrels, and black turnstones.

Marine Mammals

Many marine mammals in the Pacific Northwest are likely to be affected by sea-level rise both directly, through lost habitat, and indirectly, through reductions in important food sources. In particular, the loss of estuarine and ocean beaches would reduce important haul-out and pupping areas for harbor seals in Puget Sound. In addition, if sea-level rise contributes to significant declines in salmon, forage fish, and other critical foods, it could have a major impact on a number of marine mammals in the region, including otters, orcas, minke whales, and sea lions.

Additional Climate and Non-climate Stressors

Complicating matters is the fact that sea-level rise is not the only consequence of global warming that will affect the Pacific Northwest. The Climate Impacts Group at the University of Washington (Snover, 2005) has identified a number of other climate changes for the region that could have a significant impact on coastal habitats. For example:

- Decreased snowpack and earlier snowmelt are expected to contribute to lower summer streamflows, higher winter streamflows, and a change in the timing and extent of freshwater inputs into marine waters.
- An increase in the percentage of winter precipitation falling as rain rather than snow is likely to increase flooding in Puget Sound watersheds.
- Higher average water temperatures and changes in water and soil salinity could change the mix of plant species in coastal marshes and the viability of invertebrates that play a key role in the health of the marsh systems. Temperature-driven shifts in plankton could ripple throughout the food web, changing the composition of invertebrates, fish, and mammal communities.
- Increased algal productivity in surface waters and changes in coastal upwelling due to warmer ocean temperatures could exacerbate hypoxia events and lead to more-intense dead-zones off the Washington and Oregon coasts.

While it is beyond the scope of this study to address how these and other additional changes might affect coastal habitats and the fish and wildlife that depend on them, there is no question that they will have a profound impact on the region.

Moreover, these impacts will be experienced at the same time as the numerous other stressors that threaten the region's coastal resources as the human population grows. Without meaningful action to address these multiple threats the future of the region's coastal habitats, the fish and wildlife they support, and the livelihoods and quality of life of the people who depend on them will be dramatically and irretrievably different from what they are today.

IMPLICATIONS FOR COASTAL MANAGEMENT AND RESTORATION

The year 2100 may seem like a long way off, but the reality is that we are making decisions today that will ultimately affect our natural resources, land use, and even our climate well beyond that time. Fortunately, we also have an opportunity to anticipate, minimize, and sometimes prevent some serious problems in the future – including those related to global warming – by taking a longer-term, more comprehensive approach to managing our resources today (Bauman, et al., 2006).

In devising strategies that balance competing demands for coastal resources now and in the future, relevant decision makers must consider how numerous factors will influence coastal habitats, water resources, and infrastructure. Effective coastal management requires the integration of diverse information, from projected climate change and ecological impacts to expected regional population growth and future development patterns. Recent advances in scientific understanding of the regional and localized consequences of global warming and the vulnerability of species and ecosystems will go far in helping people develop and promote appropriate solutions.

By examining the intersection of two important pieces of the coastal management puzzle – sea-level rise and critical coastal habitats – this study provides resource managers and other relevant decision makers with much-needed information. The model results illustrating likely habitat conversions under probable sea-level rise scenarios can help individuals assess the risks to specific localities and identify reasonable steps to manage these risks. The appropriate response strategies will vary from region to region, taking into account results from this study along with other studies to identify more localized impacts of sea-level rise and examine the impacts of additional stressors on coastal resources.

Changing the Forecast for Coastal Habitats: A Plan of Action

The most important action the region and nation must take to prevent the possibly overwhelming loss of fish and wildlife due to global warming is to reduce greenhouse gas emissions (see Box 2). However, there will be some more warming in the next century due to the greenhouse gases that are already in the atmosphere along with those that will inevitably be emitted in the next few decades as we transition to new greener technologies.

The unavoidable warming of the next century will have a significant impact on fish and wildlife, making it necessary to develop adaptation strategies to help species cope with those changes that are inevitable, including some sea-level rise, as well as to build in the flexibility to deal with some significant impacts that may be unforeseen. In particular, it will be critical to account for global warming in habitat restoration efforts, explicitly consider climate-related uncertainties in coastal management, and anticipate sea-level rise when planning for coastal development. The National Wildlife Federation recommends consideration of the following general principles for coastal management given the threat of sea-level rise:

Habitat restoration in the Nisqually National Wildlife Refuge (U.S. Fish & Wildlife Service)

1. Account for Global Warming in Habitat Restoration Efforts

There are numerous efforts currently underway to restore and protect the Pacific Northwest's coastal habitats and the species they support. The increased emphasis on ecosystem-based approaches in many of these plans and programs will no doubt help the region deal with the multitude of stressors at play, including global warming. In some cases, continuing to focus attention on non-climate stressors will also make the region's coastal ecosystems much more resilient to the effects of global warming. For example, efforts to remedy habitat fragmentation will enable wildlife to move more easily to a new location if the current one is no longer suitable due to climate shifts. Likewise, reducing sources of water and air pollution will make wildlife better able to withstand climate-related stressors.

However, failure to also explicitly take the impacts of sea-level rise and other global warming impacts into consideration in coastal restoration and protection plans will make it much more difficult, if not impossible, to meet our important conservation goals (Battin, et al., 2007). For example, most salmonid species, which have been the focus of restoration efforts for many years, rely extensively on nearshore marine and estuarine habitats. Yet across all sites examined in this study, there is likely to be a 65-percent loss of estuarine beach, a 44-percent loss of tidal flats, and extensive conversion of coastal fresh and brackish marsh to transitional and saltmarsh if sea level rises 0.69 meters (27.3 inches). These changes will have a significant impact on the ecological function of coastal systems. Successful management of

Box 2. Minimizing the Threat:
The Importance of Reducing Greenhouse Gas Emissions

Scientists are optimistic that the impacts of global warming can be lessened if significant action is taken within the next few decades to reduce the emissions of CO_2 and other greenhouse gases to stabilize their concentrations in the earth's atmosphere (IPCC, 2007b). However, it is important that we take meaningful steps to reduce global warming pollution as soon as possible. Once released, CO_2 stays in the atmosphere for decades, and the more that its concentration builds up, the more global warming will occur.

There is also a growing concern that the planet may well be nearing a tipping point in terms of the levels of greenhouse gases in the atmosphere, which will lead to extensive and irreparable changes to the planet's climate system (Hansen, 2004). Furthermore, without strong policy signals soon, we are likely to see significant additional investments in carbon-intensive infrastructure, which will make it much less likely that we will be able to meet this stabilization goal in the decades to come.

Scientists suggest that the worst-case scenario can only be avoided if we are able to keep additional warming to less than 2 degrees Celsius (3.6 degrees Fahrenheit) above pre-industrial levels (Hansen, 2004; O'Neill and Oppenheimer, 2002). To date, temperatures have already increased by 0.7 degrees Celsius (1.3 degrees Fahrenheit). According to the latest assessment by the IPCC, keeping global warming to within 2 degrees Celsius (3.6 degrees Fahrenheit) would require stabilizing the concentration of greenhouse gases in the atmosphere at 445-490 parts per million (ppm) of CO_2 equivalent (IPCC, 2007b). To reach this level, the growth in global greenhouse gas emissions will need to be halted within the next ten years and overall emissions cut by 50-85 percent below current levels within the next 50 years. For industrialized nations, particularly the United States, this will mean a reduction of 80 percent by mid-century, followed by further reductions toward zero by 2100.

Fortunately, the IPCC confirms that this target can be achieved "by deployment of a portfolio of technologies that are currently available and those that are expected to be commercialized in coming decades" (IPCC, 2007b, p. 25). If we start today, the United States can meet the goal of 80-percent reductions by 2050 by cutting our global warming pollution just 2 percent per year, but it will require significant policy action. An effective federal plan of action is needed to fundamentally shift the nation's energy priorities to provide incentives for investments in energy efficiency and cleaner, renewable energy technologies. The plan should include:

- Placing mandatory limits on the nation's global warming pollution.
- Making bold investments in clean and efficient energy technologies and phasing out coal and oil subsidies.
- Enacting new standards that provide incentives for renewable energy sources.
- Encouraging market-based solutions.

There are also a number of local, state, and regional actions that will make a difference. Washington and Oregon are taking an important step by setting goals to significantly reduce their greenhouse gas emissions within the next few decades and engaging with other western states to develop a regional climate change mitigation strategy. These actions establish an important foundation on which to build a meaningful strategy at the federal level.

the salmonid populations will clearly require a careful assessment of the impacts of sea-level rise and other climate changes. There are several things that restoration project managers should consider to improve the resiliency of habitats to withstand some sea-level rise, including:

- Prioritizing project sites based on ecological importance as well as vulnerability to sea-level rise.
- Expanding the area of restoration to accommodate for habitat migration.
- Restoring a diverse array of habitat types to better support ecosystem functions and improve the resiliency of fish and wildlife species.
- Considering upstream stressors that may affect sedimentation rates and other factors that affect how estuarine habitats respond to sea-level rise.

2. Explicitly Consider Climate Uncertainties

By its very nature, there will always be a degree of uncertainty about how, when, and where global warming will affect natural systems. Increased monitoring and research on the known and potential impacts on species and habitats will help close the gap in knowledge, but we will never know exactly when and where we will experience the impacts. That does not mean we shouldn't act. Rather, the very fact that there is risk – and the potential for global warming to lead to irreversible damages, such as the extinction of species – necessitates precautionary action. It is prudent to consider actions we can take now that will reduce our vulnerability as well as how to incorporate useful measures of uncertainty into our decision making.

One way to think about dealing with the risks from sea-level rise is to address the problem in a way similar to how we respond to flood hazards (Canning, 2001). When relatively little is at stake in the way of infrastructure investment, public inconvenience, or risk, we could choose to design for a conservative or low-end sea-level rise scenario. Where more is at stake, such as the decimation of habitats critical to the region's ecological and economic well-being, we should design for a mid-range or aggressive sea-level rise scenario. It may also be possible to hedge against significant losses by creating coastal habitat buffers and restoring a diversity of habitat types – much like one would diversify an investment portfolio (Hood, 2005).

3. Incorporate Sea-level Rise in Coastal Development Plans

Sea-level rise should be a major consideration in future coastal development plans, both in terms of the impacts on habitats and those on human settlements. The model simulations in this study can usefully inform decisions about coastal development. For example, by comparing the impacts of sea-level rise on habitats with and without dikes, it is possible to make a more informed decision about future shoreline protection strategies. Indeed, removing the dikes from the four sites tested in this study allows greater expansion of tidal flats at these sites. On the other hand, elimination of dikes allows significantly greater inundation of dry land. These are tradeoffs that coastal managers will need to consider.

Many other steps can be taken to anticipate sea-level rise when planning for coastal development. A recent conference organized by King County, Washington, brought together government officials, business and tribal leaders, scientists, farmers, non-governmental organizations, and other relevant stakeholders from across the region, to engage in a dialogue about climate change impacts and ways in which different sectors can anticipate, mitigate, and adapt to those impacts (Kay, 2005). Participants in the Coastal Areas Breakout Session identified a number of possible strategies to protect coastal habitats and infrastructure from sea-level rise, including:

- Discouraging development in coastal hazard areas.
- Moving or abandoning shoreline infrastructure.
- Preserving ecological buffers to allow inland habitat migration.
- Enhancing shoreline protection, recognizing the negative consequences for shoreline habitat.

For shorelines that are not already constrained by coastal armoring, one possible strategy for enhancing the resiliency of coastal habitats to sea-level rise is to establish "rolling easements." A rolling easement is a type of easement placed along the shoreline that prevents the development of bulkheads or other structures to hold back sea-level rise but allows other development activities. As sea-level rises, the easement is automatically rolled farther inland, enabling some habitat types to migrate (NOAA, 2006).

For highly-sensitive and ecologically important areas, however, it may be necessary to apply stronger coastal zoning regulations, mandatory setbacks, and other building restrictions along the shore, or consider public and/or private land acquisition. Another strategy would be to eliminate federal and state subsidies that promote coastal development and defense, such as through federal flood insurance (Reid and Trexler, 1991). Ultimately, these are decisions that must be made in a coordinated, collaborative way at both the local and regional levels.

Protected area along Port Susan Bay (Brewbooks/flickr.com)

MODEL DESCRIPTION AND DETAILED RESULTS

The National Wildlife Federation engaged sea-level rise modeling expert Jonathan Clough, of Warren Pinnacle Consulting, Inc., to simulate how sea-level rise during this century would affect coastal habitats in ten areas in Puget Sound as well as the Pacific Coast from northeastern Oregon to southwestern Washington (see Figures 4 and 5). While there have been several past studies of sea-level rise in the Pacific Northwest (see, for example, Shipman, 1989; Park, Lee and Canning, 1993; Craig, 1993; Galbraith, et al., 2005; and Hood, 2005), this study provides the most comprehensive and detailed analysis to date of the potential impacts of sea-level rise on the region's coastal habitats.

Project Background

The model used for this analysis is called Sea Level Affecting Marshes Model, Version 5.0 (SLAMM 5.0), which was designed to simulate the dominant processes involved in wetland conversion and shoreline modification under long-term sea-level rise. The model integrates information about projected global sea-level rise with area-specific NOAA tidal data, detailed wetland information from the FWS National Wetlands Inventory, regional Light-imaging Detection and Ranging (LiDAR) data, and U.S. Geological Survey (USGS) Digital Elevation Maps to project habitat changes associated with sea-level rise. Table 5 lists the coastal habitats included in the model.

This model provides greater detail than by just looking at static coastal topography alone. For example, it can assess the extent to which sea water inundation contributes to the conversion of one habitat type to another based on elevation, habitat type, slope, sedimentation and accretion and erosion rates, and the extent to which the affected area is protected by existing sea walls. It can also assess how much erosion may occur due to changes in wave action.

In addition, SLAMM 5.0 accounts for relative sea-level change for each study site. Relative sea-level rise is calculated as the sum of the historic eustatic (global average) trend, the site specific rate of change of coastal elevation due to subsidence and isostatic adjustment, and the accelerated rise, depending on the future scenario chosen. Sea-level rise is also offset by sedimentation and accretion, again using site specific average values.

Model Summary

A thorough accounting of how SLAMM 5.0 works and the underlying assumptions and equations is available in the *SLAMM 5.0 Technical Documentation* (Clough and Park, 2007). Within SLAMM 5.0, five primary processes can affect wetland fate under different scenarios of sea level rise:

- **Inundation:** The rise of water levels and the salt boundary are tracked by reducing elevations of each modeled area as sea levels rise, thus keeping mean tide level (MTL) constant at zero. The effects on each cell are calculated based on the minimum elevation and slope of that cell [cell size is 30 meters (98 feet) by 30 meters for this study].

- **Erosion:** Erosion is triggered based on a threshold of maximum fetch (the distance a wave travels) and the proximity of the marsh to estuarine water or open ocean. When these conditions are met, horizontal erosion occurs at a rate based on site-specific parameters.
- **Overwash:** Barrier islands of under 500 meters (1,640 feet) width are assumed to undergo overwash (the process by which sediments are carried over the crest of the barrier and deposited onto adjacent wetlands) during each 25-year time-step due to storms. Beach migration and transport of sediments are calculated.
- **Saturation:** Coastal swamps and fresh marshes can migrate onto adjacent uplands if the water table is affected by rising sea level close to the coast.
- **Salinity:** In a defined estuary, the effects of salinity progression up an estuary and the resultant effects on marsh type may be tracked. This optional submodel assumes an estuarine salt wedge and calculates the influence of the freshwater head vs. the saltwater head in a particular cell. (The salinity feature was not used in the Puget Sound/Pacific Coast modeling.)

The SLAMM 5.0 model incorporates a simplifying assumption that all currently-developed areas will remain protected by seawalls and other coastal armoring, so it does not project inundation of existing urban areas. This does not mean, however, that low-lying urban areas, such as parts of Olympia and Tacoma, are not also vulnerable to sea-level rise, only that the potential impacts are not captured here. For example, a 1993 study conducted for the City of Olympia, portions of which have been built on fill just a few feet above sea level, projected significant tidal flooding and inundation in the downtown area under a scenario of 4-foot relative sea-level rise by 2100 (Craig, 1993). While it is beyond the scope of this study to address impacts on the region's vulnerable developed areas, the potential for sea-level rise to cause significant and costly damage to property and infrastructure should not be ignored.

In our initial model runs, we also assumed that agricultural areas and other dry land currently protected by dikes will remain protected. Because some of these dikes are being removed to assist in habitat restoration, however, we thought it would be useful to see how sea-level rise might affect the region's coastal areas if the dikes were not there. So we conducted some simulations with no dikes protecting agricultural areas. Not surprisingly, there is a considerably greater loss of dry land at all of the modeled sites if the dikes are removed, although in several areas there is also greater expansion of some habitat types, such as saltmarsh and tidal flats.

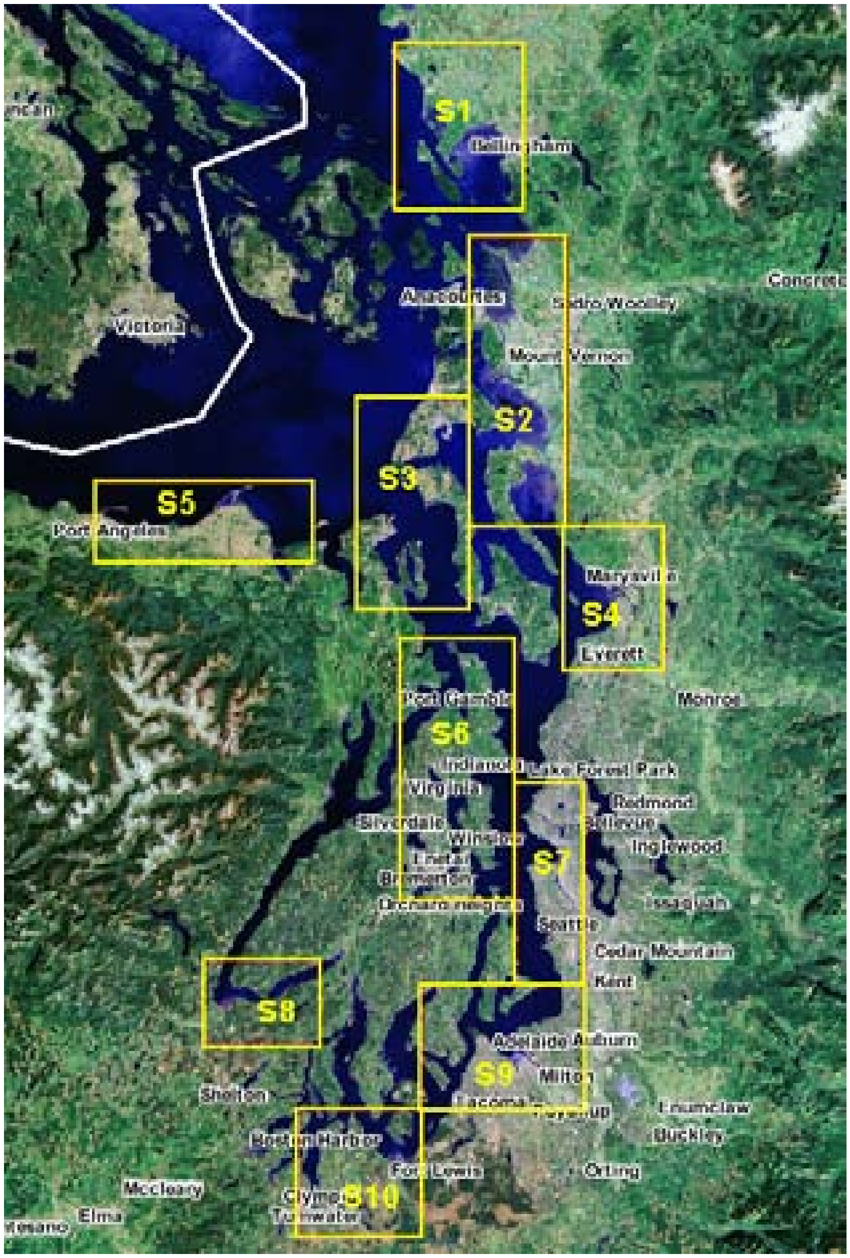
Second Beach, Washington (iStock)

Table 5. Description of Coastal Habitat Categories Modeled (Based on FWS National Wetlands Inventory Classes)		
Habitat Type	**Description**	**Representative Species**
Swamp	Palustrine forested (living or dead), and scrub-shrub.	Sitka spruce, Oregon ash, willows, red alder, red Osier dogwood, Douglas spirea, blackberry, salmon berry
Inland Fresh Marsh	Lacustrine, palustrine and riverine emergent	Cattail, bulrush, duckweed, reed canary grass, water lilies, water plantain, smartweed
Tidal Fresh Marsh	Riverine tidal emergent	Water plantain, nodding beggarticks, spike-rush, reed canary grass, cattails, and several grass species
Transitional Marsh	Estuarine intertidal scrub-shrub broad-leaved deciduous	Hooker's willow, sitka willow, sweetgale
Saltmarsh	Estuarine intertidal emergent	Seashore saltgrass, orache, saltwort, sea arrow-grass, pickleweed
Estuarine Beach	Estuarine intertidal unconsolidated shore sand or beach-bar, includes salt pans	Habitat for hardshell and softshell clam species; spawning habitat for surf smelt and sand lance; nursery corridor for out-migrating juvenile salmon
Tidal Flat	Estuarine intertidal unconsolidated shore mud/organic or flat	Burrowing invertebrates, including mud shrimp, clams, introduced oysters, snails and crabs; forage areas for marine birds; pupping area for harbor seals
Ocean Beach	Marine intertidal unconsolidated shore sand	Clams, crabs and other marine invertebrates, seabirds, shorebirds, waterfowl, marine mammals, numerous fish species
Inland Open Water	Permanently flooded/intermittently exposed freshwater	Freshwater aquatic vegetation, fish, and wildlife species
Estuarine Open Water	Estuarine subtidal	Pacific herring, sand lance, salmonid juveniles and adults, fish larvae, orca, Dall porpoise, auklets, grebes, murres
Open Ocean	Marine subtidal	Plagic fish, anadromous fish, marine mammals, other marine species
Brackish Marsh	Irregularly flooded estuarine intertidal emergent	Lyngby's sedge, slough sedge, fleshy jaumea, sea plantain, American bulrush
Inland Shore	Lacustrine, palustrine and riverine unconsolidated shore, riverine rocky shore	Riparian forest, riparian shrub
Tidal Swamp	Palustrine forest and scrub-shrub with tidal influence	Sitka spruce, Oregon ash, willows, red alder, red Osier dogwood, Douglas spirea, blackberry, salmon berry
Rocky Intertidal	Marine intertidal rocky shore	Benthic suspension feeders and multiple species of fish, including several species of rockfish
Riverine Tidal	Riverine tidal open water	True watercress, yellowcress, arrowhead, water plantain, smartweed, arrowhead
Sources: Clough and Park, 2007; Sound Science, 2007; WADNR, 2005.		

Study Sites

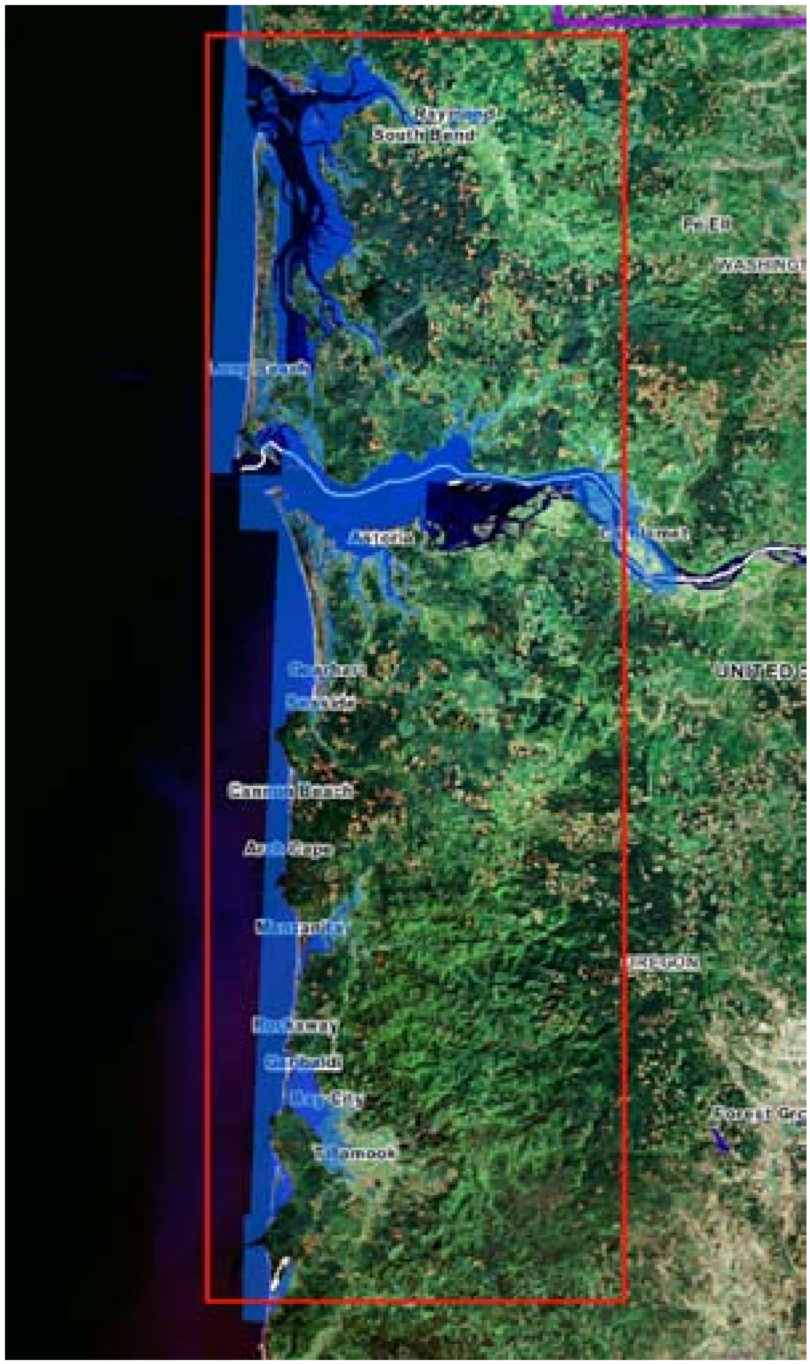
The SLAMM 5.0 model was applied to ten sites within Puget Sound, Washington, comprising over 600,000 hectares (1.5 million acres) (Figure 4).

