Condition of wetlands in the Arctic Coastal Plain of Alaska: water quality, physical habitat, and biological communities

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Introduction

The Arctic Coastal Plain of Alaska is a unique ecoregion with abundant freshwater resources bounded to the north by the Arctic Ocean and to the south by the foothills of the Brooks Range. Wetlands are ubiquitous on the Arctic Coastal Plain of Alaska because the permafrost layer inhibits drainage leading to saturated soils. Both migratory shorebirds and caribou utilize wetland habitats on the coastal plain. Wetlands and shallow ponds provide abundant insect resources for feeding shorebird adults and chicks (Brown et al. 2007). Nutrient rich wetland plants, such as sedges, emerge early and provide food during the critical post-calving period for the caribou herds on the North Slope of Alaska (Wilson et al. 2012).

In the past 30 years, annual temperatures have increased by 2.7°C and precipitation has increased by 50% in Utqiaġvik, Alaska with the most rapid temperature increases occurring in fall (Wendler et al. 2014). Observed changes to wetland habitats include increased shrub cover (Stow et al. 2004, Tape et al. 2006), increased plant biomass (both above and belowground, Hill and Henry 2011), decreases in pond area (Andresen and Lougheed 2015), decreases in total area due to deepening of the active layer and higher evapotranspiration during the growing season (Woo and Young 2006), and increases in salt-tolerant vegetation communities along the coast due to storm surges and land subsidence (Tape et al. 2013).

Human activities on the Arctic Coastal Plain, such as military installations and oil and gas exploration and development, can also alter wetland habitats by placement of fill, alterations to hydrology, and pollution from point sources. Military activities include the Distant Early Warning (DEW) radar stations along the Arctic Coast, constructed in the 1950s, which were converted to the Northern Warning System (NWS) sites of today. The Arctic Coastal Plain has some of the largest oil and gas reserves in the world. Production in Prudhoe Bay, the largest oil field in North America, began in 1969. Other major potential oil developments include the National Petroleum Reserve-Alaska (NPR-A) in the western coastal plain and the 1002 Area of the Arctic National Wildlife Refuge on the eastern coastal plain. Annual lease sales have been held for parts of NPR-A since 1999 and the 1002 Area has been recently opened by congress to oil and gas leasing.

The objective of this project was to assess the condition of freshwater resources in the Arctic Coastal Plain ecoregion of the National Petroleum Reserve of Alaska (NPR-A) (See Figure 1). Probabilistic sampling of freshwater resources was used to assess the status of and changes in quality to these valuable habitats. These habitats and resources are intrinsically dynamic and ~~are also~~ affected by direct and indirect anthropogenic activities.. Information garnered from these surveys will establish a clear benchmark of the reference condition for NPR-A habitats as there are currently minimal human disturbances (Stoddard et al. 2006).

The project was conducted as part of the National Aquatic Resource Surveys (NARS), which is a program designed to monitor the condition of fresh and coastal waters across the country. In Alaska, NARS is implemented through a collaboration between the U.S. Environmental Protection Agency, the Alaska Department of Environmental Conservation, and the University of Alaska Anchorage. This report summarizes physical habitat measurements, water chemistry samples, and plant and diatom communities collected from palustrine emergent wetlands sampled in 2011.

Methods

Study Area

The Arctic Coastal Plain ecoregion of NPR-A extends over 10.8 M acres from the Arctic Ocean on its western and northern boundaries to the foothills of the Brooks Range along its southern edge. The treeless coastal plain is underlain by continuous permafrost and has low topographic relief that inhibits drainage and results in a landscape dominated by thaw lakes and wetlands. Average monthly air temperatures on the coastal plain are below freezing for eight months of the year (October through May) with the coldest temperatures in January (-25.2˚C at Utqiaġvik and -29.6˚C at Umiat) and the warmest temperatures in July (4.9˚C at Utqiaġvik and 12.8˚C at Umiat, Western Regional Climate Center, https://wrcc.dri.edu/summary/Climsmak.html). Temperatures are moderated along the coast throughout the year. Annual precipitation is low, totaling 115 mm at Utqiaġvik and 122 mm at Umiat, with a little over half falling as rain during the summer months.

Graminoid and dwarf shrub communities dominate these regions with increases in shrub height, greater frequency of tussock tundra, and increased representation of boreal-associated taxa along the southern and inland portions. Continuous permafrost underlies the area and has substantial influence on the vegetation communities, in particular in determining the hydrological regime, substrate disturbance, and active layer depth (see Boucher et al. 2015, 2016). Shallow lakes, ponds, drained lake basins, sedge-wetlands, and freshwater marshes dominate this low-relieve landscape. A large quaternary-aged sand sheet underlies the tundra south of Teshekpuk from the Colville River to the Nigisaktuvik River in the west; the tundra in this region tends to be more well-drained, a deeper active layer; however localized redistribution of fine substrates facilitates ice aggradation and formation of polygonal tundra wetlands (Boucher et al. 2015).

Study Design

A generalized random tessellation survey design (GRTS, Stevens and Olsen 2004) was used to select sample locations. The target population identifies the habitats that are intended for sampling and the sample frame is the spatial dataset used to represent the target population in a geographic information system (GIS). Sample weights were used to estimate the sampled population extent and generate the statistical summaries for water quality parameters using the survey package in the R statistical computing software (Kincaid and Olsen 2016, R Core Team 2017). Weights were initially calculated by dividing the target population extent by the study design sample size. Where the target population was stratified, the extent and sample sizes were unique to each stratum. Weights were adjusted after implementation of the study design to account for sites not sampled due to weather, landowner denial, or not meeting the target population criteria. The study design results include the total number of sites sampled, information on sites that were not sampled, the ability of the sample frame to represent the target population, and the extent of the sampled population.

Palustrine emergent wetlands are the dominate wetland type in the survey area and was selected as the target population. The U.S. Fish and Wildlife Service's National Wetlands Inventory dataset (NWI) was used as the sample frame and palustrine emergent wetlands were selected from the NWI to represent the target population. Due to rapid changes in the coastal environment of Alaska, such as saltwater inundation and coastal erosion, the sample frame was divided into coastal and inland wetlands using the state coastal zone demarcation line as a boundary (Dasher and Lomax 2011).

Twenty base samples and 20 oversamples were selected using equal probability from within each region (coastal and inland). Fifty-four sites were evaluated. Fourteen were dropped prior to fieldwork due to landowner denial and five were dropped during fieldwork due to weather. Dropped sites were replaced by sites in numerical order within the same stratum to achieve spatial balance.

A total of 35 wetlands were sampled, 17 in the coastal region and 18 in the inland region (Figure 1). All sites visited were determined to be acceptable according to EPA protocols, indicating that the sample frame adequately represented the target population. The sampled population represents approximately 65% of all palustrine emergent wetlands in the sample frame, 95% CI [56, 73]. This proportion of the sample frame equates to 11,562 km^2 of palustrine emergent wetlands in NPR-A, 95% CI [10,067, 13,057].

Six additional sites were strategically selected and sampled based on input from locals in the surrounding communities. Many of these "targeted" sites had historical or active disturbances nearby (Table 1).

Table 1. Targeted wetlands sites.

Site number	Description
41	Formerly used defense site, very close to Arctic coast. Three ADEC contaminated sites within 500 meters of this wetland site. Cleanup complete at two sites. Third site is an old landfill that requires cleanup. Surface water samples collected in 2005 had elevated metals and hydrocarbons (ADEC Site Report: Kogru River / FUDS Western Landfill Cells 1, 2, and 3).
44	At Cape Simpson, very close to Arctic coast. Open ADEC contaminated site for legacy oil wells. Water samples high in chromium in 1990 (ADEC Site Report: BLM East Simpson # 2). Site currently managed as part of Legacy Well Program with BLM. Three other open contaminated sites from historic oil drilling approximately five km to the south.
45	At Point Lonely, very close to the Arctic coast. Part of the DEW line radar stations operated by the U.S. Air Force from 1953 to 1989. ADEC has 12 contaminated sites nearby, 11 of which are closed and one is active for PCB contaminated soil (ADEC Site Report: Lonely AFS Dewline – Module Train SS012).
47	Just outside of Utqiaġvik and close to a road. ADEC has several contaminated sites in Utqiaġvik, approximately five km away.
48	Adjacent to Inigok, no contaminated sites in this area.
50	At Wainwright radar site. Constructed as a DEW line station in 1953, converted into an unmanned short range radar station in 1994, closed by U.S. Air Force in 2008. Nine sites in ADEC contaminated sites database, all of which are closed. Air Force completed cleanup in 2013 (ADEC Site Report: Wainwright DEW Line/LIZ-3).

