



Environmental and Eelgrass Response to Dike Removal: Nisqually River Delta (2010–14)

By Renee K. Takesue



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U.S. Department of the Interior
U.S. Geological Survey

Cover. Photo of an environmental sensor measuring turbidity and temperature in an eelgrass bed near a restored tidal channel in the Nisqually River Delta, Puget Sound, Washington. Photo by Renee Takesue, U.S. Geological Survey.



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Conversion Factors

International System of Units to Inch/Pound

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
Area		
square meter (m ²)	0.0002471	acre
hectare (ha)	2.471	acre
square kilometer (km ²)	247.1	acre
square centimeter (cm ²)	0.001076	square foot (ft ²)
square meter (m ²)	10.76	square foot (ft ²)
square centimeter (cm ²)	0.1550	square inch (ft ²)
hectare (ha)	0.003861	square mile (mi ²)
square kilometer (km ²)	0.3861	square mile (mi ²)
Volume		
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	0.2642	gallon (gal)
cubic meter (m ³)	264.2	gallon (gal)
cubic centimeter (cm ³)	0.06102	cubic inch (in ³)
liter (L)	61.02	cubic inch (in ³)
cubic meter (m ³)	35.31	cubic foot (ft ³)
cubic meter (m ³)	0.0008107	acre-foot (acre-ft)
Flow rate		
cubic meter per second (m ³ /s)	70.07	acre-foot per day (acre-ft/d)
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m ³ /s)	35.31	cubic foot per second (ft ³ /s)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
Mass		
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as °C = (°F – 32) / 1.8.

Datum

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Abbreviations

CI	confidence interval
μM	micromolar
mV	millivolts
NNWR	Nisqually National Wildlife Refuge
ppm	parts per million
rpm	revolutions per minute
USGS	U.S. Geological Survey

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Abstract

Restoration of tidal flows to formerly diked marshland can alter land-to-sea fluxes and patterns of accumulation of terrestrial sediment and organic matter, and these tidal flows can also affect existing nearshore habitats. Dikes were removed from 308 hectares (ha) of the Nisqually National Wildlife Refuge on the Nisqually River Delta in south Puget Sound, Washington, in fall 2009 to improve habitat for wildlife, such as juvenile salmon. Ecologically important intertidal and subtidal eelgrass (*Zostera marina*) beds grow on the north and west margins of the delta. The goal of this study was to understand long-term changes in eelgrass habitat and their relation to dike removal. Sediment and eelgrass properties were monitored annually in May from 2010 to 2014 at two sites on the west side of the Nisqually River Delta along McAllister Creek, a spring-fed creek near two restored tidal channels. In May 2014, the mean canopy height of eelgrass was the same as in previous years in an 8-ha bed extending to the Nisqually River Delta front, but mean canopy height was 20 percent lower in a 0.3-ha eelgrass bed closer to the restored marsh when compared to mean canopy height of eelgrass in May 2010, 6 months after dike removal was completed. Over 5 years, the amount of eelgrass leaf area per square meter (m^2) in the 8-ha bed increased slightly, and surface-sediment grain size became finer. In contrast, in the 0.3-ha bed, eelgrass leaf area per m^2 decreased by 45 percent, and surface sediment coarsened. Other potential stressors, including sediment pore water reduction-oxidation potential (redox) and hydrogen sulfide (H_2S) concentration in the eelgrass rhizosphere, or root zone, were below levels that negatively affect eelgrass growth and therefore did not appear to be environmental stressors on plants. Eelgrass biomass partitioning, though less favorable in the 8-ha eelgrass bed compared to the 0.3-ha one, was well above the critical above-ground to below-ground biomass ratio of 2:1 for *Z. marina*, an indication that these plants were not at risk of a carbon deficit during low-light conditions. After 5 years, nearshore changes associated with the restoration of tidal flows to formerly diked marshes of the Nisqually River Delta appeared to have little impact on the large eelgrass bed extending from Luhr Beach to the Nisqually River Delta front; however, restoration appears to be contributing to the decline of a small eelgrass bed closer to the restoration area.

Introduction

Nearshore habitat restoration in the U.S. Fish and Wildlife Service Nisqually National Wildlife Refuge (NNWR) in the Nisqually River Delta (also referred to as “the delta”) began in September 2009 to return tidal flow to 308 hectares (ha) of the delta that was diked off in the early 1900s. By November 2009, 7 kilometers (km) of dikes were removed around freshwater marshes in the NNWR (fig. 1A, B). It was hypothesized that sediment and organic matter from the former freshwater marsh would be mobilized and transported to the nearshore region by ebb tidal currents, and that some of this material

would be deposited in eelgrass beds along McAllister Creek. Potential increases in suspended sediment concentration would decrease water clarity, and this, coupled with the accumulation of fine-grained terrestrial sediment and organic matter in nearby eelgrass (*Zostera marina*) beds was of concern because both these factors can negatively affect eelgrass growth. Turbidity decreases the amount of photosynthetically active radiation (PAR) needed by eelgrass for growth (Zimmerman and others, 1991), and an increase in the accumulation of fine sediment and organic matter can lead to the build-up of sulfides in the eelgrass rhizosphere (root zone) to levels that are toxic to plants (Holmer and others, 2006). Long-term monitoring of environmental and eelgrass characteristics began in May 2010 near restored tidal channels on the west side of the delta to quantify the response to dike removal, identify long-term trends, and infer whether changes were associated with restoration activities.

Site Description

McAllister Creek is a spring-fed creek on the west side of the Nisqually River Delta into which restored tidal channels drain (fig. 1B). Monitoring was conducted at two sites on the west bank of McAllister Creek, 200 meters (m) north and 300 m south of the Luhr Beach boat ramp, designated Luhr N and Luhr S (fig. 1C). North (seaward) of the boat ramp, McAllister Creek crosses intertidal mud flats and flows to the delta front, and a continuous 8-ha eelgrass meadow extends along its west bank (fig. 1A). South (landward) of the boat ramp, the channel of McAllister Creek is confined between a bluff to the west and marsh platforms to the east (fig. 1C). Eelgrass occurs in discrete beds and patches in the landward portion of McAllister Creek. The eelgrass bed monitored at Luhr S was 0.3 ha in area.

