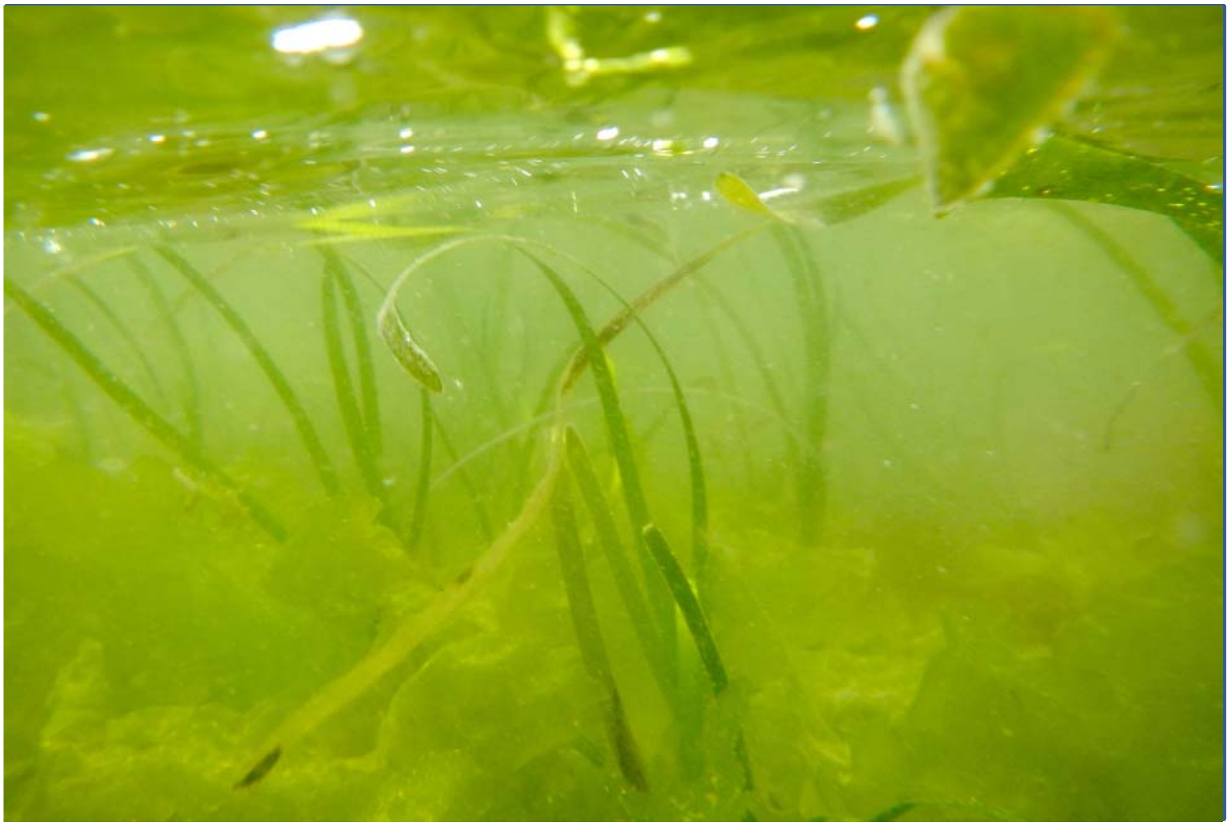
NATURAL RESOURCES



Nitrogen as an Eelgrass Stressor in Puget Sound, 2014

March 11, 2014

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Peter Goldmark - Commissioner of Public Lands

Cover photo: Dumas Bay, Central Puget Sound 2013

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Frederick T. Short
Nearshore Habitat Program
Aquatic Resources Division

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Reference as: Short FT. 2014. Nitrogen as an Eelgrass Stressor in Puget Sound, 2014, Aquatic Resources Division, Washington State Department of Natural Resources, Olympia, WA. 37p.

Contents

Executive Summary

Eelgrass is a critical component of the Puget Sound ecosystem, creating habitat for juvenile salmon, Dungeness crabs and numerous other species as well as stabilizing the seafloor, filtering near shore waters and contributing to the food web. Recognizing the importance of eelgrass to Puget Sound, the Puget Sound Partnership established eelgrass as a "Vital Sign" for assessing the status and health of the Sound and identified eelgrass as a primary indicator of ecosystem recovery.

Although DNR's long-term eelgrass monitoring in Puget Sound shows no detectable change in Sound-wide eelgrass area between 2000 and 2012, eelgrass in some parts of the Sound is experiencing stress and showing localized declines. The focus of this document is to consider nitrogen as a stressor to eelgrass in Puget Sound, so that managers can prioritize and address this potential problem as it impacts eelgrass health. The intent of the paper is to elevate nitrogen within the discussion of more universally understood stressors within Puget Sound. Failure to incorporate nitrogen reduction strategies into a comprehensive recovery strategy could undermine efforts to meet the 2020 recovery target. Without such actions, the Puget Sound Partnership goal of a 20% increase in eelgrass distribution by 2020 will not be met. The Partnership's effort to recover previously lost eelgrass areas and habitat functions is an important step to regaining the full health of the Sound and maintaining its long-term sustainability and productivity.

Increasing nitrogen concentrations, measured as nitrate by the Department of Ecology, have been seen throughout the Sound over the past 12 years and much of this is believed to derive from human sources. Nitrate levels are increasing more rapidly within the Sound than in the Strait of Juan de Fuca, indicating sources of nitrogen from the watershed. In several locations in South Puget Sound and Hood Canal, eelgrass has been observed growing with typical symptoms of nitrogen over-enrichment including loss of plants at the deep edge of the bed, nuisance seaweed overgrowth, and heavy epiphyte loads.

It is well known that nitrogen is an indirect stressor that promotes phytoplankton blooms in the water column, thereby decreasing the amount of light reaching eelgrass growing on the seafloor. Eelgrass requires relatively high levels of underwater light for photosynthesis and growth. Elevated nitrogen also promotes the growth of nuisance seaweeds that shade and smother eelgrass, and of epiphytes, which attach to the leaves of the plants. In the spring when eelgrass is growing fastest, phytoplankton blooms can extend over much of Puget Sound, attenuating the light reaching the eelgrass. On a worldwide basis, nitrogen and sediment loading are considered the two main stressors to eelgrass and other species of seagrass.

Efforts to reduce Sound-wide nitrogen loading need to be incorporated into a comprehensive recovery strategy in order to maintain and expand the crucial Sound-wide eelgrass resource. In other places around the country, targeted management has focused on nitrogen point sources initially because ameliorative technology is readily available; non-point sources are also a major factor that can be addressed simultaneously, but they are more diffuse and intractable. Other estuaries nationwide have ignored the early-warning eelgrass indicator and the degrading impact of nitrogen to eelgrass and spent many millions of dollars to recover eelgrass habitat and estuarine health once they have been lost. What is good for eelgrass is good for Puget Sound.

1 Introduction

Eelgrass is an important element of Puget Sound, providing food, habitat, and many ecological functions while acting as an indicator of the Sound's health. Eelgrass (*Zostera marina* L.) has been selected as a "Vital Sign" and indicator for the Puget Sound Partnership's annual assessment of the Sound's status. A 20% increase in eelgrass area by the year 2020 is one of the PSP's goals to improve the health of the Sound (SOS 2013).

Eelgrass is an underwater flowering plant, a species of seagrass, that forms fringing beds along the edges of the Sound's waterways as well as vast meadows across many of its bays (Figure 1-1). As it grows rooted in the seafloor, it stabilizes sediments, filters particles and nutrients from the water, and provides food and shelter to numerous organisms including juvenile salmon and Dungeness crab. As its leaves decompose it becomes part of the food web. Eelgrass is a widely distributed and well-studied temperate seagrass species that grows in Europe, both coasts of North America, and east Asia.

Eelgrass grows on the seafloor, and thus it relies on light that has passed through the water column for its photosynthesis (Thom et al. 2008). Therefore, eelgrass requires clear water for optimum health and anything that reduces water clarity ultimately degrades eelgrass. The main factors reported to impact ocean water clarity worldwide are excess nitrogen loading and high sediment loading (Short and Wyllie-Echeverria 1996, Duarte et al. 2008).

Recent assessments of the global status of seagrasses show that these important marine plants are declining worldwide due to degradation of the coastal oceans (Short et al. 2007, Waycott et al. 2010, Short et al. 2011). Throughout its vast range, including the State of Washington, eelgrass is subject to stressors that can threaten and impact its survival, health, distribution and restoration (Thom et al. 2001a). Here in Puget Sound, a recent eelgrass stressor assessment was completed and published in 2011 as a report to the Washington State Department of Natural Resources (Thom et al. 2011). Thom and others (2011) listed all the possible stressors of eelgrass, natural and human-induced, and created a threat score of stressors but did not emphasize nitrogen per se.

Additional information related to nitrogen increases warrants reconsideration of the role of nitrogen in Puget Sound (NOAA National Estuarine Eutrophication Assessment, http://www.eutro.us/). Nitrogen concentrations in Puget Sound waters are increasing (Bos et al. 2013b), coinciding with recent observations of eelgrass exhibiting typical signs of nitrogen stress (Department of Natural Resources, Submerged Vegetation Monitoring Program (SVMP) video transects 2012-2013 and pers. obs.). Excess nitrogen and sediment loading are the two primary stressors of seagrasses worldwide (Short et al. 2011) and have affected estuaries across the United States from Chesapeake Bay to Tampa Bay and San Francisco Bay. Nitrogen impacts can be ameliorated with ecosystem resource management. Consequently, the nitrogen stressor is the focus of this report.

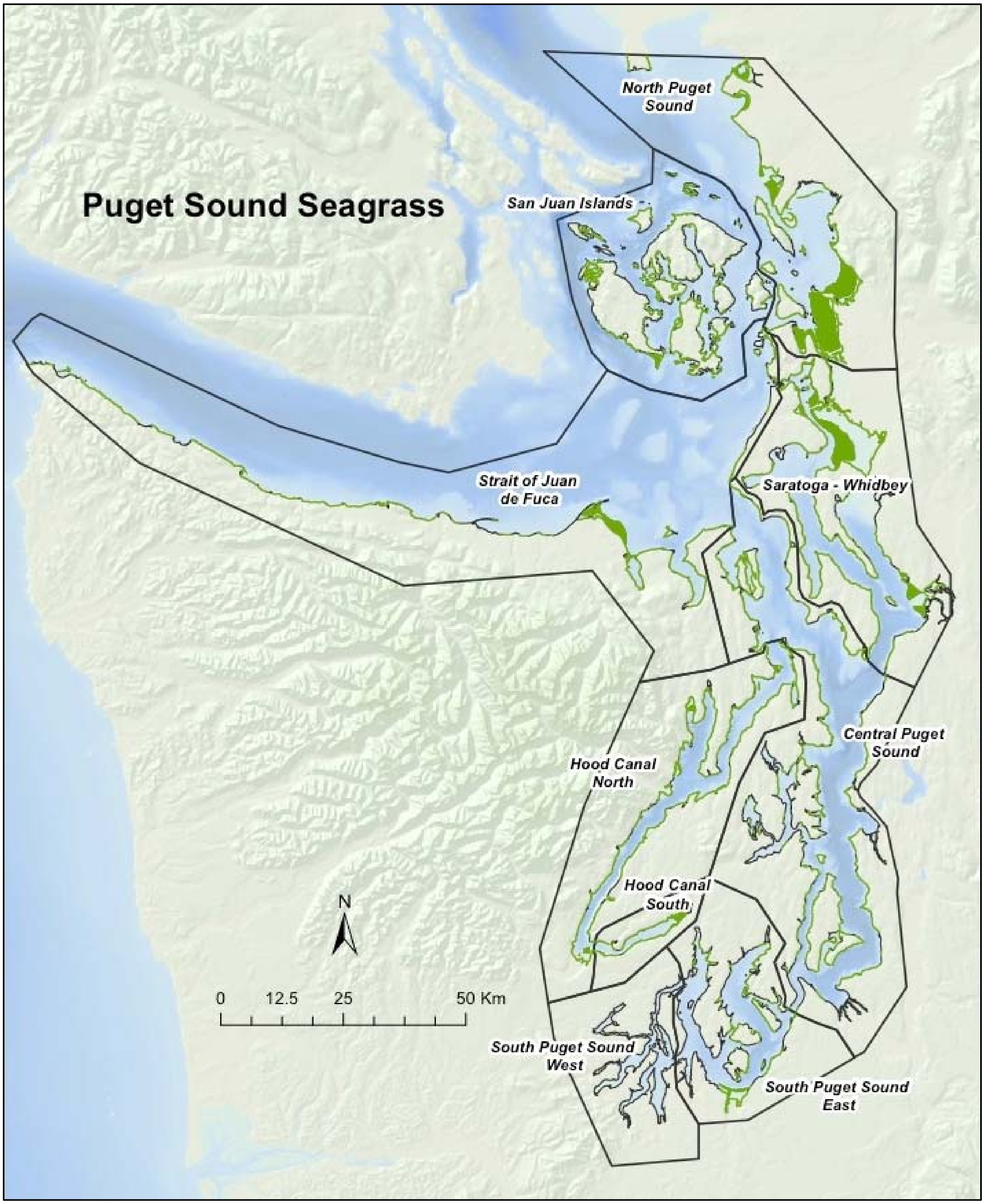


Figure 1-1. Seagrass distribution in Puget Sound (green) based on both aerial surveys collected as part of the Washington State ShoreZone Inventory, 1994-2000 and DNR eelgrass monitoring, 2000-2012 SVMP nearshore sampling (https://fortress.wa.gov/dnr.servicessa/dataweb/dmmatrix.html). The extent of eelgrass shown is estimated based on available data and represents the best eelgrass spatial information for Puget Sound.

