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Key Points:

- Sea-level rise, sea-ice loss, and permafrost thaw interact to increase storm flooding, salinization, and sedimentation
- Rapid physical changes over decadal time scales are leading to the widespread transformation of coastal ecosystems this century
- Ecological shifts will alter bird habitat use and numerous Yup'ik communities are facing relocation of their low-lying villages

Supporting Information:

Supporting Information may be found in the online version of this article.

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Interacting Sea-Level Rise, Sea-Ice Loss, Storm Flooding, Erosion, and Permafrost Thaw Threaten Ecosystems, Wildlife, and Communities on the Yukon-Kuskokwim Delta

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Abstract The Yukon-Kuskokwim Delta has the largest intertidal wetland in North America, is a globally critical breeding area for waterbirds, and is home to the largest regional indigenous population in the Arctic. Here, coastal tundra ecosystems, wildlife, and indigenous communities are highly vulnerable to sea-ice loss in the Bering Sea, sea-level rise, storm flooding, erosion, and collapsing ground from permafrost thaw caused by climate warming. These drivers interact in non-linear ways to increase flooding, salinization, and sedimentation, and thus, alter ecosystem trajectories and broader landscape evolution. Rapid changes in these factors over decadal time scales are highly likely to cause transformative shifts in coastal ecosystems across roughly 70% of the outer delta this century. We project saline and brackish ecotypes on the active delta floodplain with frequent sedimentation will maintain dynamic equilibrium with sea-level rise and flooding, slightly brackish ecotypes on the inactive floodplain with infrequent flooding and low sedimentation rates will be vulnerable to increased flooding and likely transition to more saline and brackish ecotypes, and fresh lacustrine and lowland ecotypes on the abandoned floodplain with permafrost plateaus will be vulnerable to thermokarst, salinization and flooding that will shift them toward brackish ecosystems. This will greatly affect bird nesting and foraging habitats, with both winners and losers. Already, some Yup'ik communities are facing relocation of their low-lying villages. The societal challenges and consequences of adapting to these changing landscapes are enormous and will require a huge societal effort.

Plain Language Summary The Yukon-Kuskokwim Delta in western Alaska has the largest intertidal wetland in North America, is a globally critical breeding area for waterbirds, and is home to the largest regional indigenous population in the Arctic. Increasing sea-level rise, sea-ice loss, and storms in the Bering Sea are driving changes in flooding, erosion, salinization, sediment and organic-matter accumulation, plant damage and vegetation shifts, ground-ice aggradation and permafrost thaw on the delta, but these processes interact in non-linear ways across inland gradients. We developed a conceptual model of how interactions among these factors will lead to the widespread transformation of coastal ecosystems over decadal time scales, although the changes vary by landscape. The projected changing flooding regimes and ecological shifts will affect bird nesting and foraging habitats, and are likely to affect bird populations, with both winners and losers. Already, 10 of 18 Yup'ik communities on the outer delta have severe flooding, erosion and permafrost thaw problems and are facing relocation of their low-lying villages. The societal challenges and consequences of adapting to these changing landscapes are enormous and will require a huge societal effort.

1. Introduction

The Yukon-Kuskokwim Delta (YKD) in western Alaska is the seventh largest delta in the world and the largest delta in the Arctic (Thorsteinson et al., 1989). The YKD provides ∼67,000 km^2 of high quality bird habitat, and is one of the most important breeding areas for migratory waterbirds in the world (Gill & Handel, 1990). YKD ecosystems also sustain one of the largest indigenous populations in the Arctic (Young & Bjerregaard, 2019). Living in 56 villages, ∼30,000 Yup'ik residents rely heavily on subsistence resources, including marine mammals, moose, fish, birds, and edible plants (Fienup-Riordan & Rearden, 2012). With mean annual air temperatures

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in the region projected to warm by 5°C by 2100 under a medium emissions scenario (https://snap.uaf.edu/tools/community-charts), sea-level rise, sea-ice loss, increased storm surges, and permafrost thaw will interact to drive large changes in YKD landscapes and ecosystems, with potentially severe impacts to wildlife populations, subsistence resources, and Native villages. Here, we synthesize decades of coastal research to assess past and future impacts of climate-related changes in one of the most ecologically productive and indigenously populated regions of the Arctic.

Deltaic ecosystems and societies are particularly vulnerable to the combined threats of climate change, sea-ice loss, sea-level rise, and storm flooding that interact with low-lying, extremely flat topography (Douglas, 2010; Nienhuis et al., 2023; Vermaire et al., 2013). On the YKD, storm flooding can extend inland as much as 30 km (Terenzi et al., 2014), and greatly affects the composition and productivity of coastal habitats by altering salinity and depositing sediment (Jorgenson & Ely, 2001). Patterns of storm inundation, salinization, erosion, and sedimentation, however, are likely to increase in frequency and magnitude from changing climate, increase sea temperatures (Hu et al., 2024), decreasing sea ice (Stabeno & Bell, 2019) and sea-level rise (Passeri et al., 2015), yet their interactions and consequences on coastal ecosystems are poorly understood. Complicating the prediction of effects of sea-level rise on coastal ecosystems are non-linear feedbacks among inundation, plant growth, organic-matter accretion, sediment deposition and compaction, and tectonic land movements (Saintilan et al., 2023). Adding to this complexity is the potential widespread but localized surface collapse after thawing of permafrost that underlies most higher terrain on the delta (Denali Commission, 2019; Hjort et al., 2022; Jorgenson & Roth, 2010).

Within the Yukon Delta National Wildlife Refuge, the outer coastal plain is the most productive region for waterbirds (Ely & Raveling, 1984; Lyons et al., 2024; Sedinger et al., 1994). The YKD is the breeding area for the entire Alaskan populations of Emperor Goose (*Anser canagicus*) and Taverner's Cackling Goose (*Branta hutchinsii taverneri*), >60% of Pacific Brant (*Branta bernicla*), and about 80% of the Greater White-fronted Goose (*Anser albifrons*) population. It also supports the greatest density and diversity of shorebirds using intertidal habitats in Alaska (Gill & Handel, 1990), and is an important autumn staging area for shorebirds in the Pacific flyway because of the high abundance of subtidal invertebrates that provide energy for lengthy non-stop migrations. The ability of intertidal habitats to support these diverse bird populations, however, is affected by the constraint of aquatic and terrestrial ecosystems within narrow environmental gradients (Jorgenson & Ely, 2001). In turn, herbivory by geese provides strong feedbacks to habitat composition and productivity (Person et al., 2003) and trace gas exchange (Kelsey et al., 2016), and climate warming may induce a mis-match between spring bird arrival, chick hatching, and forage availability and quality (Choi et al., 2019; Saalfeld et al., 2019). While habitat use among various coastal bird species is fairly well documented, how bird populations will respond to changing habitats is largely unknown.

The YKD has been the central homeland of the Yup'ik people for thousands of years (Shaw, 1998). As the largest of Alaska's five indigenous cultural groups, they have a rich heritage of traditional ways, or "yuuyaraq," a term that encompasses the interactions with community, traditional knowledge, and spiritual balance, and is supported by elder's words of wisdom, or "qanruyutet" (Fienup-Riordan & Rearden, 2014). Much of the population maintains a subsistence lifestyle that relies on hunting, fishing, and plant gathering (Fienup-Riordan, 2007; Herman-Mercer et al., 2019). Administratively and ecologically, this large region is complex, including diverse ecosystems, federal and state administrative boundaries and regulatory authorities, and three Native regional corporations, making it a challenge to assess how communities will be affected by climate change, and how they can mitigate and adapt to changes.

To assess the vulnerability of coastal ecosystems, wildlife, and indigenous communities on the YKD to climate change we focused on four research questions: (a) How do the major biophysical drivers of coastal change (sea-level rise, sea-ice loss, storm surges, salinization, sedimentation, permafrost dynamics, and soil development) interact to amplify or dampen ongoing changes? (b) What are vulnerabilities of coastal ecosystems and what ecotypes and landscapes are most vulnerable? (c) How may avian populations respond to projected ecosystem change, within the context of other biotic and human interactions? and (d) How will human coastal communities likely be affected by and adapt to ecosystem and landscape changes? Data addressing these questions were derived from newly collected field data from an existing, long-term ecological monitoring network, published and unpublished research and case studies, and internet archives. We synthesized data on impacts relevant to human and natural systems using a hybrid approach of reviewing existing information and

10.1029/2025EF006015

incorporating original research, and identified uncertainties and information gaps that limit our understanding of potential future trends.