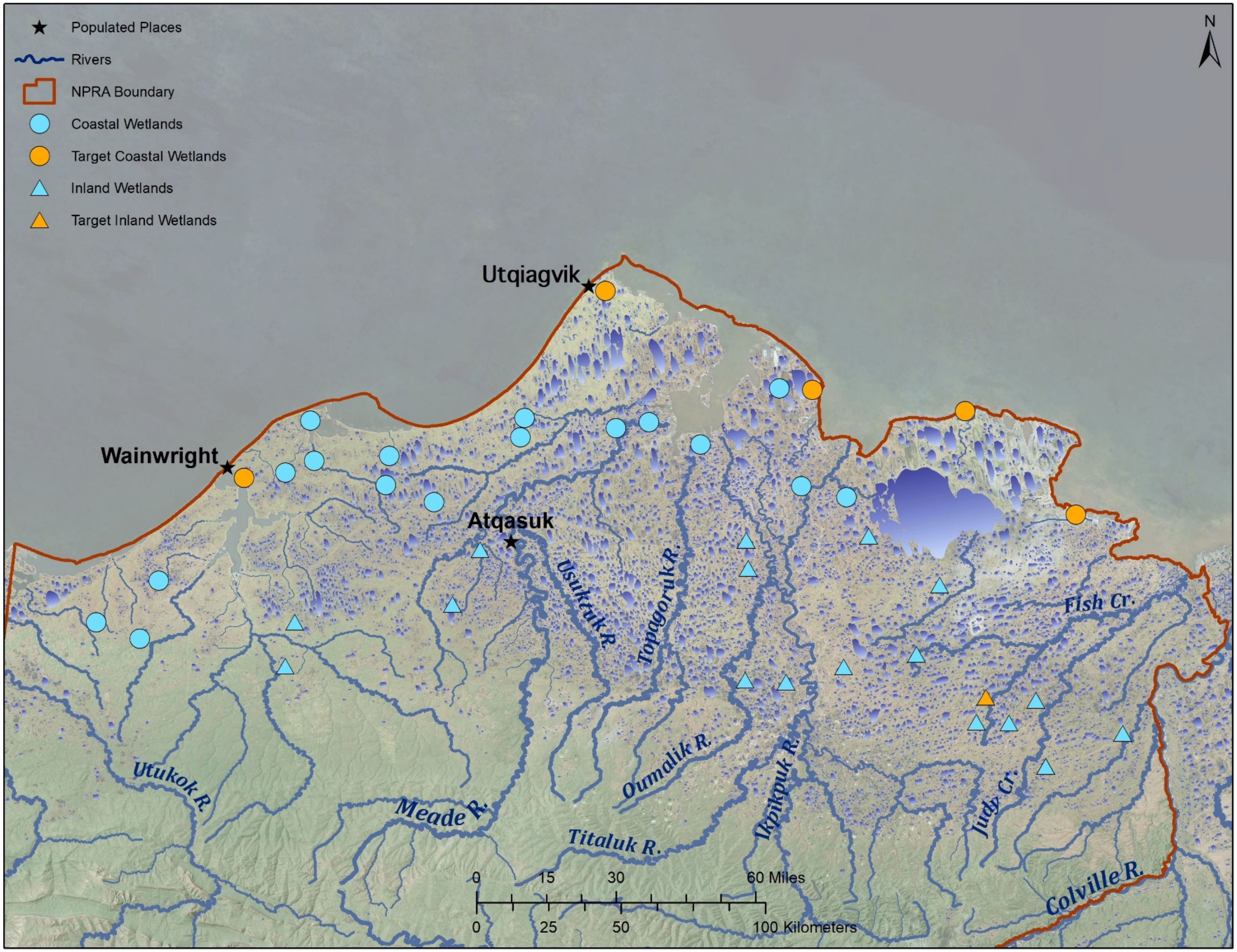

Figure 1. Map of wetland sites in the Arctic Coastal Plain of NPR-A.

Field Sampling

Field work was conducted from July 6th to August 1st 2011. The index period was selected to capture normal hydrologic conditions after the spring freshet and peak flowering of vascular plants. Water quality was characterized at sites with adequate standing water (~ 15 cm) using in-situ field measurements in addition to laboratory samples of major ions, nutrients, dissolved solids, algal toxins, and chlorophyll *a*. Habitat characteristics measured at each wetland site included maximum water depth, organic layer depth, and active layer depth. Wetland soils were sampled for metals, nutrients, stable isotopes, and particle sizes across three soil horizons at each site. Soil horizons are layers in the soil profile whose physical characteristics are different from the layers above and below them.

All field sampling was conducted within the assessment area (AA), a circular plot with a 40 meter radius (approximately 5,000 m^2). Within the AA, five 100 m^2 vegetation plots were laid out; one at the AA center and the others spaced 10 to 20 meters away from the AA center in each of the four cardinal directions. Two quadrats of 1 m^2 and 10 m^2 were nested inside each vegetation plot. Plant species cover was recorded along with the smallest quadrat in which it occurred. The cover of all mosses, peat mosses (*Sphagnum* spp.), and standing water was also estimated for each vegetation plot. All unknown plant taxa were collected and final identifications were made at the UAA Herbarium.

Diatoms were sampled by suctioning up the surface layer of submerged soils using a 50-mL syringe. Diatoms were processed and identified at UAA. Detailed field operations and lab methods manuals are provided on the U.S. EPA National Aquatic Resource Survey website (https://www.epa.gov/national-aquatic-resource-surveys/manuals-used-national-aquatic-resource-surveys).

Results and Discussion

Physical Habitat

Palustrine emergent wetlands sampled ranged from expansive low-relief polygonal tundra on the northern Arctic Coastal Plain to smaller and more isolated wetlands in the Brooks Range foothills on the southern margin of the ecoregion (Figure 2). Coastal and saline-influences were evident for five sites proximal to the Beaufort and Chukchi sea coasts.

Figure 2. Example of wetland habitats in low relief polygonal tundra on the Arctic Coastal Plain of NPR-A.

Maximum water depths at the 41 wetland sites ranged from 1 to 115 cm and total cover of surface water ranged from 0 to 100% (Figure 3). Water depth and cover were weakly correlated (*r* = 0.42 based on log-transformed depth). There were six sites without standing water and ten sites did not have adequate water to sample for the water quality characterization (see Water Quality section). Average active layer depth across all sites was 50 cm and the average organic horizon depth was 67 cm. Moss cover in the vegetation plots was over two times higher at the inland than the coastal plots (> 50% versus 25%), although the peat-forming S*paghnum* moss occurred more frequently in the coastal sites.

All soil variables are averages based on sampling from three horizons, typically the top horizons. We also inspected raw values by horizon and noted significant differences or patterns with depth, although these patterns may be confounded by cryoturbation, which results in mixing of soil horizons in frozen soils (Ping et al. 1998). Soil particle sizes were analyzed for percent clay, silt and sand from different horizons at 32 of the 41 sites. Sand percentages were higher at the inland wetlands (13 of the 18 inland sites were on the sand sheet) and silt and clay percentages were higher at the coastal wetlands (Figure 3). Sand was the dominant particle in all soils averaging greater than 75% across NPRA, while both clay and silt made up less than 20% across all wetlands. Cation exchange capacity (CEC) measures the ability of the soil to absorb positive particles and indicates soil water holding capacity, buffering potential, and fertility, since many soil nutrients are positively charged. Both clay particles and organic matter increase the cation exchange capacity (CEC) in the soil because they are negatively charged. CEC values averaged 32 mEq/100 g across all 38 sites, although there was a large range from 6 to 78 mEq/100 g. The targeted wetlands had much higher CEC values, possibly because five of the six were very coastal, and cold temperatures would likely slow decomposition and increase the organic content of these soils. The CEC values decreased dramatically with soil depth: mean values for horizons one through three across all sites were 49, 21, and 19 mEq/100 g. CEC values were positively correlated to clay content (r = 0.50). Carbon to nitrogen ratios (C:N) can be a useful indicator of nitrogen limitation in soils with higher ratios indicating slower decomposition rates. C:N for 40 wetland sites averaged 19 with a range from 13 to 53. These ratios are consistent with mineral and organic soils collected near Toolik Lake, Alaska (C:N from 15 to 45) that experienced higher decomposition rates during incubations with added nitrogen (Lavoie et al. 2011).