2

The Nitrogen Stressor

Elevated nitrogen is evaluated as a possible stressor to eelgrass in Puget Sound. Nitrogen stress increases as human population increases but can be ameliorated by adaptive management. There are many other stressors to eelgrass, some of which are exacerbated by elevated nitrogen. Management, both new and ongoing, that addresses the nitrogen stressor will improve the health of the eelgrass resource and the health of Puget Sound.

2.1 Evidence for Nitrogen as an Eelgrass Stressor in Puget Sound

Elevated nitrogen in the Sound

Recent data from water quality monitoring in Puget Sound show significant increases in nitrogen concentrations (Krembs 2013) not included in the Thom et al. 2011 stressor report. The overall increase in average water column nitrogen measurements for the Sound (Figure 2-1) is comprised of data from the 19 monitoring stations sampled monthly from 1999 through 2012 by the Department of Ecology (http://www.ecy.wa.gov/programs/eap/mar_wat/surface.html). Of the fourteen sites throughout the Sound with significantly increasing long-term trends (Figure 2-2), thirteen show nitrogen increases (3-10 µM N increase per decade) greater than the increases seen in the water entering from the Strait of Juan de Fuca (2 µM N increase per decade), indicating there are watershed sources of nitrogen within the Sound itself. The increase in average nitrogen concentrations (Figure 2-1 and 2-2) may be linked to anthropogenic sources (Bos et al. 2013a).

Puget Sound receives its major input of nitrogen from Pacific upwelling sources; however, human sources and rivers also contribute to the nitrogen load. (Khangaonkar et al. 2012, Bos et al. 2013b). The high background nitrogen level from incoming Pacific Ocean water (Figure 2-3), and the high productivity of planktonic primary producers, as well as both the planktonic consumers and shellfish that make up a balanced ecosystem in Puget Sound, all make for a naturally high-nitrogen environment. The rapidly increasing nitrate concentrations further into the Sound beyond the Strait of Juan de Fuca station suggest that watershed nitrogen sources contribute to the Sound’s nitrogen level (Figure 2-2). Watershed nitrogen inputs build on the already relatively high levels of oceanic nitrogen, increasing the nitrogen exposure of the entire system. Nitrogen loading rates to parts of Puget Sound per area watershed drainage for 2006-07 were greater than loading to Chesapeake Bay or San Francisco Bay (Mohamedali et al. 2011).

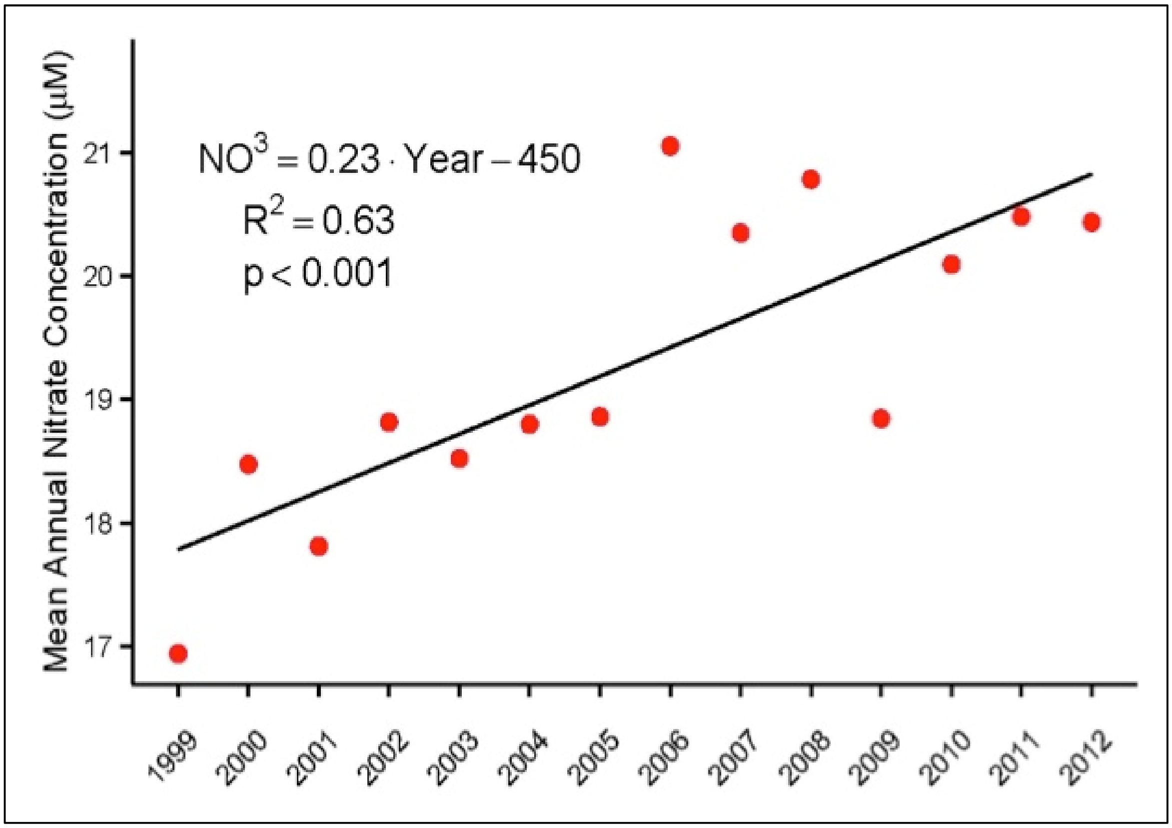


Figure 2-1. Increasing surface water nitrogen, as nitrate concentration, over time in Puget Sound, based on the 19 stations with data extending from 1999 through 2012 (data from Eyes Over Puget Sound monitoring program, Department of Ecology, State of Washington). http://www.ecy.wa.gov/programs/eap/mar_wat/data.html

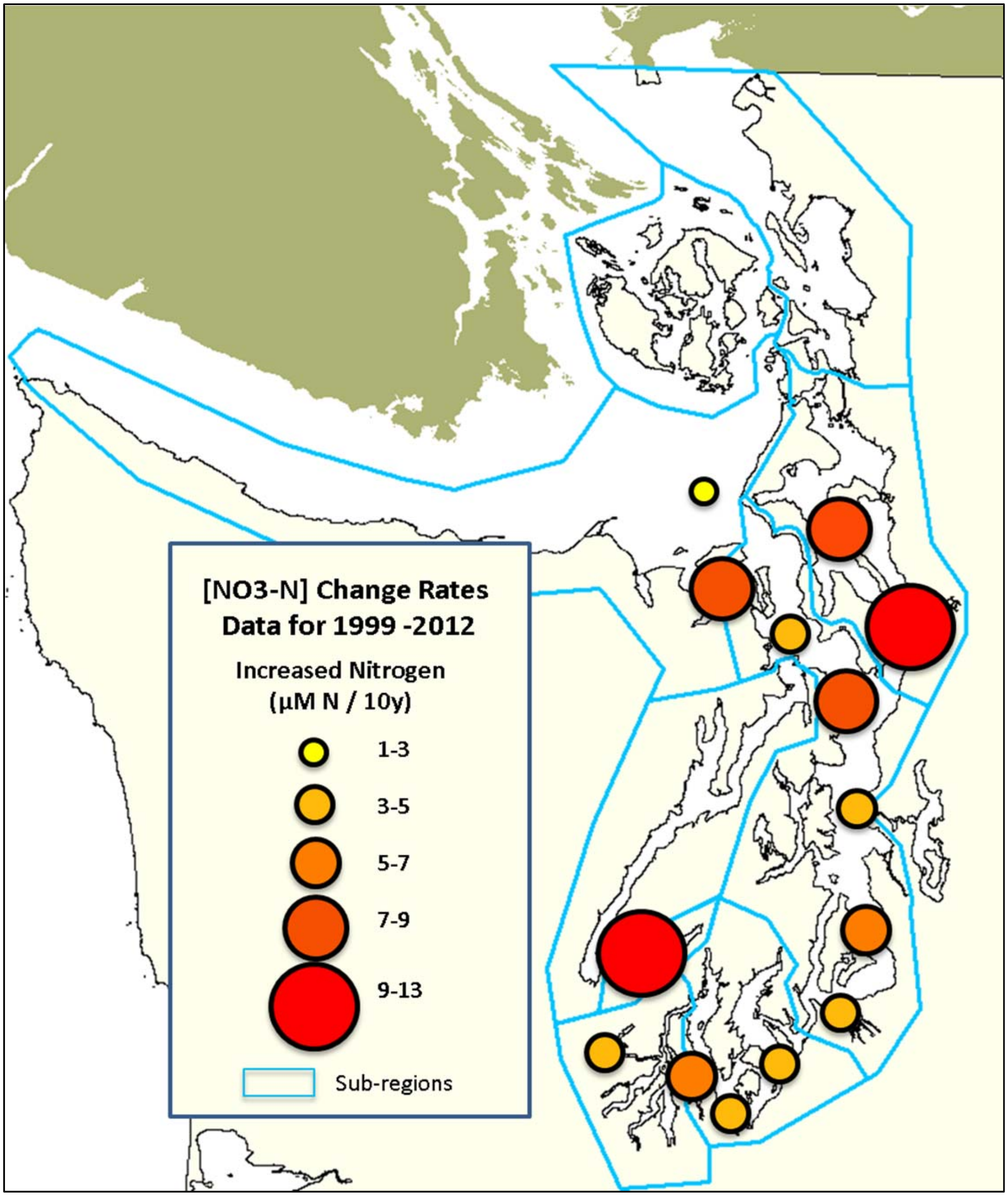


Figure 2-2. Puget Sound nitrogen data: change in annual average nitrate concentration per decade shows increases in nitrogen throughout the Sound. The rate of increase in nitrate concentration (standardized as µM per decade) for 1999 – 2012 indicates that nitrogen is increasing faster within the Sound (values between 3 and 10 µM/10y) than in the water entering the Strait of Juan de Fuca, suggesting watershed sources of nitrogen to the Sound. Fifty-six stations were sampled at various intervals by the Department of Ecology; of these, there were 19 stations with data extending from 1999 through 2012 and of these 19 stations, 14 showed a significant increasing trend in nitrogen. Data from EOPS, Department of Ecology, State of Washington.

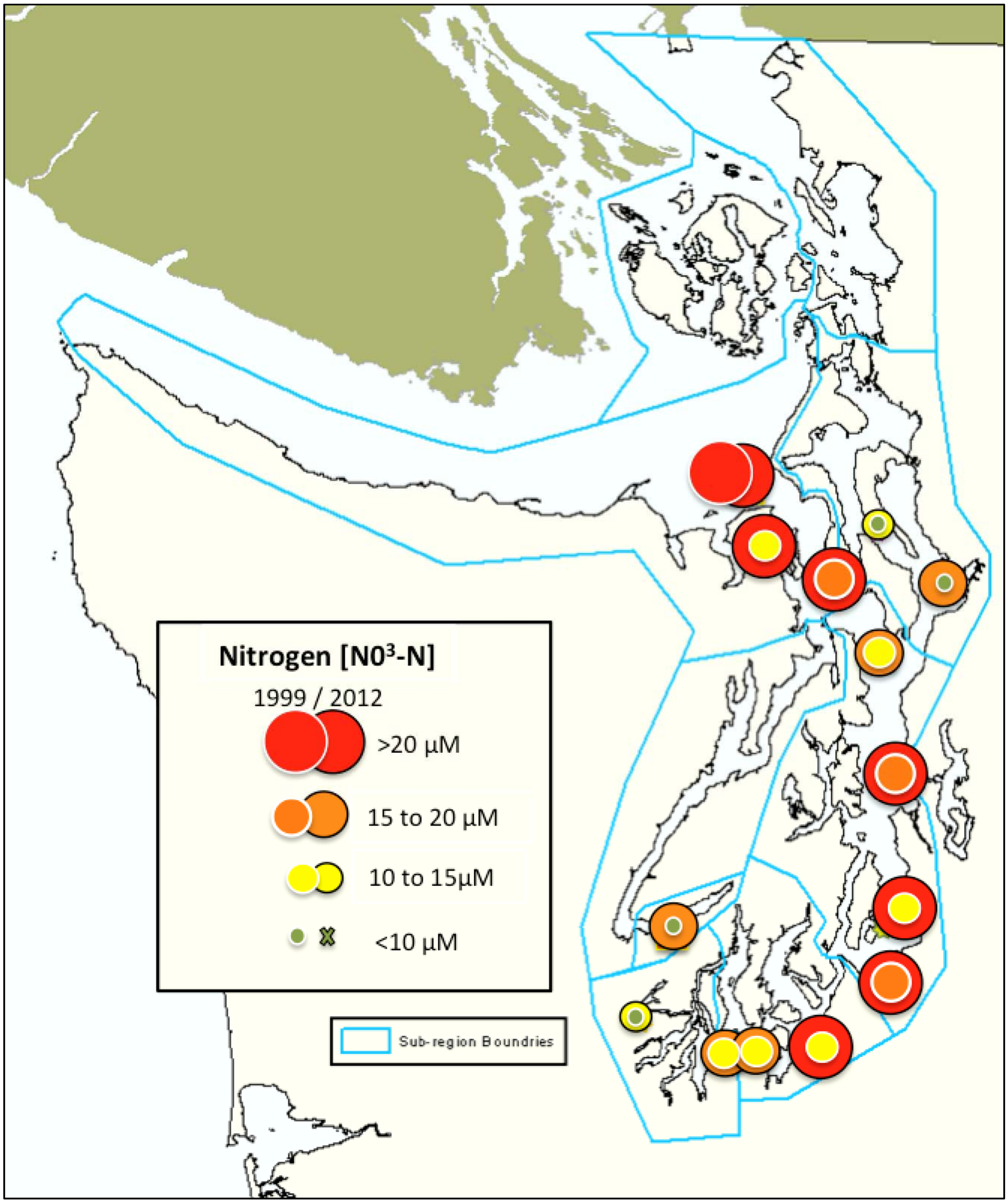


Figure 2-3. Puget Sound surface water nitrate concentrations, [NO_3], in micromoles per liter (µM). Underlaid dots show average nitrogen concentration in Puget Sound for 2012; overlaid dots are for 1999; x indicates no low values in 2012. Nitrate concentrations increased at all sites; the increase at the Strait of Juan de Fuca site was the smallest in the Sound (Figure 2-2). Data from EOPS, Department of Ecology, State of Washington, including only sites with significant trends having data over ten or more years.