2. Methods

2.1. Biophysical Drivers of Coastal Change

Sea-level Rise: Data (1992−2024) on past relative sea-level (RSL) rise at Nome, Alaska, (nearest station to the YKD) were obtained from the National Oceanographic and Atmospheric Administration (NOAA) (https://tidesandcurrents.noaa.gov/sltrends/) and were compared to the global average historical rate during 1993–2022 (https://sealevel.nasa.gov/). Projections on future RSL at Nome were obtained from NASA (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool?) based on the intermediate emissions scenario (SSP3-7.0).

Sea-Ice Loss: Median monthly extents of sea ice (>15% concentration) for 1981–2010 and trends in winter maximum extents (March) during 1979–2022 were obtained from the National Snow and Ice Data Center (https://noaadata.apps.nsidc.org/NOAA/G02135/north/monthly/shapefiles/shp_median/), which analyzes changes based on satellite observations. Projections of future monthly sea-ice extents for the Bering Sea were obtained from Douglas (2010).

Storm Tracks and Density: Here we update the analysis of storm tracks by Mesquita et al. (2009) by using data (2004–2022) for the storm tracks from the data set extratropical storm track compiled by the University of Manitoba (Crawford et al., 2021). The process of creating the storm track data consists of applying a minimum filtering algorithm that identifies the centroids of low-pressure zones on successive (3-hourly interval) mean sea-level pressure data sets, and then applying a second algorithm that assigns centroids of low-pressure zones an event code that represents contiguous storm events. There is some filtering needed to weed out very short-duration lows or spurious features. The result is a series of lines, one for each storm event, that tracks its life-cycle path from genesis to lysis. Each line has vertices at three-hourly intervals. The vertices of the resultant storm tracks data set can be plotted as dots on a map. While this can work, it tends to be visually cluttered and it does not provide a quantitative basis for comparing different time periods, such as seasons. A density plot is superior. To prepare a density plot a series of grid points are laid over the domain. Each grid-point forms the center of a circle of 0.25 M km^2. Within each circle, all storm track vertices are counted. The resultant count is assigned to the grid-point and the next grid-point is similarly assessed. When all grid-points have a count number assigned to them they can be contoured to form the density maps. It is important to note that the method is not designed to provide a contour count of individual storms, but rather, an assessment of storminess. The intent is to convey the extent to which storm activity could be affecting the coast. To that end, a single storm that loiters for a week is the same as a series of daily storms moving through an area over the same week.

Storm Surges and Water Levels: Information on peak storm-surge heights updates data from Terenzi et al. (2014). Our update includes information compiled from tide gauge measurements at Nome, our local tide gauges, and historical observations. Peak water-level observations (relative to mean sea level for Nome (station 9468756)) were obtained from NOAA (https://tidesandcurrents.noaa.gov/). We maintained water-level recorders (Hobo Water Level recorders, U20-001-04, 0.5–1 hr intervals) at three stations (TG1, TG2, TG3) near Transect T5 (Figure S1 in Supporting Information S1) at the mouth of the Tutakoke River for various periods from 2007 to 2017. The loggers were installed in pipes buried in mud at the bottom of tidal guts to avoid ice scouring during winter; the installations were near the lower tidal range, but did not capture the full tidal range. Pressure data were converted to water depths using Hoboware software (Onset corporation) by incorporating barometric pressure data from a nearby air sensor. Because the sensors did not capture all lower-low-water levels, we calculated a median water depth over the period of observations (3–9 years) for each station and used that to estimate sensor height relative to mean sea level. Elevation differences among the three stations were measured by a leveling survey using an autolevel and rod, and used to adjust sensor elevation heights. Data are archived at the Arctic Data Center (Jorgenson, 2025a).

Salinization: We updated the data on surface water and near-surface groundwater as initially reported by Jorgenson and Ely (2001). In our update, we include measurements made from 2007 to 2023 at 174 stations. Measurements were made of water depth above or below the ground surface in small wells (PVC plastic pipe, 25 mm diam., 0.3–1.0 m deep) and for electrical conductivity (EC) using portable probes (Oakton EC/pH meter).

Mean EC values were calculated by ecotype and geomorphic unit. Salinity and sediment (below) data are archived at the Arctic Data Center (Jorgenson, 2025b).

Sedimentation and Erosion: We updated the data on surface-accretion rates as initially reported by Jorgenson and Ely (2001). In our update, surface-accretion (organic matter and mineral sediment) rates were obtained at 93 stations along 11 transects (Figure S1 in Supporting Information S1) by measuring depth of materials relative to thin paint layers that were sprayed on the surface during various years from 1994 to 2016. The last measurements were made in 2023, a year after ex-Typhoon Merbok became an extratropical storm as it extended into the Bering Sea (hereafter, ex-Typhoon Merbok). Rates were calculated as thickness of material accumulated over the painted layers divided by years since the paint layer was established. We then calculated mean surface-accretion rates by ecotype and geomorphic unit. Distribution of erosion hotspots were derived the Landsat satellite time-series of images processed by Macander et al. (2014). Here we digitized polygons of the outlines of the larger erosion patches.

Soil Development: The soil stratigraphy information is an update of soil characteristics as presented in Jorgenson (2000) and includes data from additional soil sampling locations (Figure S2 in Supporting Information S1) and radiocarbon dating using the same methods. In this paper, we only present some representative profiles to illustrate the stratigraphic differences among geomorphic units. The ^{14}C ages were determined at WHOI-NOSAMS and were calibrated to calendar years using the intcal20 method. Overall, the soils database includes data tables for site environmental characteristics, soil stratigraphy, soil physical characteristics of samples, radiocarbon samples, and vegetation cover (Jorgenson & Kanevskiy, 2025).

Permafrost Dynamics: Permafrost dynamics were assessed through field surveys, remote sensing of landscape change using optical imagery, and topographic differences quantified by airborne lidar. The more recent topographic surveys of permafrost plateaus provide an update to permafrost distribution and changes initially reported by Jorgenson (2000). The remote sensing of landscape change and permafrost loss summarizes data from Jorgenson et al. (2018) without updated information. These data were obtained by point sampling and manual image interpretation of a time series of historical airphotos and high-resolution satellite imagery from ∼1948 to ∼2016 at 12 locations. Airborne lidar data were collected by Kodiak Mapping, Inc. (Palmer, AK, USA) between 27 June and 2 July 2009, and were used by Whitley et al. (2018) to map permafrost. Here we simply use a portion of the lidar imagery to illustrate permafrost topography and thermokarst development. The projection of permafrost loss in response to climate warming uses the output of the Permafrost Laboratory at the University of Alaska (courtesy of Vladimir Romanovsky). For future permafrost changes, we used the projected mean annual soil temperatures at 2-m depth based on the GIPL2 permafrost model using an intermediate (RCP4.5) emissions scenario (Marchenko, 2023).

2.2. Vulnerabilities of Coastal Ecosystems

We assessed likely changes in coastal ecosystem types (ecotypes) in response to sea-level rise, storm-surge flooding, salinization, surface accretion, and permafrost loss. We developed a conceptual model of the pathways of ecological transitions and the drivers affecting those transitions. These conceptual pathways are supported by an ecological land classification and the environmental relationships described by Jorgenson (2000), by field observations we have made over the course of our field monitoring since 1994, and photo-interpretation of a time-series of high-resolution imagery (Jorgenson et al., 2018).

To project landscape-level changes across the region, we used the mapping of ecological landscapes (co-varying associations of ecotypes) done for the YKD (Jorgenson & Dissing, 2010) to spatially extrapolate the vulnerability of coastal ecosystems to sea-level rise, storm flooding, salinization, and permafrost degradation. Aggregation from ecotype level to landscapes was based on the ecological hierarchy developed by Jorgenson (2000).

2.3. Response of Avian Populations to Ecosystem Change

We compiled and synthesized information on the dominant bird populations obtained from published and unpublished reports. First, we summarized the status and trend of key birds from published literature. We then evaluate how our projected changes in ecotypes (habitats) could affect their nesting and foraging based on habitat use reported in the literature and on field experience.