Stable isotopes of carbon and nitrogen were analyzed on one to three horizons at all sites but one. Soil organic matter δ^{13}C values are generally similar to or slightly enriched when compared to the dominant vegetation. Carbon fractionation for plants with the C_3 photosynthesis pathway, which encompasses nearly all plants in the region, results in δ^{13}C around -28‰ (Fry 2006). Average δ^{13}C in wetlands soils were -24‰. There were four sites (3, 7, 37, and 38) with much higher δ^{13}C values (~ -10‰) in one or more horizons, which may originate from glaciomarine deposits. Seagrasses and marine macroalgae δ^{13}C values range from -10 to -21 ‰(Khan et al. 2015) and glaciomarine deposits are extensive along the Beaufort Sea coast and extend inland towards the eolian sand deposit (pers. comm. Torre Jorgenson). δ^{15}N increases with depth in soils due to more rapid loss of ^{14}N during decomposition (Fry 2006). Most of the wetland soils were slightly enriched compared to atmospheric values, with δ^{15}N values ranging from -1.1 to 3.8‰ and an average of 1.0‰. There were no increases in average δ^{15}N with deeper soil horizons possibly reflecting the low decomposition rates in high arctic soils.

Metals were analyzed in samples from one to four soil horizons at 38 wetlands sites resulting in 93 metals samples. The percentage of samples below detection limits were very low, except for tungsten: antimony (1% ND), cadmium (5% ND), mercury (1% ND), selenium (1% ND), and tungsten (39% ND). All samples below detection limits were replaced with one half the detection limit for further analysis.

Results were averaged across all horizons for comparing differences between targeted, coastal and inland sites (Figure 4). For several of the metals, concentrations were higher in the targeted sites, possibly indicating relic contamination. These included antimony, copper, nickel, selenium, strontium, and zinc. Site 48, which was next to Inigok, had the highest concentrations across all sites for several metals: antimony, chromium, molybdenum, nickel, and zinc. These values were outliers (greater than 1.5 times the inter-quartile range) for both the targeted sites and for all wetland sites in NPR-A. Site 41 had the highest value for tin across the dataset, which was over three times higher than any other site sampled. Site 5, a random wetland, had the second highest values for nickel and zinc, both of which were outliers, in addition to elevated concentrations of several other metals. For the remaining metals, concentrations in the targeted sites were within the ranges found for the background population (randomly selected coastal and inland sites). These included arsenic, barium, beryllium, cadmium, cobalt, lead, manganese, mercury, selenium, silver, tungsten, and vanadium.

Concentrations of metals in each horizon were compared to 2016 human health cleanup standards for the Arctic Zone (18 AAC 75 Article 3) and also the NOAA Screening Quick Reference Tables for inorganics in soil (Table 2). There were five exceedances of the ADEC 2016 cleanup standard for arsenic at sites 5, 10, 20, 36, and 40; all of which were randomly selected sites (i.e., no known anthropogenic influence) distributed across the study area. Arsenic occurs naturally in soils throughout Alaska (Gough et al. 1988) and because the five sites weren't near to one another, natural weathering is the most probable source.

All but four metals had exceedances of the NOAA screening levels (silver, strontium, tin, and tungsten had no exceedances). Metals with concentrations above the NOAA screening levels in more than 10% of the samples included antimony (40% of samples), arsenic (41%), barium (100%), cadmium (95%), chromium (100%), cobalt (100%), copper (83%), lead (100%), manganese (27%), mercury (14%), nickel (75%), selenium (43%), vanadium (100%), and zinc (98%). As many of these sites were part of the random draw and had no known or observed local anthropogenic influences, potential sources for the metals include natural weathering of parent materials or atmospheric deposition from local or distant sources. Metals that are known to accumulate in soils due to long-range atmospheric transport include lead, zinc, cadmium, mercury, arsenic, antimony, and selenium (Steinnes and Friedland 2006). Local sources include drilling and incinerator operations at the Prudhoe Bay oil field (Snyder-Conn et al. 1997) or other satellite fields. Distinguishing natural sources from long-range transport can be difficult and an examination of metals in mosses across Arctic Alaska indicated that atmospheric deposition of metals appears to be low (Ford et al. 1995). One of the random wetlands with elevated metals was located on the eastern boundary of NPR-A, approximately 55 km downwind from the Alpine oil field. More detailed investigations would be required to determine contaminant sources for this site.

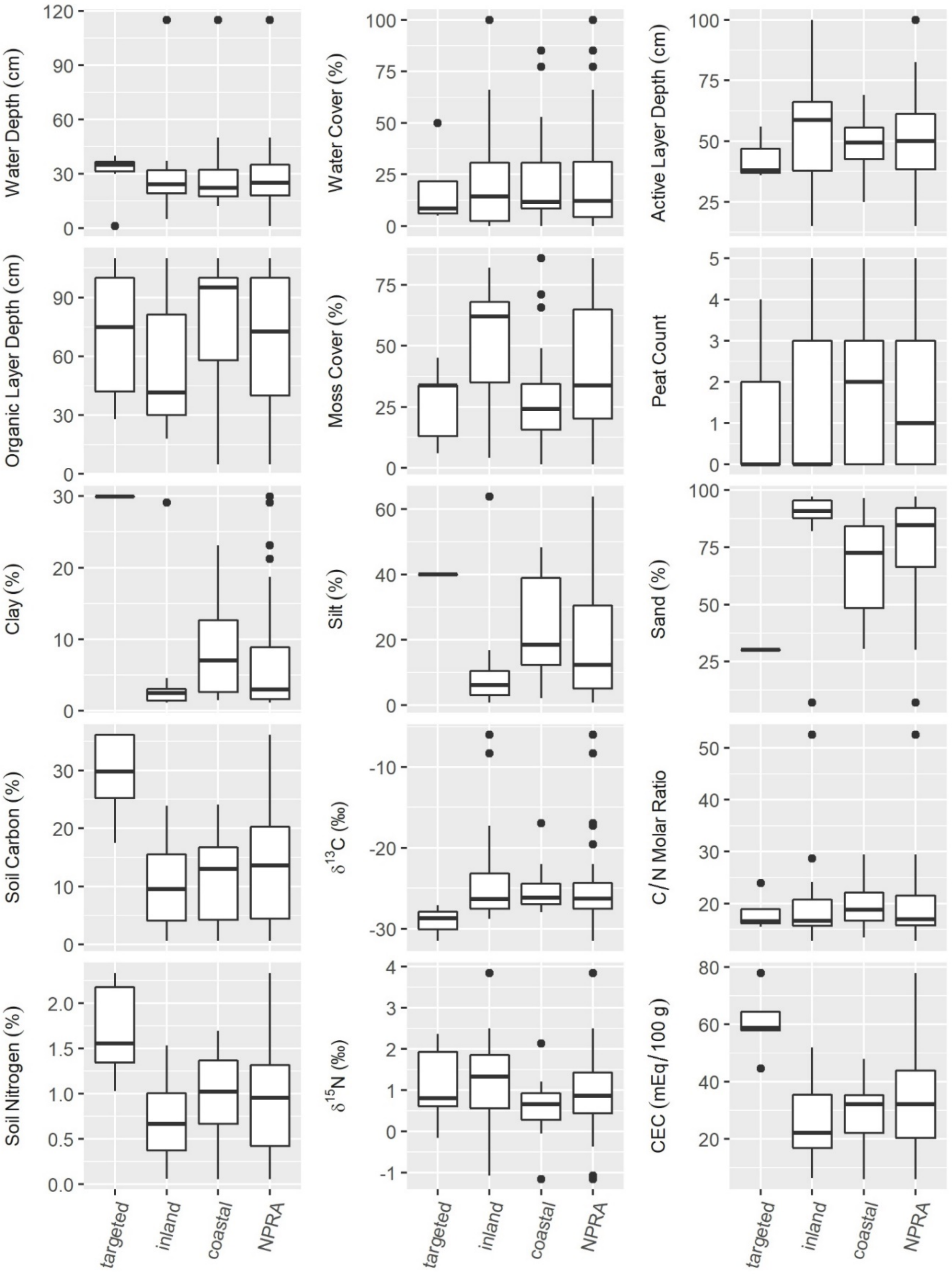

Figure 3. Box and whisker plots for wetland habitat variables for targeted, inland, coastal, and all sites combined (NPR-A). Boxes include the 25th – 75th percentiles of the data, whiskers extend to 1.5 times the interquartile range, and individual points are outliers.