SVMP eelgrass monitoring sites with typical symptoms of high nitrogen

Parts of South Puget Sound, Central Puget Sound, and southern Hood Canal showed signs of eutrophication in the early 1990s (Mackas and Harrison 1997). Recently, nuisance algal overgrowth (Figure 2-4) and the persistent phytoplankton blooms seen in aerial photographs of Hood Canal (Figure 2-5, EOPS 2013, Moore et al. 2013) suggest those conditions continue. About half of the SVMP monitoring sites in these sub-regions show loss of eelgrass at the deep edge of the bed (see below), a sign of reduced light reaching the seafloor, coincident with nitrogen increases (Rivers 2008). Observations made at locations in Puget Sound over the past 18 months have identified areas where typical symptoms of excess nitrogen are occurring in eelgrass meadows, including green water of limited clarity, extensive phytoplankton blooms (EOPS 2013), excessive nuisance seaweeds entangling the eelgrass, and heavy epiphyte loads on the eelgrass blades to the point that eelgrass does not look green (as seen for example in Figure 2-4 and pers. obs.). Such evidence is coincident with many locations where eelgrass decline has been identified (Short 2013).

Nitrogen stresses eelgrass indirectly; that is, its effects on eelgrass occur through stimulated production of phytoplankton and of nuisance seaweeds, which in turn affect eelgrass growth via shading. When eelgrass growing at the deep edge of a meadow receives inadequate light for photosynthesis, the eelgrass dies, and its distribution is limited to shallower waters that are still receiving enough light for the plants to grow. Three SVMP sites in the South Puget Sound East sub-region (Figure 1-1) showed measured declines in eelgrass area (SOS 2013); in all three, eelgrass has retreated from the deep edge of the bed (see for example, Figure 2-6). In the Hood Canal South sub-region, three of the five SVMP sites identified as declining in area (SOS 2013) showed loss at the deep edge of some sampling transects and a fourth site experienced total loss of eelgrass. Based on inspection of the transect data, four additional South Puget Sound East sites also showed some loss of eelgrass at the deep edge (SVMP unpub.); the remaining seven sites in this sub-region were inconclusive. The same analysis of five additional Hood Canal South sites found two sites with losses at the deep edge of some transects. At several of the South Puget Sound East and Hood Canal South eelgrass monitoring sites, not only is there a loss of eelgrass at the deep edge of the bed, but at the shallow edge as well, possibly due to nuisance seaweed overgrowth (SVMP unpub.).

SVMP data for the San Juan Island sub-regions are showing eelgrass decrease without nitrogen-related symptoms (SVMP unpub.), likely the result of other stressors. More analysis is underway and additional monitoring will illuminate the nature of the stressors involved. Also, in the Strait of Juan de Fuca and some other locations in the Sound, there is high water column nitrogen (Figure 2-3) but the eelgrass continues to thrive because these areas usually have clear ocean water. Monitoring of the Saratoga Whidbey sub-region shows three stations with increasing eelgrass, as yet unexplained.

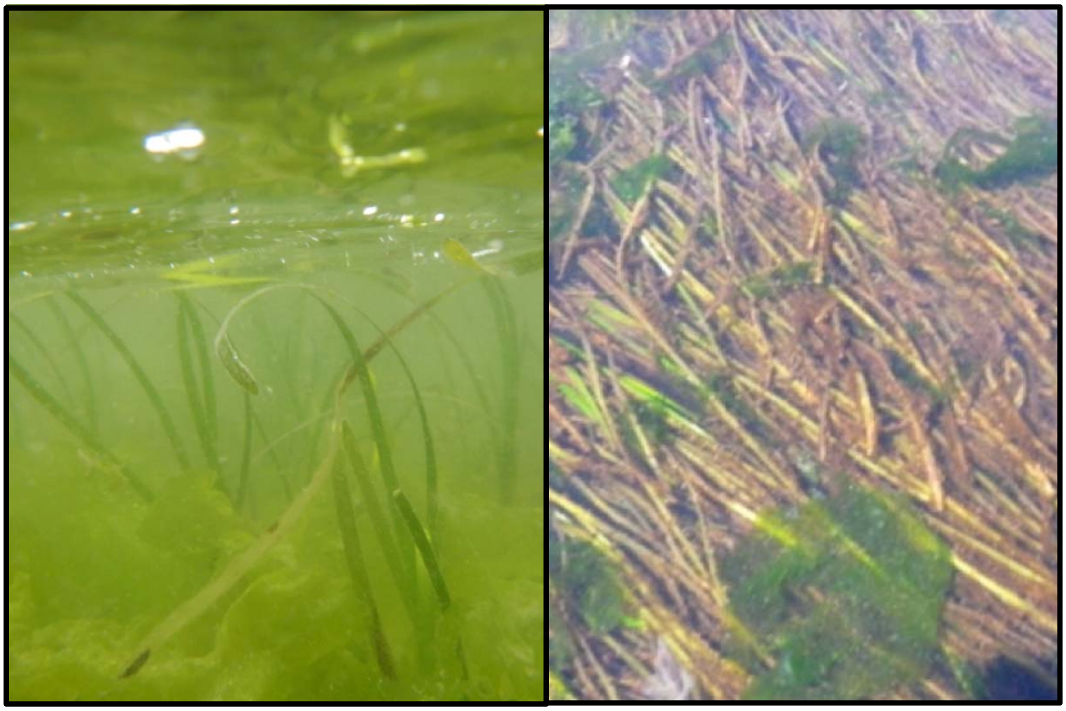


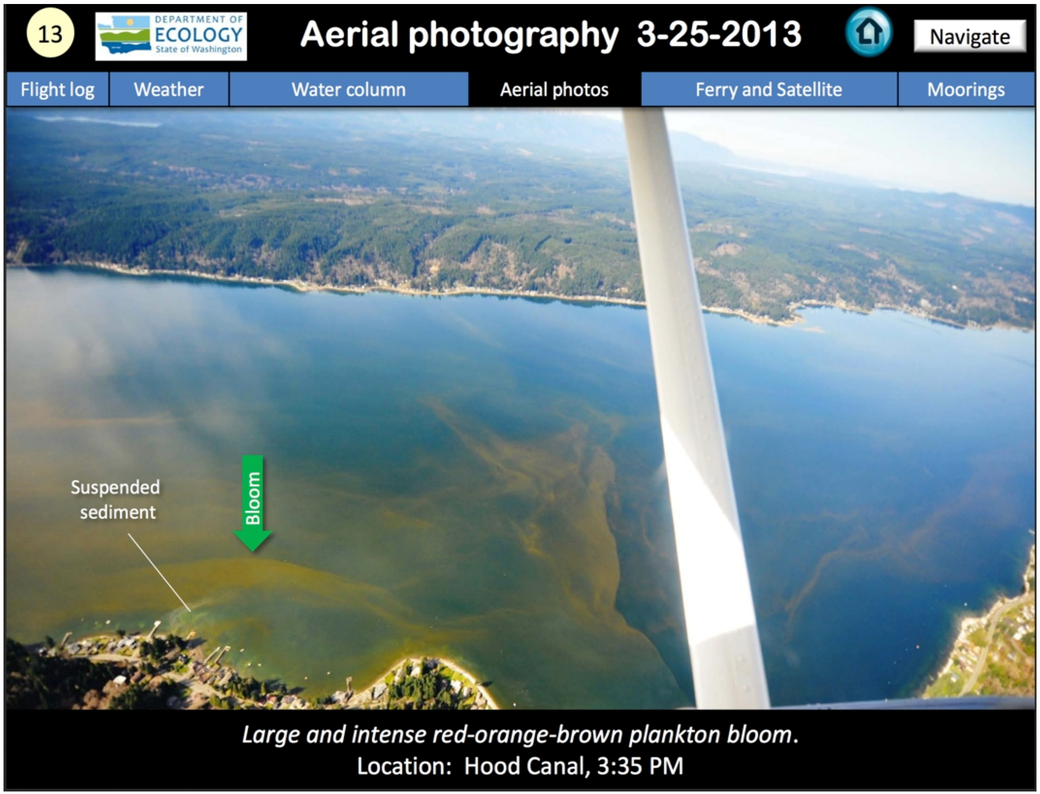
Figure 2-4. Eelgrass in Puget Sound, 2013 showing: overgrowth of nuisance seaweed (*Ulva*) and green water from phytoplankton (chlorophyll) in Central Puget Sound (left); excessive ulvoid seaweed and epiphytes coating intertidal eelgrass leaves in Hood Canal (right).

Aerial photography 2-26-2013

Early near-surface spring plankton bloom. Location: Hood Canal, 2:42 PM

Aerial photography 3-25-2013

Large and intense red-orange-brown plankton bloom.
Location: Hood Canal, 3:35 PM



Aerial photography 3-25-2013

Large and intense red-orange-brown plankton bloom.
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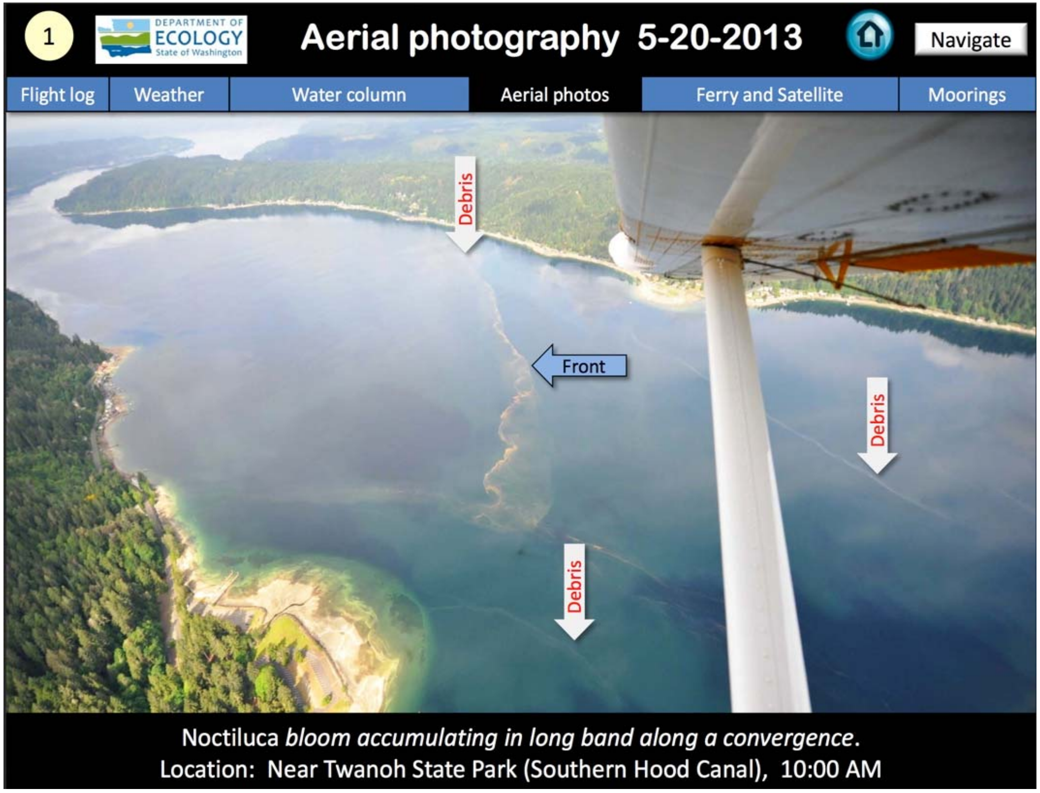

Aerial photography 5-20-2013

Noctiluca *bloom accumulating in long band along a convergence.*
Location: Near Twanoh State Park (Southern Hood Canal), 10:00 AM

Figure 2-5. Phytoplankton blooms in southern Hood Canal: on February 26, two on March 25, and on May 20, 2013 (Eyes Over Puget Sound monitoring program, Department of Ecology, State of Washington).
http://www.ecy.wa.gov/programs/eap/mar_wat/surface.html