To aggregate this information across species and provide a landscape-based perspective, we developed a map of generalized distribution of "Narrow" and "Broad" coastal groups based on published surveys (Gill & Handel, 1990; Lyons et al., 2024; Saalfeld et al., 2017; Sedinger et al., 1994) and our field experience. The narrow coastal bird group includes black brant, common eider, black turnstone, semipalmated sandpiper, dunlin, and red phalarope, which mainly use ecotypes associated with tidal flats and active floodplains. The broader coastal group includes the greater white-fronted goose, emperor goose, cackling goose, spectacled eider, tundra swan, western sandpiper, rock sandpiper, bar-tailed godwit, red-necked phalarope, black-bellied plover, and ruddy turnstone, which use inactive and abandoned floodplains but also overlap with the narrow coastal group (Lyons et al., 2024).

Finally, we put the impacts of projected habitat changes in perspective with other factors affecting bird populations and discuss how birds can interact with biophysical drivers to alter ecosystem trajectories.

2.4. Vulnerabilities of Indigenous Communities to Ecosystem Change

To assess the vulnerability of indigenous communities we synthesized local observations, compiled case histories of individual villages and storm events, and summarized governmental responses and adaptation approaches. The local observations highlight a small portion of the large number of local observations compiled by (Fienup-Riordan & Rearden, 2012, 2014). We selected these observation examples to compare with data collected by government agencies and universities. The case histories, storm information, and governmental activities were compiled and synthesized from news reports, governmental reports, and websites, as referenced in the body of the paper. We developed an integrated geohazard rating system that averages the rankings for the potential risks of flooding, erosion, and permafrost thaw based on the rankings from the Denali Commission's statewide threat assessment (Denali Commission, 2019). In our integrated rating, however, we increased the flood ranking component for five (Chefornak, Kwigillingok, Nightmute, Nunam Iqua, Tununak) of 20 of the villages on the outer delta (including Bethel and Napaskiak just outside the boundary), based on updated flood impact assessments (Buzard, Overbeck, et al., 2021) and effects of ex-Typhoon Merbok, and reduced the permafrost ranking for one village (Chevak). The analysis. Photographs were obtained off the internet and Twitter (now X) and the photographers are cited.

3. Results and Discussion

3.1. Drivers of Ecosystem Change

3.1.1. Bering Sea in Transition: Sea-Level Rise, Sea-Ice Loss, and Storm Surges

Relative sea level (RSL) at Nome on the northeastern Bering Sea coast, the long-term tidal gaging station for the region, has been rising at 4.2 mm/yr (±2.1 mm/yr, 95% CI) based on NOAA data from 1992 to 2024 (https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9468756). This is similar to the global average of 4.4 mm/yr (±0.4 mm/yr) during 1993–2022 (https://sealevel.nasa.gov/). RSL at Nome is projected by NOAA to rise by 0.24 m by 2050, and 0.70 m by 2100 under an intermediate (SSP3-7.0) scenario relative to a 1995−2014 baseline (Figure S3 in Supporting Information S1, https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool?). By 2100, the rate of sea-level rise is projected to be 9.7 mm/yr. There is large uncertainty regarding the rate of sea-level rise, however. Sea-level at Nome is projected to rise 1.02 m by 2100 at the 83rd percentile under the intermediate SSP3-7.0 scenario (Figure S3 in Supporting Information S1) and 1.15 m at the 83rd percentile under the high SSP5-8.5 scenario. In our analysis, we use the projections for the intermediate scenario.

Sea-ice formation in the Bering Sea greatly impacts marine ecosystems by affecting the thermodynamics of the shallow sea, altering productivity and the food web, and providing a resting and foraging platform for marine mammals (Hunt et al., 2022). Winter sea ice is also important for adjacent terrestrial ecosystems because it moderates air temperatures, reduces precipitation, and reduces storm flooding (Frost et al., 2021). Sea-ice coverage has been monitored continuously with satellites since 1979, showing a long-term trend of decreasing winter sea ice (Figure 1). While highly variable, sea ice typically forms along the coast by November, reaches full extent in March, and starts retreating from the YKD coast in May. In April 2018, residents of western Alaska were dismayed by the early disappearance of sea ice and the restrictions it created by inhibiting sea-ice travel and hunting (Cornwall, 2019). For the Bering Sea, median March ice extent is projected to decline by 60% by 2100 under a "business as usual scenario" (A1B) (Douglas, 2010). The median ice-free season in the Bering Sea is projected to increase from 5.5 to 8.5 months by 2100, associated with a 2-month delay in freeze and a 1-month

10.1029/2025EF006015

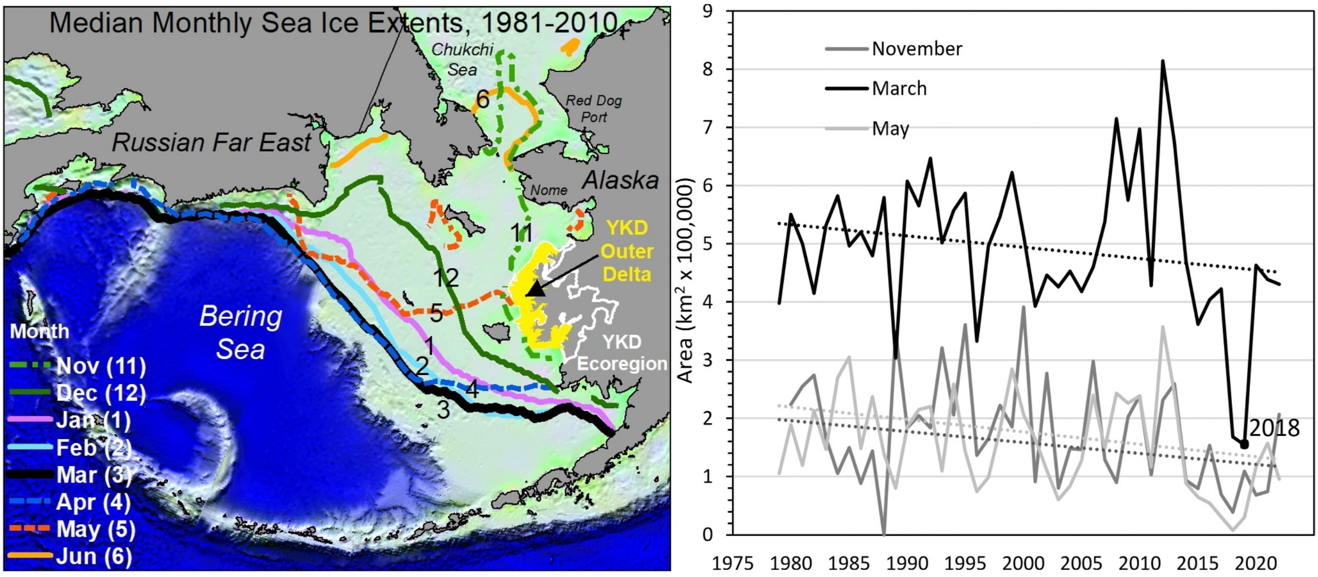

Figure 1. Median monthly extents of sea ice (>15% concentration) for 1981–2010 (left) and trends in November (early winter), March (maximum) and May (late winter) extents during 1979–2022 (right) based on satellite observations (data from National Snow and Ice Data Center).

advance in melt. This will have large ramifications for winter storms and coastal flooding, particularly during May and November. Declining winter ice also influences the distribution of marine mammals and reduces access to marine mammals by subsistence hunters (Erickson & Mustonen, 2022).