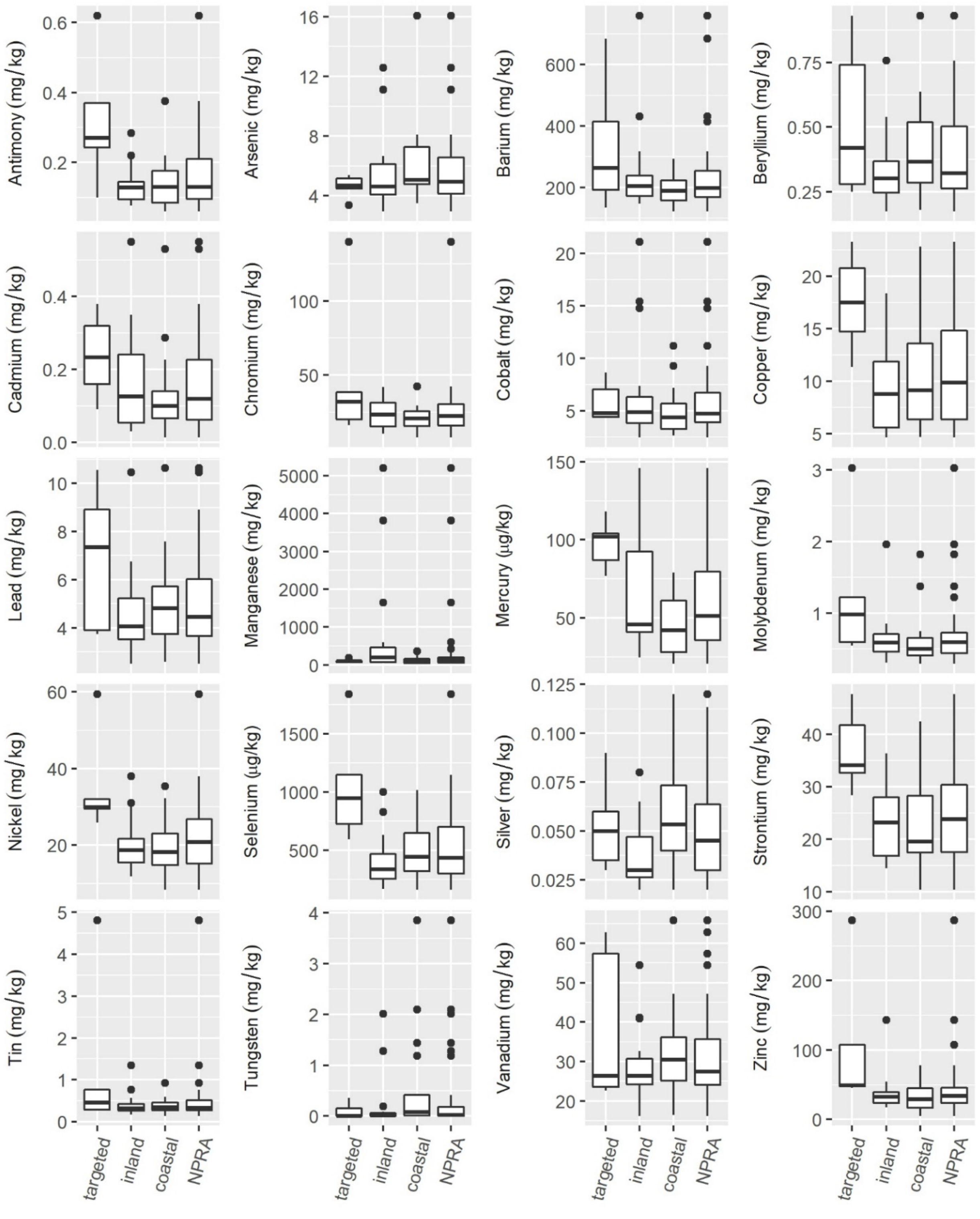

Figure 4. Box and whisker plots for soil metals for targeted, inland, coastal, and all sites combined (NPR-A). Boxes include the 25th – 75th percentiles of the data, whiskers extend to 1.5 times the interquartile range, and individual points are outliers.

Table 2. ADEC cleanup levels and NOAA screening levels for metals in soils.

Metal	ADEC 2016 Human Health Cleanup Level (mg/kg)[1]	NOAA Screening Quick Reference Table for Inorganics in Soil (mg/kg)[2]
Antimony	55	0.142
Arsenic	12	5.7
Barium	25,000	1.040
Beryllium	270	1.060
Cadmium	120	0.002
Chromium	100,000	0.4
Cobalt	NA	0.14
Copper	5500	5.4
Lead	400	0.053
Manganese	NA	220
Mercury	14	0.1
Molybdenum	NA	2
Nickel	2600	13.6
Selenium	680	0.52
Silver	680	2
Strontium	NA	NA
Tin	NA	7.62
Tungsten	NA	NA
Vanadium	680	1.59
Zinc	41,000	6.62

[1] from 18 AAC 75 Article 3. NA = not listed.

[2] Used most restrictive value from Eco-SSL, converted from parts per billion dry weight. NA = no Eco-SSL value or Dutch Standard provided in table.

Water Quality

Water quality samples were collected at all wetlands with adequate standing water for sampling (Table 3). Adjusted weights were used to plot continuous distribution functions for all water chemistry parameters, except those parameters with high percentages of non-detect samples (Appendix A). Total nitrogen was not analyzed, but Kjeldahl nitrogen, which includes organic nitrogen and ammonia, can be added to nitrate + nitrite to obtain total nitrogen. Nitrate + nitrite results were below detection limits at the majority of sites so Kjeldahl nitrogen results were used as an estimate of total nitrogen for comparisons with other studies.

Table 3. Number of sites and water quality samples.

Study	Sub-population	Total Sites	Water Quality Samples
Wetlands	Targeted	6	5
	Coastal	17	13
	Inland	18	13
	Total	41	31

Water quality parameters sampled at 31 wetland sites included ammonia, nitrate + nitrite, Kjeldahl nitrogen (organic nitrogen + ammonia), phosphorus, dissolved oxygen, pH, specific conductivity, temperature, algal toxins and chlorophyll *a*. Ten wetlands did not have sufficient standing water to collect water quality samples, although in-situ parameters were measured using the water quality probe at two of these sites. The majority of results were below method detection limits for algal toxins (100% non-detect, ND), nitrate-nitrite (96% ND), and ammonia (96% ND). Kjeldahl nitrogen and total phosphorus had six and five sites, respectively, with results below detection limits. Non-detects were replaced with one half the detection limit for these parameters in order to estimate population statistics. Raw results were used to estimate medians and ranges for four populations: all wetlands in NPR-A, coastal wetlands, inland wetlands, and targeted wetlands (Figure 5).

Wetlands had very low concentrations of inorganic nitrogen, as almost all samples were below detection limits. Kjeldahl nitrogen that is almost entirely organic nitrogen (and not readily available for plants), was mostly below 3 mg/L and the median across NPR-A was 1.6 mg/L. Total phosphorus concentrations were below 0.1 mg/L, except for one outlier, and the median value across NPR-A was 0.05 mg/L. N:P ratios ranged from less than 1 to 120 indicating potential for both N and P limitation. Chlorophyll *a* concentrations (an indicator of phytoplankton abundance) were mostly less than 5 µg/L and the median across NPR-A was 1.7 µg/L.

In-situ water quality measurements indicate that dissolved oxygen concentrations are generally quite low in wetlands, pH values were slightly acidic (< 6.6), and temperatures spanned a normal range for Alaskan freshwaters. DO, pH, and temperature are all highly variable through the day; temperatures increase during the day due to solar radiation while pH and dissolved oxygen increase throughout the day due to photosynthesis (Nimick et al. 2011). Field crews typically sampled two wetland sites a day so these values represent the range of daily conditions and should not be used to compare individual sites (e.g. measurements from a site sampled in the morning may be biased low and measurements from a site sampled in the afternoon may be biased high). Specific conductance values were mostly below 300 µS/cm in the undisturbed sites and below 500 µS/cm in the targeted sites. Across NPR-A, the median value was 96 µS/cm. Coastal wetlands tended to be colder and have lower dissolved oxygen and higher specific conductance. Although oxygen solubility increases at colder temperatures, it decreases with salinity, which may have limited the amount of dissolved oxygen in the coastal wetlands. Specific conductance was negatively correlated with the distance to the coast (*r* = -0.63) indicating that a major driver of conductivity at the wetland sites was saltwater from coastal storms, either as sea spray or inundation (Kling et al. 1992, Lim et al. 2001). Five of the six targeted wetlands were located on the coast, which likely influenced their higher specific conductance concentrations.