Figure 4: Map of Sites 1-10 Modeled within Puget Sound



The model was also applied to the mouth of the Columbia River including Willapa Bay, Astoria, and Tillamook (Figure 5). The modeled study area for this site alone was approximately 571,000 hectares (1.4 million acres).

Figure 5: Map of Site 11



Sea-level Rise Scenarios

SLAMM 5.0 was run using mean and maximum sea-level rise projections (Table 6) computed by global climate models for the IPCC Third Assessment Report (IPCC, 2001). We chose to use model results for the A1B greenhouse gas emissions scenario, which is a midrange estimate of future emissions. As described in detail in the *Special Report on Emissions Scenarios* (IPCC, 2000), the A1 family of emissions scenarios assumes that the future world includes very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. In particular, the A1B scenario assumes that energy supply will be balanced across all sources.

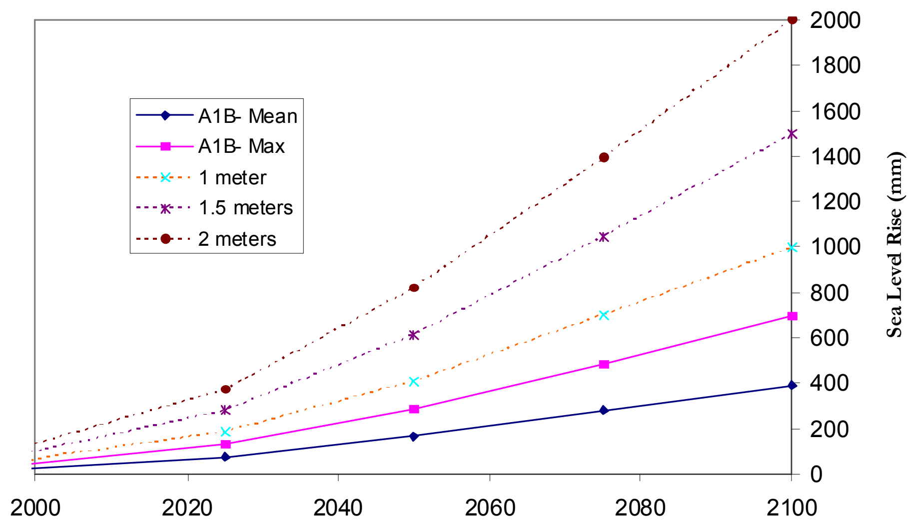
At the time we conducted this analysis, the details of the IPCC's Fourth Assessment Report (IPCC, 2007a) were not yet available. A subsequent review of the sea level projections in IPCC (2007a) revealed that, had the numbers been reported in a comparable manner (e.g., used similar assumptions for uncertainties), the sea-level rise projections for the 2001 report and the 2007 report would be similar (IPCC, 2007a). Under the A1B scenario, IPCC (2007a) suggests a likely range of 0.21-0.48 meters (8.3-18.9 inches) of sea level rise by 2090-2099, "excluding future rapid dynamical changes in ice flow," and perhaps as much as 0.68 meters (26.8 inches) over that time if the rate of ice flow increases as some models predict. The IPCC (2001) A1B-mean and max scenarios that were run as a part of this project fall within this estimated range, predicting 0.38 and 0.69 meters (15.2 and 27.3 inches), respectively, of global average sea level rise by 2100 (Table 6).

Table 6. IPCC 2001 Sea Level Rise Projections for the Moderate A1B Scenario

	Min	Mean	Max
2025	0.03 meters (1.1 inches)	0.08 meters (3.0 inches)	0.13 meters (5.0 inches)
2050	0.06 meters (2.5 inches)	0.17 meters (6.6 inches)	0.28 meters (11.2 inches)
2075	0.1 meters (3.9 inches)	0.28 meters (11.0 inches)	0.49 meters (19.1 inches)
2100	0.13 meters (5.1 inches)	0.39 meters (15.2 inches)	0.69 meters (27.3 inches)

Some recent studies indicate that sea level might rise faster than reported in either IPCC (2001) or IPCC (2007a) due to much faster melting of Greenland and Antarctica ice fields in the past few years than previously observed (Chen, Wilson, and Tapley, 2006; Otto-Bliesner, et al., 2006; Overpeck, et al., 2006; Rignot and Kanagaratnam, 2006; Rahmstorf, 2007). To account for this possibility, SLAMM 5.0 was also run assuming 1 meter (39.4 inches), 1.5 meters (59.1 inches), and 2 meters (78.7 inches) of global average sea-level rise by the year 2100. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure 6).

Figure 6: Summary of Sea-level Rise Scenarios Utilized



For simplicity, this report will focus on the A1B-Max scenarios for 2050 and 2100 and the 1.5-meter (59.1 inch) scenario for 2100. Full model results are available from the National Wildlife Federation for all five scenarios discussed above. Table 7 shows the relative amount of sea-level rise by study site based on these scenarios and the relative land elevation changes discussed in the Appendix.

Table 7. Relative Sea-level Rise by Study Site

	2050 A1B Max (0.28 meters/11.2 inches)	2100 A1B Max (0.69 meters/27.3 inches)	2100 1.5 Meter (59.1 inches)
Site 1	0.28 meters (11.1inches)	0.68 meters (26.9 inches)	1.45 meters (58.6 inches)
Site 2	0.35 meters (13.6 inches)	0.78 meters (30.8 inches)	1.59 meters (62.5 inches)
Site 3	0.42 meters (16.4 inches)	0.89 meters (35.1 inches)	1.70 meters (66.8 inches)
Site 4	0.36 meters (14 inches)	0.80 meters (31.3 inches)	1.60 meters (63 inches)
Site 5	0.30 meters (11.8 inches)	0.71 meters (27.9 inches)	1.51 meters (59.6 inches)
Site 6	0.36 meters (14 inches)	0.80 meters (31.3 inches)	1.60 meters (63 inches)
Site 7	0.32 meters (12.6 inches)	0.76 meters (29.9 inches)	1.57 meters (61.7 inches)
Site 8	0.34 meters (13.3 inches)	0.77 meters (30.5 inches)	1.58 meters (62.2 inches)
Site 9	0.34 meters (13.2 inches)	0.77 meters (30.4 inches)	1.58 meters (62.1 inches)
Site 10	0.34 meters (13.3 inches)	0.77 meters (30.5 inches)	1.58 meters (62.2 inches)
Site 11	0.34 meters (13.2 inches)	0.77 meters (30.4 inches)	1.58 meters (62.1 inches)

Model Results by Study Site

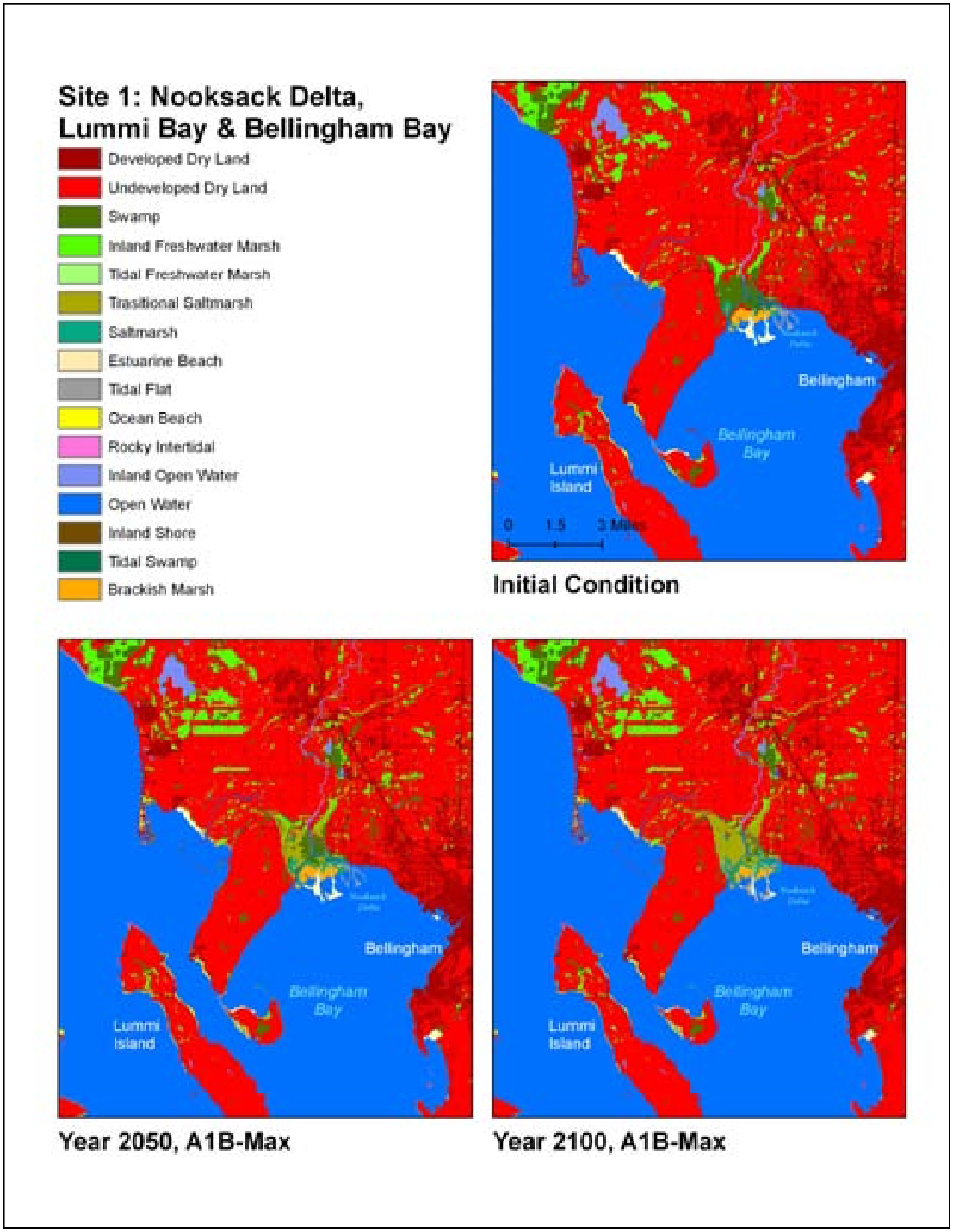
Site 1: Nooksack Delta, Lummi Bay, and Bellingham Bay

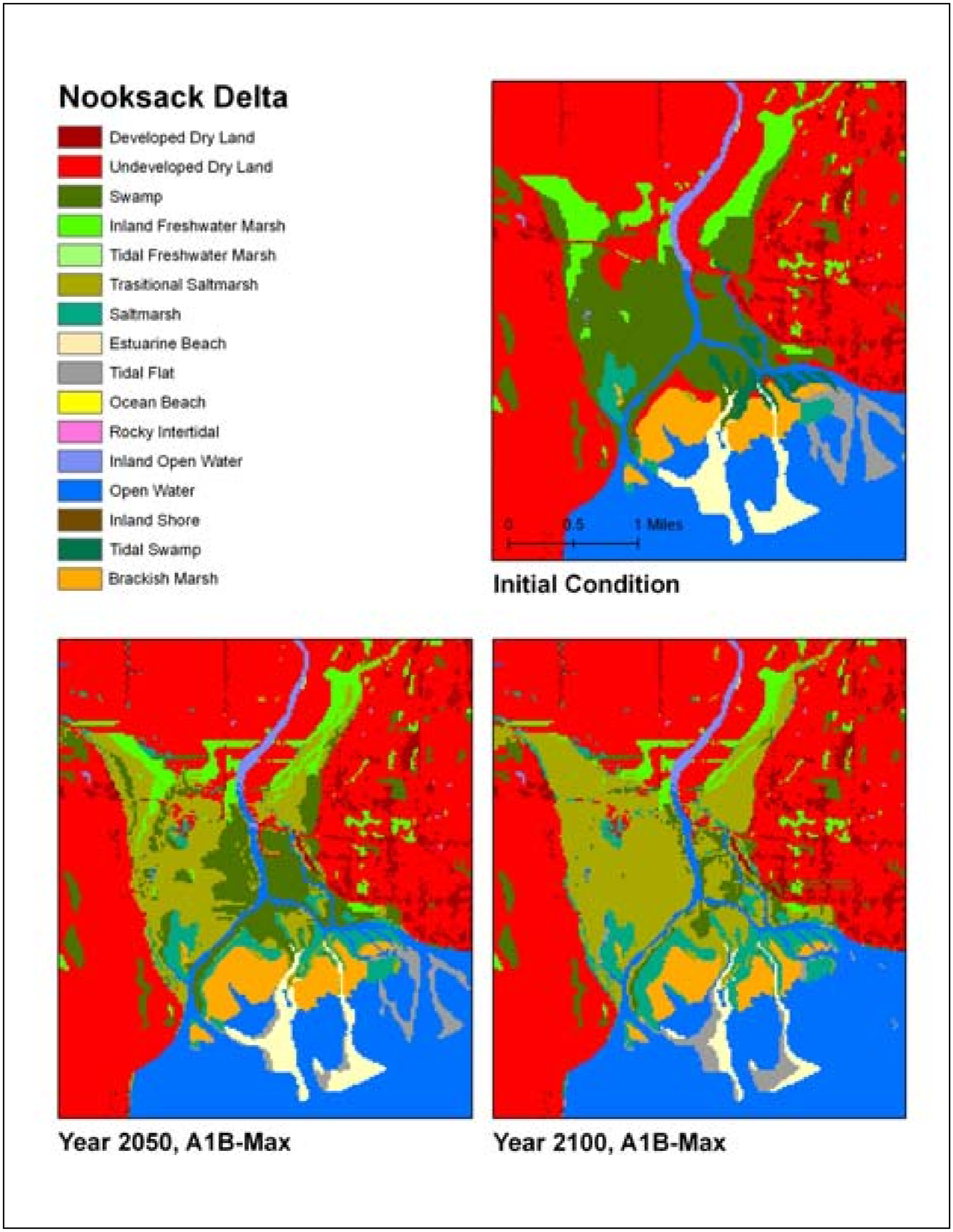
This site encompasses the Nooksack estuary, which enters Puget Sound at Bellingham Bay, and the Lummi delta at Lummi Bay. Nearshore habitats are characterized by estuarine marshes, coastal swamp, eelgrass, and kelp beds. Although there has been significant coastal development at Bellingham and much of nearshore habitat in the region has been altered by levees, roads, and other modifications, it remains a critical area for natal and non-natal Chinook, summer chum, and bull trout and is an important foraging site for numerous species of shorebirds and waterfowl. The region is also part of the core summer habitat for the endangered Southern Resident orca population (National Marine Fisheries Service, 2006).

Due to the presence of dikes at this site (see the section on dikes in the Appendix), and relatively high dry land elevations, the majority of effects occur in the wetlands southwest of Marietta (Nooksack River delta). Depending on the scenario chosen, these swamp lands and wetlands are either in the process of transitioning to saltmarsh or have completely transitioned to that category. Transitional marsh, in this case, refers to dry land, swamp, or fresh marsh that has been inundated by salt water but is still at too high of an elevation to have completely transformed into saltmarsh. Estuarine beach declines 42-84 percent by 2100 under the A1B Max and 1.5-meter (59.1 inch) scenarios respectively, as does one-fourth of swamp area.

Sunset over Bellingham Bay (iStock)

Table 8. Projections of Habitat Changes for Site 1 [A1B Max for 2050, 2100 and 1.5 Meters for 2100)]							
	Area of Habitat Type in Hectares (Acres)				Percentage Change (Relative to Totals for This Site)		
	Initial Condition	**2050 (+0.28 meters/11.2 inches)**	**2100 (+0.69 meters/27.3 inches)**	**2100 (+1.5 meters/59.1 inches)**	**2050 (+0.28 meters/11.2 inches)**	**2100 (+0.69 meters/27.3 inches)**	**2100 (+1.5 meters/59.1 inches)**
Undeveloped Dry Land	26,857 (66,365)	26,144 (64,603)	26,066 (64,410)	26,002 (64,252)	3% loss	3% loss	3% loss
Developed	5,103 (12,610)	5,103 (12,610)	5,103 (12,610)	5,103 (12,610)	No change	No change	No change
Swamp	1,715 (4,238)	1,516 (3,746)	1,362 (3,366)	1,298 (3,207)	12% loss	21% loss	24% loss
Inland Fresh Marsh	2,420 (5,980)	2,660 (6,573)	2,617 (6,467)	2,601 (6,427)	10% expansion	8% expansion	7% expansion
Tidal Fresh Marsh	11 (27)	11 (27)	11 (27)	11 (27)	No change	No change	No change
Transitional Marsh	1 (2)	359 (887)	546 (1,349)	101 (250)	24,856% expansion	37,789% expansion	6,915% expansion
Saltmarsh	38 (94)	198 (489)	219 (541)	717 (1,772)	416% expansion	469% expansion	1,788% expansion
Estuarine Beach	178 (440)	158 (390)	104 (257)	29 (72)	11% loss	42% loss	84% loss
Tidal Flat	154 (381)	195 (482)	188 (465)	300 (741)	26% expansion	22% expansion	95% expansion
Ocean Beach	104 (257)	118 (292)	95 (235)	2 (5)	14% loss	8% loss	98% loss
Inland Open Water	547 (1,352)	530 (1,310)	525 (1,297)	523 (1,292)	3% loss	4% loss	4% loss
Estuarine Open Water	15,065 (37,226)	14,529 (35,902)	14,130 (34,916)	14,212 (35,119)	4% loss	6% loss	6% loss
Open Ocean	16,635 (41,106)	17,386 (42,962)	17,985 (44,442)	18,141 (44,827)	5% expansion	8% expansion	9% expansion
Brackish Marsh	150 (371)	142 (351)	117 (289)	41 (101)	5% loss	22% loss	73% loss
Tidal Swamp	40 (99)	1 (2)	1 (2)	1 (2)	97% loss	97% loss	97% loss
Rocky Intertidal	32 (79)	28 (69)	19 (47)	6 (15)	13% loss	41% loss	81% loss
Riverine Tidal	53 (131)	28 (69)	18 (44)	18 (44)	48% loss	66% loss	67% loss

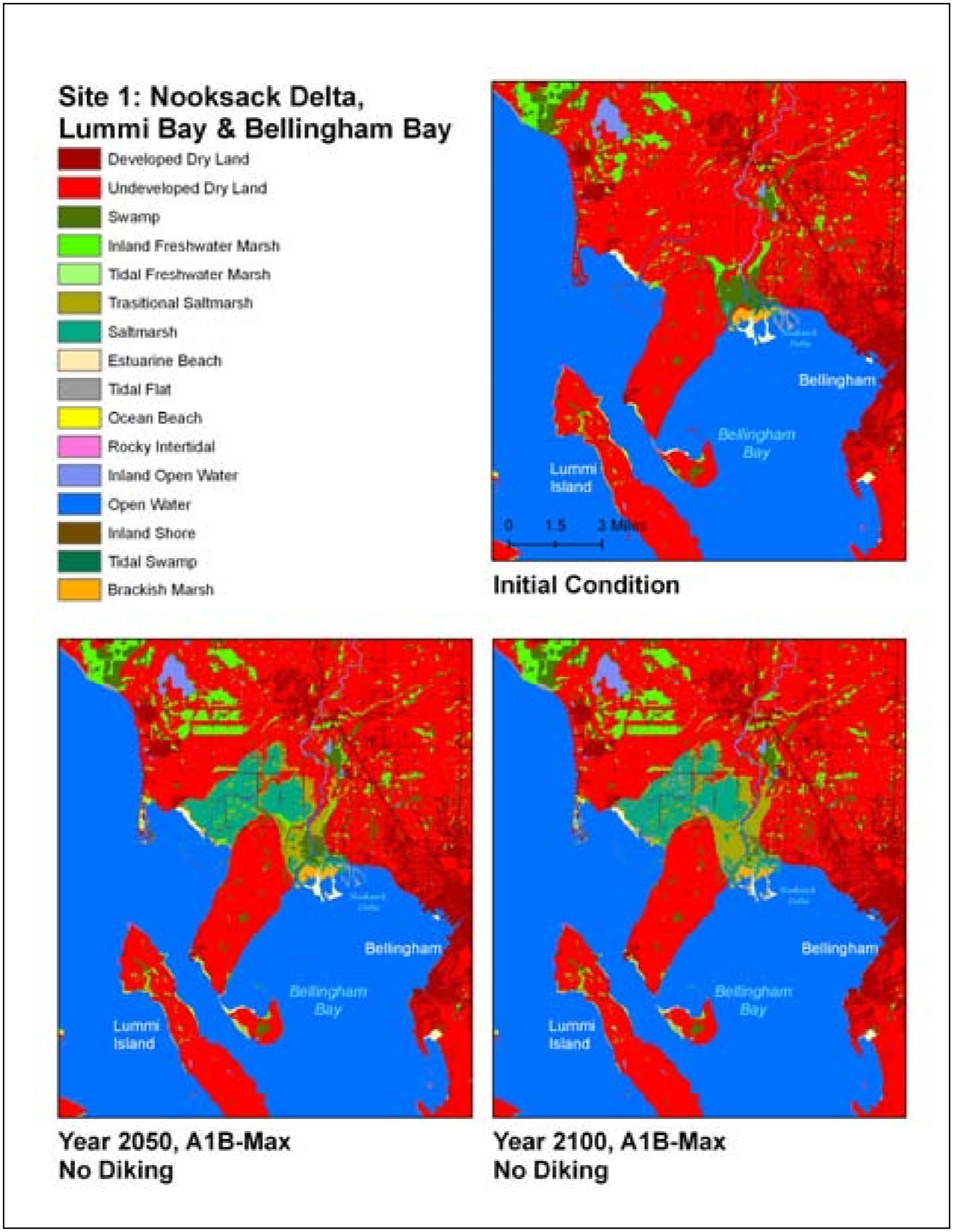

Site 1: Nooksack Delta,
Lummi Bay & Bellingham Bay
Developed Dry Land
Undeveloped Dry Land
Swamp
Inland Freshwater Marsh
Tidal Freshwater Marsh
Trasitional Saltmarsh
Saltmarsh
Estuarine Beach
Tidal Flat
Ocean Beach
Rocky Intertidal
Inland Open Water
Open Water
Inland Shore
Tidal Swamp
Brackish Marsh
Bellingham
Bellingham Bay
Lummi Island
0 1.5 3 Miles
Initial Condition
Year 2050, A1B-Max
Year 2100, A1B-Max


Nooksack Delta
Developed Dry Land
Undeveloped Dry Land
Swamp
Inland Freshwater Marsh
Tidal Freshwater Marsh
Trasitional Saltmarsh
Saltmarsh
Estuarine Beach
Tidal Flat
Ocean Beach
Rocky Intertidal
Inland Open Water
Open Water
Inland Shore
Tidal Swamp
Brackish Marsh
0
0.5
1 Miles
Initial Condition
Year 2050, A1B-Max
Year 2100, A1B-Max

Site 1 was also run without agricultural dikes to simulate the results of dike removal at this site. When dikes and seawalls are removed from the farmland in the center of this map, all the grazing land at this location is subject to conversion to transitional and saltmarsh and even tidal flats given the more aggressive sea-level rise scenarios.