The North Pacific is a region of intense storm generation and movement (Mesquita et al., 2009). Although fewer storms track northward through the Bering Sea compared to the Gulf of Alaska, storms can be powerful if they undergo strong re-intensification. In the Bering Sea, mean seasonal counts of storm centers from 2004 to 2022 were about a quarter higher during fall and winter compared to spring and summer (Figure 2). During fall, maximum counts occur in the Gulf of Alaska (~70 storms), with a secondary maximum in the eastern Bering Sea

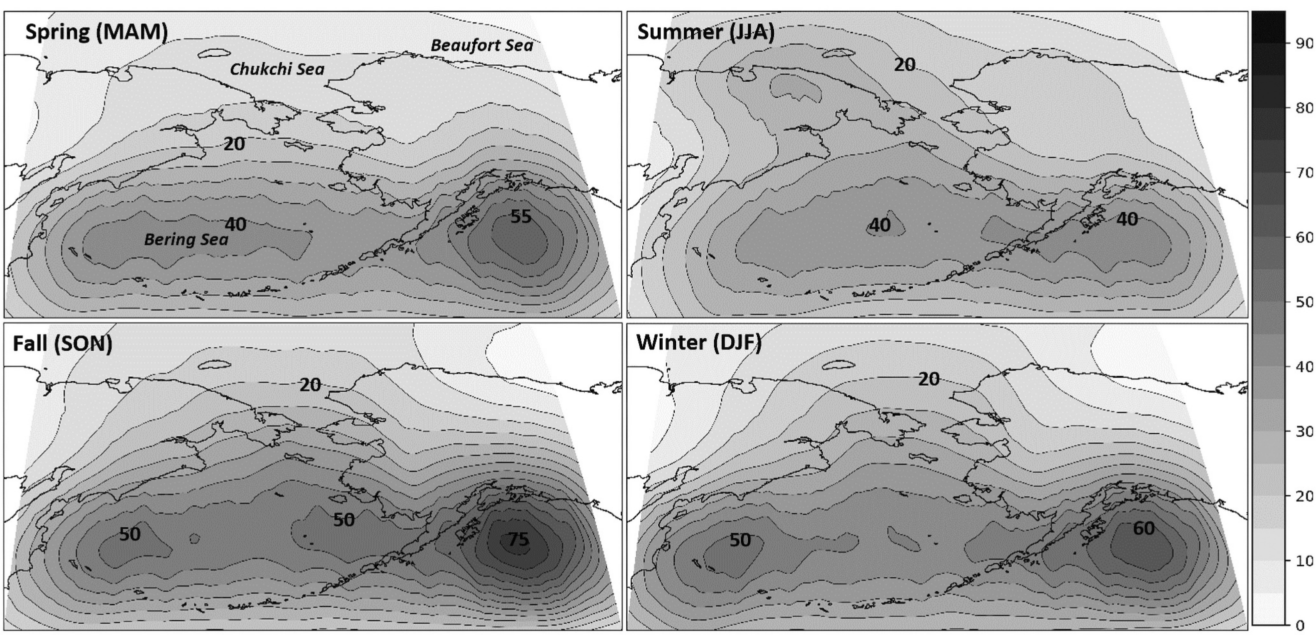

Figure 2. Storm counts by season in the Bering Sea region from 2004 to 2022 derived from reanalysis-based mean sea-level low-pressure centers shaded according to the mean seasonal count of storm centers within a 0.25 M km^2 spherical cap (data from Crawford et al. (2021)).

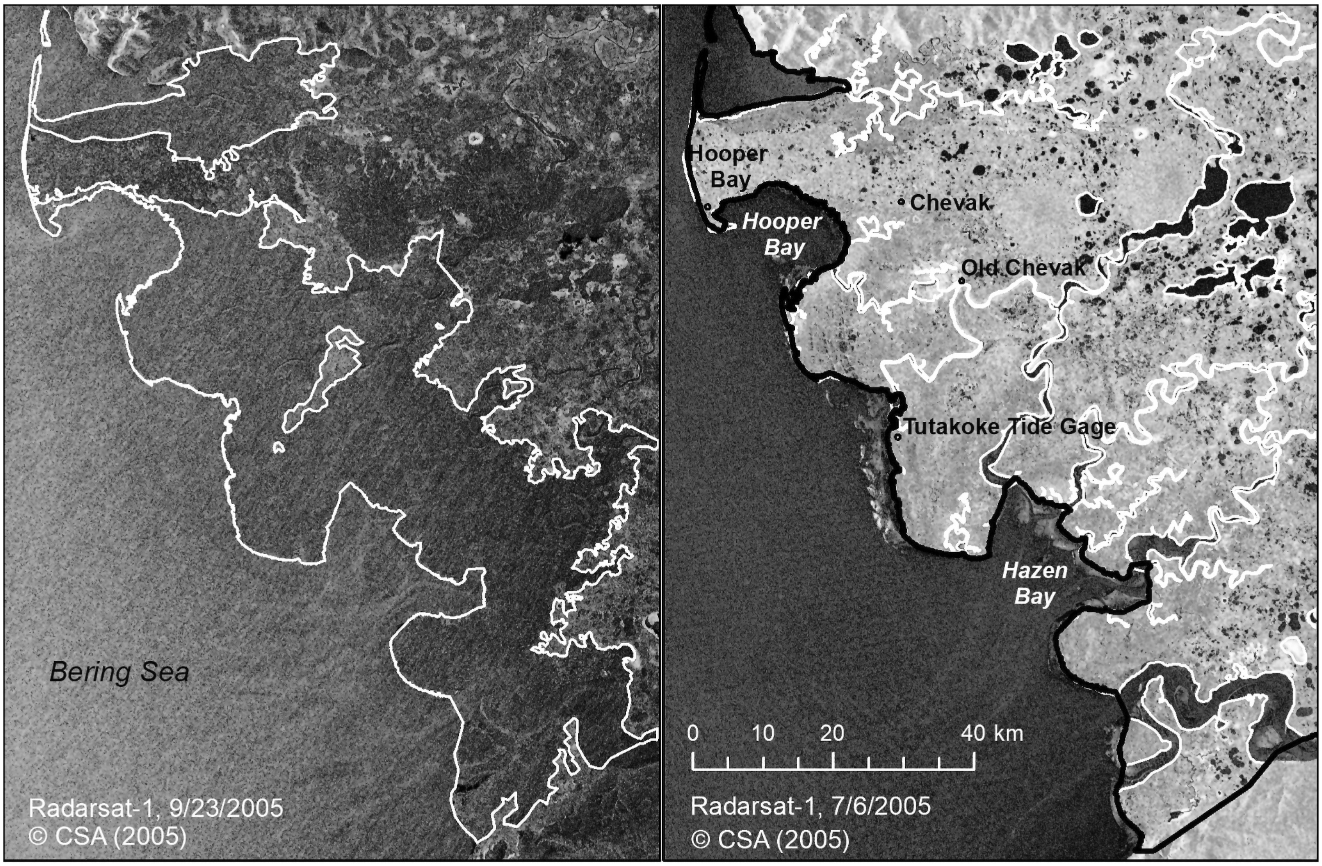

Figure 3. Extent of coastal flooding in the central portion of the YKD during the 23 September 2005 storm (left) as captured with Radarsat SAR imagery, in comparison to the land during normal water levels on 6 July 2005 (right). At its furthest point, flooding extended up to ~35 km inland.

and offshore of the YKD (~50), with a strongly decreasing northward gradient toward the northern Bering and southern Chukchi seas (~30). The high concentration of storms in the eastern Bering Sea frequently puts the YKD in the path of storms with the potential to bring strong surges. Tide gauge data for Nome suggest there has been an increase in storms during the last decade: of the 30 large storms (peak water levels exceeding 1.5 m amsl) since 1998, 10 occurred during 1998–2006, 7 during 2007–2015, and 13 during 2016–2024. The increase in peak water levels during the recent period, however, may be in part due to reduced sea ice. Mesquita et al. (2009) also found a weak trend in increasing storminess using storm track data from 1948 to 2008. The higher occurrence of large storms during the recent period is consistent with the accelerated warming of sea temperatures in the North Pacific (Hu et al., 2024). Large storms that caused significant coastal flooding in the YKD have predominantly occurred in the fall, including those on 11 November 1974, 20 August 1978, 25 October 1996, 23 September 2005, and 10 November 2011 (Terenzi et al., 2014), as well as the recent ex-Typhoon Merbok on 17 September 2022 (Table S1 in Supporting Information S1). The 2011 and 2022 events, in particular, were of historical significance resulting in widespread and severe coastal impacts. Impacts of ex-Typhoon Merbok on the YKD were particularly severe because windspeeds along the storm track were highest toward the central delta (Figure S4 in Supporting Information S1).

Storm-surge flooding of low-lying coastal ecosystems and villages can be extensive in the region due to the extremely flat topography of the outer delta (Kinsman & DeRaps, 2012; Terenzi et al., 2014). Long-term water-level monitoring stations are maintained at only two locations: Nome and Red Dog Dock, with storm-surge heights and flooding extent irregularly recorded around Native villages. In the YKD, little is known about the full extent of flooding inland from the coast, although fortuitous acquisition of synthetic aperture radar imagery and optical imagery on cloud-free days indicate inland flooding can affect enormous areas (Terenzi et al., 2014). The 2005 storm showed flooding extended inland as much as 35 km (Figure 3), while crest gauges at Tutakoke recorded a peak stage of 3.0 m above mean sea level (amsl) and the Nome tide gauge recorded a peak stage of

2.68 m. For the large 9 November 2011 storm, the tide gauge at Nome had a peak water level of 2.69 m, while our tide gauge at Tutakoke recorded 2.87 m amsl based on our new 2017 local tidal datum (Figure S5 in Supporting Information S1). In comparison, the water level at Red Dog Dock reached 1.46 m amsl; the highest water level recorded there was during a winter storm in February 2011 when the sea was covered by ice (Wicks & Atkinson, 2017). During ex-Typhoon Merbok, Nome had a peak water level of 2.91 m. In the central outer delta, we estimated the peak water level for ex-Typhoon Merbok was ~3.9 m (±0.3 m) amsl at the coast based on inland drift lines, far exceeding our estimate of 3.2 m for the largest previous storm in 1974 (Table S1 in Supporting Information S1). The greater open-water fetch for the YKD compared to the northern Bering contributes to the larger surges in the YKD.