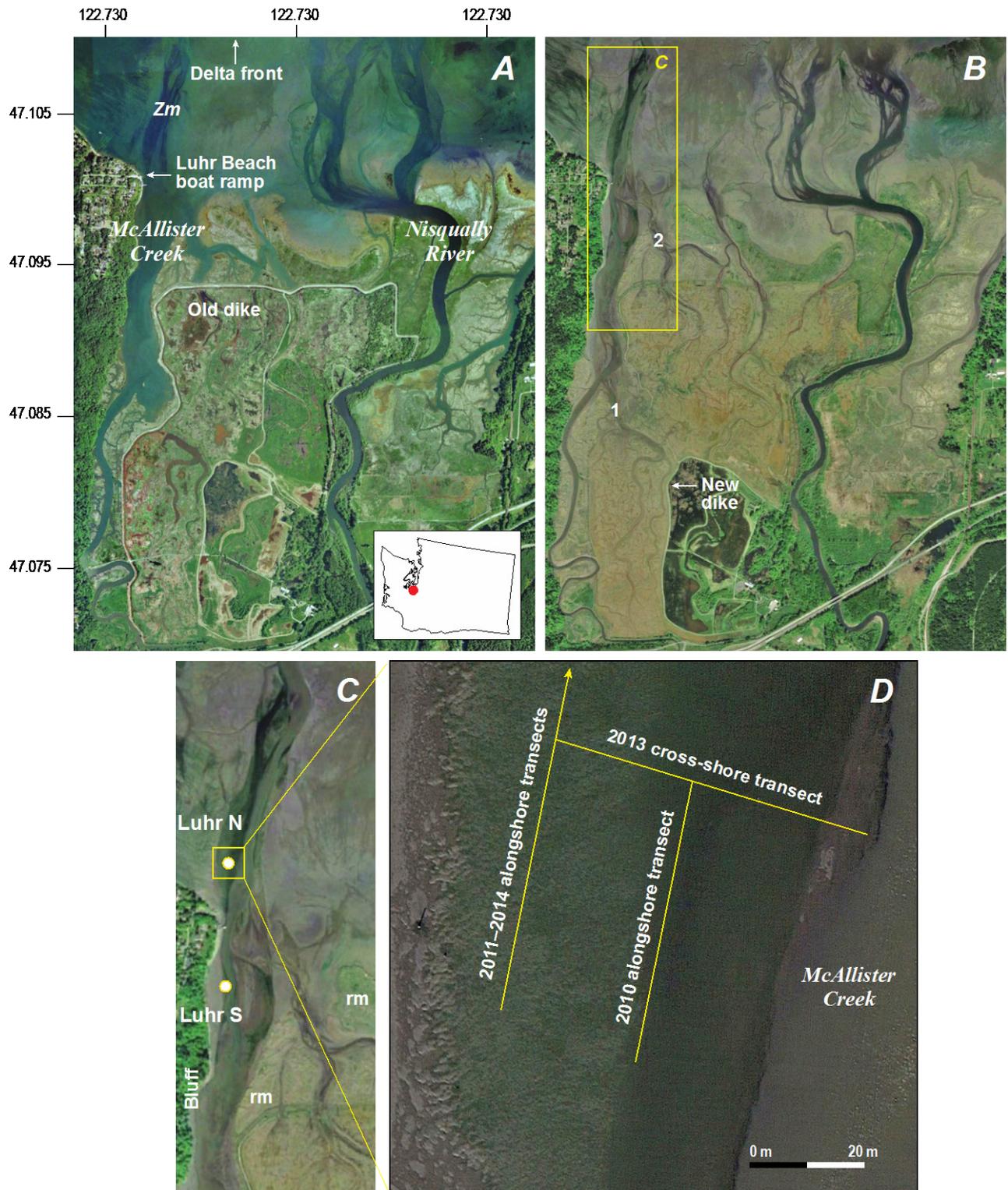


Figure 1. Satellite images of the Nisqually River Delta, Washington (Google Earth). *A*, The delta in mid-2009 with the old dike; *Zm* is the 8-ha *Zostera marina* bed. *B*, The delta in mid-2015 with the new dike; 1 and 2 are restored tidal channels that drain to McAllister Creek. *C*, Locations of monitoring sites at Luhr N and Luhr S; *rm* are remnant marsh platforms. *D*, Approximate locations of eelgrass transect by year.

Methods

Environmental and Eelgrass Properties

Environmental and eelgrass properties were measured annually from 2010 to 2014 in the month of May, when above-ground (shoot) biomass of intertidal Puget Sound eelgrass peaks (Phillips, 1972). *Z. marina* leaves persist on shoots from several weeks to more than a month, whereas rhizomes persist in the sediment for several years. Their growth patterns provide insights into environmental conditions over different time scales. Intertidal eelgrass beds were accessed during a 4- to 5-day window around the lowest low tides in May, which varied from early to late in the month. Eelgrass morphology and growth (shoot density, leaf length and width, number of leaves, above-ground (AG) and below-ground (BG) biomass, and rhizome internode lengths) were measured in 10 quadrats across a 100-meter-long shore-parallel transect at each site, when possible (see details in appendix 1). The initial alongshore transect at Luhr N (May 2010) was approximately midway between the intertidal and subtidal edges of the eelgrass bed (fig. 1D). In 2011, the substrate was too muddy to allow reoccupation of this site, and the transect was moved 20 m closer to the intertidal edge of the eelgrass bed, where the ground was firmer (fig. 1D). In May 2013, *Z. marina* characteristics were additionally determined in the cross-shore direction at Luhr N to quantify how plant characteristics varied with tidal depth across the tidal flat (fig. 1D). Water column turbidity, surface and subsurface sediment grain-size distribution (sediment texture), subsurface reduction-oxidation potential (redox) of pore waters, and subsurface hydrogen sulfide (H₂S) concentration of pore waters were measured in short sediment cores collected in the eelgrass beds at Luhr N and Luhr S. Detailed descriptions of the methods are given in appendix 1.

Results

Turbidity

When the turbidity sensors (SLOBS) were recovered after deployment, they were found to be fouled by drifting macroalgae (*Ulva* species) that interfered with backscatter measurements and produced erroneously high readings at one or both sites during each deployment (see appendix 2). In 2011–14, macroalgae was manually removed from the SLOBS during each morning or early afternoon low tide of the 4–5 day deployment to allow an accurate backscatter measurement on the following flood tide. It may be possible to estimate minimum turbidity levels over the Luhr N and Luhr S eelgrass beds; however, high, rather than low, turbidity levels would be more likely to impact eelgrass growth.

Prerestoration Sediment Texture From Sediment Cores

Surface sediment was not collected at the monitoring sites prior to dike removal, so prerestoration sediment grain-size distributions were determined from records in sediment cores. Rooted, mature eelgrass plants (>1 year old, see section on eelgrass rhizomes) were present when cores were collected in May 2010. Therefore, sediment in and below the root zone, or rhizosphere, was in place for at least 1 year, meaning it was deposited before dike removal. Below the rhizosphere (>6 centimeters [cm]), sediment texture varied between 10 to 16 percent fines at Luhr N and averaged 7 percent fines at Luhr S (fig. 2). In the rhizosphere (2–6 cm), sediment texture became finer toward the surface at Luhr S (fig. 2) and was variable at Luhr N. Prerestoration sediments in the rhizosphere and deeper at Luhr N and S had a coarser texture than that of the active surface layer (0 to 2 cm). The overall sediment texture was finer at Luhr N than at Luhr S (fig. 2).