Table 9. Projections for Habitat Changes for Site 1 with No Dikes
(A1B Max for 2100)

	Area of Habitat Type in Hectares (Acres)		Percentage Change (Relative to Totals for This Site)
	Initial Condition	**2100 (+0.69 meters/27.3 inches)**	**2100 (+0.69 meters/27.3 inches)**
Undeveloped Dry Land	26,857 (66,365)	24,259 (59,945)	10% loss
Developed	5,103 (12,610)	5,103 (12,610)	No change
Swamp	1,715 (4,238)	1,348 (3,331)	21% loss
Inland Fresh Marsh	2,420 (5,980)	2,517 (6,220)	4% expansion
Tidal Fresh Marsh	11 (27)	11 (27)	No change
Transitional Marsh	1 (2)	1,019 (2,518)	70,679% expansion
Saltmarsh	38 (94)	1,532 (3,786)	3,927% expansion
Estuarine Beach	178 (440)	112 (277)	37% loss
Tidal Flat	154 (381)	270 (667)	75% expansion
Ocean Beach	104 (257)	108 (267)	5% expansion
Inland Open Water	547 (1,352)	499 (1,233)	9% loss
Estuarine Open Water	15,065 (37,226)	14,196 (35,079)	6% loss
Open Ocean	16,635 (41,106)	17,995 (44,467)	8% expansion
Brackish Marsh	150 (371)	114 (282)	24% loss
Inland Shore	8 (20)	8 (20)	No change
Tidal Swamp	40 (99)	0 (0)	99% loss
Rocky Intertidal	32 (79)	19 (47)	41% loss
Riverine Tidal	53 (131)	2 (5)	97% loss


Site 1: Nooksack Delta,
Lummi Bay & Bellingham Bay
Developed Dry Land
Undeveloped Dry Land
Swamp
Inland Freshwater Marsh
Tidal Freshwater Marsh
Trasitional Saltmarsh
Saltmarsh
Estuarine Beach
Tidal Flat
Ocean Beach
Rocky Intertidal
Inland Open Water
Open Water
Inland Shore
Tidal Swamp
Brackish Marsh
Bellingham
Bellingham Bay
Lummi Island
0 1.5 3 Miles
Initial Condition
Year 2050, A1B-Max
No Diking
Year 2100, A1B-Max
No Diking

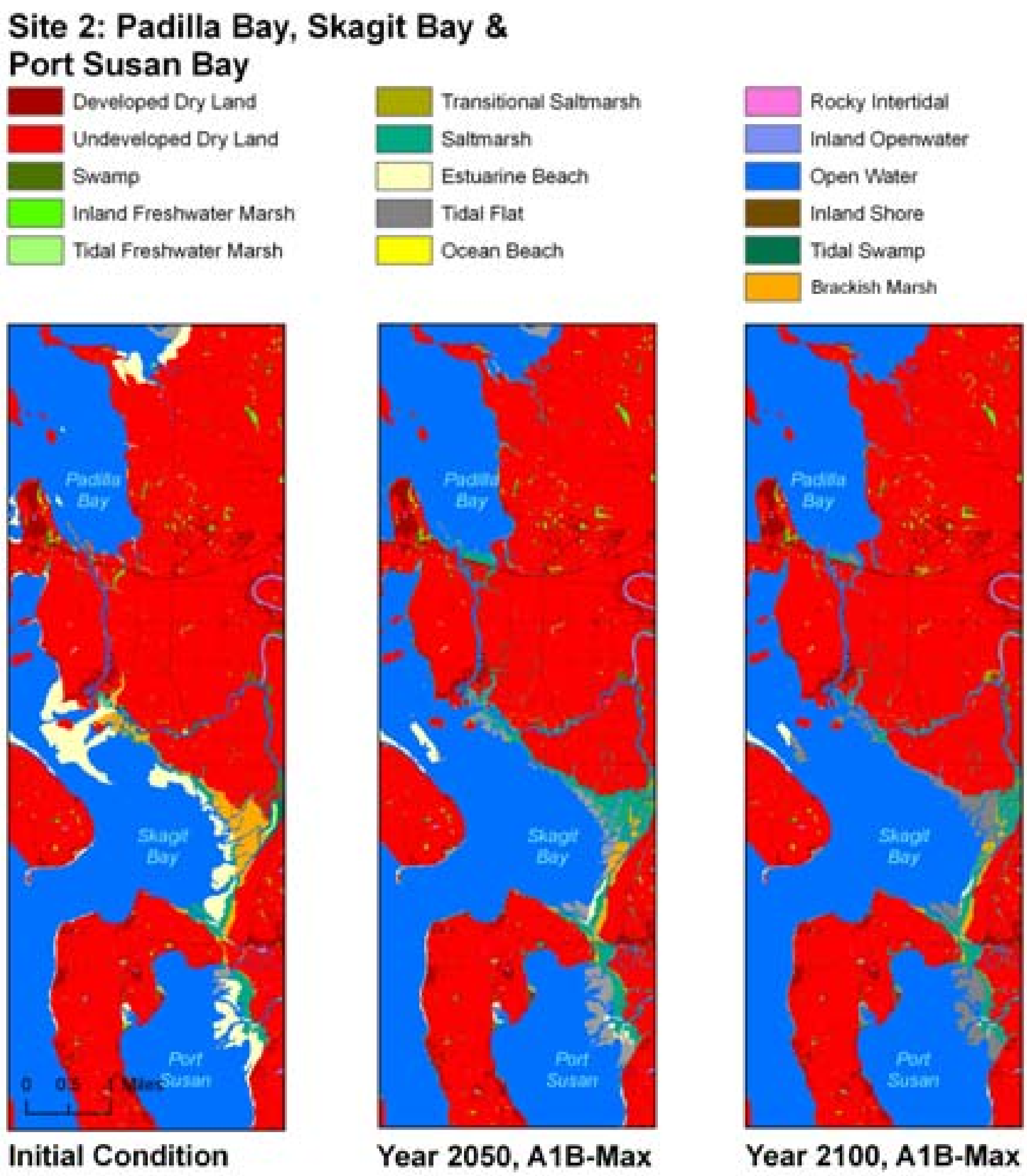
Site 2: Padilla Bay, Skagit Bay, and Port Susan Bay

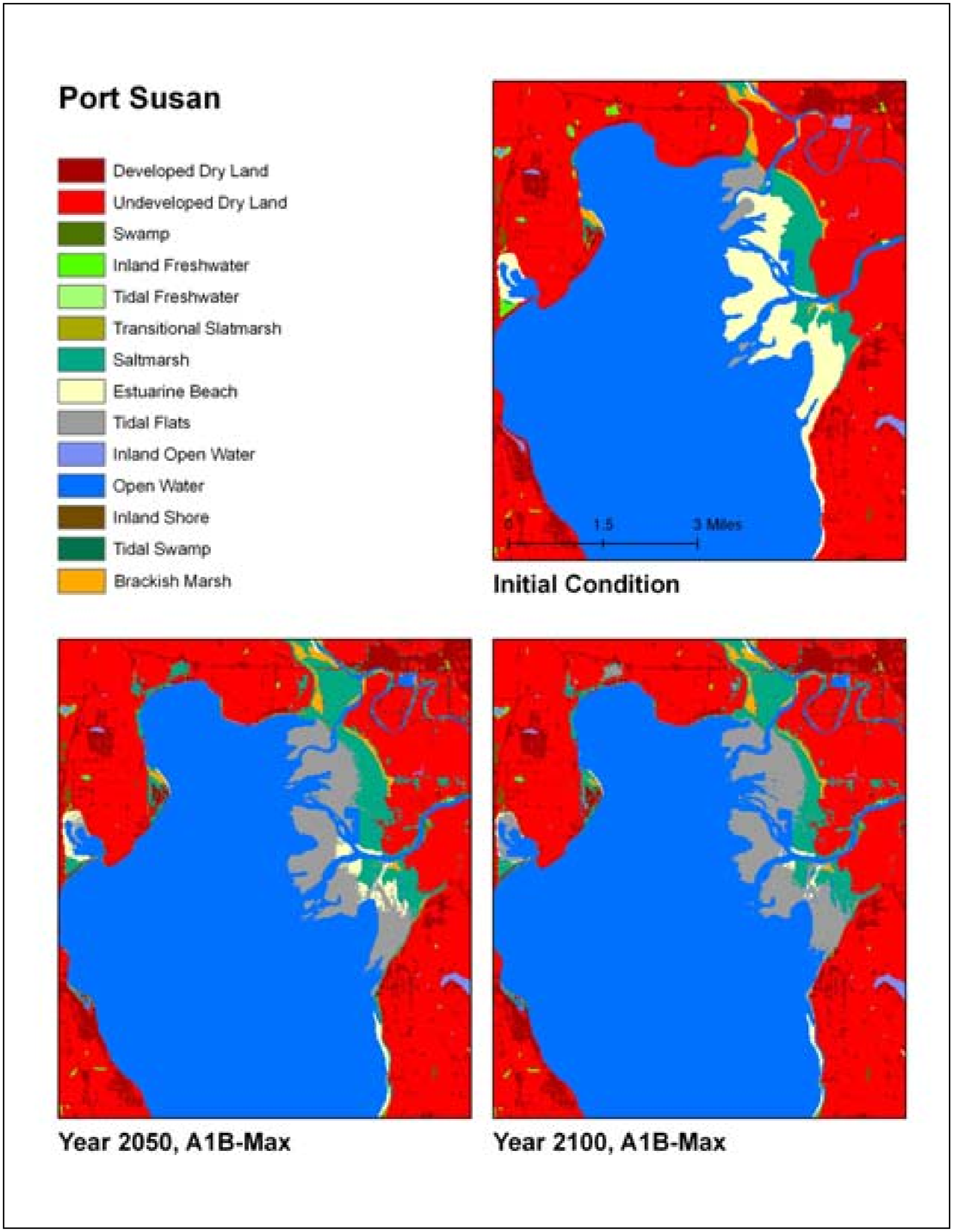
This site includes Padilla Bay and part of Samish Bay to the north as well as Skagit and Port Susan bays in the south. Historically, these sites have included some of the most extensive wetlands, tidal flats, eelgrass beds and other habitats in Puget Sound. While both Padilla and Samish bays have experienced reduced freshwater/marine water mixing since the construction of agricultural dikes, Padilla Bay is still highly productive given its extensive eelgrass meadow, and it supports a thriving Dungeness crab fishery. The lower part of this study site covers the estuaries of the Skagit and Stillaquamish rivers, two of the largest sources of freshwater into Puget Sound. The estuarine wetlands in these areas have been significantly reduced from historic levels due to diking and draining for agricultural development, making its remaining habitat even more important for natal Chinook salmon and other fish. It also supports thousands of shorebirds, waterfowl, bald eagles, and other wildlife. Significant areas of both Padilla Bay and Skagit Bay are protected as refuges.

Much of the dry land for Site 2 is protected by dikes and is not subject to inundation. This means that marshes and beaches that are trapped up against the sea-walls may be especially subject to loss (conversion to saltmarsh or tidal flats). Saltmarsh is predicted to increase at this site under most scenarios as brackish marsh becomes subject to more regular ocean-water inundation and is converted to saltmarsh. This process of inundation causes brackish marsh to decline by 77-97 percent by 2100 under these scenarios. Some small regions of dry land are predicted to convert to transitional marsh as sea water rises to inundate them. Large tracts of Skagit Bay that were coded as estuarine beach are predicted to be permanently or semi-permanently flooded under all scenarios run, converting to estuarine open water or tidal flats depending on the degree of flooding predicted.

Skagit Bay (iStock)

Table 10. Projections of Habitat Changes for Site 2 [A1B Max for 2050, 2100 and 1.5 Meters for 2100]							
	Area of Habitat Type in Hectares (Acres)				Percentage Change (Relative to Totals for This Site)		
	Initial Condition	2050 (+0.28 meters/11.2 inches)	2100 (+0.69 meters/27.3 inches)	2100 (+1.5 meters/59.1 inches)	2050 (+0.28 meters/11.2 inches)	2100 (+0.69 meters/27.3 inches)	2100 (+ 1.5 meters/59.1 inches)
Undeveloped Dry Land	45,482 (112,388)	43,800 (108,232)	43,606 (107,753)	43,480 (107,441)	4% loss	4% loss	4% loss
Developed	4,215 (10,415)	4,215 (10,415)	4,215 (10,415)	4,215 (10,415)	No change	No change	No change
Swamp	485 (1,198)	362 (895)	328 (811)	283 (699)	25% loss	32% loss	42% loss
Inland Fresh Marsh	665 (1,643)	504 (1,245)	491 (1,213)	481 (1,189)	24% loss	26% loss	28% loss
Tidal Fresh Marsh	76 (188)	12 (30)	11 (27)	10 (25)	84% loss	85% loss	87% loss
Transitional Marsh	29 (72)	406 (1,003)	468 (1,156)	243 (600)	1,313% expansion	1,531% expansion	747% expansion
Saltmarsh	931 (2,301)	2917 (7,208)	1,854 (4,581)	1,315 (3,249)	213% expansion	96% expansion	41% expansion
Estuarine Beach	3,670 (9,069)	597 (1,475)	329 (813)	44 (109)	84% loss	91% loss	99% loss
Tidal Flat	289 (714)	1,618 (3,998)	2,061 (5,093)	2,801 (6,921)	460% expansion	613% expansion	869% expansion
Ocean Beach	0 (0)	3 (7)	0 (0)	0 (0)	NA	NA	NA
Inland Open Water	342 (845)	291 (719)	281 (694)	269 (665)	15% loss	18% loss	21% loss
Estuarine Open Water	33,546 (82,894)	35,976 (88,899)	36,892 (91,162)	37,695 (93,146)	7% expansion	10% expansion	12% expansion
Open Ocean	875 (2,162)	1,178 (2,911)	1,482 (3,662)	1,500 (3,707)	35% expansion	70% expansion	71% expansion
Brackish Marsh	1,414 (3,494)	432 (1,067)	332 (820)	41 (101)	69% loss	77% loss	97% loss
Inland Shore	30 (74)	27 (67)	27 (67)	27 (67)	10% loss	10% loss	10% loss
Tidal Swamp	202 (499)	34 (84)	22 (54)	10 (25)	83% loss	89% loss	95% loss
Rocky Intertidal	1 (2)	<1 (<2)	<1 (<2)	<1 (<2)	4% loss	12% loss	27% loss
Riverine Tidal	278 (687)	155 (383)	126 (311)	114 (282)	44% loss	55% loss	59% loss

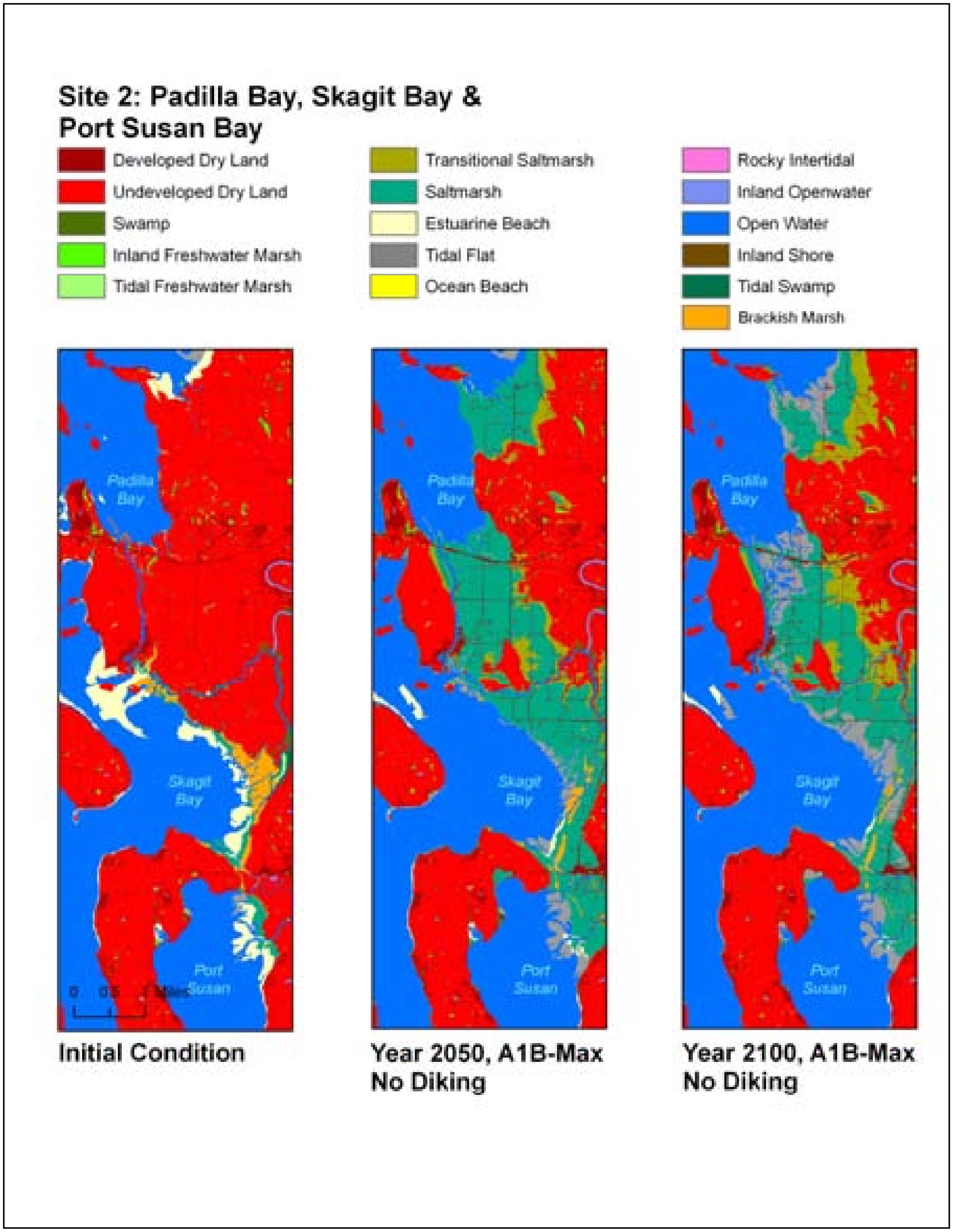

Site 2: Padilla Bay, Skagit Bay &
Port Susan Bay
Developed Dry Land
Undeveloped Dry Land
Swamp
Inland Freshwater Marsh
Tidal Freshwater Marsh
Transitional Saltmarsh
Saltmarsh
Estuarine Beach
Tidal Flat
Ocean Beach
Rocky Intertidal
Inland Openwater
Open Water
Inland Shore
Tidal Swamp
Brackish Marsh
Padilla Bay
Skagit Bay
Port Susan
0 0.5 1 Miles
Initial Condition
Year 2050, A1B-Max
Year 2100, A1B-Max


Port Susan
Developed Dry Land
Undeveloped Dry Land
Swamp
Inland Freshwater
Tidal Freshwater
Transitional Slatmarsh
Saltmarsh
Estuarine Beach
Tidal Flats
Inland Open Water
Open Water
Inland Shore
Tidal Swamp
Brackish Marsh
0
1.5
3 Miles
Initial Condition
Year 2050, A1B-Max
Year 2100, A1B-Max

Site 2 was also run without dikes to simulate the results of dike removal at this site. Huge tracts of dry land (40 percent, or more than 18,000 hectares/44,478 acres) would be converted to saltmarsh and transitional marsh at this site if dikes were removed.

Table 11. Projections for Habitat Changes for Site 2 with No Dikes
(A1B Max for 2100)

	Area of Habitat Type in Hectares (Acres)		**Percentage Change (Relative to Totals for This Site)**
	Initial Condition	**2100 (+0.69 meters/27.3 inches)**	**2100 (+0.69 meters/27.3 inches)**
Undeveloped Dry Land	45,482 (112,388)	27,361 (67,611)	40% loss
Developed	4,215 (10,415)	4,215 (10,415)	No change
Swamp	485 (1,198)	315 (778)	35% loss
Inland Fresh Marsh	665 (1,643)	476 (1,176)	28% loss
Tidal Fresh Marsh	76 (188)	11 (27)	85% loss
Transitional Marsh	29 (72)	4,147 (10,247)	14,346% expansion
Saltmarsh	931 (2,301)	11,331 (28,000)	1,115% expansion
Estuarine Beach	3,670 (9,069)	329 (813)	91% loss
Tidal Flat	289 (714)	4,793 (11,844)	1,559% expansion
Ocean Beach	0 (0)	3 (7)	NA
Inland Open Water	342 (845)	270 (667)	21% loss
Estuarine Open Water	33,546 (82,894)	37,371 (92,346)	11% expansion
Open Ocean	875 (2,162)	1,483 (3,665)	70% expansion
Brackish Marsh	1,414 (3,494)	332 (820)	77% loss
Inland Shore	30 (74)	27 (67)	10% loss
Tidal Swamp	202 (499)	22 (54)	89% loss
Rocky Intertidal	1 (2)	1 (2)	12% loss
Riverine Tidal	278 (687)	41 (101)	85% loss


Site 2: Padilla Bay, Skagit Bay & Port Susan Bay
Developed Dry Land
Undeveloped Dry Land
Swamp
Inland Freshwater Marsh
Tidal Freshwater Marsh
Transitional Saltmarsh
Saltmarsh
Estuarine Beach
Tidal Flat
Ocean Beach
Rocky Intertidal
Inland Openwater
Open Water
Inland Shore
Tidal Swamp
Brackish Marsh
Padilla Bay
Skagit Bay
Port Susan
0 0.5 1 Miles
Initial Condition
Year 2050, A1B-Max No Diking
Year 2100, A1B-Max No Diking

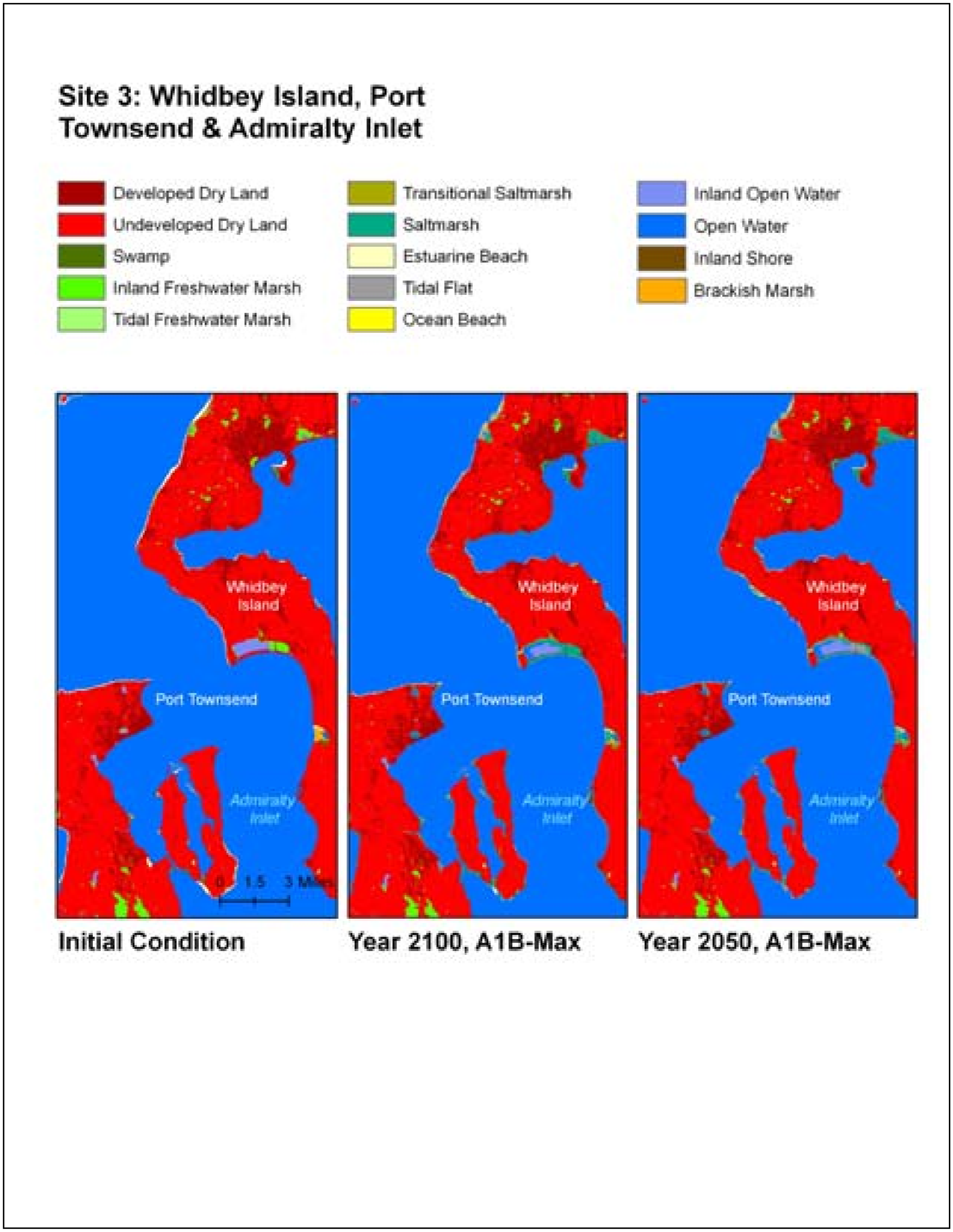
Site 3: Whidbey Island, Port Townsend, and Admiralty Inlet

This site, which includes parts of Whidbey Island, the Port Townsend area, and Admiralty Inlet between them, has significant areas of beach and offers important habitats for salmonids, forage fish, shellfish, shorebirds, and diving birds. While Whidbey Island, which is the largest island in Washington State, has some spawning streams for chum salmon, most of the nearshore habitat at this site is important for migratory Chinook salmon from Puget Sound's major river watersheds. The area is facing increasing pressure for coastal residential development, which has led to bulkheading and other shoreline modifications.