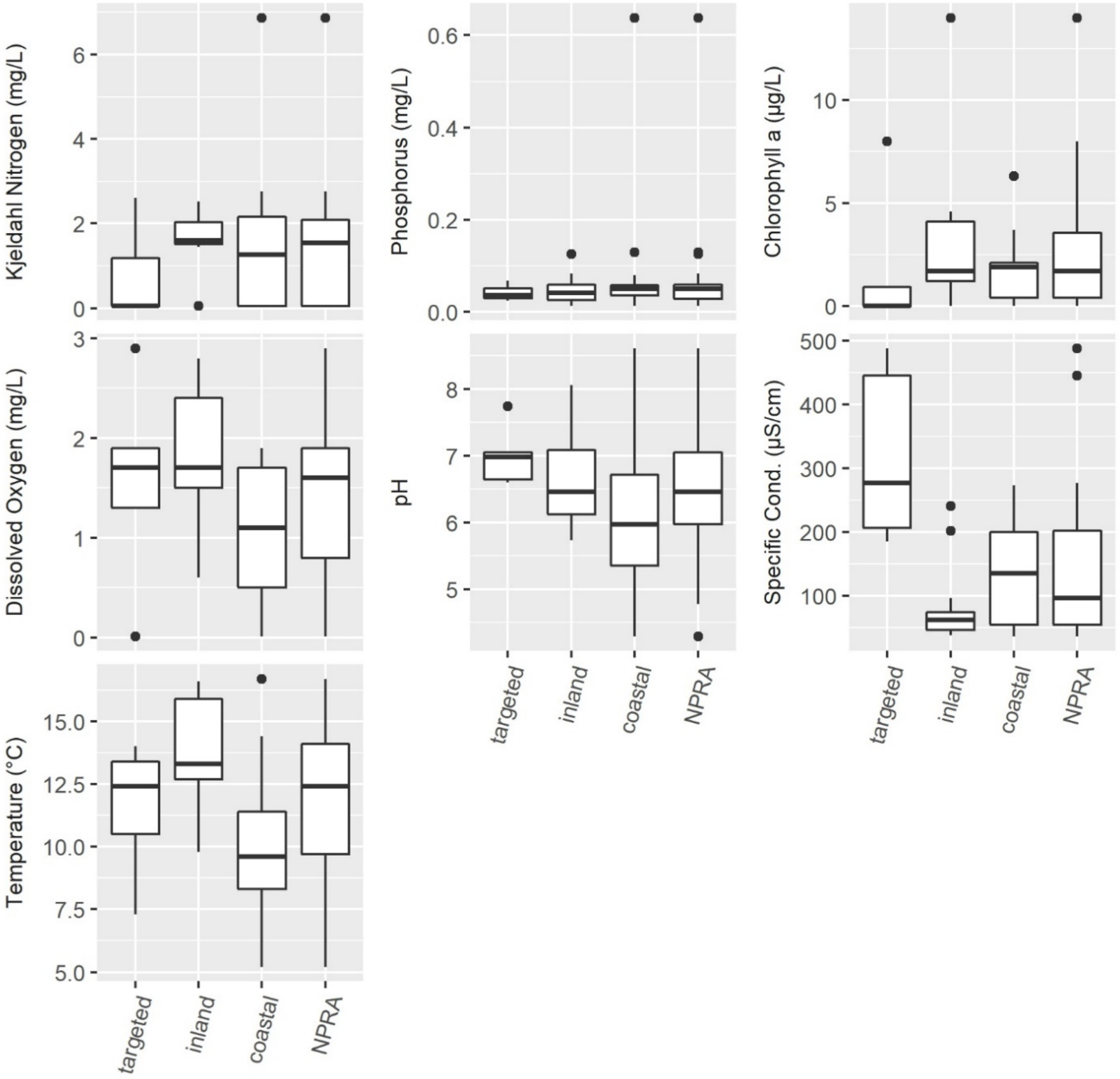

Figure 5. Box and whisker plots for wetland water quality parameters for targeted, inland, coastal, and all sites combined (NPR-A). Boxes include the 25th – 75th percentiles of the data, whiskers extend to 1.5 times the interquartile range, and individual points are outliers.

Biological Communities

For each of the biological community datasets, we used several measures to investigate patterns in diversity. We calculated gamma, alpha, and beta diversity to investigate differences across communities and studies at different scales. Gamma diversity is the total number of species identified. Alpha diversity is the mean number of species for all sites. Beta diversity was calculated as the gamma diversity divided by the alpha diversity and reflects the number of distinct communities in a dataset; a beta diversity of one indicates that every site shares the same species. Shannon and Simpson diversity indices include information on species abundances and were calculated for each site and averaged for each study. Shannon's index was calculated as

$$H' = \sum_{i=1}^{S} p_i * \ln(p_i),$$

where p_i is the proportion of species i and S is the total number of species. Shannon's index is the log of the number of species of equal abundance. Simpson's index was calculated as

$$Diversity = 1 - \sum_{i=1}^{S} p_i^2,$$

where p_i is the proportion of species i and S is the total number of species. Simpson's index represents the likelihood that two randomly chosen individuals will be different species. For both indices, higher values indicate higher diversity. We also explored common and rare taxa for each community as taxa that occurred at 50% or more of the sites and taxa that occurred at less than 5% of the sites, respectively. Frequencies and abundances for all taxa are provided in Appendix B.

Differences in community composition were analyzed across targeted versus random sites and coastal versus inland sites. In addition, we compared sites on versus off the sand sheet for the wetland plants because the sand sheet is a factor known to influence plant communities in NPR-A. For each comparison, we used permutational multivariate analysis of variance to assess differences in composition across the groups (Anderson 2001). We investigated significant indicator species for each group, based on frequency and abundance, using indicator species analysis (ISA, Dufrêne and Legendre 1997). The unbalanced sample sizes for the targeted (n = 6) and random groups (n = 35) biased the ISA results by increasing the number of indicator taxa for the group with a smaller sample size. For example, taxa that occurred in three sites in both the targeted and random groups had much higher relative frequencies (and relative abundances) in the targeted group (50% versus 9%). This results in higher indicator values for the targeted group and more significant indicator species.

Non-metric multidimensional scaling (NMS) ordinations for each community were used to visualize differences in community composition by site and group (Minchin 1987). Rare species were removed (frequency < 5%) and abundances were log-transformed to remove the influence of small abundant taxa prior to ordination. Sites are shown as points in the ordination; points closer together are more similar in community composition while points further away are more different. Site numbers and group membership were overlaid on each ordination.

We used vector fitting to examine relationships between environmental gradients and community composition. Vector fitting uses ordination axis scores to predict the environmental variable in a multiple regression. Vectors added to the ordination point in the direction of maximum correlation to the ordination and are scaled by their correlation coefficient. Significant relationships between environmental variables and ordinations were assessed by randomly permuting the environmental variable 1000 times and calculating the proportion of times the squared correlation coefficient was higher than the observed value. Prior to vector fitting, physical habitat and water quality variables were examined for outliers, normality, and collinearity using pairwise plots. Several variables were log-transformed to improve normality and facilitate the detection of relationships to the ordination.

We investigated concordance between plant and diatom community composition by comparing their NMS ordinations using Procrustes analysis (Peres-Neto and Jackson 2001). Procrustes analysis compares two ordinations by scaling and rotating them to minimize the sum of squared residuals (m^2) between ordination scores. A correlation statistic is calculated as $R = \sqrt{(1 - m^2)}$. Significance of the m^2 statistic is calculated by comparing the number of times the observed statistic is less than the statistic calculated from 999 random permutations of the data.

All statistical analyses were run in the R statistical computing software using the tidyverse, vegan, labdsv, e1071, ggrepel, and gridExtra packages (Roberts 2016, Auguie 2017, Meyer et al. 2017, Oksanen et al. 2017, R Core Team 2017, Slowikowski 2017, Wickham 2017).