3.1.2. Salinization and Sedimentation Across Coastal Gradients

Coastal ecosystems on the outer YKD are distributed across topographic, salinity, and sedimentation gradients from the saline tidal flats to the non-saline permafrost plateaus (Jorgenson, 2000; Kincheloe & Stehn, 1991; Tande & Jennings, 1986). In our work, we differentiated four main deltaic depositional environments: *tidal flats* with characteristic black laminated fines (silt to very fine sand) resulting from reduced iron-sulfide; *active floodplains* with mottled fines indicative of frequent flooding and sedimentation; *inactive floodplains* with interbedded peat and fines from occasional flooding; and *abandoned floodplains* with thick accumulations of woody (scrub) and sphagnum peat on permafrost plateaus that have been raised by permafrost formation (Figure 4). The soil patterns reveal the role of high sedimentation rates near the coast and increased organic-matter accumulation on higher inland areas. Across this gradient, flood frequency, salinity and sedimentation decrease and peat accumulation increases, with permafrost forming on the inland abandoned floodplains. Within these geomorphic units, the microtopographic surface forms include tidal channels/guts bordered by low levees (10−20 cm high) with sandy sediments, basins or flats behind the levees that can impound floodwater, and shallow ponds. Ecotypes are closely associated with these depositional and flooding environments (Jorgenson & Ely, 2001) and are described in Table S2 in Supporting Information S1 (note hereafter "Coastal" is dropped from the formal names of saline, brackish, and slightly brackish ecotypes for brevity).

Salinity is a principal driver of the ecological transitions inland from the coast and is closely associated with frequent tidal flooding at lower elevations along the coast and with storm surges further inland (Jorgenson & Ely, 2001; Kincheloe & Stehn, 1991). Periodic monitoring of soil water and shallow ponds along 11 transects located across the central YKD (Figure S1 in Supporting Information S1) has been useful in documenting salinization from large storm events that extend far inland (Figure 5). During periods lacking substantial inland flooding, mean electrical conductivities (EC) in Slightly Brackish Wet Rariflora Sedge Meadows were typically in the 2,000−4,000 μS/cm range, but after the large 2005 storm flood that peaked at 3.0 m amsl in the central delta mean EC was still elevated in 2007 at 10,083 μS/cm. Interestingly, mean EC reached only 7,003 μS/cm after the 2022 storm, despite it being a larger storm. Unfortunately, the effects of the large 2011 storm, which occurred after the 2011 measurements were made, were not adequately documented because salts presumably had been diluted by the time of the 2015 measurements. For Moist Birch-Ericaceous Low Shrub, where mean EC levels typically were 150–400 μS/cm, EC levels were greatly increased by both the 2011 (4,930 μS/cm measured in 2015) and 2022 (6,324 μS/cm measured in 2023) storms. During years without storms, snow melt and rain diluted the salts down to normal levels as indicated by the progressive decrease in EC from 2007 to 2010 after the 2005 storm. We also note that salinity levels are highly variable across the landscape due to variations in surface elevations, distance from coast, distance from slough, and storm surge distribution. Salt damage was evident from all three large storms, particularly after the 2005 storm. Monitoring in 2007 found extensive salt-killed dwarf shrubs and mosses and formation of shallow thermokarst moats along the margins of permafrost plateaus, as well as scattered small patches of salt-killed meadows on the inactive floodplains (Figure 5). In 2023, we found partially salt-killed dwarf shrubs and mosses in scattered patches across the tops of the permafrost plateaus. We suspect that seasonal ground conditions during flooding (i.e., whether the ground is frozen or snow is present) can also affect salinization.

Sediment deposition associated with large storm events and distance from tidal rivers is a large driver of surface topography (Olson & Lang, 2020), and the sediment is a large contributor of nutrients that make coastal ecosystems very productive (White et al., 2019). As this region is distant from the modern Yukon and Kuskokwim rivers, it is not subject to riverine processes, so sedimentation is solely due to coastal flooding. Monitoring of paint patches used to measure surface accretion (sediments and organics) across coastal ecosystems revealed mean

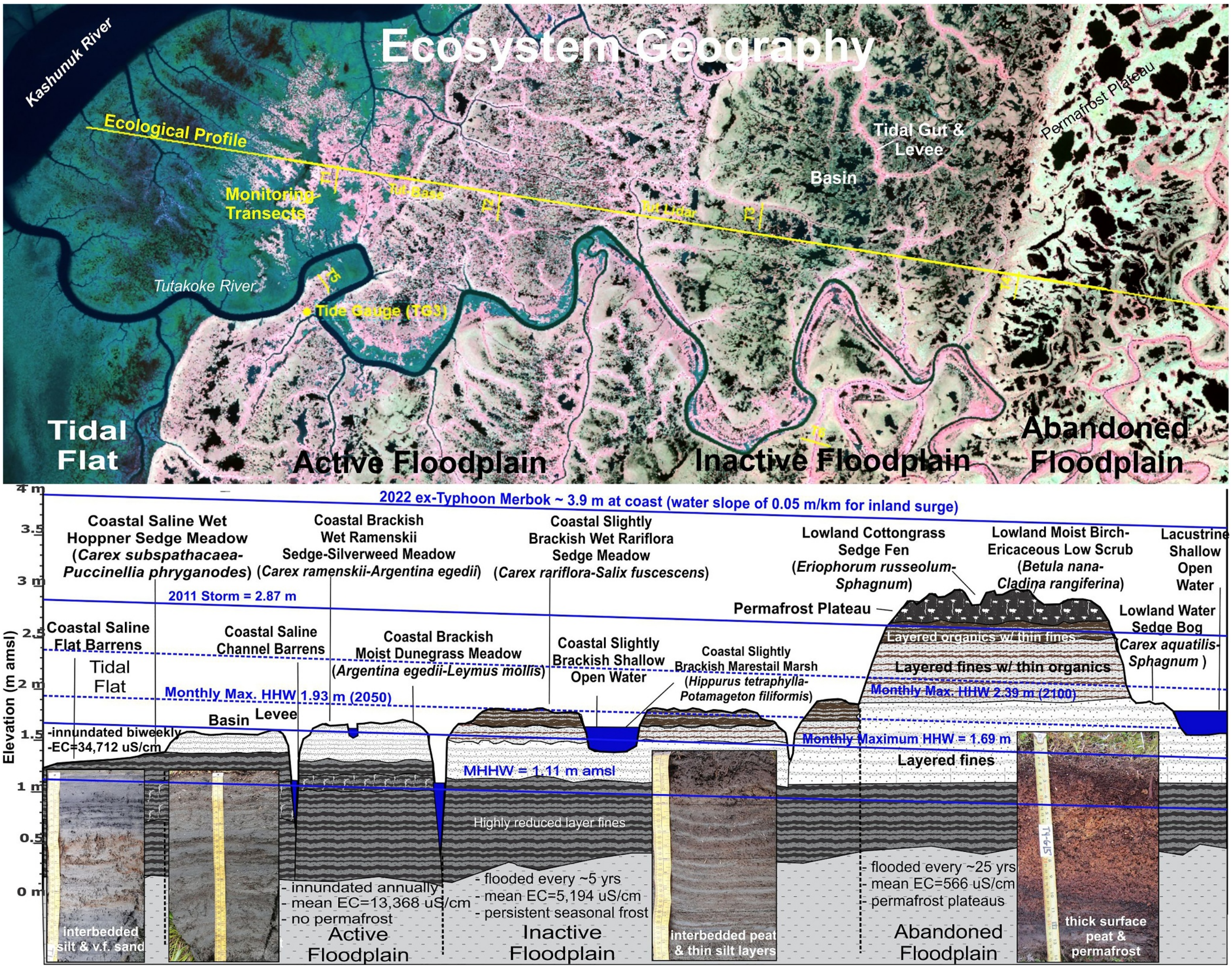

Figure 4. Ecological profile for the outer coast of the YKD illustrating relationships among geomorphic depositional environments, vegetation, soils, and flooding regimes. Mean higher high water (MHHW) and monthly maximum HHW are based on tide gauge data at Tutakoke 2007–2017. Projected monthly maximum HHW based on NOAA projected sea-level rise at Nome of 0.24 m by 2050 and 0.70 m by 2100. Note the distinctive tidal guts and levees (bright pink) on the inactive floodplain that are indicative of the effects of sea-level rise already impinging on the inland landscape (see Figure S6 in Supporting Information S1 for high-resolution topography). Representative soil profiles are shown at bottom illustrating changes in sedimentation (gray) and organic layer accumulation (brown) across the toposequence.