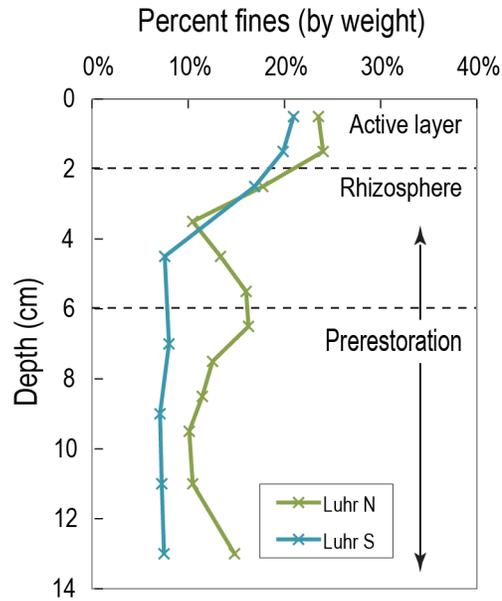


Figure 2. Graph showing variation with depth of the sediment fine fraction (percent fines) in sediment cores collected in May 2010 at Luhr N and Luhr S. Dashed lines show the approximate depths (in centimeters) of the active surface layer, rhizosphere, and prerestoration intervals.

Postrestoration Changes in the Surface Layer

Year-to-year changes of sediment properties of the active surface layer (0–2 cm) were compared to gain insight about temporal changes following dike removal. Surface sediment texture at both sites coarsened between 2010 and 2012, then became finer in 2013 (fig. 3, left column). From 2010 to 2013, year-to-year changes in surface sediment grain-size distributions varied in the same direction, either coarser or finer, at both sites. This pattern diverged in 2014 when surface sediment at Luhr N became considerably finer, while that at Luhr S changed little. Surface sediment at Luhr N had a higher proportion of fines than at Luhr S in all years except 2012, when the two were similar. Over the 5-year period, the mean percentage of fine sediment in the active surface layer was higher at Luhr N and lower at Luhr S compared to May 2010 (fig. 3, left column). In all years, surface sediment was well oxygenated (redox potential, also known as Eh, was 0 to 200 millivolts [mV], not shown), light brown in color, and had no detectable H₂S (not shown).

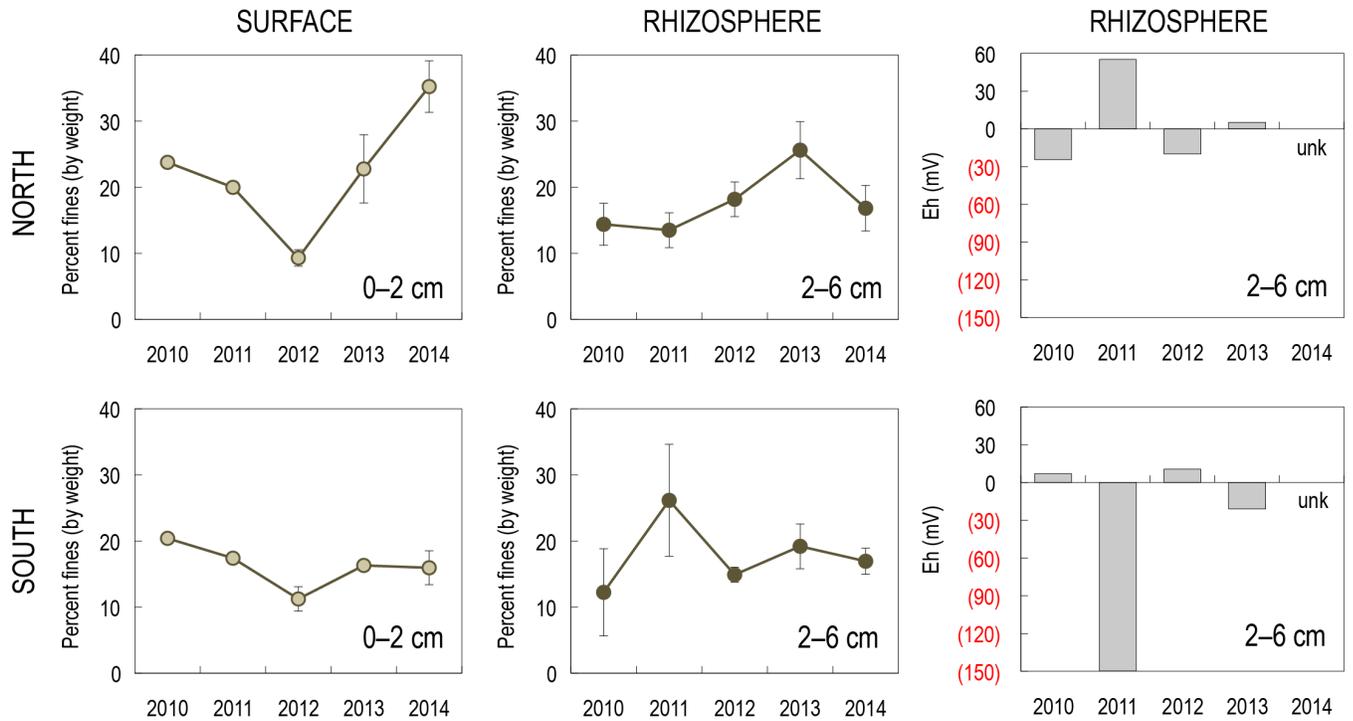


Figure 3. Graphs showing year-to-year changes in the sediment fine fraction (percent fines) in the active surface layer (left column) and rhizosphere (middle column) and sediment pore water redox values, also known as Eh, in the rhizosphere (right column). Top row, Luhr N; bottom row, Luhr S. Values are averages over the specified sediment intervals. Red numbers in parentheses indicate negative values. Error bars show $\pm 1 \sigma$. [cm, centimeters; unk, value unknown; mV, millivolts.]