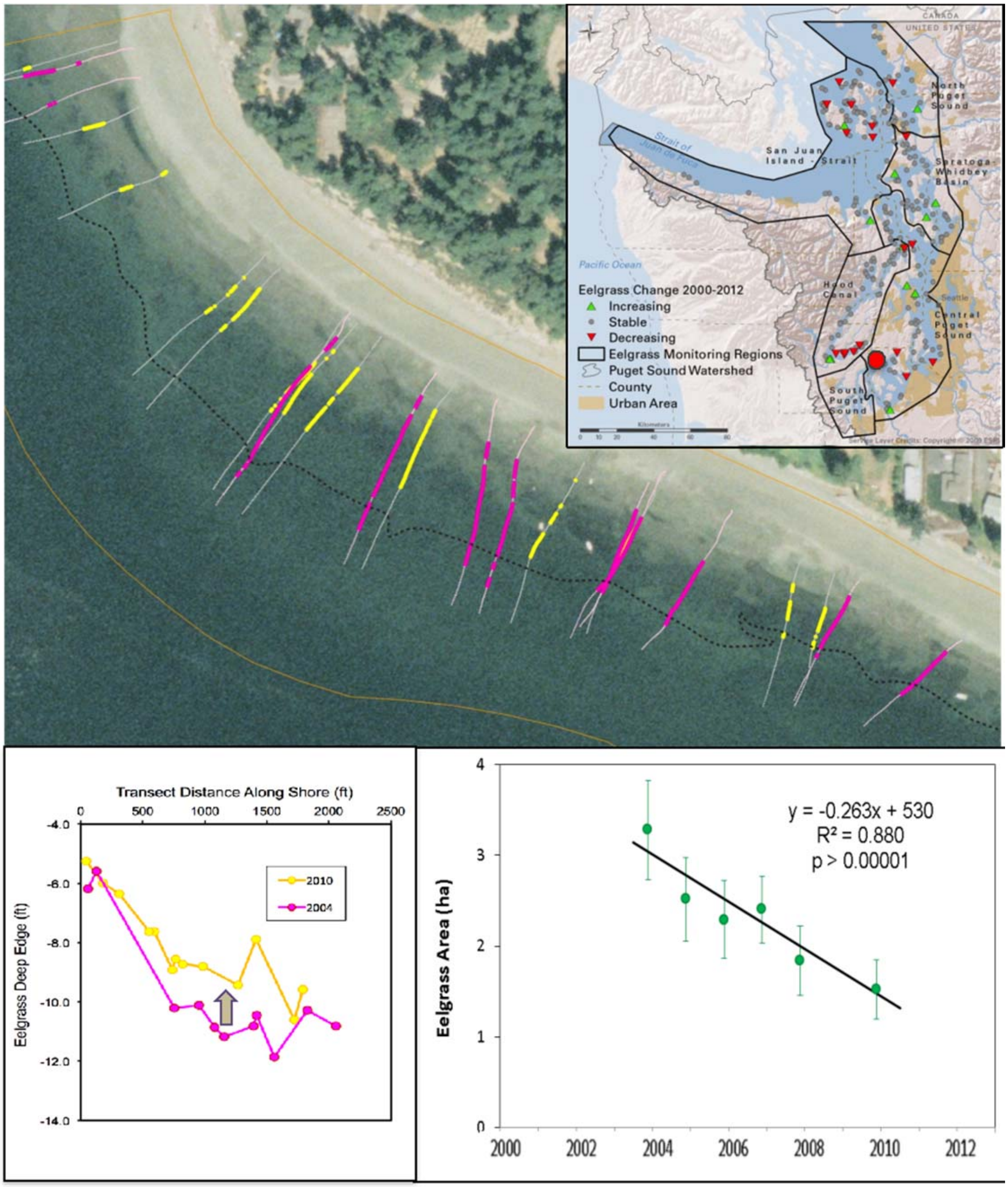

Figure 2-6. Eelgrass decline at the deep edge: monitoring site transects (SVMP 2011) in South Puget Sound, superimposed on an aerial photograph, showing transects of eelgrass in 2004 (pink) extending deeper than the 9-foot depth contour (dashed black line) and in 2010 (yellow) shallower than the 9-foot depth contour (top image). On the map of SVMP sites, red dots indicate declining sites and the large red dot indicates the location of the aerial photograph. The graph (lower left) compares the deep edge in 2004 (pink) to that of 2010 (yellow): the arrow helps visualize the retreat of the deep edge. The graph (lower right) shows the significant declining trend in eelgrass at this site between 2004 and 2010.

Chlorophyll and phytoplankton in Puget Sound

A major result of increasing nitrogen is the increase in plankton production (measured as chlorophyll) that creates high concentrations of microscopic particles in the water, thereby limiting the amount of light that can penetrate to the seafloor. Nitrogen stimulates the growth of phytoplankton, which in turn stimulates the growth of zooplankton, heterotrophic dinoflagellates, and even jellyfish, all of which, suspended in the water column, reduce the amount of light penetrating into the Sound's waters. Eelgrass, growing rooted in the bottom, requires high light levels to grow successfully; these light levels are impacted by high chlorophyll and the resultant reduced water clarity. With lower light, over time, the plants are not able to grow as deep. Eelgrass is less dense and has less biomass when grown under reduced light conditions, as seen in controlled experiments (Short et al. 1995). No specific data on chlorophyll or water clarity is available for the nearshore areas of Puget Sound where eelgrass occurs (Figure 1-1). Analysis of the Department of Ecology's Sound-wide monitoring data revealed no significant changes in chlorophyll or water clarity in these surface waters less than 8 m in depth (Hannam and Short, unpub.), although some increases in water clarity and decreases in amount of chlorophyll were seen when waters from 0-50 m were integrated (Bos et al. 2013b, Friedenberg et al. 2013).

Satellite imagery provides a good tool for assessing the spatial distribution of chlorophyll (Engel 2012) and provides spatial information on chlorophyll distribution for Puget Sound. Two images show the chlorophyll levels in Puget Sound in spring of 2011: April 29 shows moderate chlorophyll distribution and May 17, high chlorophyll distribution after a rainfall event (Figure 2-7). Daily chlorophyll data from the Department of Ecology's Victoria Clipper water quality monitoring shows that the phytoplankton blooms persist throughout the spring (Sackmann and Krembs 2013). Together, these images yield an overview of how widespread and persistent chlorophyll patterns and levels can be in spring. Spring is the primary eelgrass growing season (Thom et al. 2008) when eelgrass is most vulnerable to reduced light levels and the time of year when nitrogen loading from rivers has been shown (for Central and South Puget Sound) to exceed that of loading to the Sound from wastewater treatment facilities (Mohamedali et al. 2011). The persistence and extent of chlorophyll seen in the satellite imagery demonstrates a potential impact that elevated nitrogen, via chlorophyll, can have on eelgrass over wide areas of the Sound.

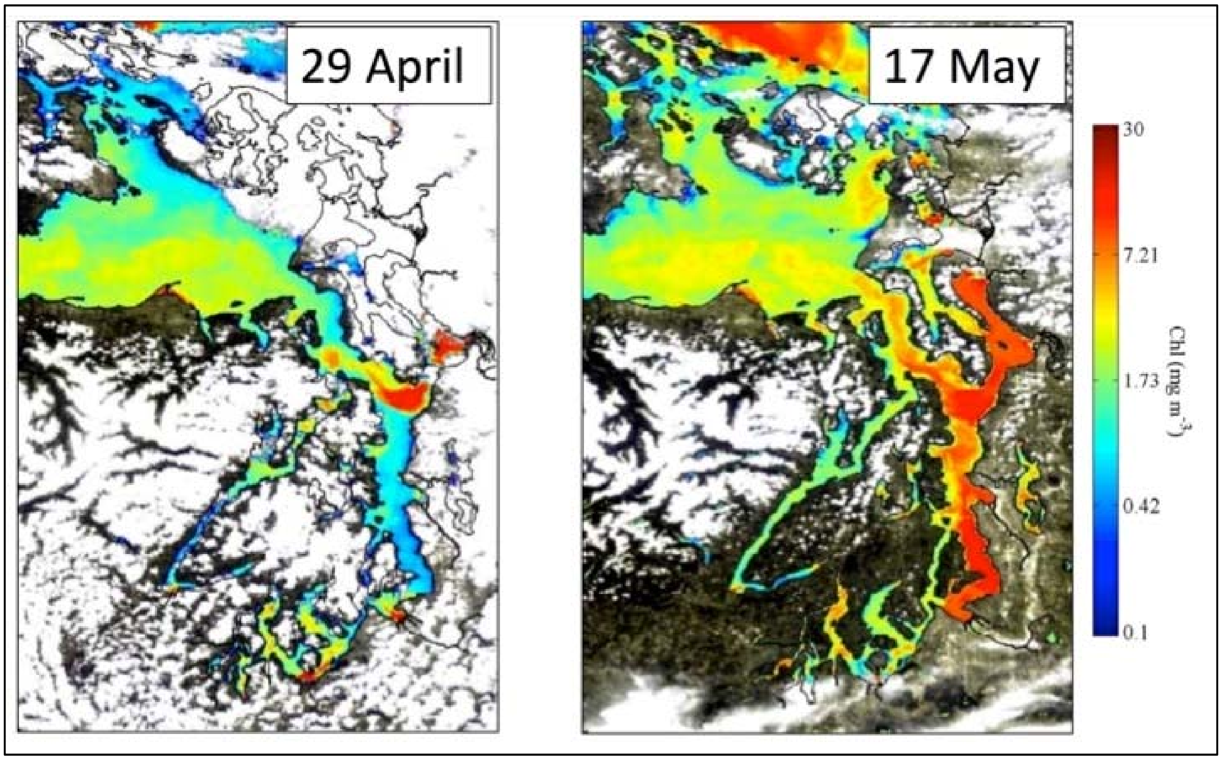

Figure 2-7. Satellite imagery of Puget Sound showing chlorophyll concentrations (log scale) in spring 2011. The April image shows several scattered areas of high chlorophyll in the Sound (white areas are snow or cloud cover). The May image was obtained shortly after a rapid rise in river discharge; the chlorophyll bloom has intensified and spread throughout the Sound. MERIS Satellite Ocean Color – Chlorophyll – 2011 (Eyes Over Puget Sound monitoring program, Department of Ecology, State of Washington). http://www.ecy.wa.gov/programs/eap/mar_wat/eops/EOPS_2013_09_11.pdf

Nuisance seaweed and epiphytes in Puget Sound

The other nitrogen impact to eelgrass is overgrowth of nuisance seaweeds, which respond quickly to excess nitrogen in shallow water and grow rapidly, shading and smothering eelgrass beds (Short and Burdick 1996, Nelson and Lee 2001). For example, in Hood Canal, there are many areas where overgrowth of nuisance seaweed and algal epiphytes is stressing eelgrass, such as near Coon Bay (Figure 2-4) and in Lynch Cove (as seen in SVMP 2013 video transects). Similar effects of excess nitrogen loading have also been seen in South Puget Sound and Central Puget Sound, where shallow and somewhat restricted embayments show the same kind of nuisance seaweed and algal epiphyte overgrowth as seen in experimental studies of nitrogen enrichment (Short et al. 1995, Burkholder et al. 2007) and in eutrophic estuaries elsewhere, e.g., Chesapeake Bay (Batiuk et al. 2000).

In field experimental studies in Puget Sound, Nelson and Lee (2001) found that reducing ulvoid algae by 50% resulted in 45% greater eelgrass shoot density. For Puget Sound, the 2000 – 2008 distribution of ulvoid algae (Figure 2-8), assessed based on the SVMP video transects (Nelson and Melton 2011), provides an idea of the spatial extent of nuisance seaweeds. The widespread distribution of ulvoids (Figure 2-8, Nelson and Melton 2011) suggests that, even six years ago, eelgrass in Puget Sound was impacted by seaweed overgrowth (Nelson et al. 2008). Excess nitrogen also promotes the growth of epiphytes (Willams and Ruckelshaus 1993, Thom et al. 2001b, Diefenderfer et al. 2005, McGlathery et al. 2007). Epiphytic algae grow on eelgrass leaves and cause substantial impacts to eelgrass via shading and smothering when epiphyte density and biomass become too great (Williams and Ruckelshaus 1993).

Evidence from other parts of the country

The issue of nitrogen loading into near shore waters is not unique to Puget Sound. Nation-wide, all developed estuaries have problems of nutrient pollution and experience the negative effects of excess nitrogen entering the ecosystem (Nixon and Buckley 2003, Bricker et al. 2007). In many cases, state governments and municipalities have taken on the challenge of reducing nitrogen inputs by limiting the discharge of human sewage effluent and upgrading sewage treatment, including large systems like Chesapeake Bay, Long Island Sound, Boston Harbor (MA), and Tampa Bay, as well as smaller estuaries like Waquoit Bay (MA), Mumford Cove (CT), and Great Bay (NH), to mention a few (Short and Burdick 1996, Batiuk et al. 2000, Greening and Janicki 2006, Beem and Short 2010, Vaudry et al. 2010, Taylor et al. 2011).

In all of these systems, the loss of seagrass was a prime indicator of the degradation of water clarity and ecosystem function due to excess nitrogen. Some of these estuaries that initiated management activities several years ago to reduce nitrogen levels are now showing recovery of the ecosystem, and in several places the seagrass has begun to return naturally with improved water clarity, and/or successful seagrass restoration has been possible. Among these, Tampa Bay, Boston Harbor (MA) and Mumford Cove have shown successful seagrass recovery after nitrogen reduction (Greening and Janicki 2006, Leschen et al. 2010, Vaudry et al. 2010, respectively).

The impact of excess nitrogen on eelgrass growth and survival has been extensively demonstrated in scientific research (see review, Burkholder et al. 2007). Enrichment experiments with eelgrass in the laboratory, in outdoor tanks, and in the field have all shown that eelgrass is increasingly stressed as excess nitrogen levels increase (Short et al. 1995, Lee et al. 2004, Burkholder et al. 2007), resulting in dense phytoplankton blooms that shade the plants, as well as excessive epiphytes attached to the leaves and overgrowth by seaweeds.