cumulative accretion from 1996 to 2023 varied four-fold from 39.1 mm in Slightly Brackish Wet Rariflora Sedge Meadow on inactive floodplains to 157.7 mm in Brackish Moist Willow Dwarf Scrub on levees on active floodplains (Figure 5). On active floodplains, most of the accumulation was from very fine sand, whereas, on the inactive floodplains most of the material added was organic. During periods without major storms, the added material was mostly organic. Both the 2005 and 2022 storms added substantial amounts of sediment on the active floodplains: in Brackish Moist Willow Dwarf Scrub mean accretion increased by 72 mm from 1998 to 2007 and by 63.2 mm from 2015 to 2023. In contrast, in Slightly Brackish Wet Rariflora Sedge Meadows mean accretion was 30.8 cm from 1998 to 2007 with substantial mineral input, with very little material added thereafter and consisted mostly of organics. Interestingly, even though the 2022 storm had higher water levels, sediment deposition on the inactive floodplains was only a few millimeters or less. While long-term subsidence in the region is poorly understood, we consider it to be negligible because we have obtained numerous radiocarbon ages of 5–7 ka bp at depths of 1–2 m that indicate the surface is relatively stable.

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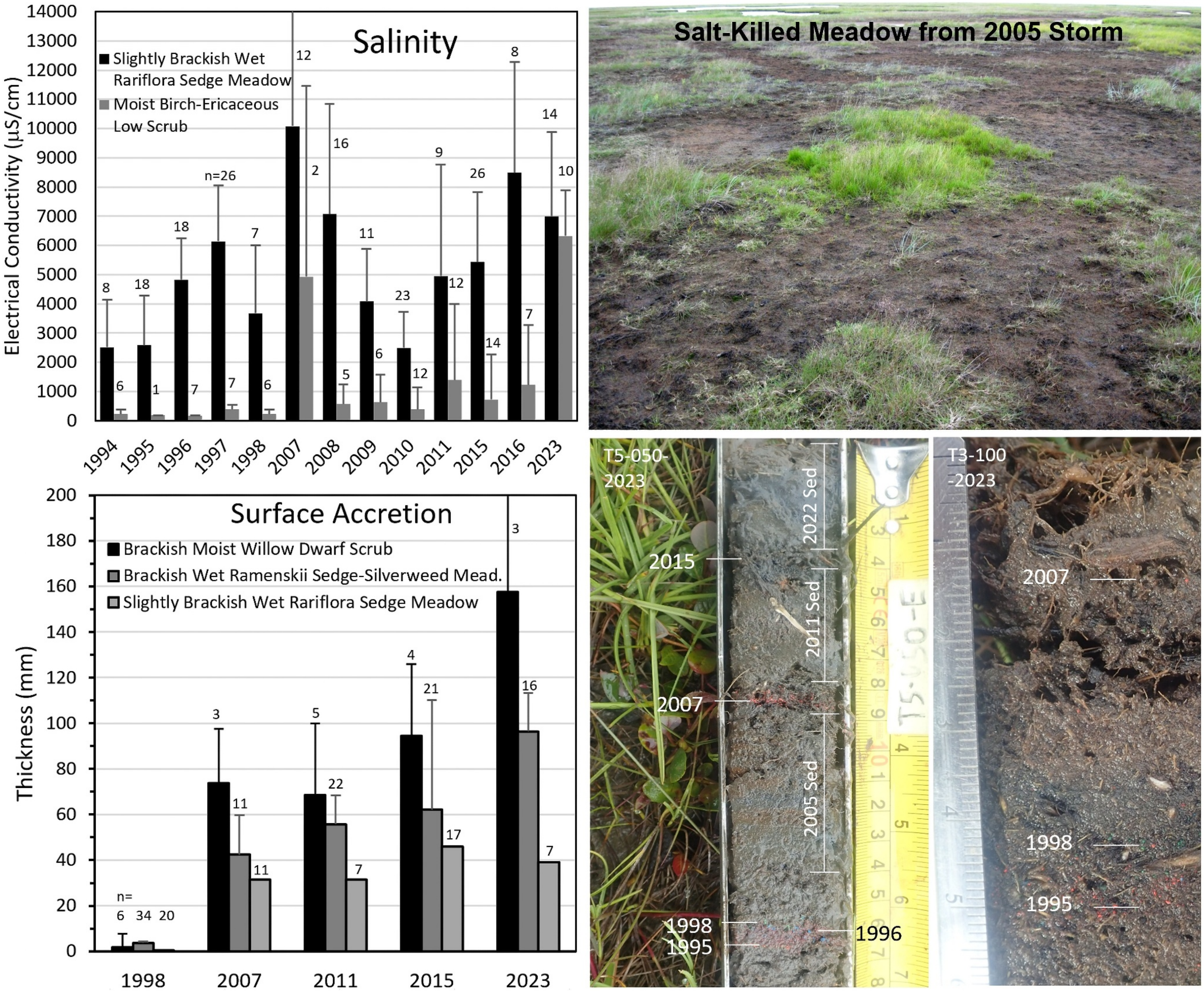

Figure 5. Mean (±SD) electrical conductivity (salinity indicator, sample size shown above bars, upper left) and mean (±SD) surface accretion (sediment and organics) from 1994 to 2023 for select ecotypes. Upper right photo shows salt damage (bare soil) in Slightly Brackish Wet Rariflora Sedge Meadow from 2005 storm, with newly colonizing Ramensk's Sedge (*Carex ramenskii*, bright green patch in center). Lower right photos shows surface accretion (in cm) above paint patches in an active (left) and inactive (right) floodplain. Large storm flooding occurred in 2005, 2011, and 2022; note the high salinity levels observed in 2007 show the persistence of the 2005 salinization.

3.1.3. Landscape Evolution: Soil Development and Permafrost Dynamics

Soil stratigraphy can be used to indicate depositional environments, permafrost development, and environmental history (Dupré, 1980). Soil stratigraphy in the central coast of the YKD shows a complex history of depositional environments, with widely varying lithofacies sequences, differing ages by depth, and frequent abrupt discontinuities in ages indicating erosional periods (Figure 6). The numerous ^{14}C ages from the early to middle Holocene (8,280−7,380 cal yr BP, 7,470−6,490 ^{14}C yr BP) at elevations of 0.2–1.0 m amsl in the tidal flats indicate underlying sediments may be eolian loess deposits formed on the exposed Bering Land Bridge before the region was inundated by early Holocene sea-level rise, because the soils are too old to be marine deposits. Numerous studies have shown that relative sea level (RSL) reached near current levels around 7 ka BP coincident with the final phase of North American deglaciation (Lambeck et al., 2014; Leonard et al., 2018). Our oldest ages (3,790−3,400 ^{14}C yr BP, 4,170−3,640 cal yr BP) at the base of interbedded silts and organics at 1.5−1.8 m amsl on inactive floodplains associated with infrequent flooding indicate the outer delta became established around 4 ka BP.