Postrestoration Changes in the Rhizosphere

Year-to-year changes of sediment properties of the rhizosphere (2–6 cm) were compared to gain insight about temporal changes following dike removal. Prior to 2014, sediment pore water in the rhizosphere of the Luhr N eelgrass meadow was oxygenated to slightly reducing ($Eh > -30$ mV; fig. 3, right column) and had no measurable H_2S (not shown). The Luhr S rhizosphere was also oxygenated, or slightly reducing, except in 2011, when pore waters were moderately reducing ($Eh = -150$ mV; $H_2S = 2.2$ parts per million [ppm], or 63 micromolar [μM]), which was consistent with a large fraction of fine sediment in the substrate (26 percent fines). In 2014, a new Eh electrode was used, and it measured a five times larger range of Eh values in pore water (whose H_2S content was three times lower in 2014 than in 2010–13) compared to the previous electrode, suggesting it had a different sensitivity to Eh. Multipoint calibrations of the two electrodes, which would be needed to cross-calibrate the sensitivities of the electrodes, were not performed at the time of the study, therefore it is not known whether Eh values measured in 2014 were comparable to those from previous years. The 2014 Eh data will not be discussed further.

Eelgrass Shoots

Between May 2010 and 2014, mean eelgrass shoot densities at Luhr N increased from 110 to 146 shoots per m^2 , but this change was not statistically different at the 95 percent confidence level (fig. 4). The mean increase did not appear to be related to the lower tidal depth at which the shoots were

counted in 2010 because shoot densities were no different at this depth than at the depth of the 2011–14 shoot counts (appendix 3). Canopy heights of eelgrass measured in May 2010 were not directly comparable to those in subsequent years because there was a tidal depth dependent variation of leaf length (appendix 3). Measurements in the cross-shore direction showed that eelgrass canopy heights were up to 24 percent higher at the tidal depth of the 2010 measurements than at the tidal depth of the 2011–14 measurements. If the mean canopy height measured in 2010, 117 ± 10 cm (95 percent confidence interval [CI], $n=10$), were reduced by 24 percent to 89 cm to allow comparison with 2011–14 data, then there did not appear to be any change in mean canopy heights at the 95 percent confidence level between 2010 and 2014 at Luhr N (fig. 4). Mean leaf widths did not change from 2010 to 2014 (not shown), and as a result, there was a very small but not statistically significant increase in available eelgrass leaf area from 55 to 60 m^2 of leaf per m^2 of seabed at Luhr N (fig. 4).

At Luhr S, there was a 20 percent decrease in mean canopy height and a 35 percent decrease in mean shoot density between 2010 and 2014 (fig. 4). This resulted in a large decrease in eelgrass leaf area between 2010 and 2014. The large 95 percent CIs of mean shoot densities at Luhr S reflected the presence of bare or sparsely vegetated patches in the eelgrass bed. The narrowing of CIs over 5 years (fig. 4) reflects infilling of bare or sparsely vegetated patches, resulting in more uniform shoot densities across the bed.

Waypoints taken by hand-held GPS (Garmin 78sc, 3-m accuracy) showed that the north edge of the Luhr S eelgrass bed extended 10 m and 30 m further alongshore in 2013 and 2014, respectively, compared to 2010.

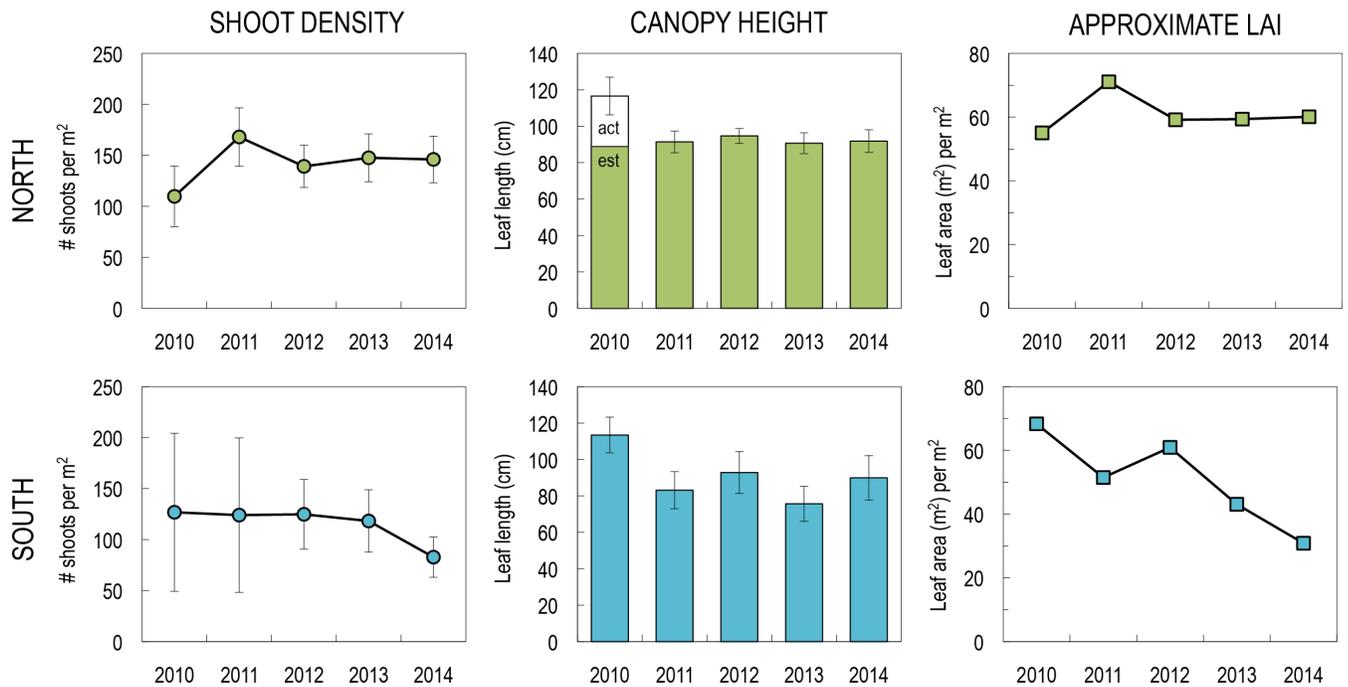


Figure 4. Graphs showing year-to-year changes in mean shoot density, canopy height (leaf length), and the approximate leaf area index (LAI) at Luhr N (top row) and Luhr S (bottom row). Error bars show the ± 95 percent confidence interval (CI); $n=10$ except for Luhr N in 2012 ($n=11$) and Luhr S in 2013 ($n=9$). [#, number; m^2 , square meter; cm, centimeter; act, actual value; est, estimated value.]

Eelgrass Rhizomes

Z. marina rhizomes are multisegmented and laterally branching (fig. 5A). The beginning and end of a rhizome segment is marked by a node that forms when a new leaf emerges (Phillips, 1984). The distance between two rhizome nodes is referred to as the internode length. Nodes and leaves of *Z. marina* form approximately every 14 days in temperate latitudes (Phillips, 1984; Lee and others, 2006), and the internode length can vary with the season (Phillips, 1972). In winter, when irradiance and the length of the photoperiod decreased, rhizome internode lengths of Nisqually eelgrass were short (December/January minima, fig. 5B, C). In spring, when light was more plentiful, internode lengths increased and peaked in May of each year (fig. 5B, C).