Dry land in this portion of Puget Sound is of sufficient elevation to escape too much conversion even in the more aggressive sea-level rise scenarios. The small fringes of wetlands at this site are subject to change, however. Brackish marsh and fresh marsh and a small portion of low-lying dry lands at this site are predicted to be inundated with salt water and to convert to saltmarsh and tidal flats. A combination of inundation and erosion is predicted to have significant effects on the beaches of this site, especially on western Whidbey Island. Overall, 80-85 percent of beaches are predicted to be lost at this site by 2100 under these scenarios.

Whidbey Island shoreline (iStock)

Table 12. Projections of Habitat Changes for Site 3 [A1B Max for 2050, 2100 and 1.5 Meters (59.1 inches) for 2100]							
	Area of Habitat Type in Hectares (Acres)				Percentage Change (Relative to Totals for This Site)		
	Initial Condition	2050 (+0.28 meters/11.2 inches)	2100 (+0.69 meters/27.3 inches)	2100 (+ 1.5 meters/ 59.1 inches)	2050 (+0.28 meters/11.2 inches)	2100 (+0.69 meters/27.3 inches)	2100 (+ 1.5 meters/ 59.1 inches)
Undeveloped Dry Land	25,165 (62,184)	24,233 (59,881)	24,160 (59,701)	24,090 (59,528)	4% loss	4% loss	4% loss
Developed	4,212 (10,408)	4,212 (10,408)	4,212 (10,408)	4,212 (10,408)	No change	No change	No change
Swamp	139 (343)	98 (242)	94 (232)	92 (227)	30% loss	33% loss	34% loss
Inland Fresh Marsh	764 (1,888)	544 (1,344)	542 (1,339)	540 (1,334)	29% loss	29% loss	29% loss
Tidal Fresh Marsh	11 (27)	11 (27)	11 (27)	11 (27)	No change	No change	No change
Transitional Marsh	0 (0)	210 (519)	161 (398)	104 (257)	NA	NA	NA
Saltmarsh	57 (141)	771 (1,905)	526 (1,300)	340 (840)	1271% expansion	814% expansion	497% expansion
Estuarine Beach	456 (1,127)	128 (316)	92 (227)	69 (171)	72% loss	80% loss	85% loss
Tidal Flat	28 (69)	247 (610)	434 (1,072)	474 (1,171)	770% expansion	1,425% expansion	1,565% expansion
Ocean Beach	18 (44)	98 (242)	83 (205)	<1 (0)	435% expansion	350% expansion	99% loss
Inland Open Water	345 (853)	227 (561)	222 (549)	215 (531)	34% loss	36% loss	38% loss
Estuarine Open Water	25,968 (64,168)	26,171 (64,670)	26,268 (64,910)	26,479 (65,431)	1% expansion	1% expansion	2% expansion
Open Ocean	18,524 (45,774)	18,780 (46,406)	18,941 (46,804)	19,131 (47,247)	1% expansion	2% expansion	3% expansion
Brackish Marsh	79 (195)	34 (84)	21 (52)	10 (25)	57% loss	74% loss	88% loss
Inland Shore	<1 (<2)	<1 (<2)	<1 (<2)	<1 (<2)	29% loss	49% loss	70% loss
Tidal Swamp	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Rocky Intertidal	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Riverine Tidal	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA


Site 3: Whidbey Island, Port Townsend & Admiralty Inlet
Developed Dry Land
Undeveloped Dry Land
Swamp
Inland Freshwater Marsh
Tidal Freshwater Marsh
Transitional Saltmarsh
Saltmarsh
Estuarine Beach
Tidal Flat
Ocean Beach
Inland Open Water
Open Water
Inland Shore
Brackish Marsh
Whidbey Island
Port Townsend
Admiralty Inlet
0 1.5 3 Miles
Initial Condition
Year 2100, A1B-Max
Year 2050, A1B-Max

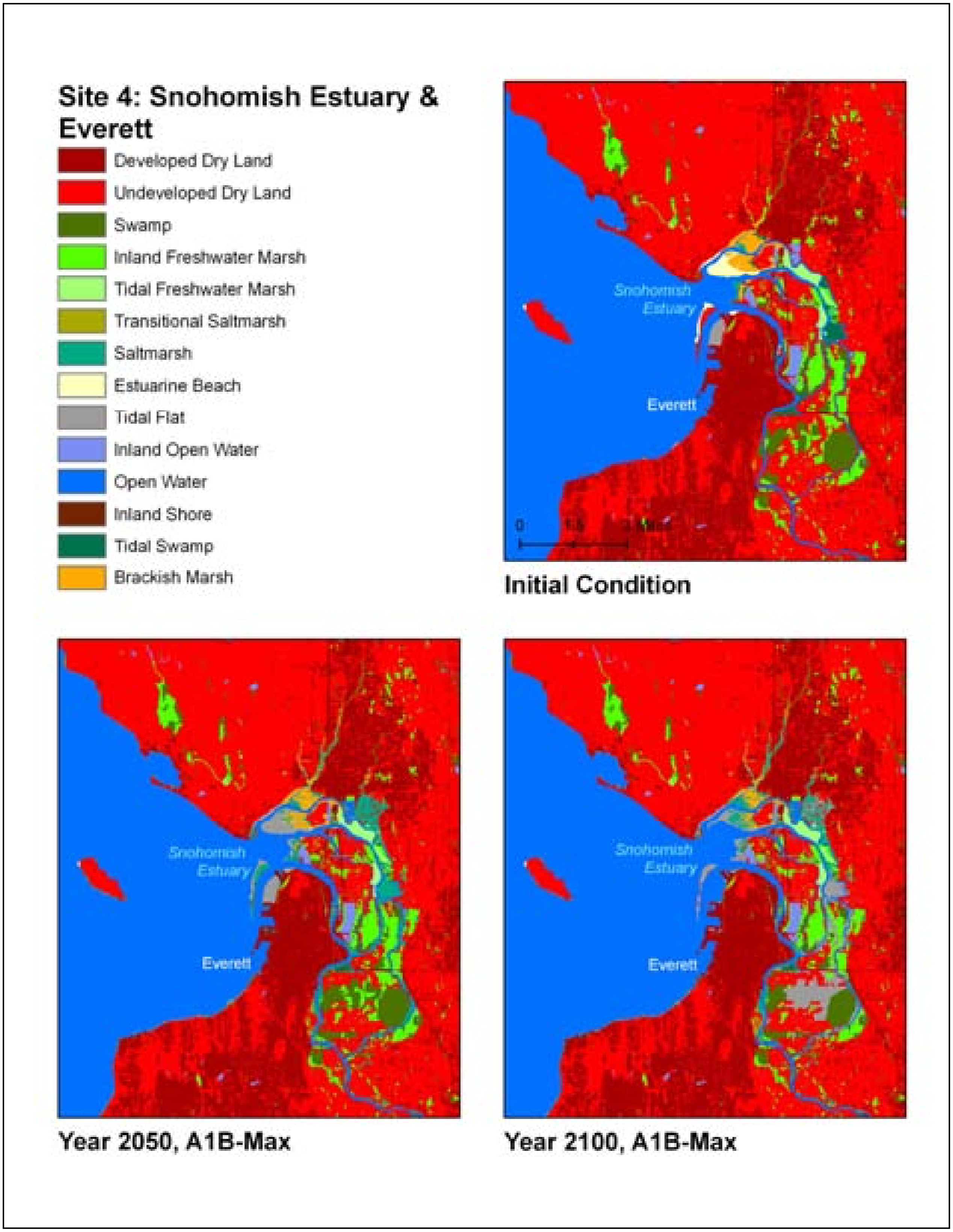
Site 4: Snohomish Estuary and Everett

This site is largely characterized by the Snohomish River delta and estuary at Possession Sound. Although the region has seen a significant decline in its floodplain wetlands and estuarine marsh area from historical levels due to conversion for agriculture and other land uses as well as significant coastal armoring and development around Everett, it still contains some of the most important remaining coastal marsh habitat in Puget Sound. The area supports hundreds of species of birds, seals, otters, and other wildlife and is a critical area for threatened Chinook and other salmonids. Accordingly, there are some significant efforts underway to protect remaining habitat from further degradation and restore the ecological function of nearshore systems.

Extensive dikes protect the low-lying dry land and marshes within Everett. This reduces the predicted effects of sea-level rise for this site. The model was also run without dikes and those results are presented in Table 14. Assuming that dikes in this area are able to withstand the predicted increases in sea level rise, the most significant prediction at this site is the inundation of brackish marsh and inland fresh marsh north of Smith Island and west of Marysville. However, it is not unreasonable to suggest that, because many of the dikes in this area were constructed with wood waste from lumber mills and other degradable materials, they may be vulnerable to damages associated with sea-level rise. The Tulalip Tribe and other stakeholders in the region are currently working to remove some of the region's dikes to restore habitat.

Gull in Mukilteo (iStock)

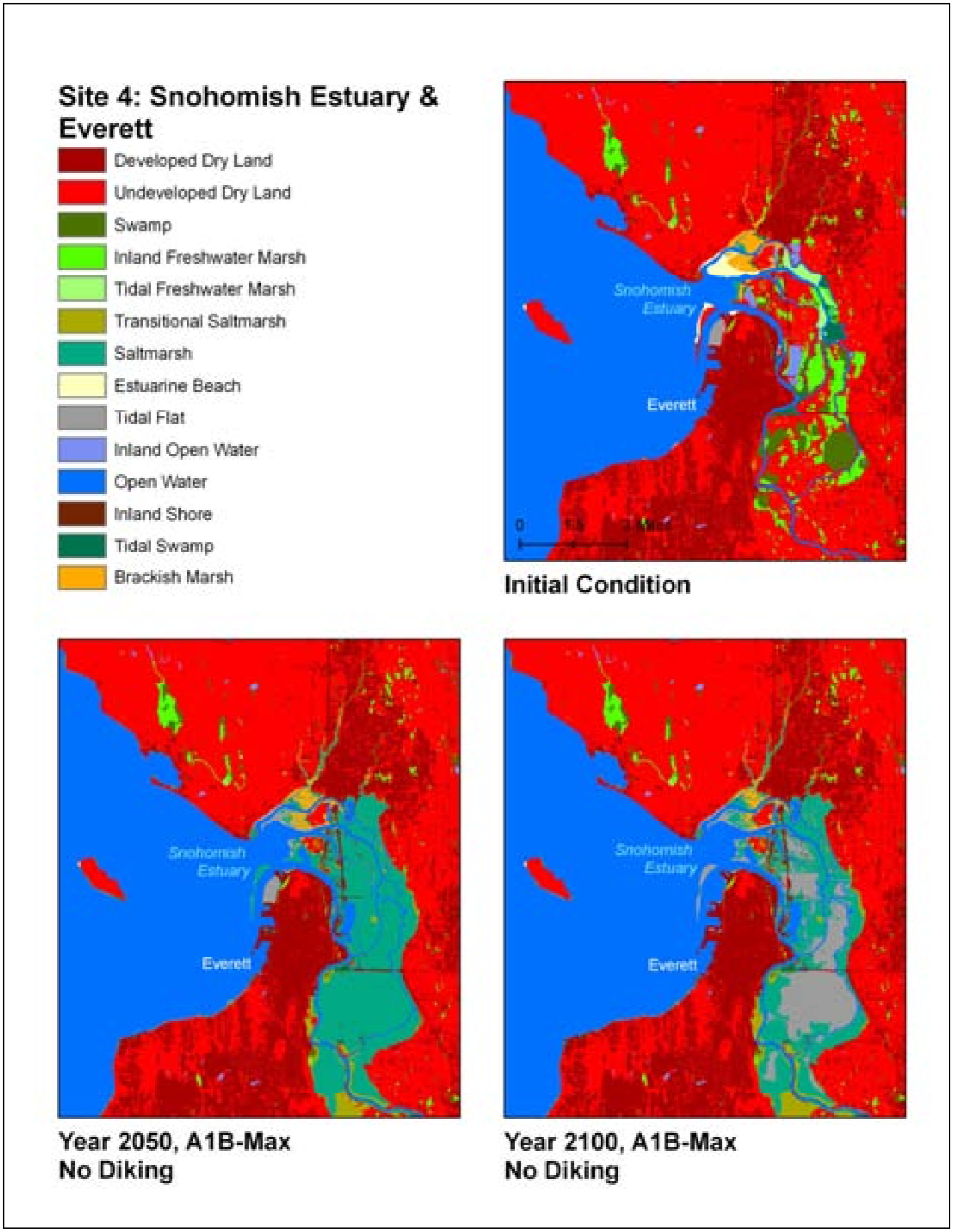
Table 13. Projections of Habitat Changes for Site 4 [A1B Max for 2050, 2100 and 1.5 Meters (59.1 inches) for 2100]							
	Area of Habitat Type in Hectares (Acres)				Percentage Change (Relative to Totals for This Site)		
	Initial Condition	2050 (+0.28 meters/11.2 inches)	2100 (+0.69 meters/27.3 inches)	2100 (+1.5 meters/ 59.1 inches)	2050 (+0.28 meters/11.2 inches)	2100 (+0.69 meters/27.3 inches)	2100 (+1.5 meters/ 59.1 inches)
Undeveloped Dry Land	21,608 (53,395)	20,911 (51,672)	20,844 (51,507)	20,806 (51,413)	3% loss	4% loss	4% loss
Developed	9,309 (23,003)	9,309 (23,003)	9,309 (23,003)	9,309 (23,003)	No change	No change	No change
Swamp	1,014 (2,506)	1,002 (2,476)	831 (2,053)	815 (2,014)	1% loss	18% loss	20% loss
Inland Fresh Marsh	1,498 (3,702)	1,418 (3,504)	1,266 (3,128)	1,247 (3,081)	5% loss	15% loss	17% loss
Tidal Fresh Marsh	155 (383)	148 (366)	146 (361)	146 (361)	5% loss	5% loss	5% loss
Transitional Marsh	0 (0)	176 (435)	160 (396)	87 (215)	NA	NA	NA
Saltmarsh	29 (72)	750 (1,853)	482 (1,191)	444 (1,097)	2,459% expansion	1,522% expansion	1,425% expansion
Estuarine Beach	158 (390)	10 (25)	7 (17)	3 (7)	94% loss	96% loss	98% loss
Tidal Flat	68 (168)	173 (427)	347 (857)	546 (1,349)	155% expansion	411% expansion	706% expansion
Ocean Beach	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Inland Open Water	370 (914)	329 (813)	326 (806)	326 (806)	11% loss	12% loss	12% loss
Estuarine Open Water	12,199 (30,144)	12,565 (31,049)	13,130 (32,445)	13,237 (32,709)	3% expansion	8% expansion	9% expansion
Open Ocean	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Brackish Marsh	229 (566)	163 (403)	121 (299)	13 (32)	29% loss	47% loss	94% loss
Inland Shore	6 (15)	6 (15)	6 (15)	5 (12)	1% loss	3% loss	13% loss
Tidal Swamp	166 (410)	43 (106)	37 (91)	30 (74)	74% loss	78% loss	82% loss
Riverine Tidal	486 (1,201)	292 (722)	283 (699)	279 (689)	40% loss	42% loss	43% loss


Site 4: Snohomish Estuary & Everett
Developed Dry Land
Undeveloped Dry Land
Swamp
Inland Freshwater Marsh
Tidal Freshwater Marsh
Transitional Saltmarsh
Saltmarsh
Estuarine Beach
Tidal Flat
Inland Open Water
Open Water
Inland Shore
Tidal Swamp
Brackish Marsh
Snohomish Estuary
Everett
Initial Condition
Year 2050, A1B-Max
Year 2100, A1B-Max

The results are much different when Site 4 is run without the protective effects of the dikes. 16 percent of dry land is predicted to be converted to marsh or even tidal flats and open water under the A1B Max scenario. According to LiDAR data for this site, elevations of many dry-lands and freshwater wetlands along the Snohomish River are at or below mean tide level.

Table 14. Projections for Habitat Changes for Site 4 with No Dikes (A1B Max for 2100)

	Area of Habitat Type in Hectares (Acres)		Percentage Change (Relative to Totals for This Site)
	Initial Condition	**2100 (+0.69 meters/27.3 inches)**	**2100 (+0.69 meters/27.3 inches)**
Undeveloped Dry Land	21,608 (53,395)	18,129 (44,798)	16% loss
Developed	9,309 (23,003)	9,309 (23,003)	No change
Swamp	1,014 (2,506)	363 (897)	64% loss
Inland Fresh Marsh	1,498 (3,702)	465 (1,149)	69% loss
Tidal Fresh Marsh	155 (383)	11 (27)	93% loss
Transitional Marsh	0 (0)	933 (2,305)	NA
Saltmarsh	29 (72)	2,237 (5,528)	7,548% expansion
Estuarine Beach	158 (390)	7 (17)	96% loss
Tidal Flat	68 (168)	1,709 (4,223)	2,422% expansion
Ocean Beach	0 (0)	0 (0)	NA
Inland Open Water	370 (914)	192 (474)	48% loss
Estuarine Open Water	12,199 (30,144)	13,728 (33,923)	13% expansion
Open Ocean	0 (0)	0 (0)	NA
Brackish Marsh	229 (566)	120 (257)	47% loss
Inland Shore	6 (15)	6 (15)	3% loss
Tidal Swamp	166 (410)	20 (49)	88% loss
Rocky Intertidal	0 (0)	0 (0)	NA
Riverine Tidal	486 (1,201)	65 (161)	87% loss


Site 4: Snohomish Estuary & Everett
Developed Dry Land
Undeveloped Dry Land
Swamp
Inland Freshwater Marsh
Tidal Freshwater Marsh
Transitional Saltmarsh
Saltmarsh
Estuarine Beach
Tidal Flat
Inland Open Water
Open Water
Inland Shore
Tidal Swamp
Brackish Marsh
Snohomish Estuary
Everett
Initial Condition
Year 2050, A1B-Max
No Diking
Year 2100, A1B-Max
No Diking

Site 5: Ediz Hook, Dungeness Spit, and Sequim Bay

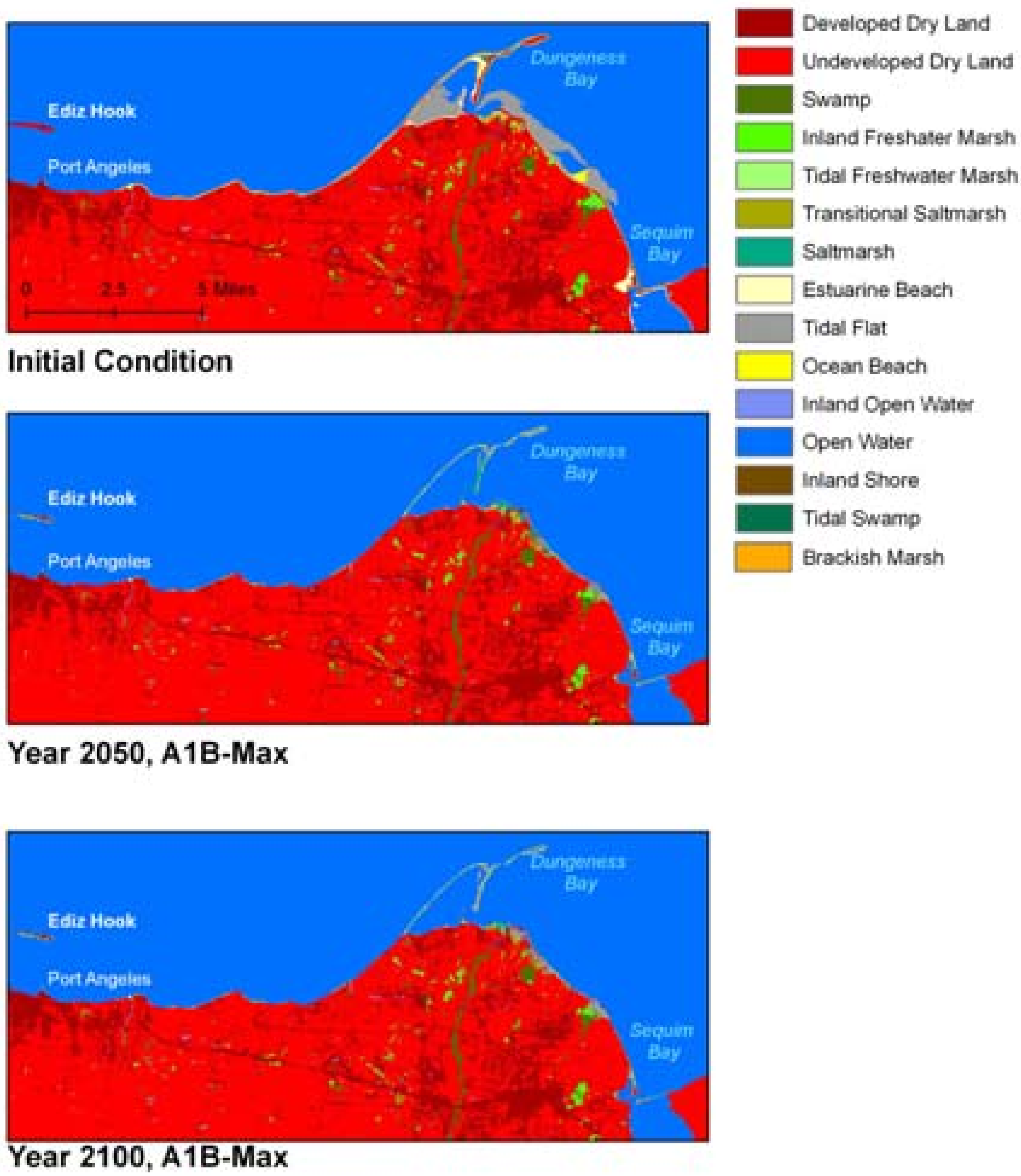
This site includes much of the northern shore of the Olympic Peninsula, from Ediz Hook near Port Angeles (east of the Elwha River delta) through Dungeness Spit and Sequim Bay. The coastal habitats in this region are considered to be critical to the functioning of the Puget Sound ecosystem given their association with the Strait of Juan de Fuca, which is the primary corridor for migrating species. The region's extensive tidal flats, marshes, and other nearshore habitats support three federally-listed salmonid species as well as provide important habitat for forage fish, shrimp, Dungeness crab, oysters, shorebirds, waterfowl, and seals. There has been considerable coastal armoring in the region, particularly near Port Angeles, and changes in waterflows due to dams, levees, dikes, and other structures have significantly altered coastal habitats. In addition, recreational use of sensitive areas such as the Dungeness Spit has contributed to reductions in wildlife populations.