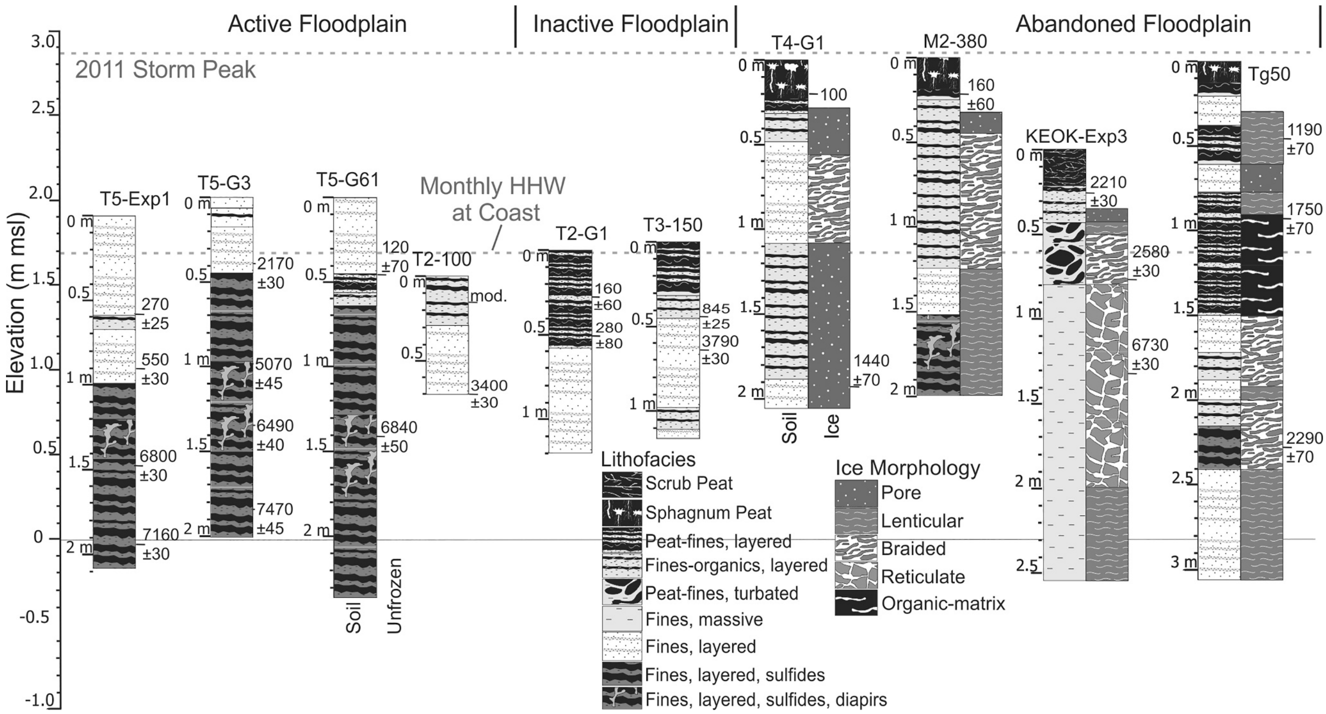

Figure 6. Soil profiles illustrating differences in lithofacies and permafrost ice morphology among delta floodplain depositional environments (updated from Jorgenson (2000)). Profiles include conventional ^{14}C ages, and water levels are given for mean monthly higher high water (HHW) and the 2011 storm peak at the coast in the central portion of the YKD. Note that abandoned floodplains are inland from the coast and thus experience lower peak water levels.

Together, these data indicate the formation and stabilization of the outer deltaic environment roughly coincided with the initial coastal settlement of the progenitors of the Yup'ik people about 3 ka BP (Shaw, 1998).

Permafrost distribution in the YKD is limited to abandoned floodplains and is always associated with thick peat. During initial permafrost formation, permafrost forms at about 0.8–1.1 m, just below the active layer. Below this depth, continued downward freezing results in ice-poor epigenetic permafrost (formed after sediment deposition ended) with predominantly pore and lenticular ice. Above this initial depth, an ice-rich layer of quasi-syngenetic permafrost forms from upward freezing in the top 0.5–1.5 m due to additional peat accumulation and slow thinning of the active layer. At two of the profiles (T4-G1, M2-380), the presence of young graminoid peat near the surface associated with inactive floodplains that lack permafrost, and occasional presence of stems and leaves of halophytic willow (*Salix ovalifolia*), indicate that much of the permafrost was formed during or since the Little Ice Age, which ended in Alaska around 1900 (core locations in Figure S2 in Supporting Information S1). At one site (Keok-Exp3), cryoturbated peat with diapirs associated with syngenetic permafrost formation and more complex reticulate ice in massive silt indicate some permafrost is much older. These elevated permafrost plateaus provided preferable locations in the past for coastal villages and subsistence camps above storm flooding.

Field monitoring, remote sensing, and modeling have shown that permafrost in the region is starting to degrade in response to regional climate warming, but can be accelerated locally through salinization. In the central portion of the YKD, ecotype mapping of Lowland Moist Dwarf Birch-Ericaceous Shrub, which is strongly associated with permafrost plateaus, indicates permafrost occupies ~6% of the coastal landscape (Jorgenson & Roth, 2010). More recently, high-resolution lidar surveys have been shown to be effective at mapping permafrost, with permafrost mainly occurring where surface elevations exceed 2.5 m (Whitley et al., 2018). Topographic surveys of permafrost plateaus in the central YKD since 1995 have shown a slight loss of permafrost along the margins of the plateaus and in water-filled pits that have developed on the plateau surface (Figure 7). Much of the loss was attributed to salinization from the 2005 storm surge, which killed vegetation and altered soil thermo-physical properties. In 2023, new thermokarst initiation was observed in a few locations, but was not as extensive as what was observed after the 2005 storm, although it may take a few years for the permafrost to respond to the salinization from ex-Typhoon Merbok. A broader remote-sensing approach to detect permafrost change based on

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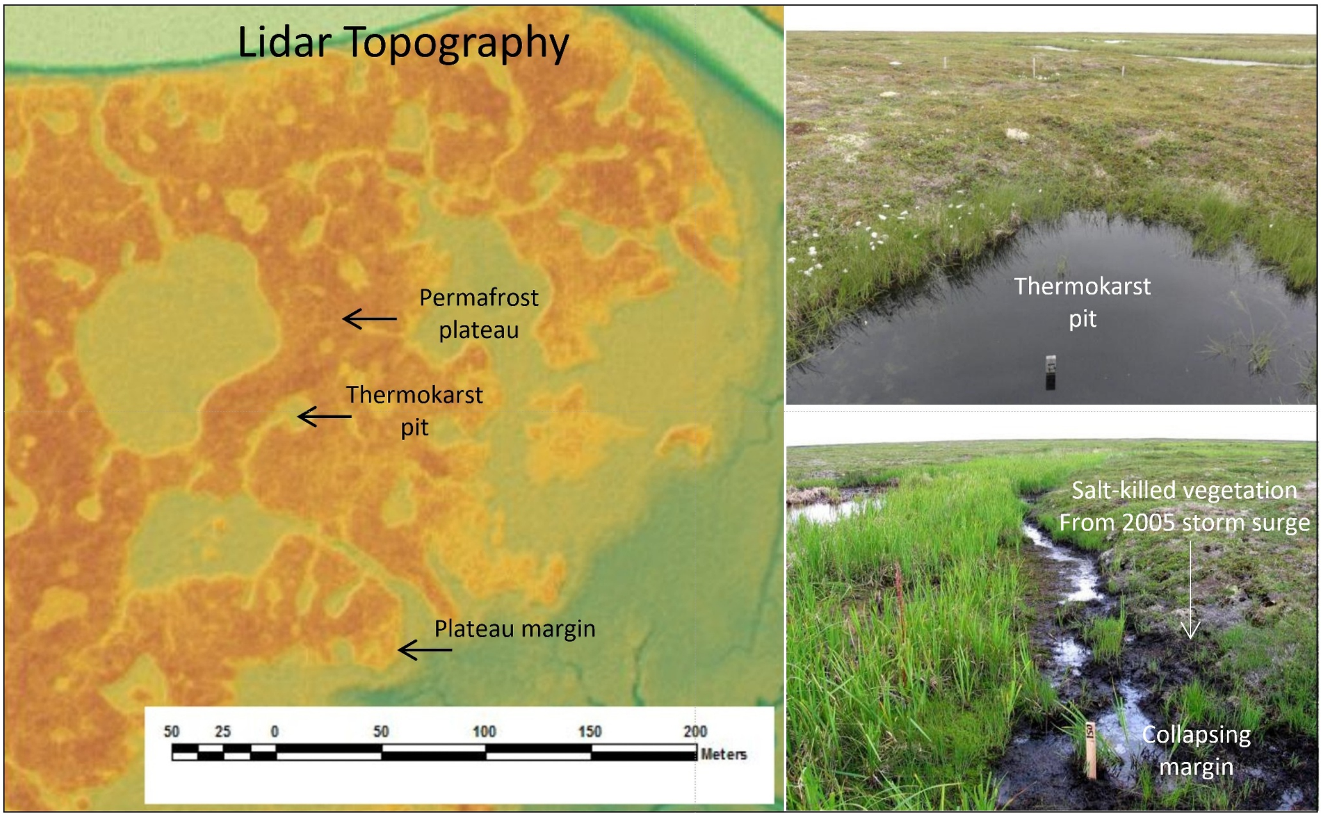

Figure 7. Lidar digital elevation model (left) showing the higher elevations (orange) on permafrost plateaus near Tutakoke. Thermokarst features associated with the permafrost plateaus include water-filled thermokarst pits (upper right) and collapsed margins (thermokarst "moat," lower right.) that typically are ~1 m lower in elevation.

photo-interpretation of a time-series of imagery from 1948 to 2016, revealed that permafrost extent associated with Lowland Moist Dwarf Birch-Ericaceous Low Shrub decreased from 24.5% to 19.5% area over 62 years (Jorgenson et al., 2018). Over this period, permafrost loss increased from 0.06 to 0.26%/yr.