The longest rhizomes of plants collected in May 2010 had 31 (Luhr N) and 37 (Luhr S) internodes. By multiplying an average 14-day interval for internode formation by the numbers of internodes on Luhr N and Luhr S rhizomes, whole-rhizome ages of 14 to 17 months, respectively, were derived, indicating that eelgrass plants collected in May 2010 were growing in situ before and during dike removal. There was little difference in winter and spring internode lengths in the months following dike removal compared to subsequent years. The maximum elongation (longest internode length) of Luhr N rhizomes, which is one measure of eelgrass growth rate, varied slightly over 5 years but without a consistent trend (fig. 6). At Luhr S, maximum elongation was on average 14 percent lower in 2012–14 compared to 2010–11; however, this amount was not statistically different at the 95 percent confidence level. In summary, there were no significant trends in eelgrass rhizome growth patterns during the 5 years following tidal restoration in the Nisqually River Delta.

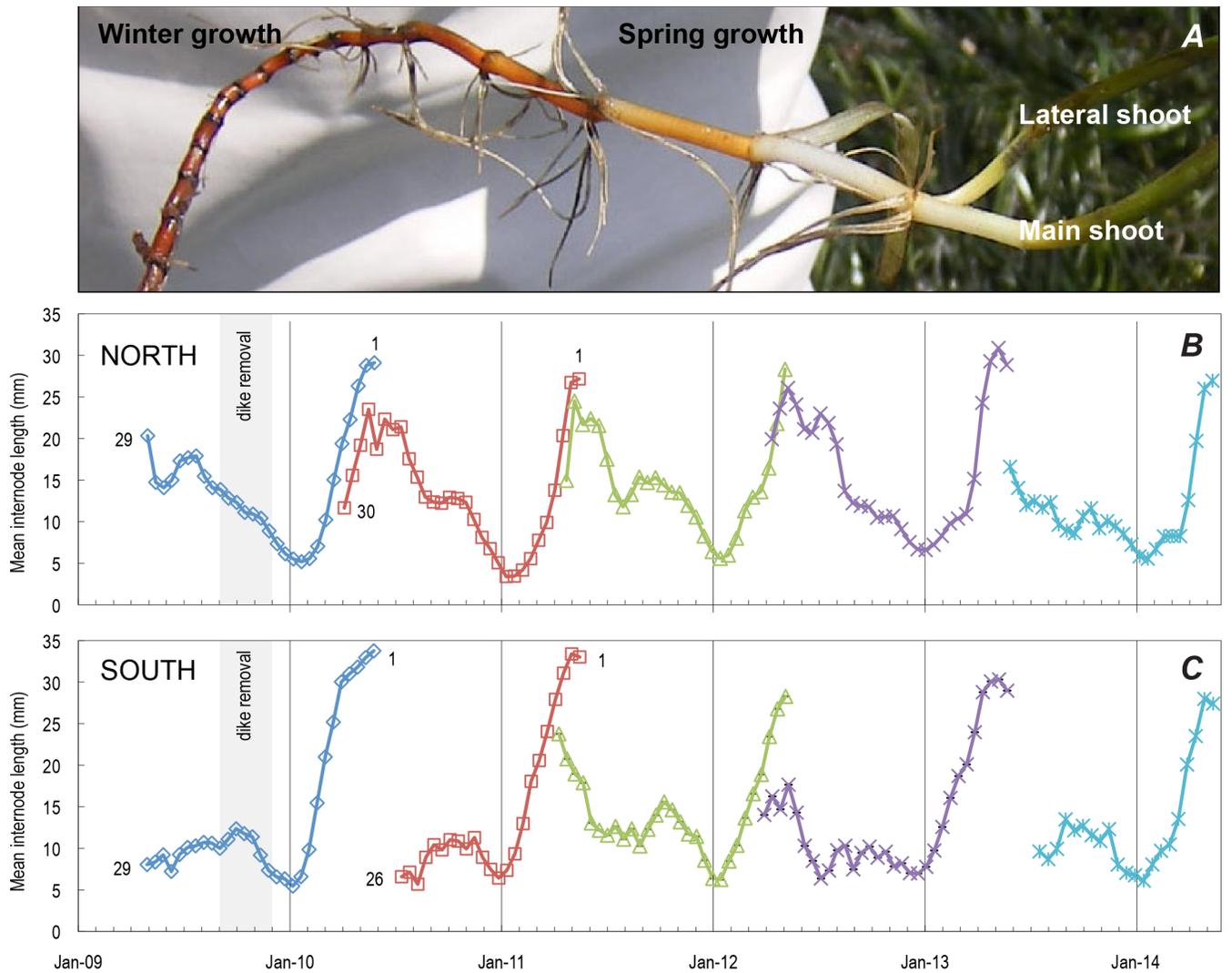


Figure 5. Eelgrass rhizomes from Luhr Beach. A, Photograph of eelgrass rhizome with segmented growth; B, mean rhizome internode lengths (in millimeters) of plants collected annually at Luhr N; and C, mean rhizome internode lengths (in millimeters) of plants collected annually at Luhr S. Colors vary with the year that rhizomes were collected. Numbers, shown for rhizomes collected in May 2010 (blue) and May 2011 (red), indicate the internode number starting with the most recently formed internode. For internodes 1–11, $n=10$ except for Luhr N in 2012 ($n=11$) and Luhr S in 2013 ($n=9$). For internodes 12 and higher, $2 \leq n \leq 10$. The shaded region shows the period when dike removal occurred.

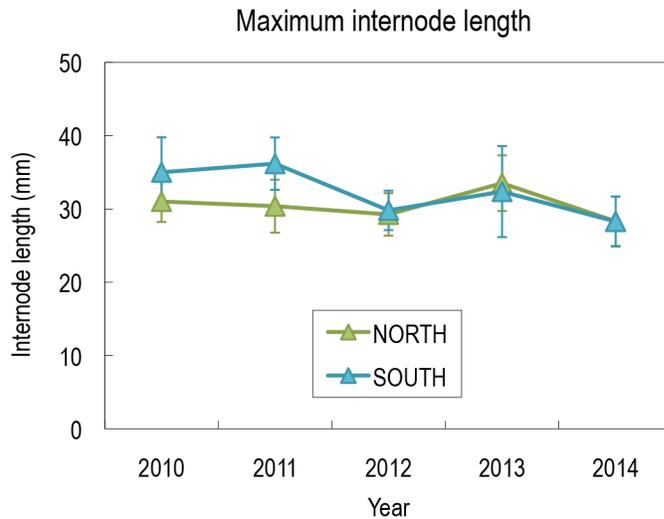


Figure 6. Graph showing year-to-year changes in the mean maximum rhizome internode lengths (in millimeters [mm]) at Luhr N and Luhr S. Error bars show ± 95 percent confidence interval (CI); $n=10$ except for Luhr N in 2012 ($n=11$), Luhr S in 2013 ($n=9$).