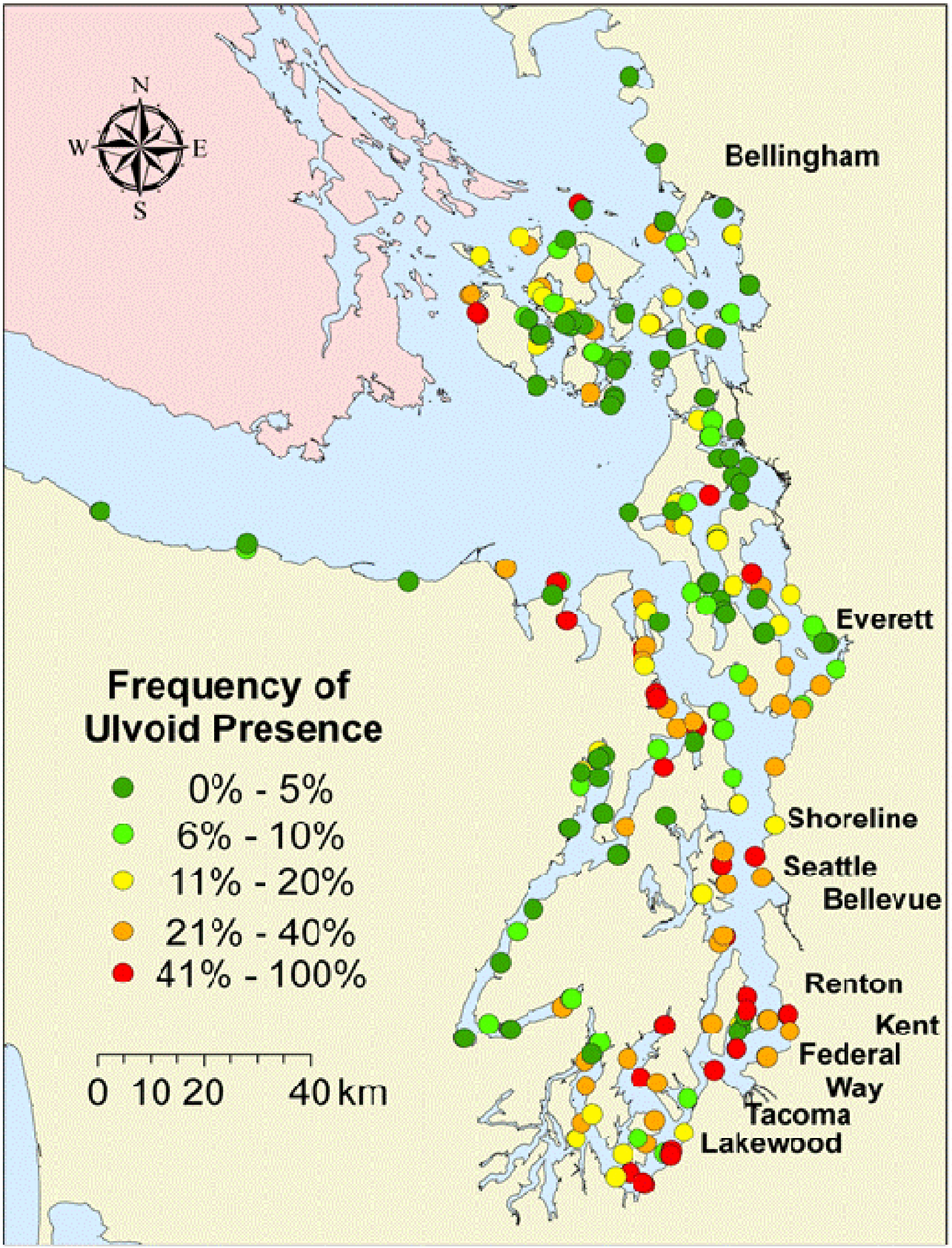

Figure 2-8. Frequency and spatial distribution of ulvoid seaweeds assessed at SVMP eelgrass monitoring sites between 2000 and 2008 (Nelson and Melton 2011). Sites >40% have the greatest impact on eelgrass.

2.2 Background – Nitrogen Dynamics in Puget Sound

Pacific upwelling sources of nitrogen

In Puget Sound a very high volume of Pacific Ocean water floods the Sound twice daily with the tides. The Pacific upwelling water is high in nitrogen (Figure 2-3) but clear. The clear water is good for eelgrass growth, but as it moves further into the Sound, its high nitrogen levels promote the growth of phytoplankton and, in the nearshore, the growth of nuisance seaweeds, both of which stress eelgrass. In the Strait of Juan de Fuca, chlorophyll levels are low and the eelgrass grows deep in the clear Pacific water; the relatively high nitrogen concentrations themselves do not pose a threat to eelgrass. Once the high-nitrogen water enters further into the Sound, it stimulates the growth of phytoplankton.

Human-derived nitrogen entering from the watershed adds to the water column nitrogen, encouraging phytoplankton growth, further reducing water clarity and limiting the amount of light reaching the eelgrass growing on the seafloor. Loss of eelgrass along the deep edge of the bed results in decline of eelgrass distribution. In shallower waters, excess nitrogen stimulates the growth of nuisance seaweeds (Nelson and Melton 2011) and epiphytic algae (Williams and Ruckelshaus 1993), further impacting eelgrass.

Anthropogenic sources of nitrogen

Other sources of nitrogen to Puget Sound and its watershed include vehicle and power plant emissions, fertilizer import, and nitrogen fixation from croplands and forestry practices (Mohamedali et al. 2011, Cope and Roberts 2013). Current-day nitrogen inputs have shifted the balance in marine ecosystems such that most systems tend not to be nitrogen limited under today's conditions (Ryther and Dunstan 1971, Bricker et al. 2007). This situation did not develop overnight. In fact, decades of human waste disposal and emissions have contributed, but in the last 20 years population growth (over half a million people per decade) and increased housing development adjacent to the Sound and its rivers have likely greatly increased the loading of nitrogen to the Sound. In Central and South Puget Sound combined as of 2007, population growth and human activities increased nitrogen loading from watershed sources (including waste water) by more than 6 times over natural conditions (Mohamedali et al. 2011). Today, the increased load of nitrogen to Puget Sound, added to the large and natural oceanic input from Pacific upwelling, has resulted in an increase in nitrogen concentrations between 1999 and 2012 (Figure 2-1 and 2-3) and a shift in the Sound's ecosystem that – from everything that is known about eelgrass throughout its global range – is increasing the stress on eelgrass populations here in Puget Sound.

The decline of eelgrass as a result of excess nitrogen loading (nitrogen over-enrichment) is well documented in the international literature (Short and Wyllie-Echeverria 1996, Orth et al. 2006) and research has determined the relationship between housing development, nitrogen loading and eelgrass decline (Figure 2-9). Although no such studies are available for Puget Sound, the human population in the Puget Sound area is over 4.5 million and will exceed 5 million by 2020; globally, there is a clear relationship that nitrogen loading correlates with population (Figure 2-10).

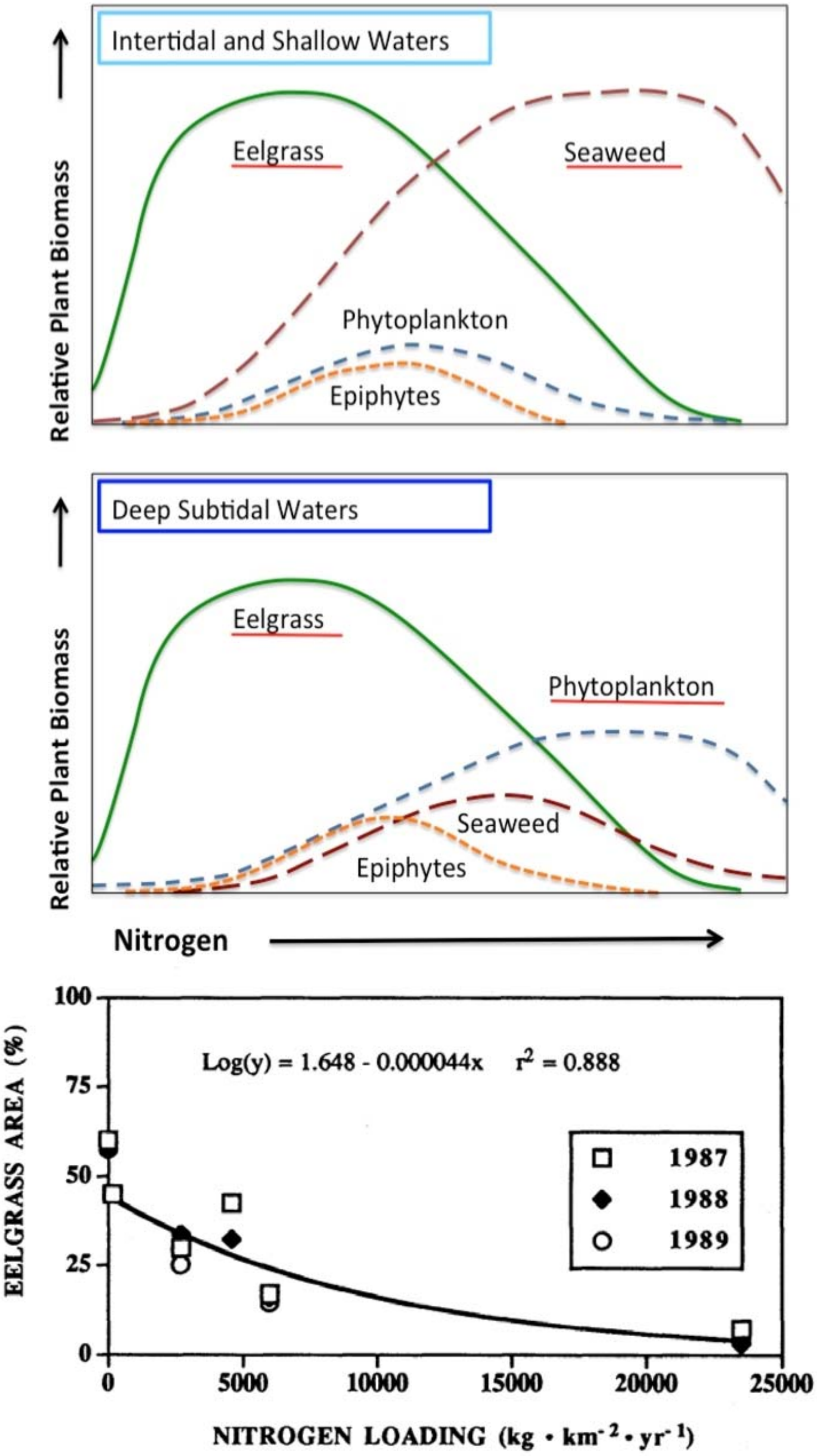

Figure 2-9. Nitrogen loading rates and their effect on eelgrass: conceptual diagrams for shallow and deep water (top); eelgrass area decrease in Waquoit Bay, MA over three years of study (bottom) with the log of eelgrass area regressed against nitrogen (Short and Burdick 1996).

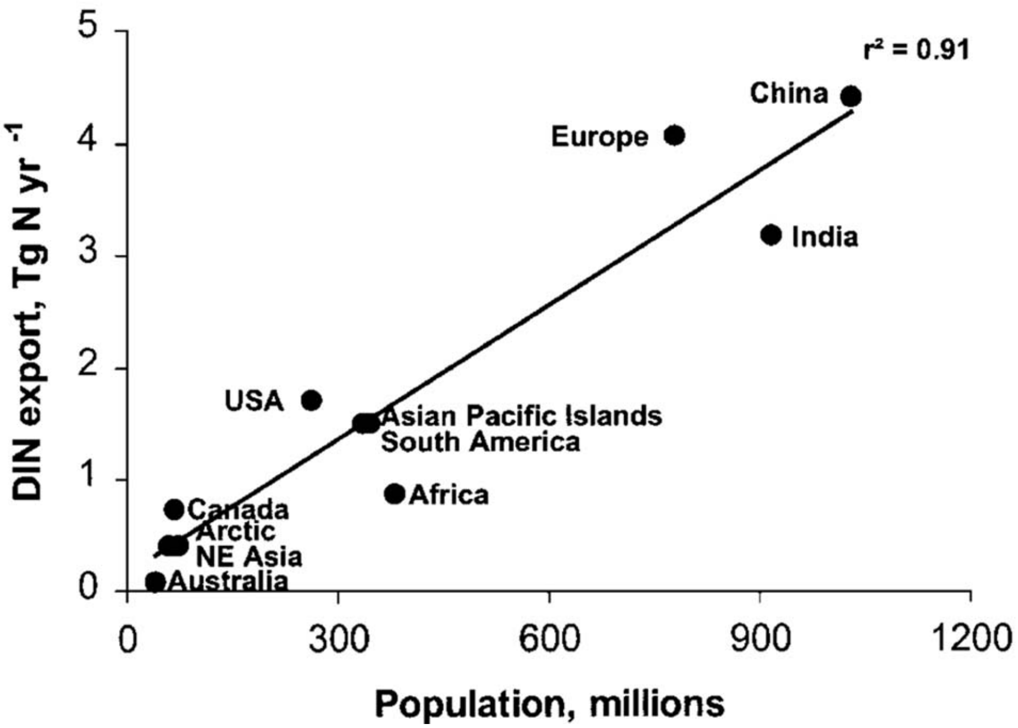

Figure 2-10. The connection between human population and nitrogen loading. Model-predicted dissolved inorganic nitrogen (DIN) export from land (i.e., nitrogen loading to coastal waters) in 1990 versus human population for major world regions (from Seitzinger et al. 2002).