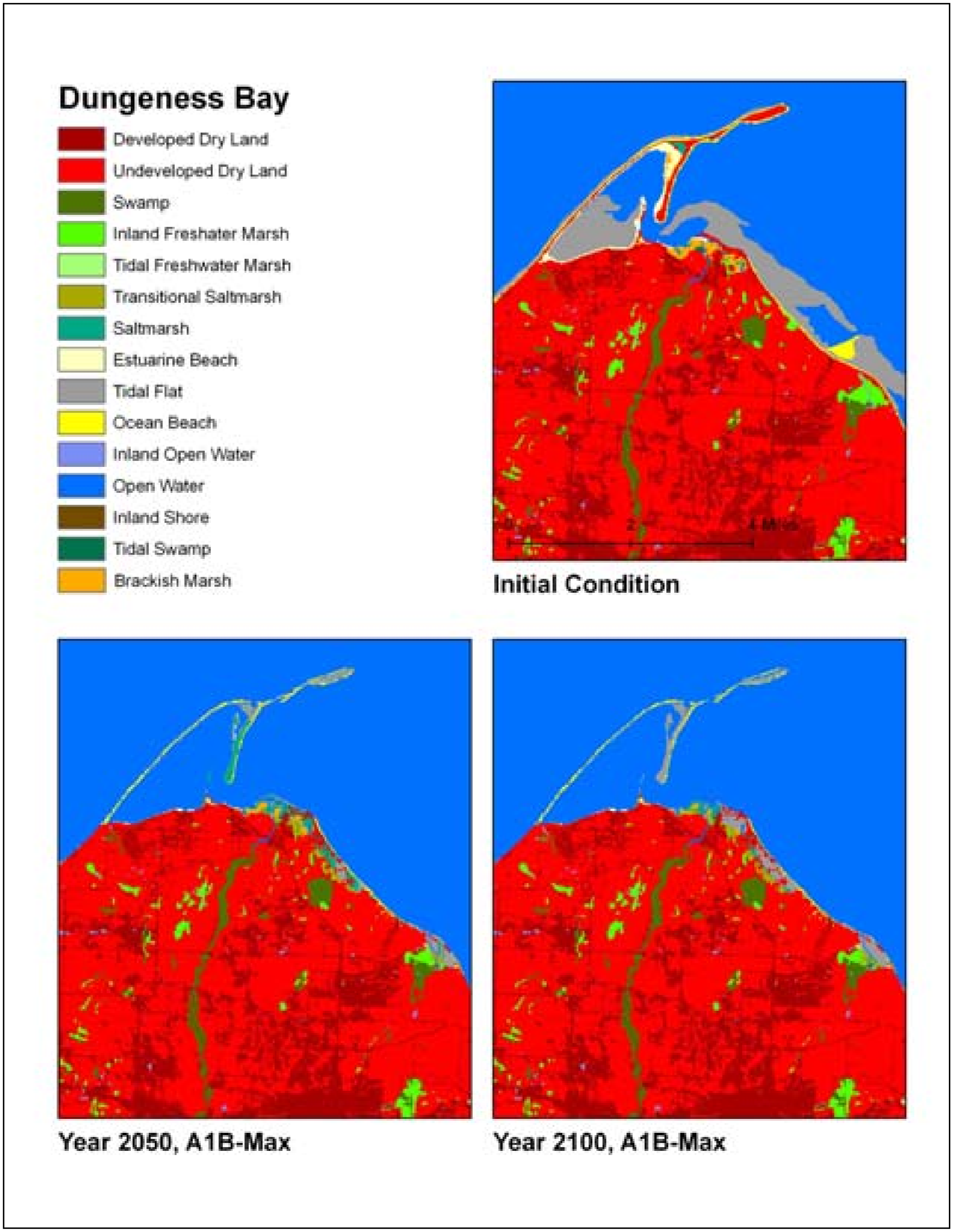
Tidal flats at this site are extremely vulnerable as is Dungeness Spit itself, especially to higher sea-level rise scenarios in which complete loss of the Spit is predicted. Dungeness Spit is predicted to be subject to inundation, erosion, and overwash due to storm events. Additionally the majority of area beaches (estuarine and ocean beaches combined) are predicted to be lost by 2100 under these scenarios. Dry land on this map is not predicted to be especially vulnerable due to its generally high elevations; only 2 percent dry land loss is predicted even given 1.5 meters (59.1 inches) of sea-level rise.

Dungeness Spit (iStock)

Table 15. Projections of Habitat Changes for Site 5 [A1B Max for 2050, 2100 and 1.5 Meters (59.1 inches) for 2100]							
	Area of Habitat Type in Hectares (Acres)				**Percentage Change (Relative to Totals for This Site)**		
	Initial Condition	**2050 (+0.28 meters/11.2 inches)**	**2100 (+0.69 meters/27.3 inches)**	**2100 (+1.5 meters/59.1 inches)**	**2050 (+0.28 meters/11.2 inches)**	**2100 (+0.69 meters/27.3 inches)**	**2100 (+1.5 meters/59.1 inches)**
Undeveloped Dry Land	20,063 (49,577)	19,787 (48,895)	19,763 (48,835)	19,735 (48,766)	1% loss	1% loss	2% loss
Developed	4,845 (11,972)	4,845 (11,972)	4,845 (11,972)	4,845 (11,972)	No change	No change	No change
Swamp	346 (855)	341 (843)	337 (833)	326 (806)	1% loss	2% loss	6% loss
Inland Fresh Marsh	346 (855)	302 (746)	295 (729)	284 (702)	13% loss	15% loss	18% loss
Tidal Fresh Marsh	3 (7)	2 (5)	2 (5)	1 (2)	31% loss	38% loss	53% loss
Transitional Marsh	0 (0)	40 (99)	44 (109)	21 (52)	NA	NA	NA
Saltmarsh	21 (52)	105 (259)	37 (91)	61 (151)	391% expansion	65% expansion	186% expansion
Estuarine Beach	161 (398)	18 (44)	11 (27)	7 (17)	89% loss	93% loss	96% loss
Tidal Flat	877 (2,167)	110 (272)	168 (415)	160 (395)	87% loss	81% loss	82% loss
Ocean Beach	172 (425)	132 (326)	128 (316)	1 (2)	23% loss	26% loss	99% loss
Inland Open Water	96 (237)	92 (227)	92 (227)	91 (225)	4% loss	5% loss	6% loss
Estuarine Open Water	1,101 (2,721)	1,664 (4,112)	1,477 (3,650)	1,200 (2,965)	51% expansion	34% expansion	9% expansion
Open Ocean	28,084 (69,397)	28,721 (70,971)	28,975 (71,599)	29,442 (72,753)	2% expansion	3% expansion	5% expansion
Brackish Marsh	60 (148)	21 (52)	10 (25)	10 (25)	65% loss	84% loss	83% loss
Inland Shore	61 (151)	61 (151)	61 (151)	61 (151)	No change	No change	No change
Tidal Swamp	9 (22)	4 (10)	3 (7)	2 (5)	62% loss	72% loss	78% loss
Rocky Intertidal	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Riverine Tidal	6 (15)	4 (10)	4 (10)	4 (10)	29% loss	32% loss	39% loss

Site 5: Ediz Hook near Port Angeles through Dungeness Spit & Sequim Bay




Dungeness Bay
Developed Dry Land
Undeveloped Dry Land
Swamp
Inland Freshater Marsh
Tidal Freshwater Marsh
Transitional Saltmarsh
Saltmarsh
Estuarine Beach
Tidal Flat
Ocean Beach
Inland Open Water
Open Water
Inland Shore
Tidal Swamp
Brackish Marsh
Initial Condition
Year 2050, A1B-Max
Year 2100, A1B-Max

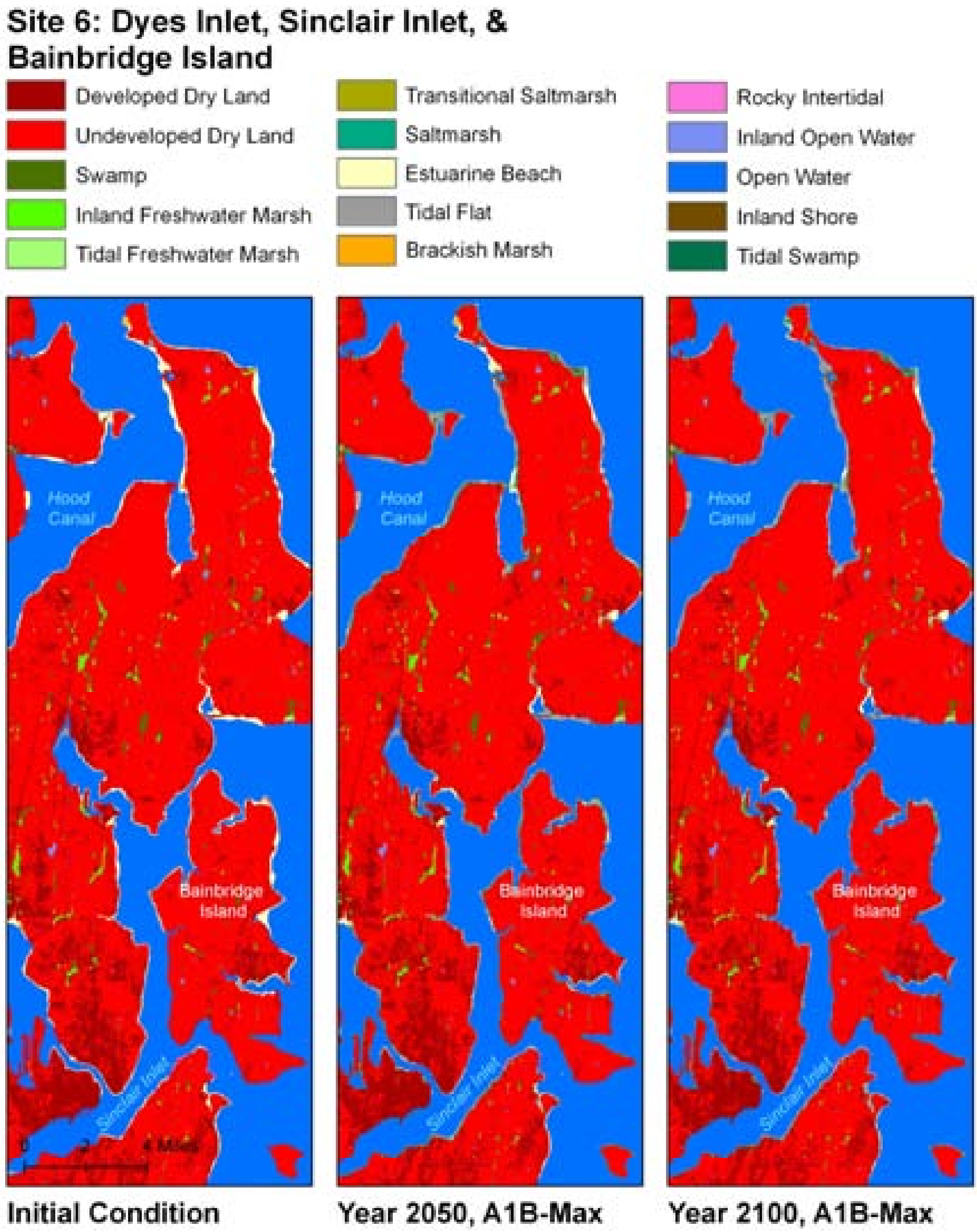
Site 6: Dyes Inlet, Sinclair Inlet, and Bainbridge Island

This site encompasses much of Washington's upper Hood Canal and the Kitsap Peninsula, including Skunk Bay and Port Gamble, Bainbridge Island, and Sinclair and Dyes inlets. The region's protected bays and inlets and its vast coastline and beaches provide critical habitat for numerous species of forage fish, shellfish, shorebirds, and other wildlife. The lack of extensive urbanization in the northern region has enabled much of its nearshore habitat to remain relatively healthy, although increasing pressure from coastal development has contributed to shoreline modifications throughout the region. The most extensive habitat loss to date has occurred in the southern region around Bremerton due to considerable urban and industrial development.

Most dry land in this portion of Puget Sound is of sufficient elevation to escape conversion even in the more aggressive sea-level rise scenarios. Over half of beach land is predicted to be lost by 2050, however, primarily converted into tidal flats. Saltmarsh and transitional marsh increase under both scenarios, primarily due to the loss of dry lands.

View of Seattle from Bainbridge island (iStock)

Table 16. Projections of Habitat Changes for Site 6 [A1B Max for 2050, 2100 and 1.5 Meters for 2100]							
	Area of Habitat Type in Hectares (Acres)				Percentage Change (Relative to Totals for This Site)		
	Initial Condition	2050 (+0.28 meters/11.2 inches)	2100 (+0.69 meters/27.3 inches)	2100 (+ 1.5 meters/59.1 inches)	2050 (+0.28 meters/11.2 inches)	2100 (+0.69 meters/27.3 inches)	2100 (+ 1.5 meters/59.1 inches)
Undeveloped Dry Land	46,088 (113,886)	45,070 (111,370)	44,922 (111,005)	44,788 (110,674)	2% loss	3% loss	3% loss
Developed	8,136 (20,104)	8,136 (20,104)	8,136 (20,104)	8,136 (20,104)	No change	No change	No change
Swamp	619 (1,530)	608 (1,502)	602 (1,488)	595 (1,470)	2% loss	3% loss	4% loss
Inland Fresh Marsh	546 (1,349)	519 (1,282)	515 (1,273)	512 (1,265)	5% loss	6% loss	6% loss
Tidal Fresh Marsh	9 (22)	9 (22)	9 (22)	9 (22)	No change	No change	No change
Transitional Marsh	0 (0)	377 (932)	320 (791)	238 (588)	NA	NA	NA
Saltmarsh	10 (25)	691 (1,707)	490 (1,211)	535 (1,322)	6,533% expansion	4,388% expansion	4,960% expansion
Estuarine Beach	1,789 (4421)	714 (1,764)	526 (1,300)	274 (677)	60% loss	71% loss	85% loss
Tidal Flat	48 (119)	743 (1,836)	963 (2,380)	722 (1,784)	1,455% expansion	1,916% expansion	1,411% expansion
Ocean Beach	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Inland Open Water	258 (638)	255 (630)	255 (630)	255 (630)	2% loss	1% loss	1% loss
Estuarine Open Water	39,112 (96,648)	39,519 (97,654)	39,916 (98,635)	40,621 (100,377)	1% expansion	2% expansion	4% expansion
Open Ocean	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Brackish Marsh	63 (156)	45 (111)	33 (82)	14 (35)	28% loss	48% loss	78% loss
Inland Shore	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Tidal Swamp	9 (22)	4 (10)	3 (7)	2 (5)	57% loss	65% loss	74% loss
Rocky Intertidal	22 (54)	21 (52)	20 (49)	10 (25)	4% loss	6% loss	53% loss
Riverine Tidal	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA


Site 6: Dyes Inlet, Sinclair Inlet, &
Bainbridge Island
Developed Dry Land
Undeveloped Dry Land
Swamp
Inland Freshwater Marsh
Tidal Freshwater Marsh
Transitional Saltmarsh
Saltmarsh
Estuarine Beach
Tidal Flat
Brackish Marsh
Rocky Intertidal
Inland Open Water
Open Water
Inland Shore
Tidal Swamp
Hood Canal
Bainbridge Island
Sinclair Inlet
0 2 4 Miles
Initial Condition
Year 2050, A1B-Max
Year 2100, A1B-Max

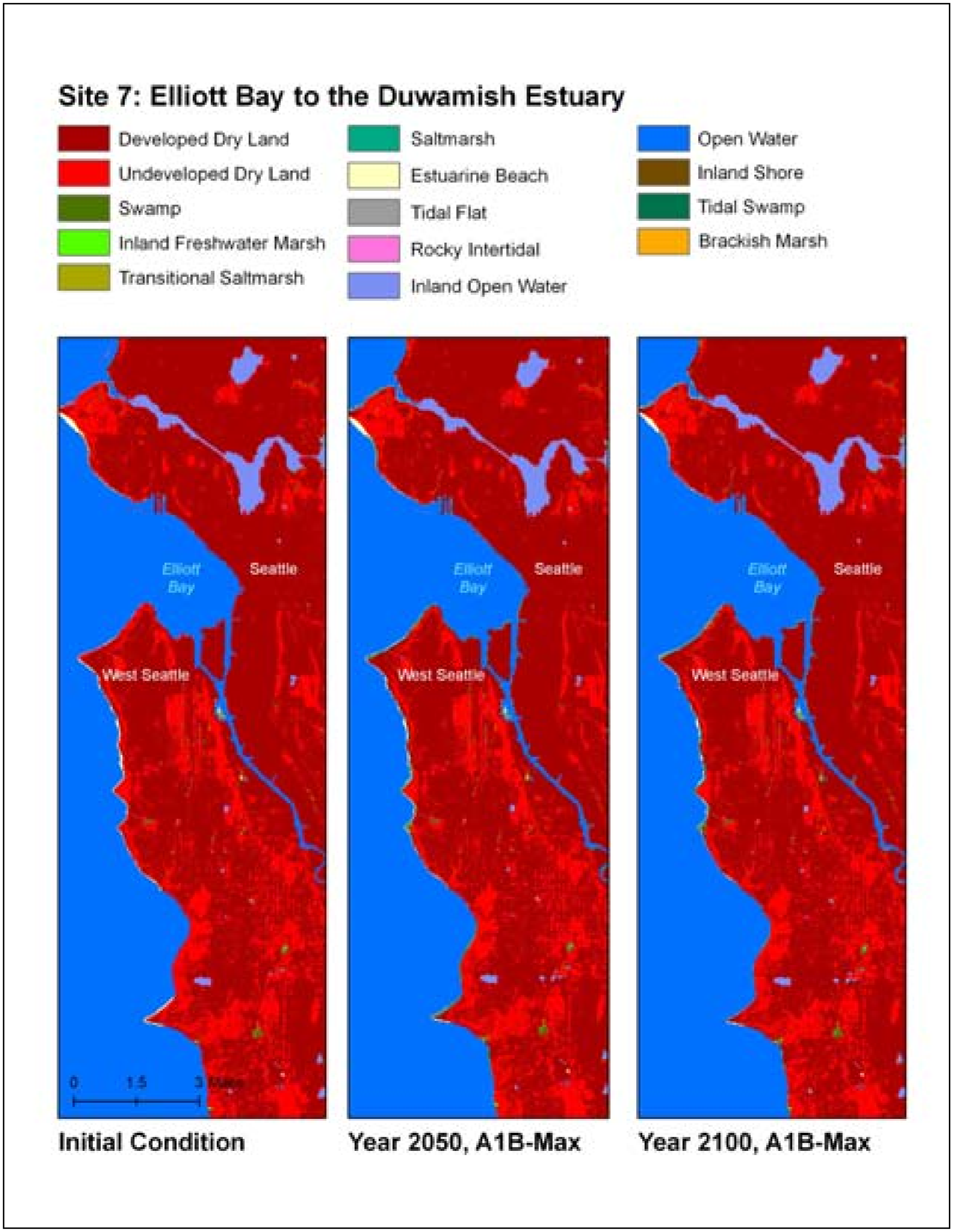
Site 7: Elliott Bay to the Duwamish Estuary

This study site covers part of the central Puget Sound sub-basin from Elliott Bay to the Duwamish estuary, which is the most industrialized and populated area of Puget Sound. The vast majority of the shallows and flats in the Duwamish estuary and Elliott Bay have been destroyed by dredging and filling for development, although there are still some important habitats remaining in the area – particularly beaches. These areas provide forage habitat for juvenile salmon, bull trout, and cutthroat trout, and they also support shellfish production. However, much of the area faces significant water quality problems from contaminated runoff.

Limited effects are predicted for the Seattle area due to a high density of development and high land elevations overall. However, 300-400 hectares (741-988 acres) of dry land are predicted to be at risk at this site, being converted to transitional marsh, saltmarsh, and tidal flats; 55-85 percent of estuarine beach at this site could be lost by 2100. Understandably, the assumption that developed areas will be protected from the effects of sea-level rise is significant at this site which is nearly 50 percent composed of developed land. If the protection of developed land was not assumed, regions along the Duwamish Waterway and Harbor Island would be subject to additional inundation effects, especially under scenarios with higher rates of sea-level rise.

View of Seattle from Kellogg Island in the Duwamish River (NOAA)

Table 17. Projections of Habitat Changes for Site 7 [A1B Max for 2050, 2100 and 1.5 Meters for 2100]							
	Area of Habitat Type in Hectares (Acres)				Percentage Change (Relative to Totals for This Site)		
	Initial Condition	2050 (+0.28 meters/11.2 inches)	2100 (+0.69 meters/27.3 inches)	2100 (+1.5 meters/59.1 inches)	2050 (+0.28 meters/11.2 inches)	2100 (+0.69 meters/27.3 inches)	2100 (+1.5 meters/59.1 inches)
Undeveloped Dry Land	6,515 (16,099)	6,245 (15,432)	6,203 (15,328)	6,153 (15,204)	4% loss	5% loss	6% loss
Developed	20,395 (50,397)	20,395 (50,379)	20,395 (50,397)	20,395 (50,397)	No change	No change	No change
Swamp	134 (331)	133 (329)	132 (326)	130 (321)	1% loss	1% loss	3% loss
Inland Fresh Marsh	63 (156)	62 (153)	61 (151)	59 (146)	2% loss	4% loss	7% loss
Tidal Fresh Marsh	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Transitional Marsh	4 (10)	72 (178)	74 (183)	83 (205)	1,538% expansion	1,571% expansion	1,780% expansion
Saltmarsh	0 (0)	182 (450)	105 (259)	96 (237)	NA	NA	NA
Estuarine Beach	118 (292)	70 (173)	53 (131)	18 (44)	40% loss	55% loss	85% loss
Tidal Flat	18 (44)	41 (101)	77 (190)	131 (324)	121% expansion	319% expansion	611% expansion
Ocean Beach	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Inland Open Water	881 (2,177)	889 (2,197)	889 (2,197)	890 (2,199)	1% expansion	1% expansion	1% expansion
Estuarine Open Water	16,697 (41,259)	16,746 (41,380)	16,848 (41,632)	16,890 (41,736)	1% expansion	1% expansion	1% expansion
Open Ocean	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Brackish Marsh	11 (27)	6 (15)	5 (12)	3 (7)	45% loss	56% loss	77% loss
Inland Shore	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Tidal Swamp	1 (2)	0 (0)	0 (0)	0 (0)	47% loss	66% loss	85% loss
Rocky Intertidal	8 (20)	6 (15)	5 (12)	5 (12)	28% loss	37% loss	44% loss
Riverine Tidal	24 (59)	22 (54)	21 (52)	19 (47)	11% loss	14% loss	20% loss


Site 7: Elliott Bay to the Duwamish Estuary
Developed Dry Land
Undeveloped Dry Land
Swamp
Inland Freshwater Marsh
Transitional Saltmarsh
Saltmarsh
Estuarine Beach
Tidal Flat
Rocky Intertidal
Inland Open Water
Open Water
Inland Shore
Tidal Swamp
Brackish Marsh
Elliott Bay
Seattle
West Seattle
0
1.5
3
Initial Condition
Year 2050, A1B-Max
Year 2100, A1B-Max

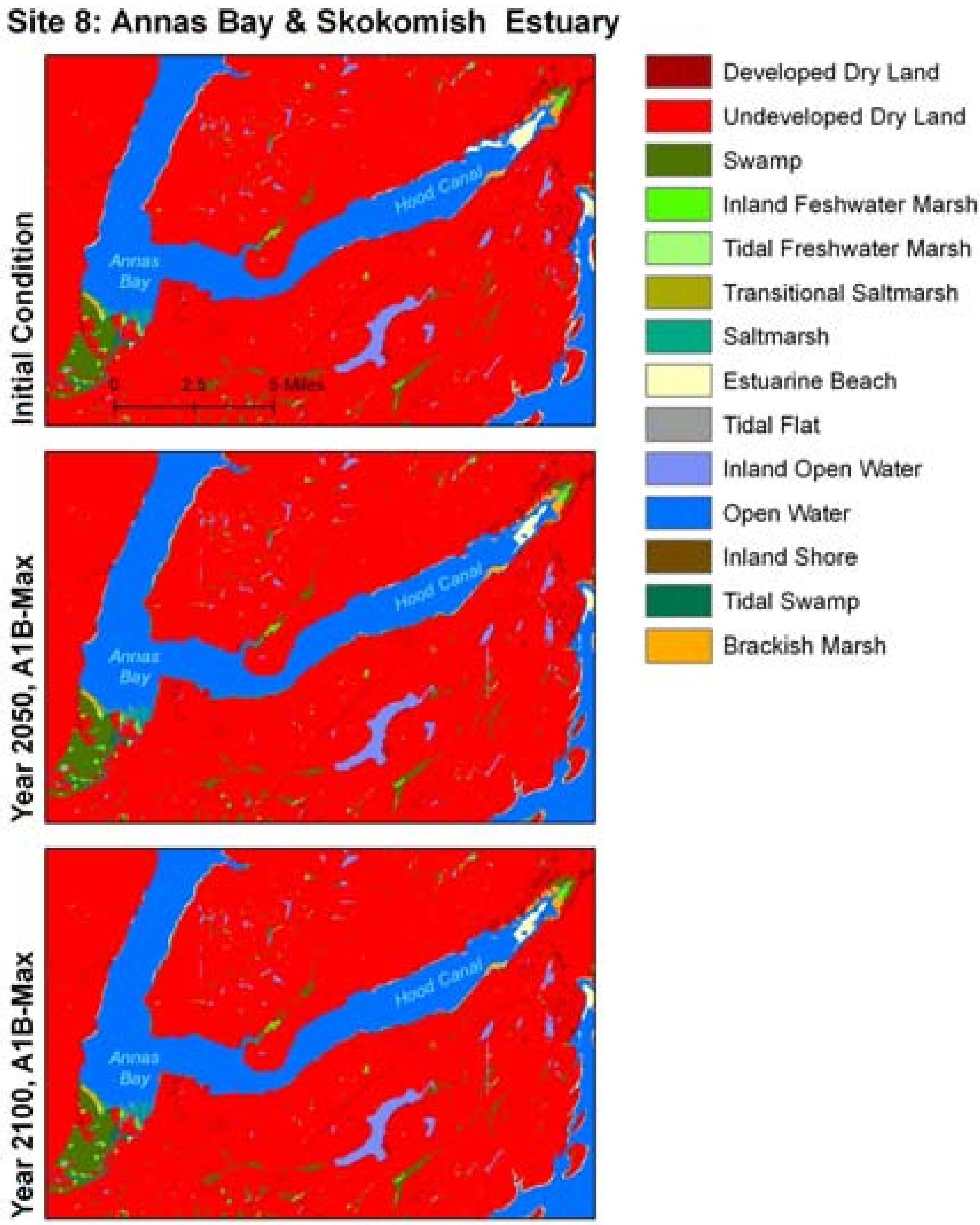
Site 8: Annas Bay and Skokomish Estuary

Annas Bay and the Skokomish River estuary in the southern part of Washington's Hood Canal have historically supported some of the region's most productive shellfish habitat. The area is also a haven for birds, seals, and other wildlife, and is a popular tourist destination. One of the biggest threats to the region's habitats has been contamination from polluted runoff, which has exacerbated low oxygen (hypoxia) events in the bay and has led to numerous closures to commercial and recreational fishing. While human activities such as development and dams upstream have been a significant part of the problem, the loss of estuarine wetlands due to diking for agricultural purposes has significantly reduced the natural capture of nitrogen that these habitats provide.