Eelgrass Biomass

Mean biomass of eelgrass shoots (AG) and roots plus five rhizome internodes (BG5) at Luhr N both initially decreased for 3 years following dike removal, and these decreases were proportionate, resulting in little change in the AG:BG5 ratio from 2010 to 2012 (fig. 7). Mean AG biomass at Luhr N did not change in 2013 and 2014, while BG5 biomass increased, resulting in lower mean AG:BG5 ratios in 2013 and 2014 (fig. 7). At Luhr S, mean AG biomass decreased for 4 years following dike removal, while overall mean BG5 biomass decreased over 5 years, with the exception of a one-time increase in 2013 (fig. 7). Compared to May 2010, the mean AG:BG5 ratio of Luhr S eelgrass was 21 to 44 percent lower in the subsequent 4 years, but this difference fell within the 95 percent CI of the 2010 mean because of the large variability that year. Mean AG:BG5 ratios were much greater than the critical value of 2:1 for *Z. marina* (Hemminga, 1998) in all years at both sites. When AG:BG ratios are less than 2:1, the respiratory carbon demand of the plant can exceed the photosynthetic carbon production, resulting in a carbon deficit that can negatively impact plant growth (Hemminga, 1998).

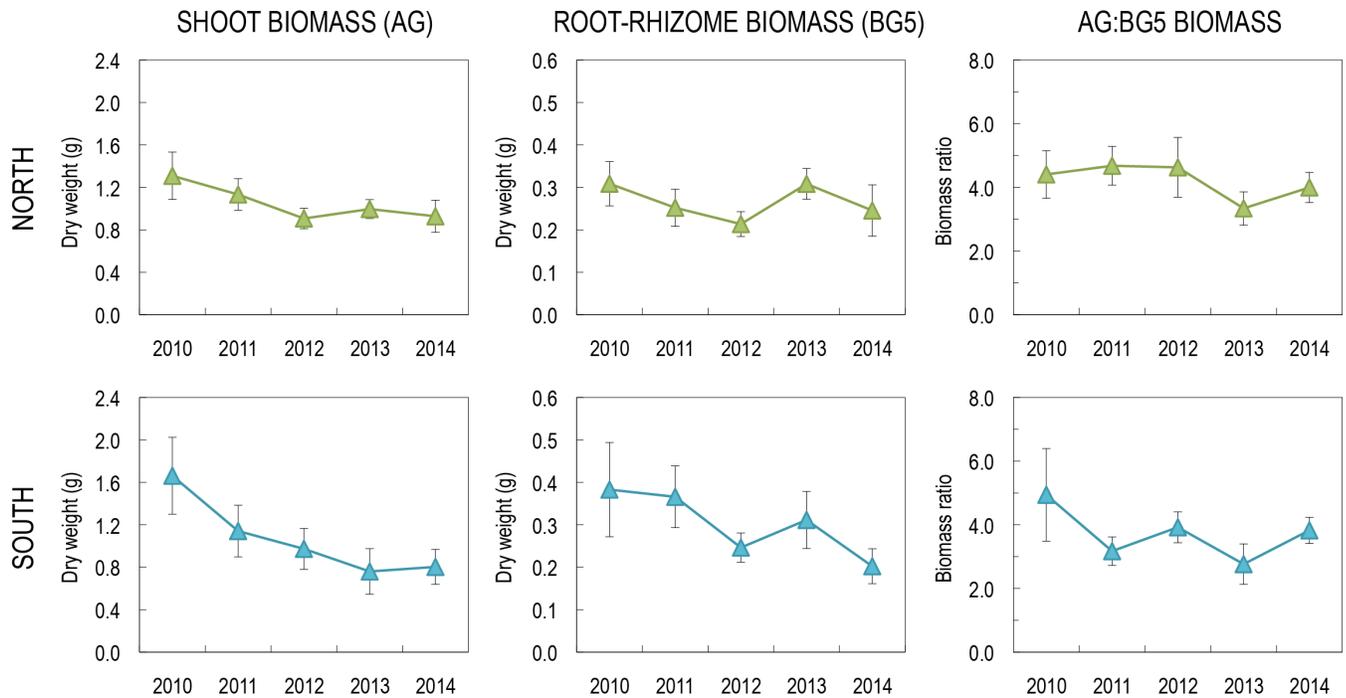


Figure 7. Graphs showing year-to-year changes in mean dry biomass (in grams [g]) of shoots (AG), roots plus five rhizomes (BG5), and the AG:BG5 ratio at Luhr N (top row) and Luhr S (bottom row). Error bars show the ± 95 percent confidence interval (CI); $n=10$ except for Luhr N in 2012 ($n=11$), Luhr S in 2013 ($n=9$).

Summary

The monitoring of environmental conditions and eelgrass growth and morphology has been conducted every May since dikes were removed in the Nisqually River Delta in late 2009 in order to quantify changes, identify temporal trends, and assess whether changes were associated with restoration activities. Eelgrass beds along McAllister Creek are in close proximity to two restored tidal creeks, whereas delta-front eelgrass beds are over 2 km away and more likely to be marine-influenced. Therefore, environmental and eelgrass changes at McAllister Creek are not necessarily representative of deltawide changes.

Hood (2004) found changes in postdike tidal channel morphology in the Skagit River Delta (140 km north of the NNWR) that were consistent with the theory that diking results in a tidal prism loss, reduced tidal flushing, and sedimentation in tidal channels seaward of the dike. If dike removal in the Nisqually River Delta resulted in a reversal of these processes, then the postrestoration system is hypothesized to have a larger tidal prism and increased tidal flushing than the prerestoration system. The coarser texture of prerestoration sediment in sedimentary records in McAllister Creek eelgrass beds compared to postrestoration sediment seems to suggest that tidal currents were stronger and more effective at winnowing away fine-grained sediment in the diked system, contrary to expectations. The age of prerestoration sediment intervals were not known, however, and could have been Holocene-age delta deposits (Barnhardt and Sherrod, 2006) rather than sediment deposited over historic time scales when the delta was diked. One explanation for the finer texture of postrestoration sediment accumulating in McAllister Creek eelgrass beds is a shift in source of sediment to one that contained a larger fine fraction. This is consistent with the hypothesis that fine-grained sediment from the restoration area would be mobilized and deposited in McAllister Creek eelgrass beds following dike

removal. Stable carbon isotope ratios of sedimentary organic matter are currently being analyzed to determine whether material accumulating in McAllister Creek eelgrass beds after restoration was more terrestrial in nature than before.