Monitoring at large plants in the Sound that treat municipal wastewater shows reduction in water flows (www.ecy.wa.gov/programs/eap/Nitrogen/Trends.html), but nitrogen loading is determined by both flow and nitrogen concentration. Since National Pollutant Discharge Elimination System (NPDES) permits rarely require nitrogen limits or reporting of effluent nitrogen concentrations, nitrogen loading cannot be determined for Puget Sound. Wastewater treatment technologies that result in greater nitrogen removal would reduce nitrogen loading to the Sound.

In Puget Sound, an additional source of nitrogen is river flow, which carries nitrogen from many watershed sources, including septic leachate and treated sewage discharge. In spring (April – June, Czuba et al. 2012), rivers carry nitrogen associated with topsoil erosion from farming activities, land clearing and runoff, along with other human-derived inputs. Spring is the prime eelgrass growing season in the Sound (March – May, Thom et al. 2008) and therefore, because of its timing, the anthropogenic riverine nitrogen load is a concern as an impact to eelgrass. Riverine nitrogen loading is difficult to assess; data from 1994-2007 indicated nitrogen in some of the major freshwater rivers showed little or no increase (Hallock 2008), but most of that study's monitoring sites were rather distant from Puget Sound and thus the data do not include waste water from most of the big cities. Also, the methodology does not capture the extensive nitrogen loading associated with storms (Oczkowski et al. 2006, Mohamedali et al. 2011). River and floodwater nitrogen inputs likely further exacerbate nitrogen loading in the Sound and stress eelgrass. Historically, much of the material was filtered from river flow by the extensive marsh and wetland systems, but since the 1800s many of these river deltas and floodplains have been diked and filled to create agricultural land and ultimately cities, diminishing their filtering capacity (Figure 2-11, Dowty et al. 2010).

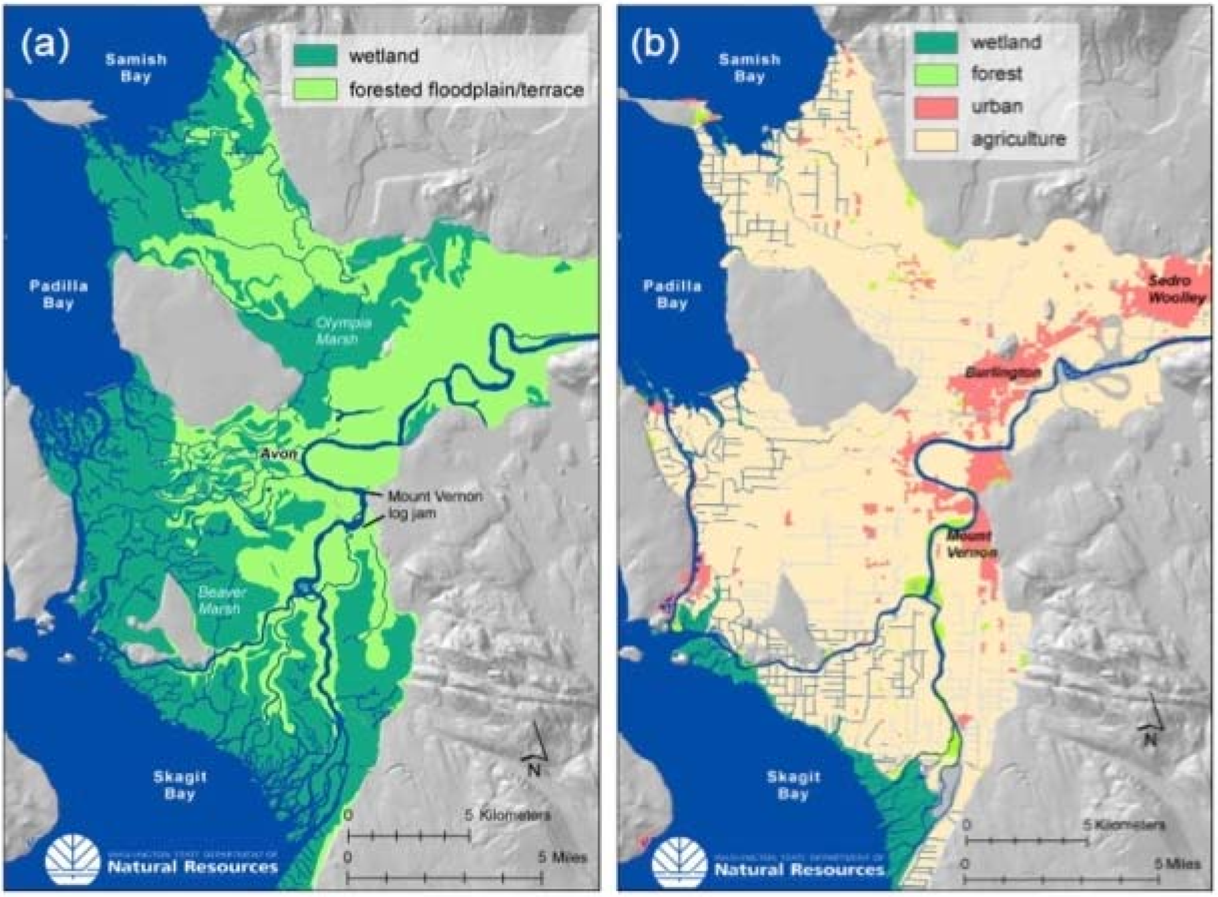

Figure 2-11. Loss of watershed filtration. The Skagit River delta (a) under historical conditions prior to ditching and diking that began in the 1860s and (b) under recent (~2000) conditions after conversion to farmland, housing development and cities (from Dowty et al. 2010, based on data produced by Collins 1998). The loss of upland and wetland filtering after watershed modification likely increased the nitrogen and sediments in river water entering Skagit Bay (eelgrass distribution not shown).

The story of nitrogen in the watershed

Nitrogen in a pristine watershed (Driscoll et al. 2003) originates via two primary pathways: 1) lightening ionizes nitrogen gas in the atmosphere and forms nitrate ions that fall to Earth (e.g., in rain), and 2) microorganisms associated with plants fix nitrogen gas from the air to form nitrogen ions (e.g., alder trees and legumes). Nitrogen ions are then used by other photosynthetic plants and continually recycled by plants in the oceans and on land; under pristine conditions, nitrogen is often the limiting factor to plant growth.

From prehistoric times to the Industrial Revolution, nitrogen occurred primarily via these natural pathways and the recycling of organic matter through decomposition. In the developed world (Driscoll et al. 2003) a third primary source of nitrogen was introduced in the 1950s when chemical fertilizer was mass-produced by fixing atmospheric nitrogen into ammonium and nitrate fertilizer. Human populations, particularly in coastal regions, expanded rapidly, in part in response to greater food production.

Developed watersheds worldwide are now faced with excessive amounts of nitrogen arising from increased food production and decomposition of the large quantity of associated organic matter. Ultimately, the issue is human and animal waste entering our coastal oceans and estuaries – even treated sewage usually carries high levels of nitrogen. In the 1970-80s, 90% of the nitrogen entering Puget Sound was from the Pacific Ocean (Mackas and Harrison 1997). The primary source of anthropogenic nitrogen entering Puget Sound, above natural sources such as ocean upwelling and atmospheric deposition, is food imported from outside the watershed and, secondarily, feed imported for animals which ultimately enter the Sound; the majority of the nitrogen in food is passed through the human body as waste.

The nitrogen concentration of the Sound's waters has risen significantly over the past decade (Figure 2-1, Bos et al. 2013a, Krembs 2013, Moore et al. 2013). Elevated nitrogen levels stress eelgrass (Short and Wyllie-Echeverria 1996, Nixon and Buckley 2003, Orth et al. 2006) by stimulating plankton production, whether the nitrogen is unrelated to human activities, or is nitrogen that has a human source. Unfortunately, under today's conditions of human population size and development, it is not possible to distinguish base level vs. excess nitrogen. The broad distribution and intensity of chlorophyll in the two Sound-wide satellite images (Figure 2-7), the EOPS (2013) photographs showing the extensive plankton blooms (Figure 2-8) and the understanding that these blooms are persistent, based on daily chlorophyll monitoring (Sackmann and Krembs 2013), suggest potentially widespread stress to eelgrass over much of the Sound during the eelgrass growing season. Additionally, the increasing nitrogen concentrations in the Sound's waters over the past decade (Figures 2-1 and 2-2, Bos et al. 2013b) together with the established impacts, suggest increasingly adverse conditions for eelgrass. Currently the human nitrogen loading impacts in Hood Canal North are not considered to be causing dissolved oxygen depletion (Cope and Roberts 2013), but human-derived nitrogen in the nearshore areas may be causing stress to eelgrass beds here and throughout the Sound.

Many other stressors to eelgrass are present in Puget Sound, some of which interact with the effects of nitrogen loading. The primary stressors amenable to adaptive management are sediment loading from the watershed, construction of new overwater structures that shade the water surface, toxic chemicals in water or sediments, boat mooring and propeller damage, traffic from ships, ferries and boats producing large frequent wakes, as well as shoreline armoring, new aquaculture activity in shallow waters, and new dredge and fill (see the Appendix and Thom et al. 2011). There are additional less management-related stressors that impact eelgrass (Thom et al. 2011). Of these, climate change and ocean acidification, are briefly discussed in the Appendix (p. 37). All these stressors identified for Puget Sound require adaptive management to support the conservation and recovery of eelgrass and some are already being addressed by State, Tribal, Federal, and local government agencies. The nitrogen stressor is a Sound-wide concern because it is so widely distributed and is trending upward.

2.3 What Managers Can Do to Reduce Nitrogen Pollution in Puget Sound

Nitrogen and its impacts to the waters and eelgrass of Puget Sound could be ameliorated with improved regulation and management. Many other large estuarine systems nationwide have undertaken this challenge, and, although costly, taking early action when indicators of nitrogen stress emerge will, in the long run, reduce both the time and costs associated with ecosystem recovery.

As mentioned, there are other factors that stress eelgrass: all need to be addressed. Many are receiving attention from the Department of Natural Resources and other agencies. However, with the documented increase in nitrogen concentrations in the Sound's waters and the intensification of other stressor impacts by nitrogen, more aggressive eelgrass protection and restoration is needed.

The anthropogenic nitrogen loading of Puget Sound is regulated by the Clean Water Act which establishes water quality standards using numerical criteria for "aquatic life use support" based on levels of dissolved oxygen in the Sound's waters (EPA 2001, Mohamedali et al. 2011, Cope and Roberts 2013). Several other large estuarine systems across the country have determined that oxygen criteria alone are not protective of eelgrass (EPA 2003) because the nitrogen thresholds calculated to satisfy the oxygen criteria are too high for long-term eelgrass survival. That is, if nitrogen levels are not more stringent than those needed to prevent severe oxygen depletion, then eelgrass will continue to decline.

Nitrogen is an important stressor of eelgrass elsewhere and shows signs of impacting eelgrass in Puget Sound. Expansion of the protective criteria for aquatic life support has been done in other locations to lower the nitrogen threshold to a point that protects eelgrass (EPA 2003, Trowbridge et al. 2009).

Nitrogen reduction cannot be done all at once, but other coastal and estuarine areas across the country have found putting off action is problematic. Early initiation of long-term efforts to preserve the eelgrass resource by lowering nitrogen inputs has resulted in more rapid and less costly improvements. The technology exists for reducing nitrogen loads to the Sound. Point sources of nitrogen are the most direct route to improvement as seen elsewhere in the country (Batiuk et al. 2000, Greening and Janicki 2006, Taylor et al. 2011).

Non-point sources of nitrogen encompass everything from inadequate septic systems, fertilizers, animal waste, and agricultural runoff, to forestry clearing and ever-increasing impervious surfaces. Many of these enter the Sound through river flow and runoff which currently do not receive adequate filtration due to losses of upland vegetation and wetlands. The reestablishment of wetland buffers and drainage control that prevent unfiltered discharge will reduce nitrogen loading to the Sound.

Rivers and floodwaters transport nitrogen from the watershed into the Sound. Historically, forests, marshes and wetlands filtered these waters but many of these watershed filters have been degraded (Figure 2-11). Current efforts by Tribal, State and Federal agencies have begun to reestablish watershed filtration through berm removal and restoration of upland areas into functioning marshes and wetlands. Efforts in the Skokomish delta have begun to restore wetland functions (NWIFC 2012). Coincidentally, recent SVMP monitoring has found expansion of the eelgrass flat on the Skokomish River delta. Although a connection between the increase in eelgrass distribution and watershed restoration has not been proven, this possibility is intriguing and needs further investigation for the benefits it might provide to the Sound’s eelgrass recovery goals.

3 Conclusions

Eelgrass is stressed by nitrogen in many areas of Puget Sound. Nitrate concentrations in the Sound's waters are increasing, a pattern seen across the United States and the developed world where nitrogen enrichment of near shore waters is a widely recognized problem. Excess nitrogen ultimately reduces water clarity and thereby reduces the light reaching eelgrass plants.

Puget Sound is a vast and well-flushed estuary with a huge eelgrass resource and tremendous productivity. However, its eelgrass resource is subject to the same human-derived stressors seen in seagrasses worldwide. Addressing excess nitrogen loading will help assure long-term eelgrass health and distribution, and ultimately, the long-term health of the Sound itself.

4 References

Antrim LD, Thom RM, and Gardiner WW. 1993. Lincoln Park Shoreline Erosion Control Project: Monitoring for Surface Substrate, Infaunal Bivalves and Eelgrass. PNL-8822, prepared for the U.S. Army Corps of Engineers, Seattle District, Seattle Washington, by Pacific Northwest National Laboratory, Richland, WA.