High land elevations for dry land and swamp make this site less likely to be influenced by sea-level rise than many of the other sites studied. The most significant change is loss of estuarine beaches, which decline by about one-third under all scenarios.

The Skokomish River delta (Wikimedia)

Table 18. Projections of Habitat Changes for Site 8 [A1B Max for 2050, 2100 and 1.5 Meters for 2100]							
	Area of Habitat Type in Hectares (Acres)				Percentage Change (Relative to Totals for This Site)		
	Initial Condition	**2050 (+0.28 meters/11.2 inches)**	**2100 (+0.69 meters/27.3 inches)**	**2100 (+ 1.5 meters/59.1 inches)**	**2050 (+0.28 meters/11.2 inches)**	**2100 (+0.69 meters/27.3 inches)**	**2100 (+ 1.5 meters/59.1 inches)**
Undeveloped Dry Land	40,510 (100,102)	40,169 (99,260)	40,125 (99,151)	40,084 (99,050)	1% loss	1% loss	1% loss
Developed	961 (2,375)	961 (2,375)	961 (2,375)	961 (2,375)	No change	No change	No change
Swamp	1,399 (3,457)	1,447 (3,576)	1,447 (3,576)	1,447 (3,576)	3% expan-sion	3% expan-sion	3% expan-sion
Inland Fresh Marsh	293 (724)	294 (726)	293 (724)	284 (702)	<1% exxpan-sion	No change	3% loss
Tidal Fresh Marsh	14 (35)	14 (35)	14 (35)	14 (35)	No change	No change	No change
Transitional Marsh	0 (0)	80 (198)	55 (136)	75 (185)	NA	NA	NA
Saltmarsh	131 (324)	280 (692)	198 (489)	195 (482)	114% expan-sion	49% expan-sion	48% expan-sion
Estuarine Beach	558 (1,379)	379 (937)	365 (902)	344 (850)	32% loss	34% loss	38% loss
Tidal Flat	0 (0)	55 (136)	92 (227)	87 (215)	NA	NA	NA
Ocean Beach	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Inland Open Water	793 (1,960)	839 (2,073)	837 (2,068)	835 (2,063)	6% expan-sion	6% expan-sion	5% expan-sion
Estuarine Open Water	9,199 (22,731)	9,342 (23,085)	9,473 (23,408)	9,537 (23,566)	2% expan-sion	3% expan-sion	4% expan-sion
Open Ocean	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Brackish Marsh	164 (405)	162 (400)	162 (400)	161 (398)	1% loss	1% loss	2% loss
Inland Shore	3 (7)	3 (7)	3 (7)	3 (7)	No change	No change	No change
Tidal Swamp	37 (91)	37 (91)	37 (91)	36 (89)	<1% loss	<1% loss	3% loss
Riverine Tidal	41 (101)	41 (101)	41 (101)	39 (96)	No change	No change	4% loss


Site 8: Annas Bay & Skokomish Estuary
Initial Condition
Year 2050, A1B-Max
Year 2100, A1B-Max
Annas Bay
Hood Canal
0
2.5
5 Miles
Developed Dry Land
Undeveloped Dry Land
Swamp
Inland Feshwater Marsh
Tidal Freshwater Marsh
Transitional Saltmarsh
Saltmarsh
Estuarine Beach
Tidal Flat
Inland Open Water
Open Water
Inland Shore
Tidal Swamp
Brackish Marsh

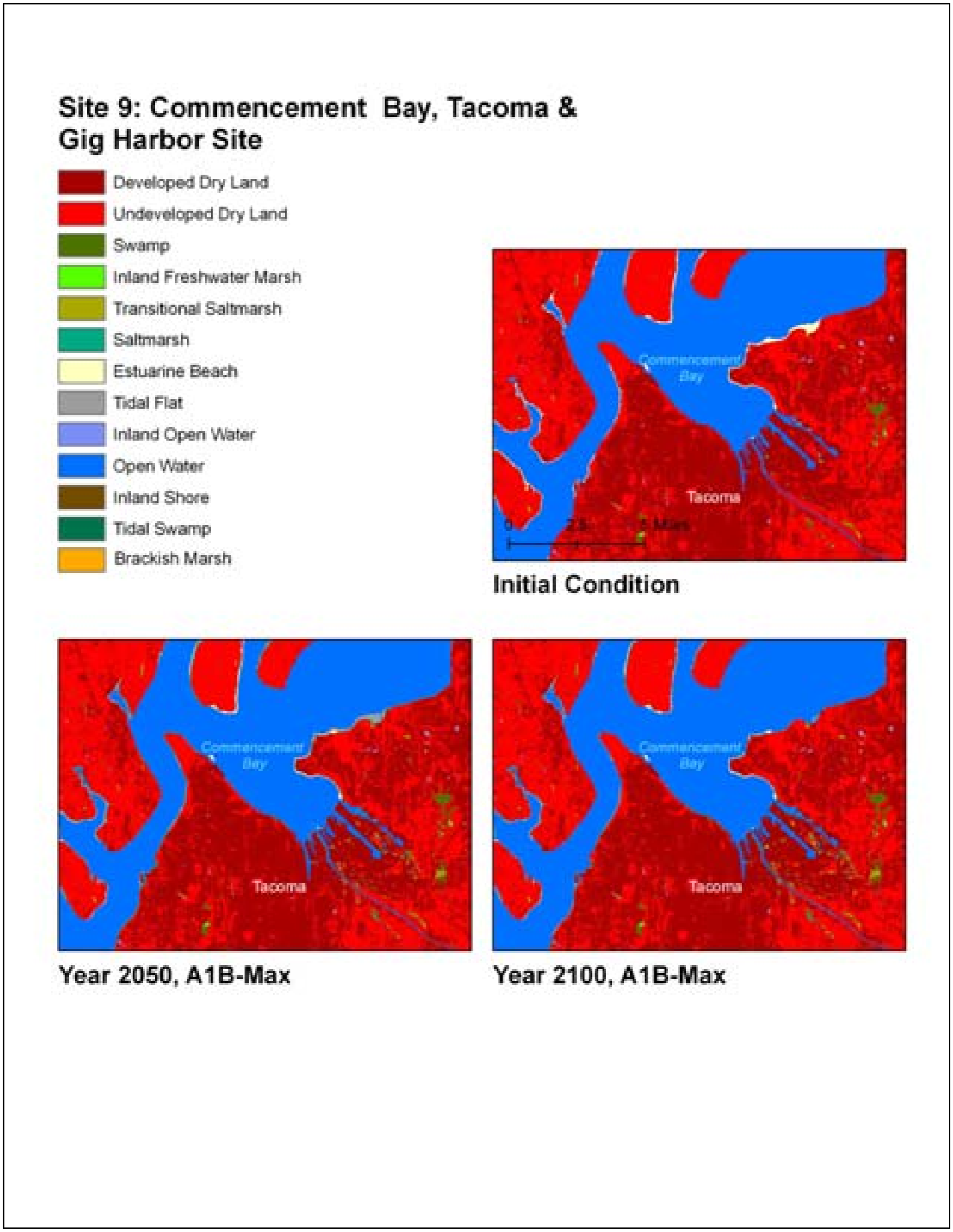
Site 9: Commencement Bay, Tacoma, and Gig Harbor

This site includes the region of South Puget Sound from Commencement Bay at Tacoma to the Gig Harbor Peninsula and southern Vashon and Maury islands. Much of the less-developed coastline in this study region is characterized by mixed sediment beaches and bluffs, with areas of tidal flats, eelgrass, and kelp beds. Extensive development and coastal armoring of the Puyallup River delta at the Port of Tacoma have damaged and destroyed vast areas of once highly-productive habitat and contributed to a considerable decline in water quality throughout the area's coastal waters.

The Tacoma area is well protected by dikes around the Puyallup River, so results of sea-level rise are limited near that river. About 3-4 percent of undeveloped dry land is predicted to be lost at this site overall though, converting to transitional marsh and saltmarsh. Over two-thirds of area beaches are predicted to be lost by 2100 due to erosion and inundation. Beaches convert to tidal flats initially and then are completely lost to estuarine open water under higher sea level rise scenarios.

Commencement Bay (iStock)

Table 19. Projections of Habitat Changes for Site 9 **[A1B Max for 2050, 2100 and 1.5 Meters for 2100]**							
	Area of Habitat Type in Hectares (Acres)				**Percentage Change (Relative to Totals for This Site)**		
	Initial Condition	**2050 (+0.28 meters/11.2 inches)**	**2100 (+0.69 meters/27.3 inches)**	**2100 (+1.5 meters/59.1 inches)**	**2050 (+0.28 meters/11.2 inches)**	**2100 (+0.69 meters/27.3 inches)**	**2100 (+1.5 meters/59.1 inches)**
Undeveloped Dry Land	23,962 (59,211)	23,196 (57,319)	23,082 (57,037)	22,980 (56,785)	3% loss	4% loss	4% loss
Developed	21,001 (51,895)	21,001 (51,895)	21,001 (51,895)	21,001 (51,895)	No change	No change	No change
Swamp	409 (1,011)	421 (1,040)	420 (1,038)	420 (1,038)	3	3	3
Inland Fresh Marsh	108 (267)	420 (1,040)	103 (255)	101 (250)	4% loss	4% loss	6% loss
Tidal Fresh Marsh	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Transitional Marsh	0 (0)	295 (729)	282 (697)	207 (512)	NA	NA	NA
Saltmarsh	0 (0)	438 (1,082)	317 (783)	387 (956)	NA	NA	NA
Estuarine Beach	743 (1,836)	269 (665)	197 (487)	71 (175)	64% loss	73% loss	91% loss
Tidal Flat	0 (0)	295 (729)	332 (820)	362 (895)	NA	NA	NA
Ocean Beach	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Inland Open Water	254 (628)	248 (613)	247 (610)	246 (608)	2% loss	3% loss	3% loss
Estuarine Open Water	19,300 (47,691)	19,526 (48,250)	19,812 (48,957)	20,024 (49,480)	1% expansion	3% expansion	4% expan-sion
Open Ocean	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Brackish Marsh	12 (30)	6 (15)	5 (12)	3 (7)	52% loss	58% loss	71% loss
Inland Shore	1 (2)	1 (2)	1 (2)	1 (2)	No change	No change	No change
Tidal Swamp	5 (12)	5 (12)	5 (12)	5 (12)	No change	No change	No change
Rocky Inter-tidal	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Riverine Tidal	74 (183)	64 (158)	63 (156)	61 (151)	13% loss	15% loss	18% loss


Site 9: Commencement Bay, Tacoma & Gig Harbor Site
Developed Dry Land
Undeveloped Dry Land
Swamp
Inland Freshwater Marsh
Transitional Saltmarsh
Saltmarsh
Estuarine Beach
Tidal Flat
Inland Open Water
Open Water
Inland Shore
Tidal Swamp
Brackish Marsh
Commencement Bay
Tacoma
0
2.5
5 Miles
Initial Condition
Commencement Bay
Tacoma
Year 2050, A1B-Max
Commencement Bay
Tacoma
Year 2100, A1B-Max

Site 10: Olympia, Budd Inlet, and Nisqually Delta

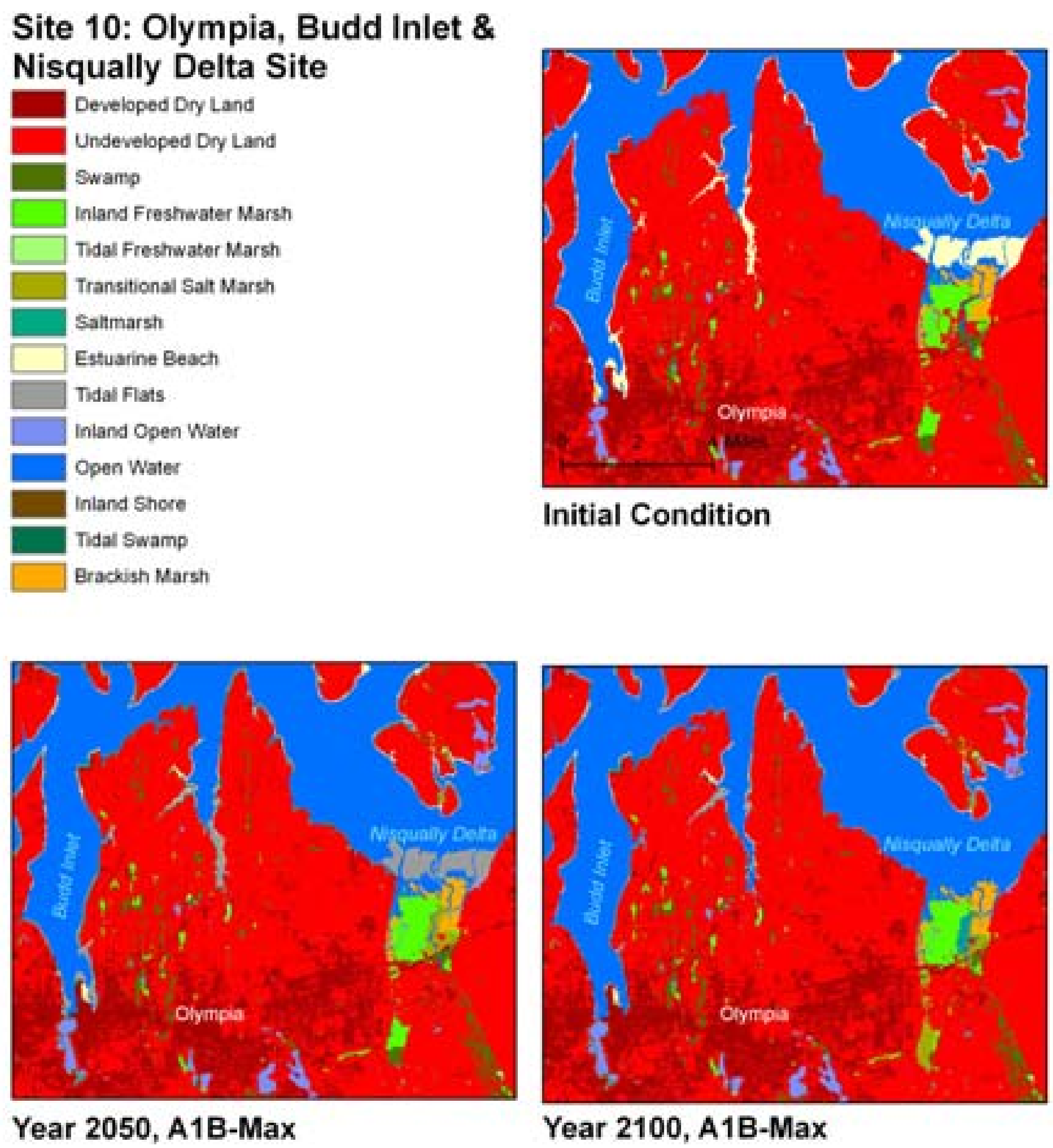
Site 10, in the southern-most area of Puget Sound, includes Olympia, Budd Inlet and the Nisqually delta. The coastline near Olympia has been heavily modified by development, but other parts of the region include considerable areas of estuarine beach, coastal marsh, and swamps and provide important habitat for salmonids, forage fish, invertebrates, shorebirds, waterfowl, and other wildlife.

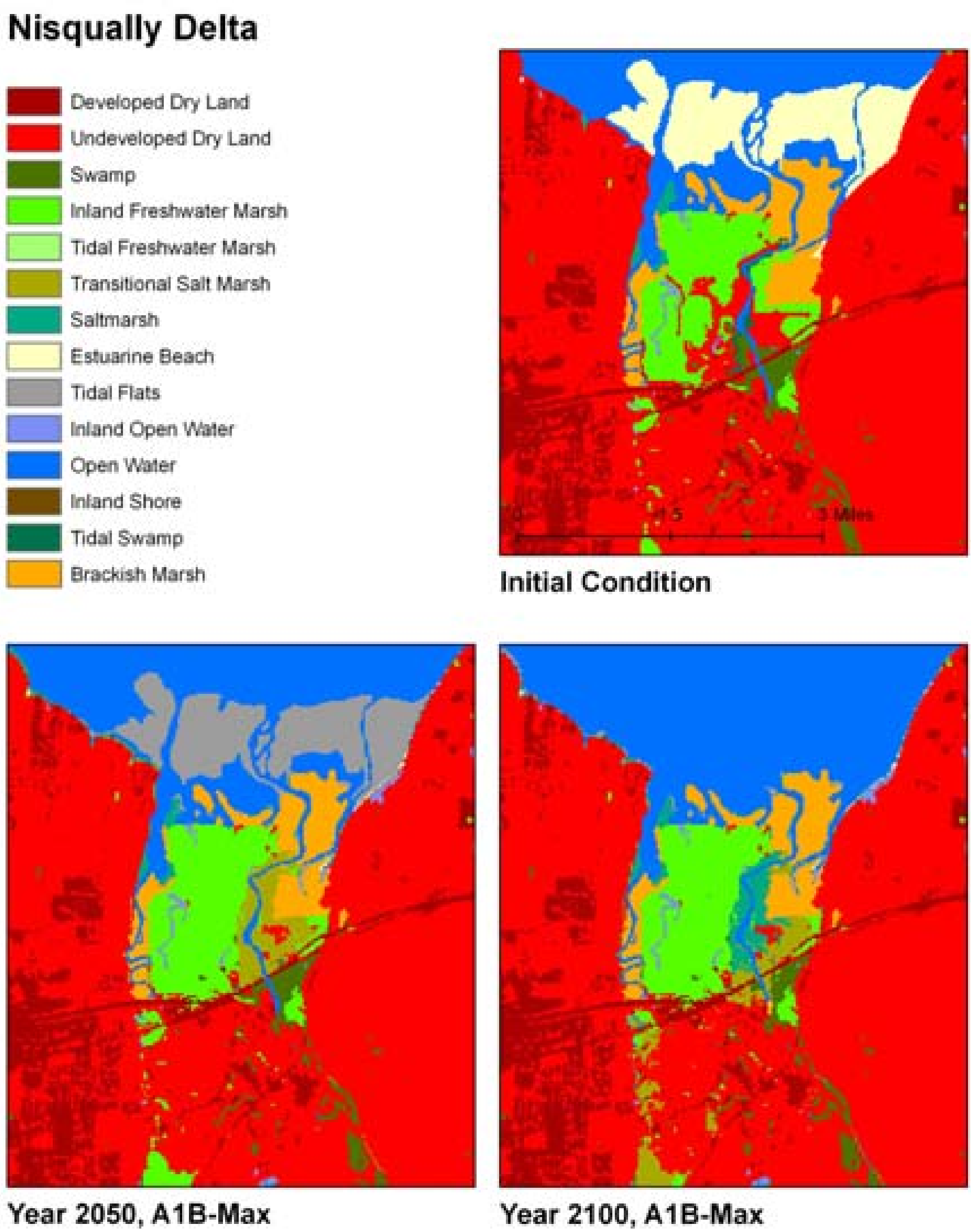
The Nisqually delta region, which includes the Nisqually National Wildlife Refuge, remains one of the largest undeveloped deltas in Puget Sound, although diking has separated freshwater and saltwater habitats in part of the delta for much of the 20th century. The largest predicted changes for Site 10 pertain to the loss of estuarine beach, including a 76-percent loss by 2050 and an 81-percent loss by 2100 under the A1B max scenario. There is also inundation of some dry lands. Tidal flat area expands significantly by 2050 then declines by 2100.

Given its importance for salmon recovery and other conservation goals, there have been significant efforts in recent years to restore parts of the Nisqually delta, including a recent project of the Nisqually Tribe to remove all of the dikes on the Pierce County side and restore tidal influence to parts of the region. In addition, the Nisqually National Wildlife Refuge management plan calls for removal of the dikes in the Thurston County side of the delta in the coming decades.

Nisqually National Wildlife Refuge (Wikimedia)

Table 20. Projections of Habitat Changes for Site 10 [A1B Max for 2050, 2100 and 1.5 Meters for 2100]							
	Area of Habitat Type in Hectares (Acres)				Percentage Change (Relative to Totals for This Site)		
	Initial Condition	2050 (+0.28 meters/11.2 inches)	2100 (+0.69 meters/27.3 inches)	2100 (+1.5 meters/59.1 inches)	2050 (+0.28 meters/11.2 inches)	2100 (+0.69 meters/27.3 inches)	2100 (+1.5 meters/59.1 inches)
Undeveloped Dry Land	21,321 (52,685)	20,674 (51,087)	20,577 (50,847)	20,491 (50,634)	3% loss	3% loss	4% loss
Developed	5,565 (13,751)	5,565 (13,751)	5,565 (13,751)	5,565 (13,751)	No change	No change	No change
Swamp	757 (1,871)	763 (1,885)	720 (1,779)	695 (1,717)	1% expansion	5% loss	8% loss
Inland Fresh Marsh	653 (1,614)	670 (1,656)	591 (1,460)	569 (1,406)	3% expansion	9% loss	13% loss
Tidal Fresh Marsh	19 (47)	20 (49)	20 (49)	20 (49)	3% expansion	3% expansion	3% expansion
Transitional Marsh	0 (0)	247 (610)	317 (783)	352 (870)	NA	NA	NA
Saltmarsh	54 (133)	374 (924)	286 (707)	325 (803)	595% expansion	422% expansion	510% expansion
Estuarine Beach	1237 (3,057)	292 (722)	236 (583)	190 (470)	76% loss	81% loss	85% loss
Tidal Flat	<1 (<2)	869 (2,147)	428 (1,058)	308 (761)	NA	NA	NA
Ocean Beach	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Inland Open Water	453 (1,119)	502 (1,240)	501 (1,238)	498 (1,231)	11% expansion	11% expansion	10% expansion
Estuarine Open Water	10,368 (25,620)	10,506 (25,961)	11,243 (27,782)	11,486 (28,383)	1% expansion	8% expansion	11% expansion
Open Ocean	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Brackish Marsh	272 (672)	245 (605)	244 (603)	231 (571)	10% loss	10% loss	15% loss
Inland Shore	7 (17)	7 (17)	7 (17)	7 (17)	9% loss	9% loss	9% loss
Tidal Swamp	14 (35)	1 (2)	1 (2)	1 (2)	91% loss	91% loss	91% loss
Rocky Intertidal	0 (0)	0 (0)	0 (0)	0 (0)	NA	NA	NA
Riverine Tidal	20 (49)	4 (10)	2 (5)	0 (0)	80% loss	92% loss	100% loss


Site 10: Olympia, Budd Inlet & Nisqually Delta Site
Developed Dry Land
Undeveloped Dry Land
Swamp
Inland Freshwater Marsh
Tidal Freshwater Marsh
Transitional Salt Marsh
Saltmarsh
Estuarine Beach
Tidal Flats
Inland Open Water
Open Water
Inland Shore
Tidal Swamp
Brackish Marsh
Budd Inlet
Nisqually Delta
Olympia
0 2 4 Miles
Initial Condition
Year 2050, A1B-Max
Year 2100, A1B-Max