After the initial increase in 2010 in the amount of fine-grained sediment in McAllister Creek eelgrass beds, there was a subsequent decrease over the next 2 years that could have arisen from winnowing of the initial material or the accumulation of new material with a slightly coarser texture. It was not possible to distinguish between these mechanisms based on the parameters measured in this study. Despite a large increase in the fraction of fine sediment in the active surface layer at the north site in 2013 and 2014, eelgrass shoot densities and canopy heights varied little, suggesting that processes that contributed to the accumulation of fine sediment did not measurably impair shoot growth in the Luhr N meadow. At the south site, Luhr S, a general coarsening trend of the active surface layer over 5 years was accompanied by a general decrease in the size of plants and the amount of eelgrass leaf habitat per square meter. Stronger tidal currents in McAllister Creek following dike removal could have coarsened the bed sediment texture at Luhr S and induced a shift in plant morphology to a shorter-leaved form to reduce frictional drag, an adaptation that has been observed in energetic environments (Peralta and others, 2006). The smaller plant size and sparser eelgrass bed at Luhr S could also be an adaptive response to a suboptimal light environment (Ralph and others, 2007), which is consistent with the hypothesis that turbidity would increase in response to dike removal.

Over the range of values observed between May 2010 and 2014, the fraction of fine sediment in the rhizosphere of McAllister Creek eelgrass beds did not generally appear to be related to reducing conditions in sediment pore waters during midday low tides in May. One exception, at Luhr S in 2011, was characterized by a large fine fraction and moderately reducing pore waters that corresponded with measurable H_2S and lower canopy height and biomass of eelgrass compared to the previous year. However, a causative relationship between pore water redox/ H_2S and plant growth is uncertain because the mean H_2S concentration in the rhizosphere was below 150 micromolar (μM), the level found to impair *Z. marina* photosynthesis and respiration (Penhale and Wetzel, 1983; Goodman and others, 1995; Holmer and Bondgaard, 2001). Furthermore, the sediment redox state can vary widely and rapidly depending on the tidal cycle, season, and oxygen exudation by eelgrass roots during photosynthesis. The timing of sampling was at a time of day and season when rhizosphere oxygenation by eelgrass should have been high and able to mitigate the build-up of H_2S . The alteration of the pore water redox state by eelgrass could explain the lack of correlation between redox and the fine fraction of sediment.

The amount of eelgrass leaf area per square meter along McAllister Creek was relatively stable over 5 years in the Luhr N (north) eelgrass meadow but declined in the Luhr S eelgrass bed. At Luhr S, there were fewer and smaller plants compared to 2010, but they were more evenly distributed across the bed, an indication that lateral shoot growth became more profuse with time. The downward shift of mean AG:BG5 ratios after 2010 at the Luhr S eelgrass bed imposed a greater respiratory carbon burden on plants. Nevertheless, eelgrass plants in the Luhr S bed had AG:BG5 ratios well above the value at which a carbon deficit can occur (Hemminga, 1998). Other stressors, such as disease or shading by epiphytes, were not evaluated in this study. The alongshore expansion of the Luhr S eelgrass bed in 2013 and 2014 suggests that new substrate that could support eelgrass was made available after dike removal, likely owing to sediment deposition along the channel margin. Landscape-scale bathymetric maps could identify new habitat available to eelgrass arising from deltawide sedimentation patterns following restoration.

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Appendix 1. Field and Lab Methods

Water Column Turbidity

Water column turbidity was measured at the top of the eelgrass canopy using self-logging optical backscatter sensors (SLOBS) with added temperature and pressure sensors (Aquatech). The top of the eelgrass canopy was approximately 90 cm above the sediment surface. The sensors recorded in burst mode, taking readings once a second (1 hertz [Hz]) for 120 second-long bursts every 15 minutes. During the initial year of study, sensors were deployed for 12 days from May 17, 2010, to May 29, 2010, with automated wipers to prevent particles from settling on the sensor windows and interfering with backscatter readings. In subsequent years, SLOBS were deployed for 4–5 days without wipers because particle build-up was not significant over the shorter period. Surface sediment (0–2 cm) was collected in replicate below the SLOBS for lab calibrations to convert optical backscatter (volts) into sediment concentration (milligrams per liter [mg/L]). Data was processed using Matlab software.

Sediment Collection

Surface sediment (0–2 cm) was collected for sediment grain-size determinations at the beginning, midpoint, and end of each eelgrass transect. Data from the three samples were averaged to obtain a mean sediment grain-size distribution for each site. The subsurface sediment column of the eelgrass bed was sampled using 3.5-inch-diameter (9-cm) push-cores with end caps. Two replicate short sediment cores (~20 cm in length) with overlying water were collected within 1 m of each other at each monitoring site, transported on ice, and stored refrigerated until processing the same day to minimize sedimentary biogeochemical reactions. Sediment cores were intentionally collected in different parts of the eelgrass bed each year to avoid resampling disturbed sediments. Sediment grain-size distributions from the replicate cores were averaged over depth intervals of interest to obtain mean values.

Sediment Pore Water Analyses

Sediment cores were split longitudinally in an oxygen-free glove bag (GlasCol) filled with high-purity nitrogen (N_2) to prevent oxygen-sensitive reactions from occurring. Sediment pore water oxidation-reduction potential (ORP, commonly called redox) was measured approximately every 1 cm down the center of each core using a combination platinum microelectrode (Lazar Research Labs) calibrated to a quinhydrone redox solution (+206 mV, Hanna Instruments). In 2014, a new redox microelectrode was used, and its calibration was 34 percent below the reference value. One-half of each core was sliced into 10 intervals 1–2 cm in thickness and packed into air-tight, acid-cleaned polypropylene 50-cc (cubic centimeter) centrifuge tubes with friction-fit closures and centrifuged at 3,900 revolutions per minutes (rpm) for 15 minutes. The centrifuge was in ambient air and at room temperature. After centrifugation, the supernatant (pore water) was drawn off in the N_2 glove bag and filtered through acid-cleaned polyethersulfone 0.2- μ m pore-size syringe-tip filters (Whatman). Filtered pore waters were used for colorimetric determination of hydrogen sulfide (H_2S) concentration using a prepackaged reagent kit with a minimum detection limit of 0.05 ppm (CHEMetrics). The remaining half of each core was subsampled into intervals 1–2 cm in thickness for sediment grain-size determinations.