Batiuk R, Bergstrom P, Kemp M, Koch E, Murray L, Stevenson C, Bartleson R, Carter V, Rybicki N, Landwehr J, Gallegos C, Karrh L, Naylor M, Wilcox D, Moore K, Ailstock S, Teichberg M. 2000. Chesapeake Bay submerged aquatic vegetation water quality and habitat-based requirements and restoration targets: A second technical synthesis. CBP/TRS 245/00. EPA 903-R-00-014, U.S. Environmental Protection Agency, Chesapeake Bay Program, Annapolis, MD.

Beem, N and Short FT. 2009. Subtidal eelgrass declines in the Great Bay Estuary, NH-ME. *Estuaries and Coasts* 32:202-205.

Björk M, Short F, Mcleod E, Beer S. 2008. Managing Seagrasses for Resilience to Climate Change. IUCN, Gland, Switzerland. 56pp.

Bos J, Krembs C, Albertson S, Friedenberg L, Keyzers M, Maloy C. 2013a. Increasing nutrients, changes in algal biomass, and large *Noctiluca* blooms in Puget Sound: is eutrophication fueling the microbial food web. Dept of Ecology, Olympia, WA. 22nd Biennial Conference of the Coastal and Estuarine Research Federation - Abstract Book, 3-7 November 2013, San Diego, CA.

Bos J, Krembs C, Albertson S, Sackmann B, Mora D, Keyzers M, Friedenberg L, Pool S, Maloy C. 2013b. Water quality: Puget Sound long-term stations. In. Moore S, K Stark, J Bos, P Williams, J Newton and K Dzinbal (Eds.). Puget Sound Waters: 2012 overview. NOAA publication. 40p. http://www.psp.wa.gov/downloads/psemp/PSmarinewaters_2012_overview.pdf

Bouwman L, Beusen A, Glibert PM, Overbeek C, Pawlowski M, Herrera J, Mulsow S, Yu R, Zhou M. 2013. Mariculture: significant and expanding cause of coastal nutrient enrichment. Environ. *Research Letters* 8:044026 (5pp) doi:10.1088/1748-9326/8/4/044026

Bricker S, Longstaff B, Dennison W, Jones A, Boicourt K, Wicks C, Woerner J. 2007. Effects of Nutrient Enrichment In the Nation's Estuaries: A Decade of Change. NOAA Coastal Ocean Program Decision Analysis Series No. 26. National Centers for Coastal Ocean Science, Silver Spring, MD. 328 pp. *ccma.nos.noaa.gov/publications/eutroupdate/front_materials.pdf*

Burdick, DM and Short FT. 1999. The effects of boat docks on eelgrass beds in coastal waters of Massachusetts. *Environmental Management* 23:231-240.

Burkholder JM, Tomasko D, Touchette BW. 2007. Seagrasses and eutrophication. *Journal of Experimental Marine Biology and Ecology* 350: 46-72.

Burkholder JM and Shumway SE. 2011. Bivalve shellfish aquaculture and eutrophication. In: SE Shumway (ed.) Shellfish Aquaculture and the Environment. John Wiley & Sons, Inc., p. 155-231.

Carman R, Taylor K, Skowlund P. 2010. Regulating shoreline armoring in Puget Sound, In Shipman, H, MN Dethier, G Gelfenbaum, KL Fresh, and RS Dinicola, (eds.), 2010, Puget Sound Shorelines and the Impacts of Armoring—Proceedings of a State of the Science Workshop, May 2009: U.S. Geological Survey Scientific Investigations Report 2010-5254, p. 49-54.

Christensen, PB, Glud RN, Dalsgaard T, Gillespie P. 2003. Impacts of long line mussel farming on oxygen and nitrogen dynamics and biological communities of coastal sediments. *Aquaculture* 218: 567-588.

Collins, B. 1998. Preliminary Assessment of Historic Conditions of the Skagit River in the Fir Island Area: Implications for Salmonid Habitat Restoration. Report to the Skagit system Cooperative, La Conner, WA. Accessed 1/29/10 at http://www.skagitcoop.org/documents/EB70_Collins1998.pdf

Cope B and Roberts M. 2013. Review and Synthesis of Available Information to Estimate Human Impacts to Dissolved Oxygen in Hood Canal. Washington State Department of Ecology Publication No. 13-03-016. https://fortress.wa.gov/ecy/publications/SummaryPages/1303016.html

Czuba JA, Magirl CS, Czuba CR, Grossman EE, Curran CA, Gendaszek AS, Dinicola RS. 2011. Sediment load from major rivers into Puget Sound and its adjacent waters. U.S. Geological Survey Fact Sheet 2011-3083

Czuba JA, Magirl CS, Czuba CR, Curran CA, Johnson KH, Olsen TD, Kimball HK and Gish CC. 2012. Geomorphic analysis of the river response to sedimentation downstream of Mount Rainier, Washington: U.S. Geological Survey Open-File Report 2012-1242, 134 p.

Diefenderfer HL, Sargent SL, Borde AB, Thom RM. 2005. Northwest Maritime Center eelgrass restoration project, Port Townsend, Washington: First-Year Monitoring Report, 2004. PNWD-3560, prepared for Northwest Maritime Center, Port Townsend, Washington, by Pacific Northwest National Laboratory, Richland, Washington.

Dowty P. 2011. Area of eelgrass depth bands in greater Puget Sound. Nearshore Habitat Program Aquatic Resources Division, Washington State Department of Natural Resources, Olympia, WA

Dowty P, Berry H, Gaeckle J. 2010. Developing Indicators and Targets for Eelgrass in Puget Sound: A Science Assessment. November 18, 2010, Nearshore Habitat Program Aquatic Resources Division, Washington State Department of Natural Resources, Olympia, WA

Driscoll, CT, et al. 2003. Nitrogen Pollution: From the Sources to the Sea. Hubbard Brook Research Foundation. Science Links^{TM} Publication. Vol. 1, no. 2.

Duarte CM, Borum J, Short FT, Walker DI. 2008. Seagrass Ecosystems: Their Global Status and Prospects. pp. 281-294. In: N.V.C. Polunin, (ed) Aquatic Ecosystems: Trends and Global Prospects. Cambridge Univ. Press. UK.

Elliott JK, Spear E, and Wyllie-Echeverria S. 2006. "Mats of *Beggiatoa* bacteria reveal that organic pollution from lumber mills inhibits growth of *Zostera marina*." *Marine Ecology* 27:372-380.

Engel EA. 2012. Satellite Remote Sensing of Chlorophyll: Significance of PAR & Spatial Scale Proceedings from the University of Washington School of Oceanography Senior Thesis, Seattle, WA. 10 p.

EOPS 2013. Eyes Over Puget Sound, Marine Water Quality Monitoring Program monthly reports and data, WA Department of Ecology, Olympia, WA. http://www.ecy.wa.gov/programs/eap/mar_wat/surface.html

EPA 2001. Nutrient Criteria Technical Guidance Manual: Estuarine and Coastal Marine Waters. U.S. Environmental Protection Agency, Office of Water, EPA-822-B-01-001. October 2001. Accessed November 6, 2008. Published Online http://www.epa.gov/waterscience/criteria/nutrient/guidance/marine/index.html.

.

EPA 2003. Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll a for Chesapeake Bay and its Tidal Tributaries. EPA 903-R-03-002. U.S. Environmental Protection Agency, Chesapeake Bay Program Office. Published Online http://www.epa.gov/region3/chesapeake/baycriteria/Criteria_Final.pdf

Erftemeijer, PLA, Lewis, RRR. 2006. Environmental impacts of dredging on seagrasses: a review. *Marine Pollution Bulletin* 52, 1553–1572.

Friedenberg, L, Bos J, Albertson S, Keyzers M, Maloy C, Sackmann B, Krembs C. 2013. Increasing nutrients, changes in algal biomass, and large *Noctiluca* blooms in Puget Sound: is eutrophication fueling the microbial food web? Pacific Estuarine Research Society, BC, Canada. https://fortress.wa.gov/ecy/publications/Summarypages/1303019.html

Gaeckle J. 2013. Outfall assessment and the effects on critical nearshore habitats. Report to Puget Sound Marine and Nearshore Protection and Restoration Program, WDFW 12-1177: DNR 12-292, Nearshore Habitat Program, Washington State Department of Natural Resources, Olympia, WA.

Greening H and Janicki A. 2006. Toward reversal of eutrophic conditions in a subtropical estuary: water quality and seagrass response to nitrogen loading reductions in Tampa Bay, Florida, USA. *Environmental Management* 38: 163–178.

Grossman, EE, George, DA, Lam A. 2011. Shallow stratigraphy of the Skagit River Delta, Washington, derived from sediment cores: U.S. Geological Survey Open File Report 2011-1194, 123 p., available at http://pubs.usgs.gov/of/2011/1194/.

Hallock D. 2008. River and stream water quality monitoring report, water year 2008, WA Department of Ecology, Olympia, WA. 38p. & Appendices. www.ecy.wa.gov/biblio/0903041.html

Krembs C. 2013. Marine Water Quality: Marine Water Condition Index. p. 112-113 In: State of the Sound 2013. Puget Sound Partnership: A Biennual Report on the Recovery of Puget Sound. Tacoma, WA.

Khangaonkar T, Long W, Sackmann B, Mohamedali T, Roberts M. 2012. Simulation of annual biogeochemical cycles of nutrient balance, phytoplankton bloom(s), and DO in Puget Sound using an unstructured grid model. *Ocean Dynamics* 62:1353–1379.

Landry J, Golden R, Karrh L, Lewandowski M. 2013. The effects of hardened shorelines on SAV in the Chesapeake and Maryland coastal bays. Coastal and Estuarine Research Federation Conference, abstract, 3-7 November 2013, San Diego, CA.

Lee, KS, FT Short, DM Burdick. 2004. Development of a nutrient pollution indicator using the seagrass, *Zostera marina*, along nutrient gradients in three New England estuaries. *Aquatic Botany* 78:197–216.

Leschen A, Ford K, Evans NT. 2010. Successful eelgrass (*Zostera marina*) restoration in a formerly eutrophic estuary (Boston Harbor) supports the use of a multifaceted watershed approach to address eelgrass loss. *Estuaries and Coasts* 33: 1340-1354.

Lewis MA, and Devereux R. 2009. Nonnutrient anthropogenic chemicals in seagrass ecosystems: fate and effects. *Environmental Toxicology and Chemistry* 28: 644–661.

Mackas DL and Harrison PJ. 1997 Nitrogenous Nutrient Sources and Sinks in the Juan de Fuca Strait/Strait of Georgia/Puget Sound Estuarine System: Assessing the Potential for Eutrophication. Estuarine, Coastal and Shelf Science 44: 1–21.

McGlathery KJ, Sundbäck K, Anderson IC. 2007. Eutrophication in shallow coastal bays and lagoons: the role of plants in the coastal filter. *Mar Ecol Prog Ser* 348: 1–18.

Mohamedali T, Roberts M, Sackmann B, Kolosseus A. 2011. Puget Sound Dissolved Oxygen Model Nutrient Load Summary for 1999-2008. Washington State Department of Ecology Publication No. 11-03-057. https://fortress.wa.gov/ecy/publications/SummaryPages/1103057.html

Moore S, Stark K, Bos J, Williams P, Newton J, Dzinbal K (Eds.). 2013. Puget Sound Waters: 2012 overview. NOAA publication. 40p. http://www.psp.wa.gov/downloads/psemp/PSmarinewaters_2012_overview.pdf

Nelson TA and Lee A. 2001. A manipulative experiment demonstrates that blooms of the macroalga *Ulvaria obscura* can reduce eelgrass shoot density. *Aquatic Botany* 71:149-154.

Nelson, AT and Melton M. 2011. Dumas Bay saltwater algae research. Final report to the City of Federal Way. Seattle Pacific University, 15p + Addendum.

Nelson TA, Haberlin K, Nelson AV, Ribarich H, Hotchkiss R, Van Alstyne KL, Buckingham L, Simunds DJ, Fredrickson K. 2008. Ecological and physiological controls of species composition in green macroalgal blooms, *Ecology*, 89: 1287–98.

Nightingale B and Simenstad CA. 2001. Overwater structures: marine issues. White Paper. Washington State Transportation Center (TRAC), University of Washington and Washington State Department of Transportation, Seattle, WA.

Nixon SW, Buckley BA. 2007. Nitrogen inputs to Rhode Island Coastal Salt Ponds - Too much of a good thing. Special Collections Publications. Paper 11. http://digitalcommons.uri.edu/sc_pubs/11

NWIFC 2012 Northwest Indian Fisheries Commission http://nwifc.org/2011/12/skokomish-tribe-monitoring-skokomish-tidelands-following-restoration-work/

Orth RJ, Carruthers TJB, Dennison WC, Duarte CM, Fourqurean JW, Heck Jr KL, Hughes AR, Kendrick GA, Kenworthy WJ, Olyarnik S, Short FT, Waycott M, and Williams SL. 2006. A global crisis for seagrass ecosystems. *BioScience* 56: 987-996.

Oczkowski AJ, Pellerin BA, Hunt CW, Wollheim WM, Vörösmarty CJ, Loder TC. 2006. The role of snowmelt and spring rainfall in inorganic nutrient fluxes from a large temperate watershed, the Androscoggin River basin (Maine and New Hampshire). *Biogeochemistry* 80: 191–203.

Patrick CJ, and Weller DE. 2013. Multi-scale controls of submerged aquatic vegetation in Chesapeake Bay. Coastal and Estuarine Research Federation Conference, abstract, 3-7 November 2013, San Diego, CA.