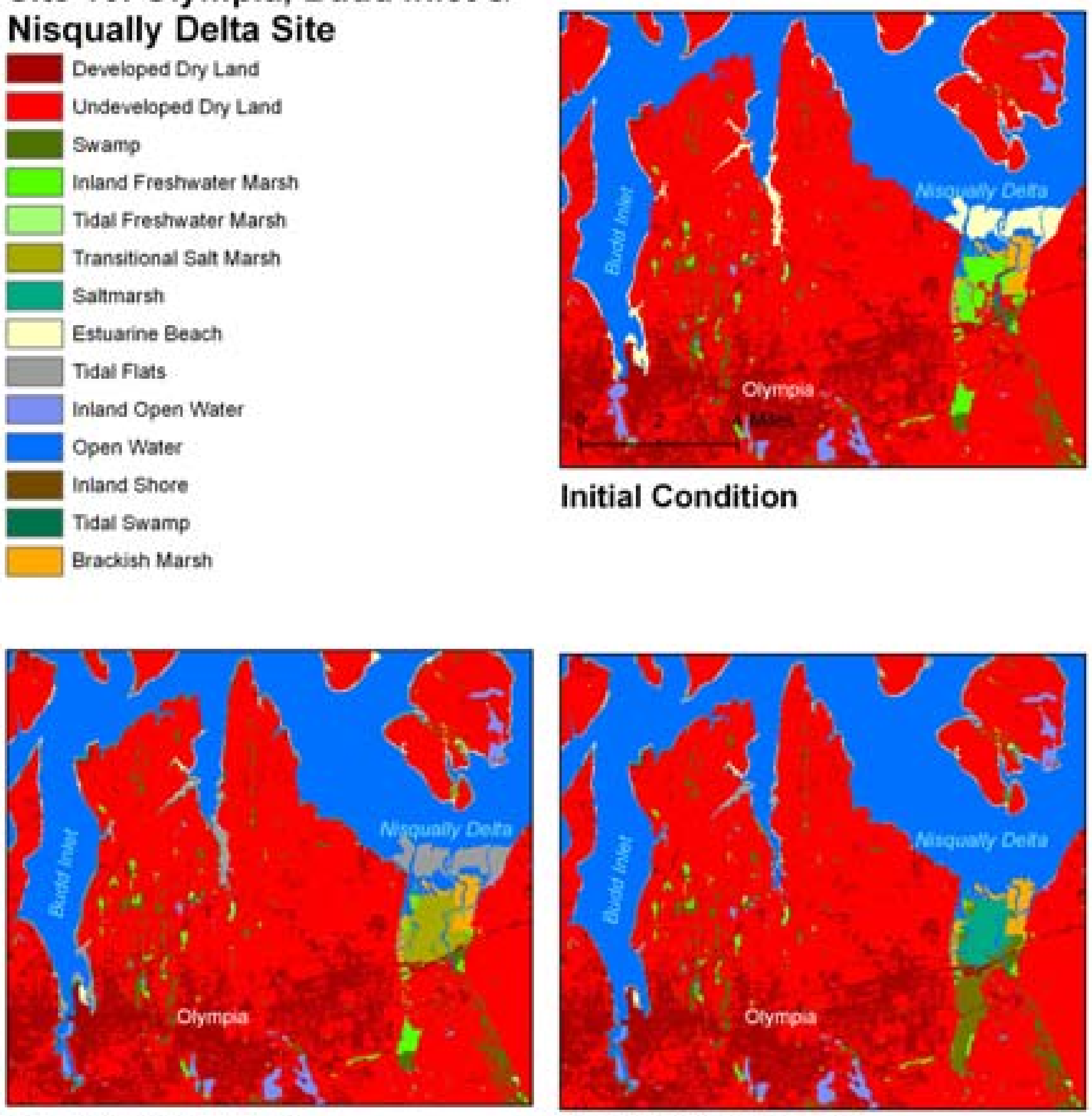
Nisqually Delta
Developed Dry Land
Undeveloped Dry Land
Swamp
Inland Freshwater Marsh
Tidal Freshwater Marsh
Transitional Salt Marsh
Saltmarsh
Estuarine Beach
Tidal Flats
Inland Open Water
Open Water
Inland Shore
Tidal Swamp
Brackish Marsh
Initial Condition
Year 2050, A1B-Max
Year 2100, A1B-Max

Site 10 was also run with the dikes protecting the mouth of the Nisqually river removed. At least half of the inland fresh marsh is predicted to be lost by the year 2100 in this scenario, being converted to transitional saltmarsh or saltmarsh due to salt water inundation.

Table 21. Projections for Habitat Changes for Site 10 with No Dikes
(A1B Max for 2100)

	Area of Habitat Type in Hectares (Acres)		Percentage Change (Relative to Totals for This Site)
	Initial Condition	**2100 (+0.69 meters/27.3 inches)**	**2100 (+0.69 meters/27.3 inches)**
Undeveloped Dry Land	21,321 (52,685)	20,315 (50,199)	5% loss
Developed	5,565 (13,751)	5,565 (13,751)	No change
Swamp	757 (1,871)	718 (1,774)	5% loss
Inland Fresh Marsh	653 (1,614)	239 (591)	63% loss
Tidal Fresh Marsh	19 (47)	20 (49)	3% expansion
Transitional Marsh	0 (0)	587 (1,451)	NA
Saltmarsh	54 (133)	623 (1,539)	1,059% expansion
Estuarine Beach	1,237 (3,057)	236 (583)	81% loss
Tidal Flat	<1 (<2)	438 (1,082)	NA
Ocean Beach	0 (0)	0 (0)	NA
Inland Open Water	453 (1,119)	424 (1,048)	6% loss
Estuarine Open Water	10,368 (25,620)	11,321 (27,975)	9% expansion
Open Ocean	0 (0)	0 (0)	NA
Brackish Marsh	272 (672)	243 (600)	10% loss
Inland Shore	7 (17)	7 (17)	9% loss
Tidal Swamp	14 (35)	1 (2)	94% loss
Rocky Intertidal	0 (0)	0 (0)	NA
Riverine Tidal	20 (49)	2 (5)	92% loss

Site 10: Olympia, Budd Inlet & Nisqually Delta Site



Initial Condition

Year 2050, A1B-Max No Diking

Year 2100, A1B-Max No Diking

Site 11: Willapa Bay, Columbia River Estuary, and Tillamook Bay

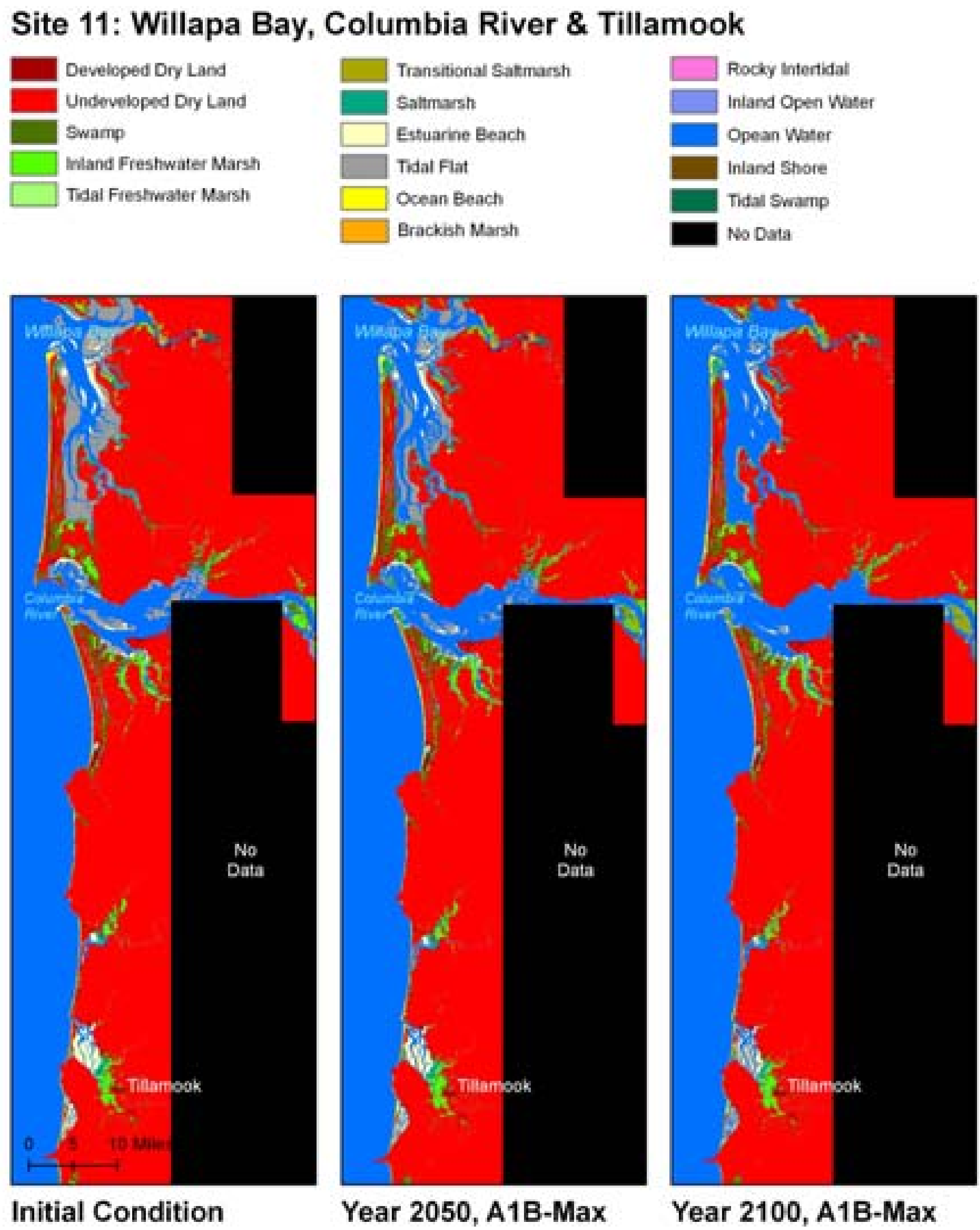
Site 11 covers the Pacific Coast from Willapa Bay in Washington through the Columbia River delta to just south of Tillamook Bay in Oregon. Each of these estuaries supports large populations of fish and wildlife. In particular, the extensive marshes and tidal flats of Tillamook and Willapa bays, including the Willapa Bay National Wildlife Refuge, provide food and habitat for tens of thousands of migrating shorebirds and waterfowl. And the Columbia River estuary is one of the most important nearshore habitat areas for the region's endangered salmonids. As with Puget Sound, coastal habitats in this region have been significantly altered or destroyed by human activities over the past century, especially in the Lower Columbia River estuary.

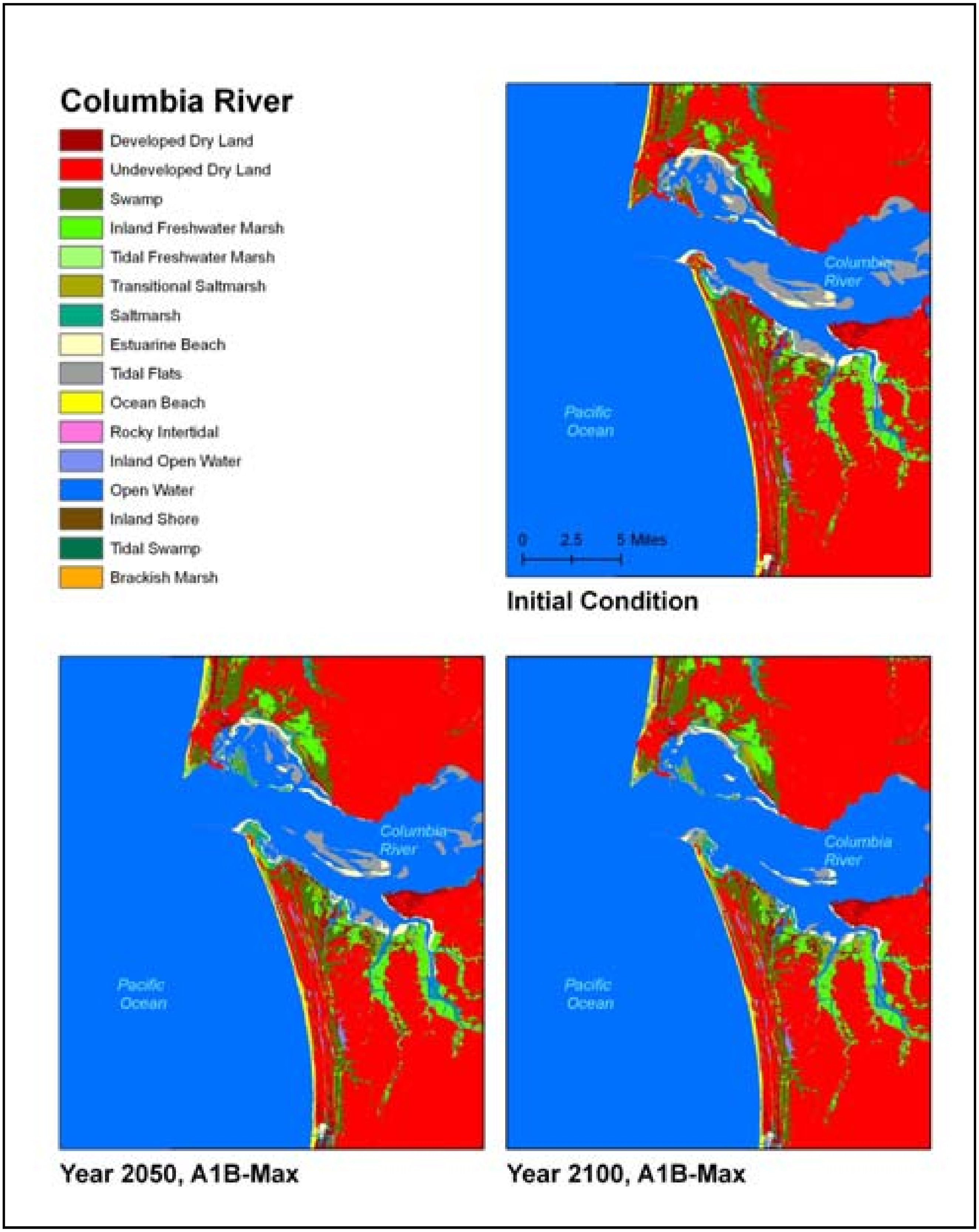
For Site 11, although dry-land loss is only predicted at two percent, this still results in a loss of at least 5,000 hectares (12,355 acres). Extensive loss of tidal flats and area beaches is predicted, especially at the more aggressive rates of sea-level rise. Inland and tidal fresh marsh are fairly vulnerable at this site due to the rise in the salt water level; these categories lose 17-37 percent of their acreage under these scenarios. Tidal swamp and brackish marsh also decline by 63 and 92 percent, respectively, and ocean beach disappears completely with a 1.5 meter (59.1 inch) sea-level rise.

Willapa Bay estuary (NOAA)

Table 22. Projections of Habitat Changes for Site 11
[A1B Max for 2050, 2100 and 1.5 Meters for 2100]

	Area of Habitat Type in Hectares (Acres)				Percentage Change (Relative to Totals for This Site)		
	Initial Condition	**2050 (+0.28 meters/11.2 inches)**	**2100 (+0.69 meters/27.3 inches)**	**2100 (+1.5 meters/59.1 feet)**	**2050 (+0.28 meters/11.2 inches)**	**2100 (+0.69 meters/27.3 inches)**	**2100 (+1.5 meters/59.1 feet)**
Undeveloped Dry Land	323,531 (799,463)	319,015 (788,303)	318,241 (786,391)	317,115 (783,608)	1% loss	2% loss	2% loss
Developed	5,976 (14,767)	5,976 (14,767)	5,976 (14,767)	5,976 (14,767)	No change	No change	No change
Swamp	11,501 (28,420)	11,095 (27,416)	10,238 (25,299)	9,319 (23,028)	4% loss	11% loss	19% loss
Inland Fresh Marsh	11,027 (27,248)	10,223 (25,262)	9,193 (22,716)	8,297 (20,502)	7% loss	17% loss	25% loss
Tidal Fresh Marsh	172 (425)	158 (390)	128 (316)	108 (267)	8% loss	25% loss	37% loss
Transitional Marsh	21 (52)	2,757 (6,813)	4,755 (11,750)	2,365 (5,844)	13,049% expansion	22,575% expansion	11,178% expansion
Saltmarsh	5,430 (13,418)	6,948 (17,169)	5,809 (14,354)	7,055 (17,433)	28% expansion	6% expansion	30% expansion
Estuarine Beach	7,004 (17,307)	5,721 (14,137)	3,704 (9,153)	1,112 (2,748)	18% loss	47% loss	84% loss
Tidal Flat	22,887 (56,555)	15,882 (39,245)	8,457 (20,898)	8,516 (21,043)	31% loss	63% loss	63% loss
Ocean Beach	3,003 (7,421)	3,168 (7,828)	2,781 (6,872)	57 (141)	6% expansion	7% loss	98% loss
Inland Open Water	2,127 (5,256)	1,569 (3,877)	1,478 (3,652)	1,395 (3,447)	26% loss	31% loss	34% loss
Estuarine Open Water	38,211 (94,421)	46,398 (114,652)	56,538 (139,708)	62,925 (155,491)	21% expansion	48% expansion	65% expansion
Open Ocean	139,074 (343,659)	141,158 (348,809)	142,966 (353,277)	146,473 (361,943)	1% expansion	3% expansion	5% expansion
Brackish Marsh	577 (1,426)	545 (1,347)	395 (976)	49 (121)	6% loss	32% loss	92% loss
Inland Shore	7 (17)	7 (17)	7 (17)	7 (17)	No change	No change	No change
Tidal Swamp	266 (657)	217 (536)	183 (452)	99 (245)	18% loss	31% loss	63% loss
Rocky Intertidal	13 (32)	10 (25)	5 (12)	1 (2)	22% loss	62% loss	93% loss
Riverine Tidal	77 (190)	54 (133)	47 (116)	32 (79)	29% loss	39% loss	58% loss


Site 11: Willapa Bay, Columbia River & Tillamook
Developed Dry Land
Undeveloped Dry Land
Swamp
Inland Freshwater Marsh
Tidal Freshwater Marsh
Transitional Saltmarsh
Saltmarsh
Estuarine Beach
Tidal Flat
Ocean Beach
Brackish Marsh
Rocky Intertidal
Inland Open Water
Opean Water
Inland Shore
Tidal Swamp
No Data
Willapa Bay
Columbia River
Tillamook
No Data
0 5 10 Miles
Initial Condition
Year 2050, A1B-Max
Year 2100, A1B-Max


Columbia River
Developed Dry Land
Undeveloped Dry Land
Swamp
Inland Freshwater Marsh
Tidal Freshwater Marsh
Transitional Saltmarsh
Saltmarsh
Estuarine Beach
Tidal Flats
Ocean Beach
Rocky Intertidal
Inland Open Water
Open Water
Inland Shore
Tidal Swamp
Brackish Marsh
Columbia River
Pacific Ocean
0 2.5 5 Miles
Initial Condition
Columbia River
Pacific Ocean
Year 2050, A1B-Max
Columbia River
Pacific Ocean
Year 2100, A1B-Max

CONCLUDING REMARKS

The Pacific Northwest's vast and beautiful coasts are truly an American treasure. Whether it is the thrill of reeling in that prized Chinook salmon in Puget Sound or spending a tranquil fall afternoon at an Oregon beach, the value that coastal resources bring to the region and nation are a legacy worth protecting.

As this report has shown, however, global warming poses a significant threat to the Pacific Northwest's coasts and the fish and wildlife they support. Left unchecked, global warming will lead to rapidly rising sea levels and coastal inundation. It will mean higher average air and water temperatures, shifts in precipitation patterns, and a significant decline in average snowpack. Making the situation worse is the fact that these impacts will fall on top of the many other problems that continue to plague the region.

But it is not too late to act. It will take some foresight, the right investments, and determination to reduce the risk of sea-level rise and other global warming impacts rather than wait for their consequences. By taking action now, people can change the forecast for the region's coasts and ensure that the economic opportunities, ecological benefits, and outdoor traditions they provide and support will endure for generations to come.

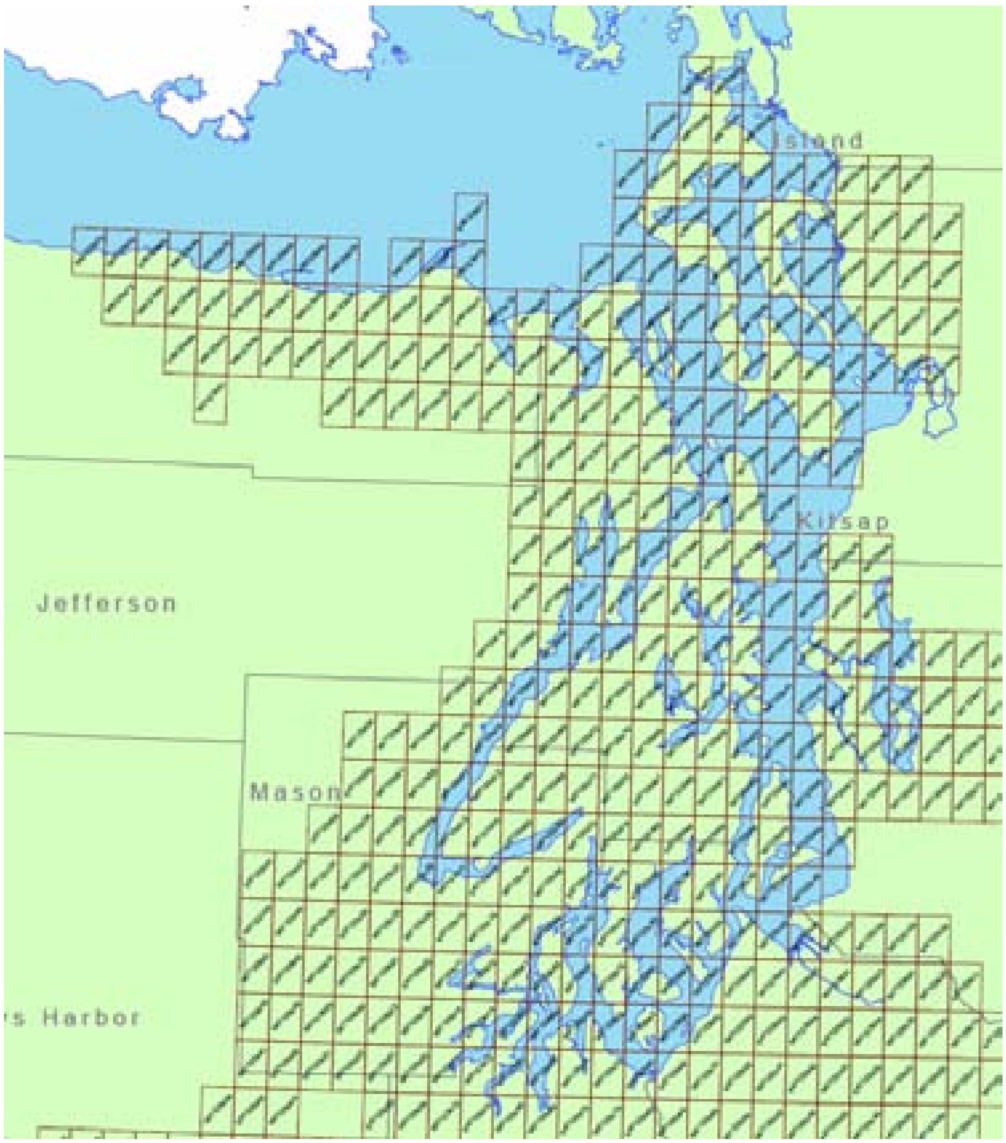
Clamming in Puget Sound (Kkilometer/flickr.com)

APPENDIX

Model Implementation

- Extensive LiDAR data were available from the Puget Sound LiDAR Consortium (http://www.pugetsoundlidar.org/). High-quality elevational data were available at this site and covered approximately 90 percent of the study area.

LiDAR Coverage, Puget Sound



- Digital Elevation Maps were downloaded using the USGS seamless data distribution tool (http://seamless.usgs.gov). These data made up the additional 10 percent non-covered study area in the Puget Sound. These data were also used for sites at the mouth of the Columbia River as LiDAR data were not available for this site.
- National Wetlands Inventory (NWI) maps were downloaded as polygons and converted to raster format with the appropriate SLAMM category (http://www.nwi.fws.gov/). NWI photo dates, from which these coverages were created, ranged from 1972 to 2000. The NWI photo date serves as the starting point for a SLAMM simulation.
- NOAA data were gathered from 36 sites to parameterize the model for tidal range, inland tidal range, and "NGVD88 to Mean Tide Level" corrections. See the figure and table below for a summary of NOAA data used to derive parameters.