Sediment Grain-Size Determinations

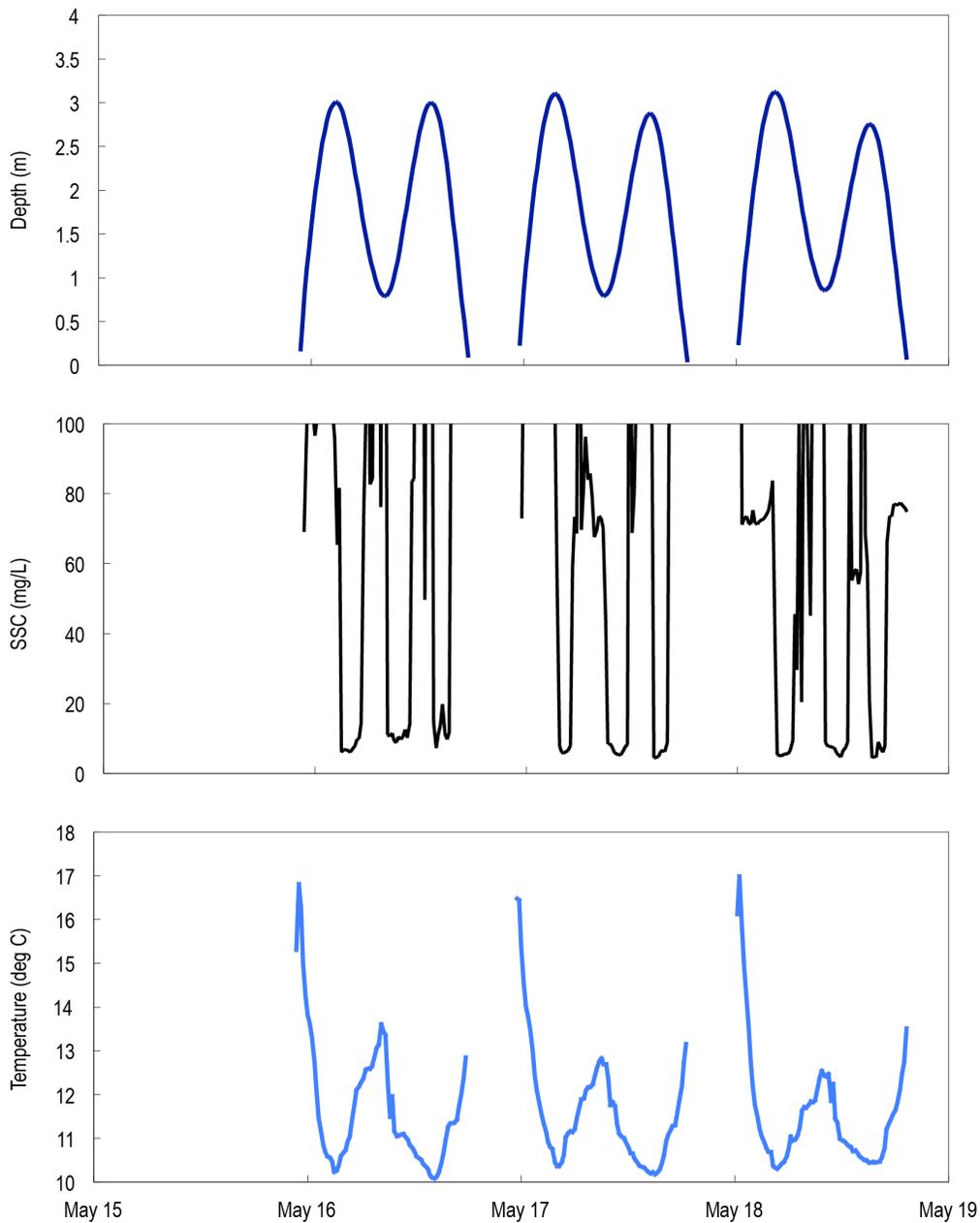
Sediment was dried at 60 °C, disaggregated in an agate mortar and pestle, and split into 1- to 2-g subsamples. The subsample was dry-sieved for 12 minutes in a dual action rotating-tapping shaker (Gilson) into five size fractions with particle diameters of >500 µm, 250–500 µm, 125–250 µm, 63–125 µm, and <63 µm. The material in each fraction was weighed using a precision balance accurate to 0.01 mg (Mettler Toledo). Fine sediment is defined as material with diameter <63 µm and includes silt and clay.

Eelgrass Properties

Eelgrass characteristics were measured at each site along fixed alongshore transects at a tidal height of –0.7 m (–2 ft) relative to mean lower low water (MLLW). The transect at Luhr N was 100 m in length, except in 2010 when only 50 m of the eelgrass meadow could be safely accessed. The transect at Luhr S was determined by the alongshore extent of the eelgrass bed and was 50 m in length in 2010–12, 60 m in 2013, and 80 m in 2014. For each transect, plant metrics were determined in 10 0.25-m² quadrats spaced evenly across the transect (that is, every 5 or 10 m at Luhr N and every 5 or 8 m at Luhr S). Shoot density (number per quadrat) was determined in each quadrat, and one plant was harvested from each quadrat and measured in the lab to determine leaf length (canopy height), leaf width, number of leaves, rhizome internode lengths, and above-ground (shoots) and below-ground (roots and rhizomes) biomass. Rhizome internode lengths were measured with a digital caliper with an accuracy of 0.1 mm. The age of the whole rhizome was calculated assuming a mean 14-day formation interval for each rhizome internode (Lee and others, 2006). Dry biomass was measured on individual plants after they were dried at 60 °C for 24 hours. Below-ground biomass was measured on the five most recently formed rhizome internodes (BG5). Five rhizome internodes were used because the formation of each rhizome node corresponds to the formation of each leaf, and there were generally five leaves on each shoot. An above-to-below-ground biomass ratio (AG:BG5) was calculated for each plant. Mean characteristics of eelgrass beds were calculated from individual measurements of 10 plants, except at Luhr N in 2012 (n=11) and Luhr S in 2013 (n=9). The mean leaf area (length × width), number of leaves, and shoot density were multiplied to give an estimate of eelgrass leaf area (m² leaf per m² seabed) at each site, here called an approximate leaf area index (a-LAI).

Appendix 2. Example of Sensor Data

Graphs show time series of water depth (top), 2-minute averages of suspended sediment concentration (SSC, middle), and 2-minute averages of water temperature (bottom) at Luhr N during May 2014. The high and variable SSC values likely reflect biofouling by macroalgae.



Appendix 3. Cross-Shore *Z. marina* Characteristics

Graphs show eelgrass characteristics along a cross-shore depth transect at Luhr N in May 2013 (fig. 1D). Data points represent single measurements (n=1). Vertical lines show where the 2010 alongshore transect intersected the cross-shore transect (fig. 1D). The cross-shore transect started (0 m mark) on the 2011–14 alongshore transect line and extended 80 m across-shore (fig. 1D).