Plants

Percent cover for all vascular plants was recorded in five 100 m^2 plots in each wetland. Cover values were averaged across the plots to obtain one measurement for each wetland site. A total of 154 native plant species were identified across all wetlands, no non-native or invasive species were observed, average site richness was 24 species, and species turnover among sites was 6.4 (Table 4). The Shannon and Simpson diversity indices were slightly lower for plants than diatoms at the same wetlands sites, likely due to the dominance of sedges (*Carex* spp. and *Eriophorum* spp.) in many of the wetlands (e.g. percent cover was greater than 40% for one of these species at 27 wetland sites). There were 10 common wetland plants that occurred in half or more of the sites and 60 rare wetland plants that occurred at only one site. Two sedges (*Carex aquatilis* and *Eriophorum vaginatum*) had the highest mean cover across all sites (37% and 15%, respectively). Several low shrubs were the next most important plant species with average cover values that ranged from 5% to 7% (*Salix pulchra*, *Betula nana*, *Vaccinium vitis-idaea*, and *Ledum palustre* ssp. *decumbens*).'

Table 4. Biodiversity indices for wetland biological communities.

Community	Study (sample size)	Gamma	Alpha	Beta	Shannon	Simpson
Diatoms	All Wetlands (37)	334	33	10.1	2.6	0.85
	Random Wetlands (31)	285	31	9.2	2.5	0.84
Plants	All Wetlands (41)	154	24	6.4	1.6	0.66
	Random Wetlands (35)	131	23	5.7	1.6	0.66

Community composition was significantly different between the coastal and inland sites ($R^2 = 0.18$, $p = 0.001$) and also the sites on versus off the sand sheet ($R^2 = 0.19$, $p = 0.001$), but we did not detect a significant difference between the random and targeted sites ($p = 0.06$). There was a single significant indicator species for the random sites, *Cassiope tetragona*, and 12 indicator species for the targeted sites (Table 5). The 35 random sites span the entire study area and encompass the range of habitats found in NPR-A, whereas five of the six targeted sites were very proximal to the coast, which likely explains the disparity in indicator species between the two groups. Three of the indicator species for the targeted sites were also indicator species for the larger group of coastal sites (*Poa arctica*, *Petasites frigidus*, and *Dupontia fisheri*). *Cassiope tetragona* was an indicator species for the inland sites and this species is a ubiquitous plant of mesic tundra, occurring on drier microsites within these arctic wetlands, such as polygonal ridges and raised high-center polygons. *Cassiope tetragona* declines in abundances with low-relief and saturated habitats in the northern portion of NPR-A.

The indicator species off and on the sand sheet closely matched the indicator species for the coastal and inland sites, respectively, making it difficult to deduce which mechanism (or both) were driving differences in composition. There were six indicator species for the coastal sites, four of which were also indicator species for sites off the sand sheet. The most important coastal species were *Carex aquatilis, Poa arctica*, *Saxifraga foliolosa*, and *Petasites frigidus*. There were 24 inland indicator species, 22 of which were also indicator species for the sand sheet. The most important inland species were *Carex lugens, Betula nana*, *Cassipe tetragona*, and *Vaccinium vitis-idaea*.

Table 5. Wetland plant indicator species for coastal versus inland sites and random versus target sites. Significant indicator species (p-values < 0.05) with indicator values ≥ 0.5 are shown.

Species	Indicator Value	p-Value	Group
Carex aquatilis	0.66	0.003	coastal
Poa arctica	0.64	0.006	coastal
Saxifraga foliolosa	0.52	0.009	coastal
Petasites frigidus	0.49	0.007	coastal
Luzula arctica	0.40	0.017	coastal
Dupontia fisheri	0.33	0.039	coastal
Carex lugens	0.79	0.001	inland
Betula nana	0.74	0.001	inland
Cassiope tetragona	0.71	0.015	inland
Vaccinium vitis-idaea	0.70	0.005	inland
Salix pulchra	0.68	0.022	inland
Ledum palustre ssp. *decumbens*	0.67	0.002	inland
Eriophorum vaginatum	0.60	0.004	inland
Pyrola minor	0.58	0.001	inland
Polygonum bistorta	0.58	0.001	inland
Andromeda polifolia	0.57	0.001	inland
Rubus chamaemorus	0.53	0.03	inland
Carex chordorrhiza	0.53	0.001	inland
Cassiope tetragona	0.77	0.036	random (inland)
Poa arctica	0.94	0.001	target (coastal)
Saxifraga cernua	0.82	0.001	target
Salix rotundifolia	0.66	0.001	target
Petasites frigidus	0.66	0.003	target (coastal)
Dupontia fisheri	0.64	0.003	target (coastal)

A total of 67 plant species that occurred at four or more sites (10% of total) were log-transformed and used for the ordination. The final wetland plant ordination had a stress of 0.10 using three axes to explain variation in community composition (Figure 6).

We inspected 12 variables as potential drivers of plant species composition: specific conductance, pH, Kjeldahl nitrogen, and total phosphorus in water samples; percent cover of moss, number of plots with peat-forming mosses, percent cover of standing water, organic layer depth, percent silt substrate, soil cation exchange capacity, soil phosphorus concentration, and soil carbon:nitrogen. Left-skewed variables were log-transformed to improve normality. There were eight significant variables ($p < 0.05$) that explained variation in plant species composition (Table 6). The ordination was rotated for interpretation so that the correlation of pH was maximized on the first axis.

Table 6. Variables significantly ($p < 0.05$) correlated to wetland plant ordination. Abbreviations in parentheses are used for the ordination.

Variable (abb.)	R^2	*p*-value
Water pH (pH)	0.57	0.001
Water specific conductance (SC)	0.56	0.001
Water Kjeldahl nitrogen (N)	0.37	0.008
Water total phosphorus (TP)	0.30	0.02
Percent cover of all moss (moss)	0.27	0.007
Presence of peat-forming mosses (peat)	0.38	0.001
Cation exchange capacity (CEC)	0.38	0.001
Soil phosphorus (soil P)	0.27	0.01

Axis 1 represents an acidity gradient with more acidic sites on the left side of the ordination and more circumneutral sites on the right side. pH was sampled from standing water in each wetland but we expect that it also characterizes the pH in the soil rooting zone of plants. The presence of *Sphagnum* moss in the vegetation plots increased as pH decreased (low axis 1 scores). Nutrient concentrations in the standing water also increased at the more acidic sites. Moss cover also loaded on axis 1 and increased at sites with higher pH. Axis 2 represents a salinity gradient from the coast inland. Inland sites would also be characterized by warmer temperatures, higher moss cover, and shallower organic layers. Axis 3 was most strongly correlated to soil cation exchange capacity and soil phosphorus, both of which increased as axis 3 scores decreased. These sites may have higher clay contents.

Substrate pH may be driven by underlying parent material, deposition of mineral inputs (windblown loess, flooding), and organic acid inputs from plants (notably *Sphagnum*, Clymo and Hayward 1982, Gough et al. 2000). Inland acidic peatland communities occur had low axis 1 scores and are found in the left portion of the ordination. These sites tend to have high representation of species such as *Eriophorum vaginatum*, *Betula nana*, *Salix fuscescens*, and *Rubus chamaemorus* and occupy foothill positions on the landscape. The less acidic foothill wetland sites had low axis 2 scores and have greater representation of species such as *Carex lugens* and *Carex saxatilis* and circumneutral sites have more *Salix reticulata*, *S. arctica*, *Dryas integrifolia*, and *Equisetum arvense*, which are species that often occupy more mesic microsites (e.g., tops of high-center polygons or ridges of low-center polygons) or that are associated with more nutrient-rich floodplain wetlands. The coastal lowland sites had high axis 2 scores and were loosely grouped. The more circumneutral coastal sites with high axis 1 and axis 2 scores have greater representation of species such as *Hierochloe pauciflora* and *Saxifraga cernua*. The arctic wetland grass, *Dupontia fisheri* is particularly representative of the most northerly coastal sites. The sites with low axis 1 and high axis 2 scores represent low diversity, primarily low-center polygon, wetland communities with high contributions of the sedges *Carex rotundata* and *Eriophorum russeolum* var. *albidum* in the ponded shallow water portions of the polygons and *Huperzia selago* and *Luzula rufescens* on the more mesic polygon ridges. Vegetation composition of sand sheet wetlands is similar to coastal plain wetlands (Boucher et al. 2015), but often has contributions of more boreal associates (such as *Saussurea angustifolia* and *Vaccinium uliginosum*), as well as taller herbaceous and shrub vegetation.

Several species were ubiquitous across the wetlands on the sand sheet: *Carex aquatilis*, *Eriophorum angustifolium*, and *Salix pulchra*. *Carex aquatilis* typically occurred at relatively high percent cover from ponded to wet-mesic habitats. *Eriophorum angustifolium* was dominant at a few sites, but was typically present at low cover. *Salix pulchra* was abundant at a number of sites, particularly on wetland sites on the sand sheet.