NOAA Stations, used for Tide Range, and MTL Corrections

NOAA Stations, Study Site ID, Tide Range, and MTL Corrections					
Station Name (WA)	ID	Site	Tide Range (m) (MHHW-MLLW)	MTL-NAVD88 (m)	Notes
Cherry Point, St. Georgia	9449424	S1	2.788		
Sandy Point, Lummi Bay	9449292	S1	2.749		
Village Point, Lummi Island	9449161	S1	2.637		
Bellingham	9449211	S1	2.594	1.399	
Sneeoosh Point, Skagit	9448576	S2	3.369	1.33	
Turner Bay, Similk Bay	9448657	S2	3.152	1.36	
La Conner, Swinomish	9448558	S2	3.154		Inland
Crescent Harbor	9447952	S3,S2	3.554	1.393	Inland
Reservation Bay	9448614	S3	2.352		Less Inland
Port Townsend	9444900	S3	2.596		Less Inland
Bush Point, Whidbey Island	9447854	S3	2.85		Less Inland
Holly Harbor Farms	9447855	S3	3.487		Inland
Sandy Point, Saratoga Pass	9447856	S4	3.432		Slightly East of S4
Glendale, Possesion Snd.	9447814	S4	3.364		Slightly East of S4
Everett	9447659	S4	3.38	1.364	
Ebey Slough, Qwuloolt	9447729	S4			Insufficient Data
Crescent Bay	9443826	S5	2.151	1.186	East of Study Site
Port Angeles, Strait	9444090	S5	2.153	1.157	
Ediz Hook	9444122	S5	2.135	1.208	
Foulweather Bluff	9445016	S6	3.097		
Hansville	9445526	S6	3.18		At East Boundary
Bangor	9445133	S6	3.374		
Poulsbo	9445719	S6	3.575		
Brownsville	9445832	S6	3.607		
Bremerton	9445958	S6	3.578	1.32	
Lofall	9445088	S6	3.263		
Seattle, Puget Sound	9447130	S7	3.463	1.317	

NOAA Stations, Study Site ID, Tide Range, and MTL Corrections (Continued)					
Station Name (WA)	ID	Site	Tide Range (m) (MHHW-MLLW)	MTL-NAVD88 (m)	Notes
Lockheed Shipyard	9447110	S7	3.47	1.31	
Union Hood, Canal	9445478	S8	3.613	1.25	
Lynch Cove Dock	9445441	S8	3.69		
Green Point	9446451	S9	4.105		Just off East Bound
Arletta	9446491	S9	4.055		Further inland
Tacoma, Comm. Bay	9446484	S9	3.605	1.345	
Tacoma	9446545	S9	3.605	1.31	
Olympia, Bud Inlet	9446969	S10	4.437	1.305	Furthest South
Budd Inlet, S. Gull Harbor	9446807	S10	4.414		somewhat inland
Yoman Point	9446705	S10	4.108		
Toke Point, WA	9440910	S11	2.719	1.206	Furthest North
South Bend, WA	9440875	S11	2.992	1.18	Inland, Willapa Bay
Bay Center, WA	9440846	S11	2.806		
Nahcotta, Willapa Bay, WA	9440747	S11	3.197		
Naselle River S. Bridge WA	9440691	S11	3.267	0.432	MTL river influenced
North Jetty, WA	9440574	S11	2.361	1.188	
Skamokawa, WA	9440569	S11	2.305	1.578	MTL river influenced
Fort Stevens, OR	9439008	S11	2.624	1.347	
Garibaldi, OR	9437540	S11	2.484		Tillamook
Netarts, Netarts Bay, OR	9437262	S11	2.089		Furthest South

- Historic sea level rise trend data were downloaded from NOAA and spatially interpolated as necessary. Data from NOAA were available from eight sites that are either immediately or tangentially relevant to the study area.

Historic Sea Level Rise Trends Measured at NOAA Stations					
Neah Bay	9443090	NA	*-1.41*	mm/yr	1934-1999
Port Angeles	9444090	S5	*1.49*	mm/yr	Trend from 1975 only
Port Townsend	9444900	S3	*2.82*	mm/yr	Trend from 1972 only
Seattle	9447130	S7	2.11	mm/yr	1898-1999
Cherry Point	9449424	S1	*1.39*	mm/yr	Trend from 1973 only
Friday Harbor	9449880	Near S1	1.24	mm/yr	1934-1999
Toke Point, WA	9440910	S11	2.82	mm/yr	Trend from 1972 only
Astoria, OR	9439040	S11	-0.16	mm/yr	1925-1999

Due to tectonic uplift on the coast of Washington, historic rates of sea level rise increase moving west to east. An increasing trend from north to south was also evident in the data. Using these general trends, historic sea level rises were assigned to the ten sites as shown in the table below. Sites 8-10, which are south of Seattle, were assigned a level of 2 millimeters per year (0.08 inches per year) (the approximate rate in Seattle).

The geographically large extent of Site 11 (Willapa Bay, the Columbia River estuary, and the north coast of Oregon) was also assigned a trend of 2.0 millimeters (0.08 inches) per year as being most representative of the entire area. The negative trend at the Astoria gage is the result of highly localized tectonic uplift. Similarly, the trend of 2.83 millimeters (0.11 inches) per year at Toke Point represents a localized subsidence. For Site 11 as a whole, keeping a "default rate" of historic sea level rise [2.0 millimeters (0.08 inches) per year] seemed the best course of action.

Assigned Historic Trends (mm/yr)	
S1	1.3
S2	2.0
S3	2.8
S4	2.1
S5	1.5
S6	2.1
S7	2.1
S8	2.0
S9	2.0
S10	2.0
S11	2.0

- Erosion rates for tidal flats and estuary beaches were set to 0.2 meters (7.9 inches) per year based on Keuler, 1988. Keuler's map of erosion rates (within Puget Sound near Port Townsend, WA) shows short-term erosion rates ranging from 0-46 centimeters (18.1 inches) per year and includes one long-term recession rate of 15 centimeters per year (5.9 inches) per year. The rate used in modeling was set towards the high end of the range reported within Keuler's findings because it pertains to both tidal flats and exposed beaches (with no tidal flat frontage). The rate is also in line with the finding of Shipman (2004, p. 89) who is quoted below:

  > "The highest erosion rates measured on Puget Sound and in the Georgia Strait occur in poorly consolidated late Pleistocene sediments where wave exposure is high. Van Osch (1990) noted bluff recession rates of 60 centimeters per year (23.6 inches per year) at Cowichan Head north of Victoria and 30-50 centimeters (11.8-19.7 inches) per year at Point Grey near Vancouver, B.C. Galster and Schwartz (1990) found that erosion rates of bluffs west of Port Angeles were as much as one meter per year before the shoreline was armored. Keuler (1988) determined rates of over 30 centimeters (11.8 inches) per year on Smith Island, the western shore of Whidbey Island, and the northern side of Protection Island, all with substantial exposures along the Strait of Juan de Fuca.
  >
  > These rates are not typical, however, and recession rates appear more commonly to be on the order of a few centimeters a year, or less, in most areas. Rates vary temporally and at any given site, retreat is likely to occur as a single mass-wasting event every few decades."

  This rate could be explored further, and perhaps a separate erosion rate for tidal flats and estuarine beaches could be used in future modeling.

- Within the modeling, Bruun's rule regarding the erosion rate of beaches (recession is roughly 100 times the change in sea level) was rarely utilized within Puget Sound. This rule only applies to "ocean beaches" that comprise just 0.05 percent (1/2000th) of the total "Puget Sound" study area (Sites 1-10).

- Erosion rates for marshes and swamps were set to SLAMM defaults. Default erosion rates are 2.0 horizontal meters (78.7 inches) per year for marshes and 1.0 meter (39.4 inches) per year for swamps. These rates are based on a combination of professional judgment and a brief literature survey. (Note also that these erosion rates presume that a threshold of maximum fetch for wave setup has been exceeded prior to the incidence of horizontal erosion. See the technical documentation for more information.)

- Accretion rates were set to 3.6 millimeters (0.14 inches) per year for saltmarshes based on Thom (1992) who measured accretion rates of low saltmarshes in the Pacific Northwest. The 95th percent confidence interval for these observations ranged from 2.4-4.8 millimeters (.09-1.9 inches) per year.

- Accretion rates were set to 3.75 millimeters (0.15 inches) per year for brackish marsh, and 4.0 millimeters (0.16 inches) per year for tidal flats. These values were based on measurements from the Altamaha River in Georgia (Personal Communication, Dr. Christopher Craft). Additionally, these rates fall at the mid point of a comprehensive literature review of accretion rates (Cahoon, Reed, and Day, Jr., 1995 and Cahoon, Day, Jr., and Reed, 1999). These rates also conform to the site-specific measurements of Thom (1992) because accretion rates in brackish marsh and tidal flats tend to exceed rates in low intertidal saltmarshes.

- In this project SLAMM 5.0 was parameterized to "protect developed" areas. That is, the model assumed that any areas that are already developed will be protected in the future through the construction of dikes or other protective measures. Developed areas were defined using percent impervious data available from the National Land Cover Database (http://www.mrlc.gov/index.asp). After testing several "percent impervious" thresholds, dry land that was at least 25 percent impervious was categorized as "developed dry land" and subsequently protected.

  The "percent impervious" data coverage was explicitly produced to screen out impervious areas that are not the result of human development (e.g. rocky intertidal locations). The metadata for the data coverage states that non-urban areas were eliminated manually and by using various processing "masks."

Dike Data Layer

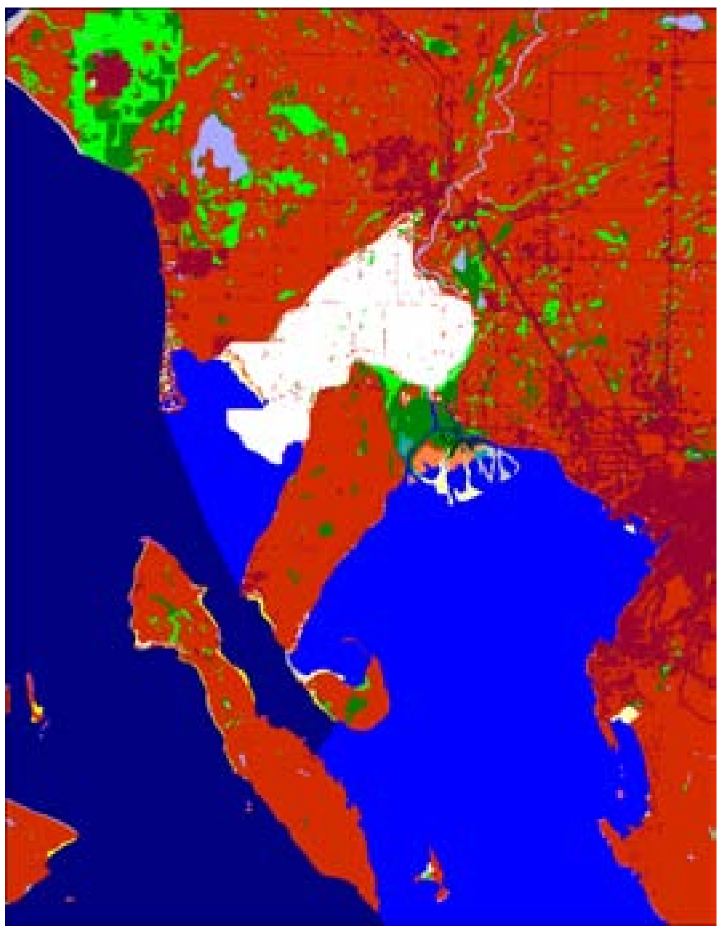
Large areas within Puget Sound are protected by dikes both for urban development and agricultural purposes. SLAMM requires an accounting of wetlands and dry land areas that are protected by the existence of dikes and seawalls. If a cell is marked as protected by a dike or levee it is not permitted to change categorization. The existence of these dikes can severely affect the ability of wetlands to migrate onto adjacent shorelines. Traditionally, when applying the SLAMM model, relevant diked areas have been determined using the NWI data layer (http://www.nwi.fws.gov/). The NWI land-type codes include a "special modifier" for all lands that are "Diked/Impounded." However, for the Puget Sound region, this approach was not feasible. The primary reason for this is that the downloaded digital NWI coverages excluded all dry lands. (These dry lands were not categorized and instead were returned as "no-data.") Therefore there was no category included and the "special modifier" could not be included either.

To work around this problem, a multifaceted approach was taken to try to produce the most complete and defensible dike layer possible. This approach included:

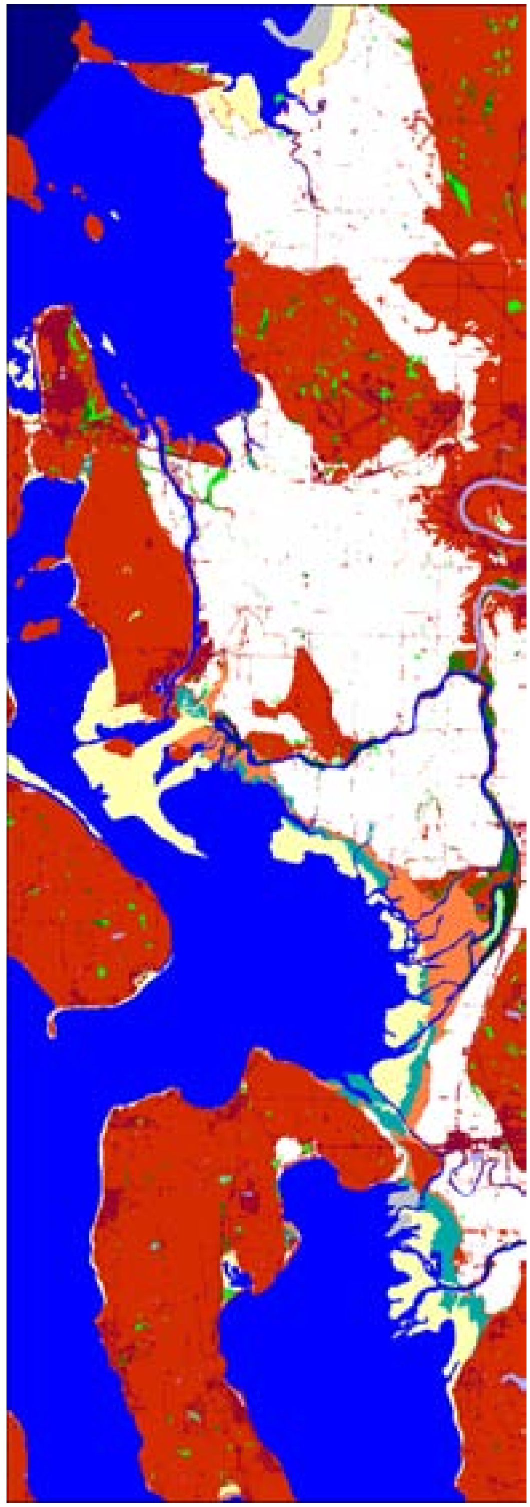
- An exhaustive search for GIS data layers that characterize dikes within Washington State was performed, but no data source was found to be completely satisfactory.
  - Several data layers were found that indicated the lat-long location of existing dikes, but not their geographical extent.
  - No data layer was available that indicated the land that was protected by these dikes, levees, or seawalls. Rather, data layers characterized the extent of these structures, and were often incomplete.
  - None of the data layers encompassed the entire geographical extent of our study area (Figures 1 and 2).
  - Available GIS data layers were used to determine where dikes were located and to confirm the results produced from the analyses described below.
- An elevational analysis was performed along with a consideration of land-use to determine which portions of the study area are likely subject to diking.
  - Land use data were available from the 2001 National Land Cover Database (NLCD http://www.mrlc.gov/index.asp)
  - Dikes and Levees are primarily agricultural in the Puget Sound regions so land-cover that was designated as "cultivated" or "grassland" that falls below a certain elevation was considered likely to be protected by dikes.
  - Dry land that fit the above agricultural designations and that was at an elevation less

than 4.6 meters above mean tide (15 feet mean sea level) was marked as diked.
  - The resulting diked coverages were compared with the GIS data above and were found to match quite closely.
- USGS topological maps often include dikes drawn on them, especially at the 1:25,000 scale.
  - The diked areas determined using land-use and elevation were checked for accuracy against existing USGS maps. Again, the coverages based on elevation and land-use matched closely with the USGS maps.
  - The coverages produced using elevation and land-use were often patchy. Using the information within the USGS maps, this patchiness could often be reduced.
  - Occasionally the geographical extents of the dikes were adjusted to match the locations found on the USGS maps.
- Site-specific knowledge of the extent of dikes (Especially at Site 10, Nisqually) was also used to adjust the dike coverages.

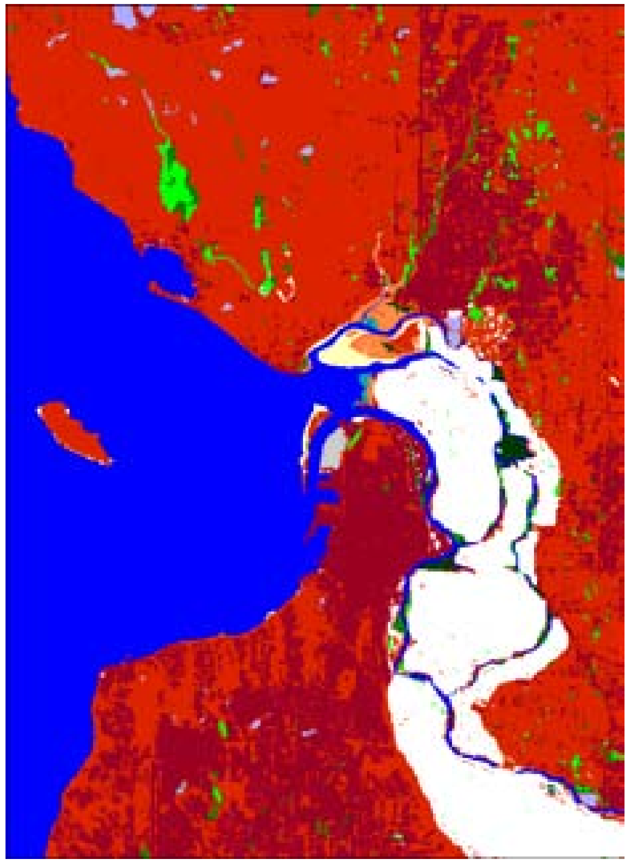
Final dike coverages for six of the most extensively diked areas are shown on the following pages:



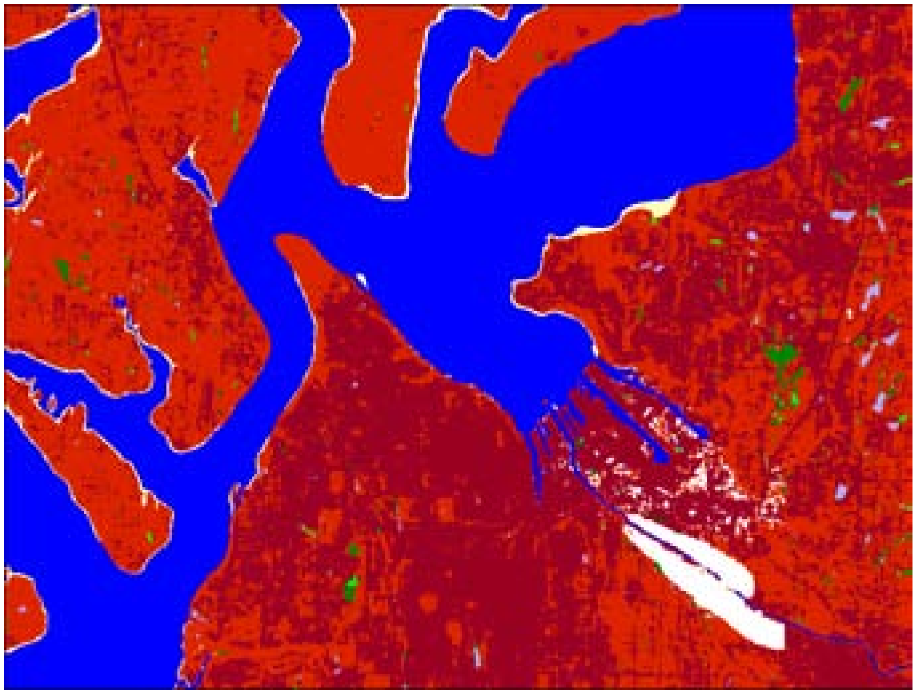
Site 1: Final dike coverage given confirmation via USGS topological maps (LUMMI BAY [WA] 1:24000, 1972). Land protected by dikes is shown in white.



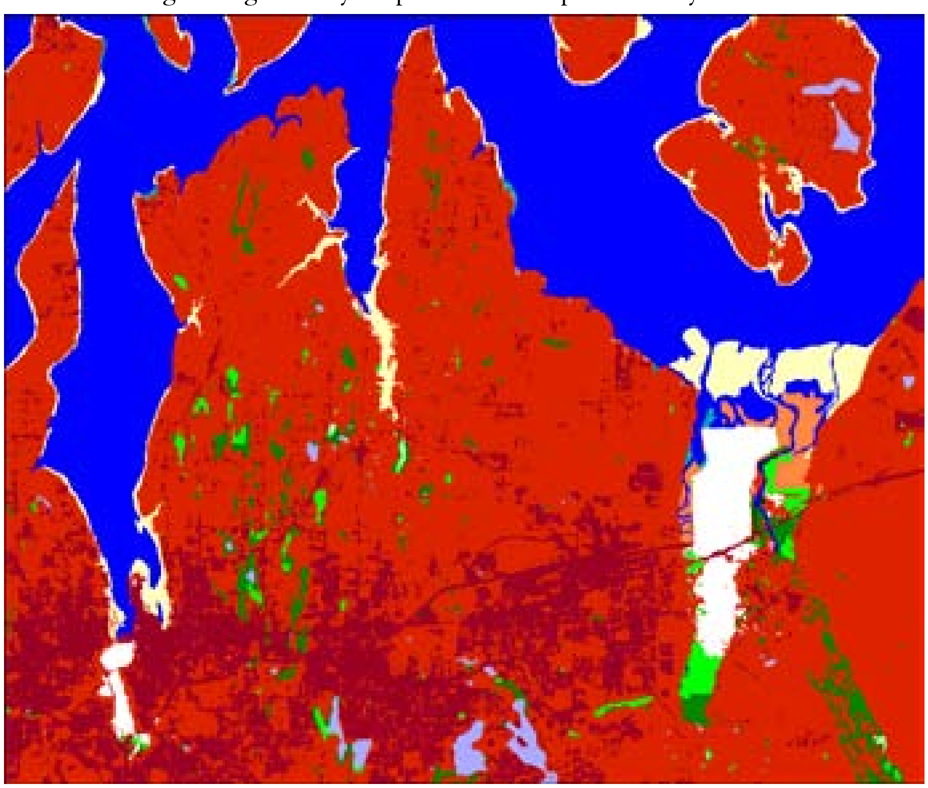
Site 2: Final dike coverage given confirmation and small adjustments based on USGS topographical maps. Land protected by dikes is shown in white.



Site 4: Dike coverage follows all of the dikes drawn on the USGS maps. Land protected by dikes is shown in white.

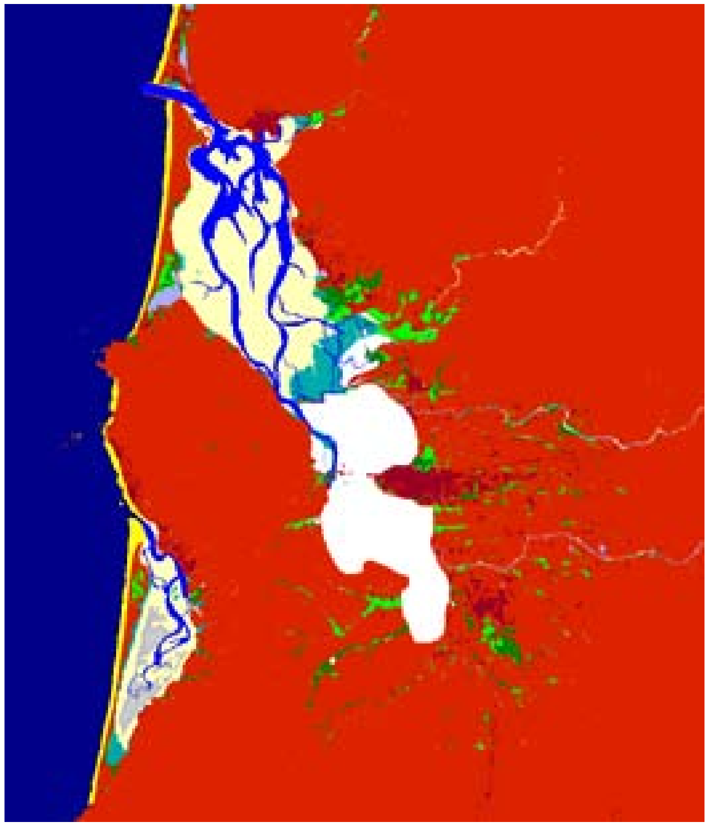


Site 9: Dike coverage along the Puyallup River. Land protected by dikes is shown in white.



Site 10: Dike coverage using USGS maps, elevation, and local knowledge. Land protected by dikes is shown in white.

Site 11: Dike Coverage for Astoria based on NWI Coverage. Land protected by dikes is shown in white.



Site 11: Dike coverage for Tillamook based on USGS/USEPA maps and wetland elevations. Land protected by dikes is shown in white.

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