PMEL NOAA 2103. www.pmel.noaa.gov/co2/story/What+is+Ocean+Acidification%3F

Ralph PJ, Tomasko D, Moore K, Seddon S, Macinnis-Ng CMO. 2006. Human impacts on seagrasses: eutrophication, sedimentation, and contamination. In: T Larkum, R Orth and C Duarte (eds.). Seagrasses: Biology, Ecology and Conservation. Springer, The Netherlands.

Reeves B. 2006. Eelgrass (*Zostera marina* L.) abundance and depth distribution in Echo Bay, Sucia Island, San Juan County, Washington State. DNR Report, Olympia, WA 10p.

Rivers D. 2008. Eelgrass (*Zostera marina* L.) dynamics and distribution at the deep edge of beds in the Great Bay Estuary, NH, Master of Science Thesis, University of New Hampshire, Durham, NH

Rumrill SS and Poulton VK. 2004. Ecological role and potential impacts of molluscan shellfish culture in the estuarine environment of Humboldt Bay, CA. Annual and Final Report 2001-04 to the Western Regional Aquaculture Center. 22 pp.

Ryther JH and Dunstan WM. 1971. Nitrogen, phosphorus, and eutrophication in the coastal marine environment. *Science* 171(3975): 1008-1013.

Sackmann B and Krembs C. 2013. Seattle-Victoria surface transects. In. Moore S, K Stark, J Bos, P Williams, J Newton and K Dzinbal (Eds.). Puget Sound Waters: 2012 overview. NOAA publication. 40p. http://www.psp.wa.gov/downloads/psemp/PSmarinewaters_2012_overview.pdf

Seitzinger SP, Kroeze C, Bouwman AF, Caraco N, Dentener F, Styles RV. 2002. Global patterns of dissolved inorganic and particulate nitrogen inputs to coastal systems: recent conditions and future projections. *Estuaries* 25: 640–655.

Short FT. 2013. Eelgrass. In: State of the Sound 2013. Puget Sound Partnership: A Biennual Report on the Recovery of Puget Sound. Tacoma, WA.

Short FT and Burdick DM. 1996. Quantifying eelgrass habitat loss in relation to housing development and nitrogen loading in Waquoit Bay, Massachusetts. *Estuaries* 19:730-739.

Short FT and Neckles H. 1999. The effects of global climate change on seagrasses. *Aquatic Botany* 63:169-196

Short FT and Wyllie-Echeverria S. 1996. Natural and human-induced disturbance of seagrasses. *Environmental Conservation* 23(1):17-27.

Short, FT, Burdick DM, Kaldy JE. 1995. Mesocosm experiments quantify the effects of eutrophication on eelgrass, *Zostera marina* L., *Limnology and Oceanography* 40:740-749.

Short FT, Dennison WC, Carruthers TJB, Waycott M. 2007. Global Seagrass Distribution and Diversity: A Bioregional Model. *Journal of Experimental Marine Biology and Ecology* 350:3-20.

Short FT, Polidoro B, Livingstone SR, et al. 2011. Extinction risk assessment of the world's seagrass species. *Biological Conservation* 144(7): 1961-1971.

SVMP unpublished: Short FT, Dowty P, Berry H, Ferrier L. in prep. Submerged Vegetation Monitoring Program Reports 2012, DNR, Olympia, WA.

Shumway SE (ed.). 2011. Shellfish Aquaculture and the Environment. John Wiley & Sons, Inc.

Simenstad CA, Garano RJ, Labbe T, et al. 2008. Assessment of Intertidal Eelgrass Habitat Landscapes for Threatened Salmon in the Hood Canal and Eastern Strait of Juan de Fuca, Washington State. Technical Report 08-01, Point No Point Treaty Council, 7999 N.E. Salish Lane, Kingston, Washington. 152 pp.

SOS. 2013. State of the Sound 2013. Puget Sound Partnership: A Biennial Report on the Recovery of Puget Sound. Tacoma, WA.

Stevens AW, and Lacy J. 2012. The influence of wave energy and sediment transport on seagrass distribution. *Estuaries and Coasts*, 35: 92–108.

SVMP 2011. Submerged Vegetation Monitoring Program Reports 2000-2011, DNR, Olympia, WA. http://www.dnr.wa.gov/ResearchScience/Topics/AquaticHabitats/Pages/aqr_nrsh_eelgrass_monitoring.aspx

Taylor DI, Oviatt CA, Borkman DG. 2011. Non-linear responses of a coastal aquatic ecosystem to large decreases in nutrient and organic loadings. *Estuaries and Coasts* 34: 745–757.

Thom RM, Parkwell TL, Niyogi DK, Shreffler DK. 1994. Effects of graveling on the primary productivity, respiration and nutrient flux of two estuarine tidal flats. *Marine Biology* 118:329-341.

Thom, RM, Borde AB, Williams GD, Southard JA, Blanton SL, Woodruff DL. 2001a. Effects of multiple stressors on eelgrass restoration projects. In: Proceedings of the 2001 Puget Sound Research Conference, Water Quality Action Team Olympia, WA.

Thom RM, Southard JA, Williams GD, Blanton S, Borde AB. 2001b. Eelgrass Restoration at West Eagle Harbor Phase III: Monitoring and Evaluation. Prepared for the Washington State Department of Transportation, Olympia Washington, by Pacific Northwest National Laboratory, Richland, WA.

Thom RM, Southard SL, Borde AB, Stoltz P. 2008. Light requirements for growth and survival of eelgrass (*Zostera marina L.*) in Pacific Northwest (USA) Estuaries. *Estuaries and Coasts* 31(5): 969-980.

Thom RM, Buenau KE, Judd C, Cullinan VI. 2011. Eelgrass (*Zostera marina* L.) Stressors in Puget Sound. Pacific Northwest National Laboratory. Sequim, WA

Trowbridge P. 2009. New Hampshire nutrient criteria for the Great Bay Estuary, Department of Environmental Services, Final (June 10, 2009) New Hampshire, Concord, NH.

USFWS. 1994. Trace elements and oil-related contaminants in sediment, bivalves, and eelgrass from Padilla and Fidalgo Bays, Skagit County, Washington, 1988. U.S. Fish and Wildlife Service, Ecological Services, Washington State Office, Olympia, WA. 27 p.

Vaudrey JMP, Kremer JN, Branco BF, Short FT. 2010. Seagrass recovery after nutrient enrichment reversal. *Aquatic Botany* 93: 237–243.

Waycott, M, Duarte CM, Carruthers TJB, Orth RJ, Dennison WC, Olyarnik S, Calladine A, Fourqurean JW, Heck Jr KL, Hughes AR, Kendrick GA, Kenworthy WJ, Short FT, Williams SL. 2009. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proceedings of the National Academy of Sciences* (PNAS) 106: 12377–12381.

Williams, B. and Betcher C. 1996. Impact of mooring buoy installations on eelgrass and macroalgae, Wash. Dept. Fish and Wildlife.

Williams, SL and Ruckelshaus MH. 1993. Effects of nitrogen availability and herbivory on eelgrass (*Zostera marina*) and epiphytes. *Ecology* 74: 904-918.

Woodruff DL, Borde AB, Southard JA, Williams GD, Thom RM. 2001. Assessment of Eelgrass *(Zostera marina)* Presence and Condition in Rich Passage During Summer 2000. PNWD-3091, prepared for the Washington Department of Transportation, Olympia, Washington, by Pacific Northwest National Laboratory, Richland, WA.

5 Appendix

5.1 Additional Eelgrass Stressors and their Interaction with Nitrogen

Beyond the Sound-wide nitrogen stressor, there are other stressors in Puget Sound that are amenable to adaptive management. All these stressors are important globally as factors that impact seagrasses; here in Puget Sound they mostly have localized impacts to eelgrass, some of which are already being addressed by State agencies.

Sediment Loading

Turbidity (suspended fine-grained sediments) in the water column from sediment loading is one of the primary stressors of seagrasses globally (Short et al. 2011). Turbidity reduces water clarity, thereby limiting the light reaching seagrass plants and reducing seagrass photosynthesis and growth (Thom et al. 2011). Also, high levels of sediment discharge can settle on eelgrass, smothering or burying the leaves. River discharge is the primary pathway for watershed fine-grained sediment to enter the Sound's waters, and such waters often carry organic matter and nitrogen (Czuba et al. 2011).

Overwater Structures

The building of overwater structures such as docks, piers and bridges often creates direct damage in the construction phase, but more critically, once built these structures reduce or eliminate light reaching the seafloor and thereby slow eelgrass growth or eliminate eelgrass meadows altogether due to light limitation (Burdick and Short 1999, Nightingale and Simenstad 2001). It is the construction of new and upgraded overwater infrastructure that is amenable to adaptive management.

Toxic Pollutants

Puget Sound has a history of logging practices that float logs in bays until the bark loosens. The bark then falls to the bottom and sulfide is produced via decomposition. Organic waste, including tree bark deposited on the seafloor, decomposes and in the process, produces hydrogen sulfide. Sulfide is toxic to eelgrass when sediment concentrations are high and can reduce eelgrass growth (Elliott et al. 2006) and ultimately kill eelgrass plants. Other toxic pollutants enter Puget Sound from many sources, primarily outfalls (USFWS 1994, Gaeckle 2013) but there is little evidence to suggest that toxicity at concentrations found in coastal environments impacts seagrass plants (Ralph et al. 2006, Lewis and Devereux 2009).

Moorings and Propellers

Boat moorings that are placed in eelgrass meadows (Williams and Betcher 1996, Nightingale and Simenstad 2001, Reeves 2006) scour an area of the seafloor around the anchor or mooring block and eliminate eelgrass. Boat and ship operations also have an impact on the bottom from their propellers; small boats that venture out of the channels into shallow waters at low tides can chop off eelgrass and uproot the plants, damaging the meadow. Larger ships, for example ferries and tugboats, create a propeller wash when navigating near shore or in shallow water, which often uproots eelgrass and washes away the sediments in eelgrass areas.

Wakes from Ships, Ferries and Boats

Vessel wakes created by passing ships or other watercraft increase the wave height and extend the depth to which turbulence in the nearshore can erode sediments, causing damage to eelgrass growing on the seafloor (Thom et al. 2011). In areas with narrow channels and high levels of routine ship traffic, e.g., the San Juan Islands, such wake impacts may be particularly detrimental to eelgrass meadows (Woodruff et al. 2001); more research is needed.

Shoreline Armoring

Shoreline armoring has been shown to have an adverse effect on submerged aquatic vegetation (Landry et al. 2013, Patrick et al 2013), but the impact to eelgrass meadows in Puget Sound, beyond observational assessments, has not been investigated (Thom et al. 1994, Carman et al. 2010). The avenues of potential stress include increased wave turbulence from reflected waves against the hardened area. Also, sediment resuspension caused by wave activity offshore of an armored shoreline increases water column turbidity and burial of eelgrass leaves (Antrim et al. 1993, Simenstad et al. 2008, Stevens and Lacey 2012). Additionally, armoring may restrict eelgrass beds by reducing normal shoreline erosion that supplies sediment to nearshore areas (Simenstad et al. 2008).

Aquaculture

The expansion of aquaculture into new areas where eelgrass occurs is amenable to adaptive management. The impact of aquaculture to eelgrass depends on the organism under cultivation and the type of aquaculture practice (Rumrill and Poulton 2004, Burkholder and Shumway 2011). As with aquaculture in other parts of the world (Shumway 2011), the primary stressor to eelgrass in Puget Sound is the direct conflict for space. Beyond this, many aquaculture practices release organic matter and nitrogen to the water, contributing to nitrogen stress (Christensen et al. 2003, Burkholder and Shumway 2011, Bouwman et al. 2013) and exacerbating shading impacts to eelgrass. On the other hand, shellfish can, to some extent, remove chlorophyll from the water by filtering out phytoplankton, which increases water clarity.

Dredge and Fill

In-water construction in the form of dredge and fill is well known as a stressor on seagrasses worldwide (see review Erftemeijer and Lewis 2006) and new projects are managed to reduce their impacts. Dredging for channels and harbors removes eelgrass from shallow intertidal and subtidal areas, and makes them too deep for eelgrass to continue to grow. The primary impacts from dredging occur in port facilities, marinas, and other navigation areas. Filling has been done extensively around Puget Sound (Thom et al. 2011) where much of the shoreline has been modified and wetlands and near shore areas have been “reclaimed.” Berm construction and channeling of marshes to create agricultural areas have been done in the past, although efforts are beginning to restore some of these wetland areas (Grossman et al. 2011).

Climate Change

The impacts of climate change on seagrasses have been reviewed in the literature (Short and Neckles 1999, Bjork et al. 2008, Duarte et al. 2008), indicating that the main climate-related factors that stress eelgrass in Puget Sound (Thom et al. 2011) are 1) temperature increase that affects eelgrass in shallow water, and 2) sea level rise that increases the depth of water over existing eelgrass beds and thereby reduces light reaching the plants. These are clearly major issues that relate to the health of the Sound and its surrounding human population. Substantial efforts are underway in Washington to ameliorate some of the impacts of climate change.

Ocean Acidification

Ocean acidification is an additional aspect of climate change resulting from increased carbon dioxide in the atmosphere and oceans that has a potentially significant impact on Puget Sound waters and particularly shellfish production (PMEL NOAA 2013, Washington Governor’s 2012 Blue Ribbon Panel on Ocean Acidification). However, eelgrass, as a photosynthetic plant, removes carbon dioxide from the water and thereby reduces ocean acidification in the Sound. Nitrogen stress to eelgrass may exacerbate local effects of ocean acidification, because excess nitrogen reduces eelgrass photosynthesis (via reduced water clarity), which in turn reduces CO_2 uptake by the plants and increases ocean water acidity.