The anthropogenically disturbed (target) sites had higher scores on axis 2 and axis 3, adjacent to a number of non-target sites, except for sites 48 and 41. The target sites are not readily floristically distinguishable with these data. However, all of these sites have rather substantial representation by *Saxifraga cernua, Poa arctica, Salix pulchra,* and *Salix rotundifolia,* and four of the five site have high cover of *Petasites frigida* (Table 5). These species often establish in disturbed habitats, including those derived from erosion and cryoturbation, and on mineral substrates. In some cases the target sites had a layer of peat and organics, but were underlain with a coarse mineral substrate (e.g., site 50). Overall the target sites had similar species richness to the random sites (27 mean number species at target site vs. 24 number of species on non-target sites). Three target sites (44, 45, and 47) cluster together and are also tightly associated in space – these sites extend from Point Barrow to Cape Halkett. Additionally, target site 50 is another impacted coastal site (Wainwright) that is floristically similar to 44, 45, and 47. Site 48 is an anthropogenically impacted site from further south (Inigok) on the sand sheet that has a variable species composition, but with greater composition of tussock and peatland-associated taxa.

One of the more iconic arctic freshwater marsh species, *Arctophila fulva*, was not recorded from these NPR-A wetland sites. This species is quite common on the Coastal Plain but is often associated with deep water emergent communities that were excluded from the survey. This grass can also form dense low-stature lawns in non-tidal, but coastal, wet to moist meadows.

Carex holostoma is an uncommon arctic wetland sedge that was encountered at five sites, including two sites where it occurred at rather high percent cover. This species was tracked as a rare plant by the Alaska Natural Heritage Program until 2012, when enough records had accumulated to suggest that it was more widespread than previously understood. This sedge has a spotty circumarctic distribution from northern Scandinavia, Greenland, northern Canada and Alaska and a few stations in northern Russia.

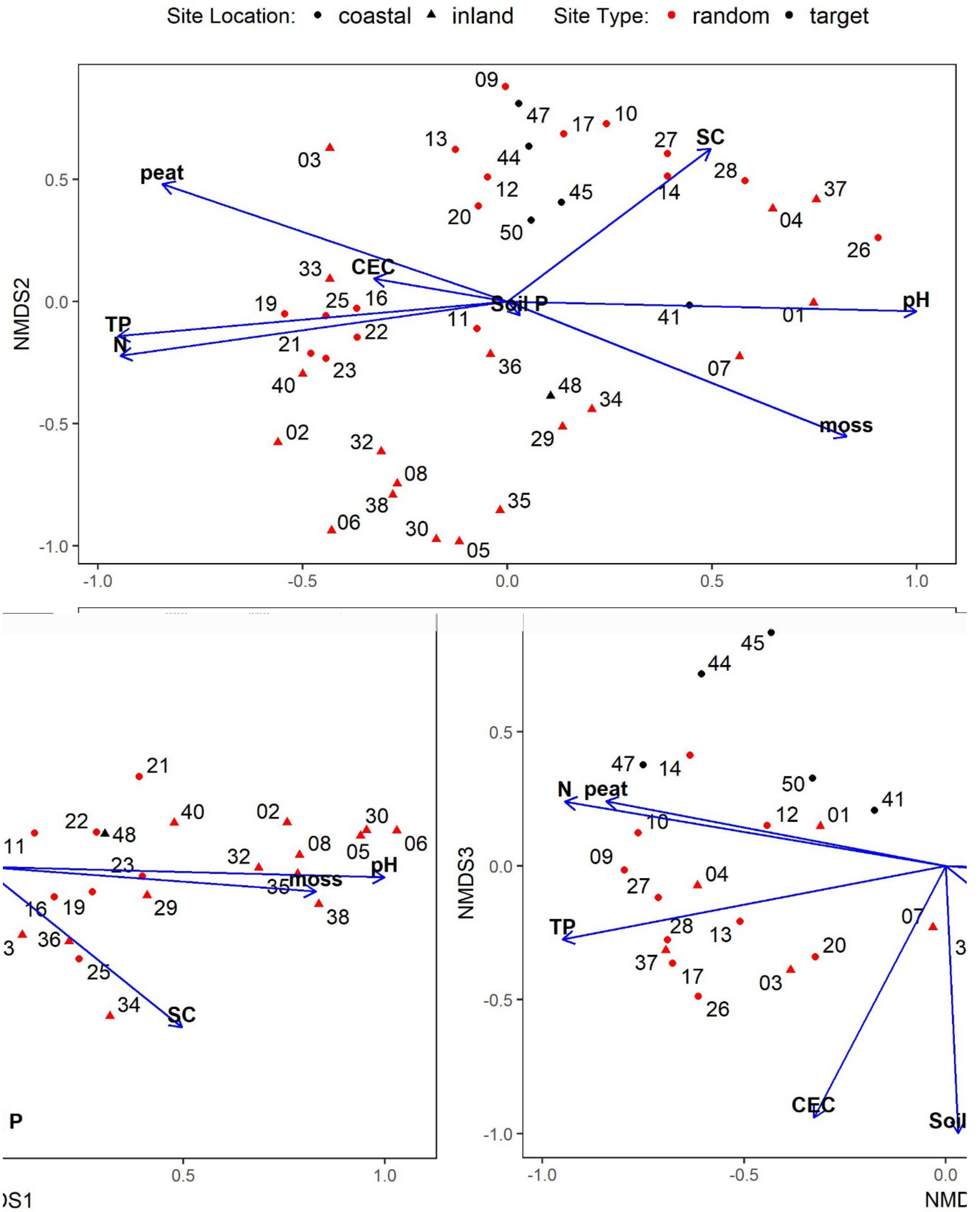

Figure 6. Wetland plant NMDS ordination. The top figure shows floristic similarity between sites (numbers) relative to Axis 1 and Axis 2 and the bottom figure shows sites relative to Axis 1 and Axis 3. N = Kjeldahl nitrogen, TP = total phosphorus, peat = count of plots with peat moss, moss = total moss cover, CEC = cation exchange capacity, and soil P = soil phosphorus.

Diatoms

Diatoms were not sampled at four wetlands because there wasn't adequate standing water (6, 30, 32, and 37). Across all 37 wetland sites, 334 diatom species were identified, average site richness was 33 species, and species turnover was 10.1 (Table 4). Diatoms had higher diversity than plant species at both the site and regional levels. Ten common diatom species occurred in half or more of the sampled sites and 156 rare species occurred at only one site sampled. The maximum relative abundance for the 10 most common diatom taxa ranged from 12% to 62%.

There were significant differences in diatom community composition between the targeted and random sites and also the inland and coastal sites, but the variance explained was low for both groupings ($R^2 = 0.05$, $p = 0.03$; and $R^2 = 0.06$, $p = 0.007$; respectively). There were three coastal indicator species and five inland indicator species (Table 7). There were no indicator species for the random sites and there were 20 indicator species for the targeted sites, only one of which was also a coastal indicator species.

Table 7. Diatom indicator species for coastal versus inland sites and random versus target sites. Significant indicator species (p-values < 0.05) with indicator values ≥ 0.5 are shown.

Species	Indicator Value	*p*-Value	Group
Eunotia mucophila (Lange-Bertalot, Nörpel & Alles) Lange-Bertalot	0.56	0.019	coastal
Tabellaria flocculosa (strain III) sensu Koppen	0.66	0.003	inland
Gomphonema lagerheimii A.Cleve	0.63	0.001	inland
Rossithidium petersennii (Hustedt) Round & Bukhtiyarova	0.57	0.002	inland
Gomphonema parvulum (Kützing) Kützing	0.79	0.001	target
Cymbopleura stauroneiformis (Lagerstedt) Krammer	0.78	0.002	target
Nupela sp. 1 NWCA AK2011	0.73	0.001	target (coastal)
Achnanthidium minutissimum (Kützing) Czarnecki	0.67	0.037	target
Stauroneis gracilis Ehrenberg	0.64	0.004	target
Gomphonema brebissonii Kützing	0.64	0.004	target
Sellaphora laevissima (Kützing) Mann	0.59	0.009	target
Caloneis silicula (Ehrenberg) Cleve	0.56	0.001	target
Nitzschia sublinearis Hustedt	0.50	0.005	target

A total of 89 diatom species that occurred at four or more wetland sites (10% of total) were log-transformed and used for the ordination. The final ordination included 37 sites (diatoms were not collected at four sites) and had three axes and a stress of 0.12 (Figure 7). We inspected specific conductance, pH, Kjeldahl nitrogen, and total phosphorus from the water samples as potential drivers of diatom species composition. Left-skewed variables were log-transformed to improve normality. All four water quality parameters were significantly ($p < 0.05$) correlated to the ordination: pH ($R^2 = 0.65$), specific conductance ($R^2 = 0.54$), Kjeldahl nitrogen ($R^2 = 0.30$), and total phosphorus ($R^2 = 0.28$). The ordination was rotated for interpretation so that the correlation of pH was maximized on the first axis.

Wetland pH explained variation in diatom community composition along the first axis of the ordination, but not for the second or third axes. Sites along the first axis of the ordination ranged from acidic (pH ~ 5, low axis 1 scores) to slightly alkaline (pH ~ 7.5, high axis 1 scores). Nutrient concentrations increased at the more acidic wetland sites; nitrogen was highest at wetland sites with low axis 1 scores and phosphorus was highest in the wetland sites with low axis 1, but high axis 2 scores. Sites with high specific conductance (> 200 µS/cm) were mostly coastal sites and had high axis 1 and axis 2 scores. This part of the ordination included several coastal wetland sites in addition to the targeted wetland at Inigok, which had a relatively high specific conductance (206 µS/cm).

Diatoms have established autoecological preferences and both pH and conductivity are important factors controlling their distributions (Birks et al. 1990, Potapova and Charles 2003). Acidophilous diatoms of the genus *Eunotia* were dominant in the acidic wetlands (pH < 5.5, n = 5), comprising an average of over 85% of the diatoms in those wetlands.

The ordinations for the two wetland communities were significantly correlated ($m^2 = 0.71$, $r = 0.54$, $p = 0.001$), indicating that similar environmental gradients were structuring plant and diatom community composition. The strong salinity and temperature gradients from the coastal to the inland wetlands are important drivers structuring both communities. For both plants and diatoms, taxa from the coastal wetland sites tolerate high levels of salinity.

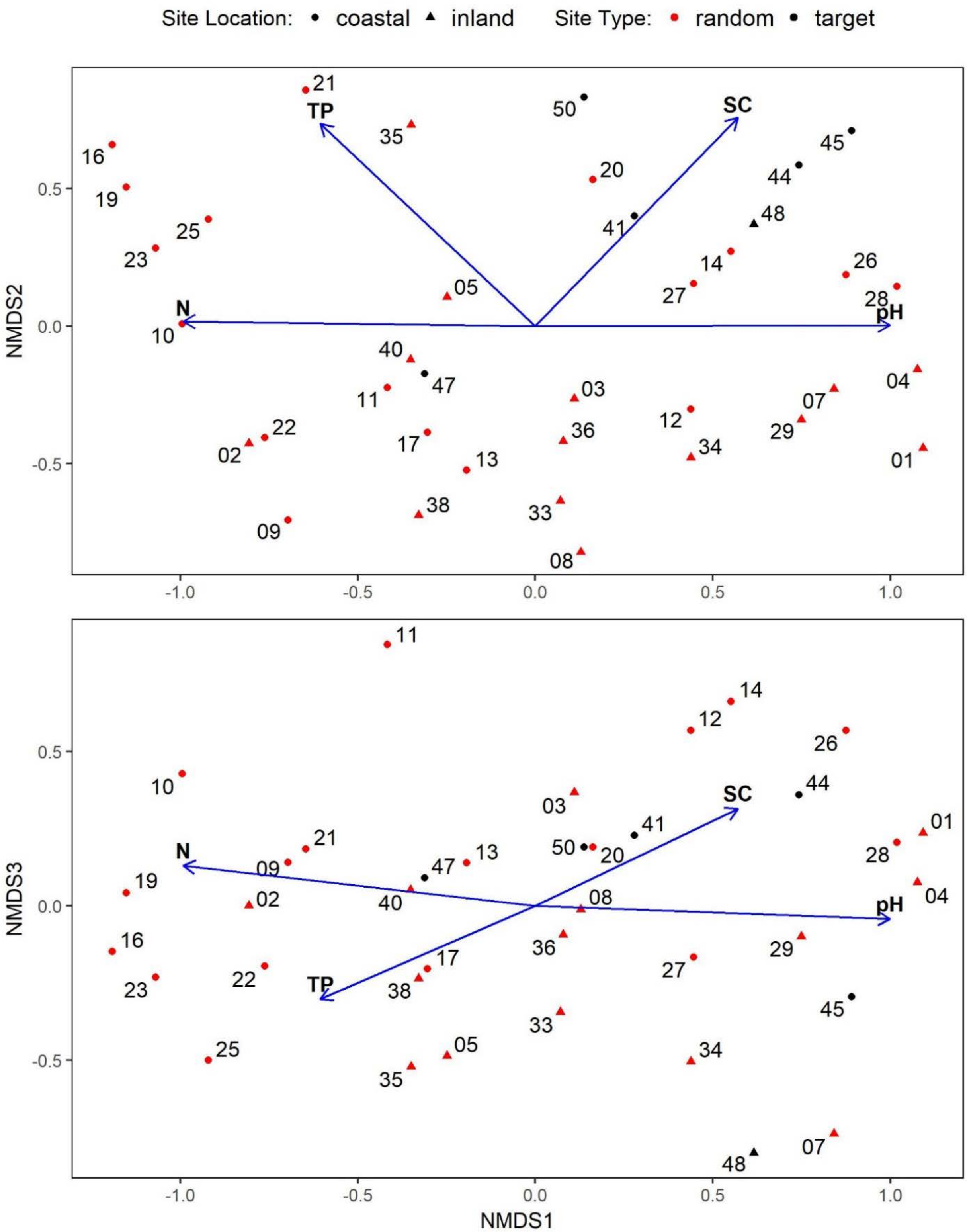

Figure 7. Wetland diatom ordination. The top figure shows diatom compositional similarity between sites (numbers) relative to Axis 1 and Axis 2 and the bottom figure shows sites relative to Axis 1 and Axis 3. N = Kjeldahl nitrogen, TP = total phosphorus, and SC = specific conductance.

Summary

This study captured the range of environmental conditions for emergent wetlands in NPR-A Alaska. The limited human disturbances in NPR-A are mostly located in coastal areas and none of the randomly selected wetlands had significant human disturbances. As such, the data summarized in this report from the random wetlands document the reference condition for these habitats in the current time period.

Emergent wetland habitats are a mixture of standing water and vegetation with deep organic layers and frozen soils within a meter of the surface. Standing water typically covers one quarter of their area and maximum depths average 30 cm. Sand is the dominant mineral substrate, although clay and silt contents are higher in the coastal wetlands. Moss cover is highly variable in these wetlands, but was higher in inland wetlands. Peat forming mosses (*Sphagnum* spp.) were more commonly observed in coastal wetlands.

Standing water in these wetlands tended to be acidic and had low dissolved oxygen. Coastal effects on water chemistry included colder temperatures and higher specific conductance. Across all wetlands, there was a large range in pH values (4.3 to 8.6) and conductivities (36 to 488 μS/cm). Nutrient concentrations in wetland habitats were generally higher than nutrients in surrounding ponds and lakes (Koch et al. 2014, Shaftel et al. 2018). Nitrogen to phosphorus ratios indicated both elements could be limiting, depending upon the site. Additionally, there were two different wetlands with very high N and P concentrations indicating spatial variability in nutrient concentrations.

Plant and diatom biological diversity was high across the randomly selected wetland sites. On average, 31 diatom and 23 plant species were observed at each wetland site. The regional species pool included 285 diatom and 131 plant species. For both communities, major drivers of community composition included pH and specific conductance. Water conductivities were highest in coastal wetlands indicating the strong influence of the Arctic coast on wetland community composition.

A secondary objective of this study was to compare reference condition wetlands with wetlands adjacent to human activities. The targeted wetland sites were located near to historic military and drilling sites, in addition to two sites by Barrow and Inigok. Because four of the five targeted sites were coastal, the physical habitat and water quality variables reflected coastal conditions. The most valuable indicators for measuring human influence were the soil metal concentrations. Two of the targeted sites had elevated concentrations of one or more metals and the site at Inigok had the highest concentrations of several metals. Five random sites had arsenic soil concentrations above ADEC cleanup values, which most likely originated from natural sources.

Overall, this study provides a critical baseline of habitat, water chemistry, and biological communities from randomly selected wetlands and five strategically selected wetlands across NPR-A. The statistically-valid reference conditions captured in this study have increased our ability to detect future changes from climate and human development that are expected to occur in this region.

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