Remote sensing of past landscape changes also reveals that coastal ecosystems are highly dynamic owing to frequent flooding, channel erosion and sedimentation, and permafrost formation and degradation (Jorgenson et al., 2018). An analysis of landscape change from 1948–1955 to 2013–2016 based on photo-interpretation of a time-series of high-resolution imagery, found 16% of area changed ecotypes during ~62 years. Lowland Moist Birch-Ericaceous Low Scrub (−5.0%), Saline Flat Barrens (−1.0%), Lacustrine Shallow Open Water (−0.5%), Brackish Shallow Open Water (−0.5%) showed the greatest decreases in area. The largest increases occurred for Lacustrine Water Sedge Meadow (3.7%), Lowland Water Sedge Bog (1.3%), Saline Wet Hoppner Sedge Meadow (0.8%), and Brackish Drained Lake Barrens (0.7%) (Table S3 in Supporting Information S1). Dominant processes affecting change were permafrost degradation (5.3%), channel erosion (3.0%), channel deposition (2.2%), vegetation colonization (2.3%) and lake drainage (1.5%). Sedimentation, water-level fluctuations, permafrost aggradation and shoreline paludification each affected <0.5% of the area (Tables S3 and S4 in Supporting Information S1).

Thermal modeling of soil temperatures at the 2-m depth by Marchenko (2023) indicates permafrost on the YKD was already unstable in 2021 and will be nearly all lost by 2050 in response to climate warming (Figure 8). Modeling indicates soil temperatures at the 2-m depth in 2021 within the outer delta zone were mostly near 0°C, while by 2050 soil temperatures were mostly in the 1−3°C range. While the modeling shows climate is a strong regional driver, remote sensing and field monitoring also show that there are strong localized effects from water impoundment in thermokarst pits leading to fragmentation within the permafrost plateaus and from salinization that contributes to thermokarst along the margins. Direct observations are consistent with modeling projections of permafrost being eliminated in this coastal zone by 2050.

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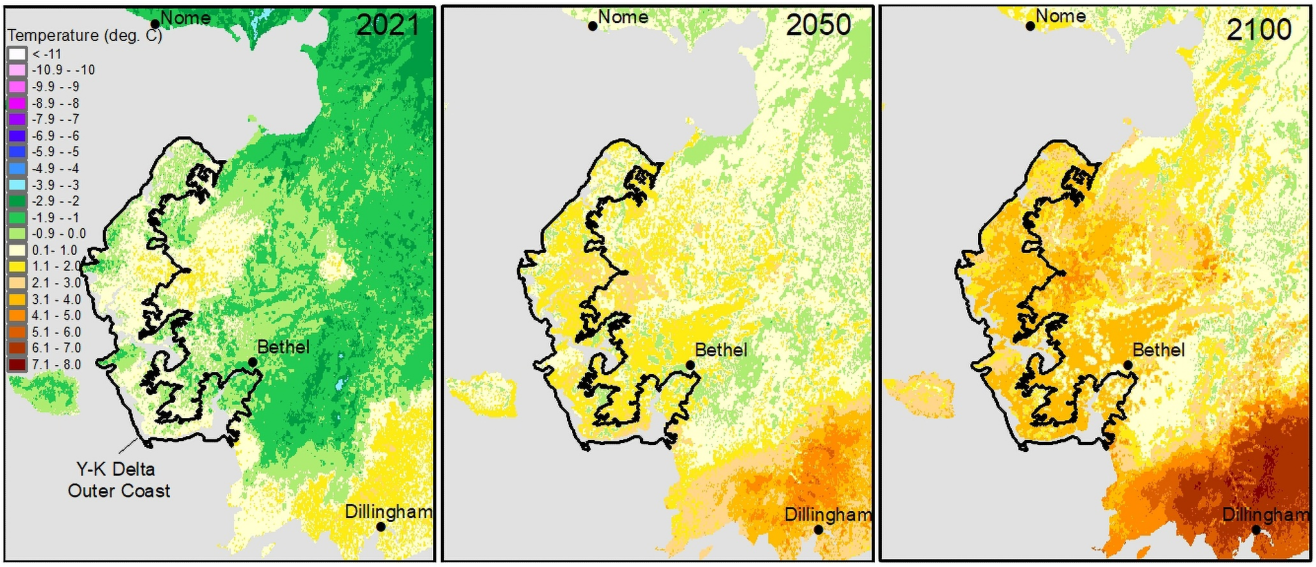

Figure 8. Projected mean annual soil temperatures at 2-m depth in the YKD region for 2021−2100 based on the GIPL2 permafrost model using an intermediate (RCP4.5) emissions scenario (Marchenko, 2023).

3.2. Vulnerability of Coastal Ecosystems

Climate warming, sea-ice loss, sea-level rise, and permafrost thaw, interact to make the outer YKD highly vulnerable to reorganization of coastal ecosystems and landscapes. Regional drivers affect localized changes in ecosystems through salinization, sedimentation, surface topography, erosion and deposition caused by channel migration, permafrost thaw, water impoundment, lake drainage, and paludification. Changes in these drivers affect the patterns and rates of transitions among ecosystems along fairly predictable pathways (Figure 9). Thus, the YKD is a highly dynamic landscape and remote sensing has shown that 16.2% of the coastal landscape has undergone changes over a ~62 years period (Jorgenson et al., 2018). Here we identify likely future trajectories in the dominant ecotypes on the YKD based on how ecotypes have responded to these drivers in the past as informed by remote sensing estimates and field observations, how the drivers are projected to change in the future, and how the physical drivers interact. In absence of quantitative models that can simulate the interactions among these drivers and incorporate the species-level and community-level responses of diverse vegetation, we identify the most likely initial and secondary ecosystem trajectories supported by current evidence, the extent of ecotypes affected, and discuss uncertainties that allow for alternative outcomes. We use the areal extent of ecotypes in the central portion of the outer delta as determined by Jorgenson et al. (2018) as rough estimates for extent of ecotypes across the broader coastal region that are at risk of change.

Sea-level rise, sea-ice loss, and increased storminess will interact to increase overbank flooding. A projected sea-level rise of 0.24 m from 2020 to 2050 (7.0 mm/yr under SSP3-7.0) will raise monthly maximum higher-high-water levels to 1.93 m amsl and allow overbank flooding of active and inactive floodplains on a monthly basis (Figure 4 and Figure S3 in Supporting Information S1). A projected sea-level rise of 0.7 m by 2100 (9.7 mm/yr by 2100) will raise peak tidal flooding to 2.39 m amsl on a monthly basis and cause overbank flooding of some abandoned floodplains. The projected loss of sea ice along the coast during May, November, and December will allow increased fetch and wave action, and thus, facilitate an increase in coastal flooding (Vermaire et al., 2013). Flooding frequency also will likely be increased by more frequent large storms associated with warming sea temperatures in the North Pacific (Hu et al., 2024). Substantial uncertainty remains, however, in how flooding frequency will change in relation to sea-level rise, sea-ice loss, and storminess, with substantial uncertainties in sea-level rise being the dominant factor.

Increasing salinization from more frequent flooding is highly likely to cause large losses in slightly brackish and lowland ecosystems on the inactive and abandoned floodplains more distant from the coastline. Past large storms have raised electrical conductivity to above 8,000 µS/cm (Figure 5), near or beyond the tolerance for most plants on slightly brackish to fresh soils on the inland portions of the delta. While remote sensing did not detect any salt-

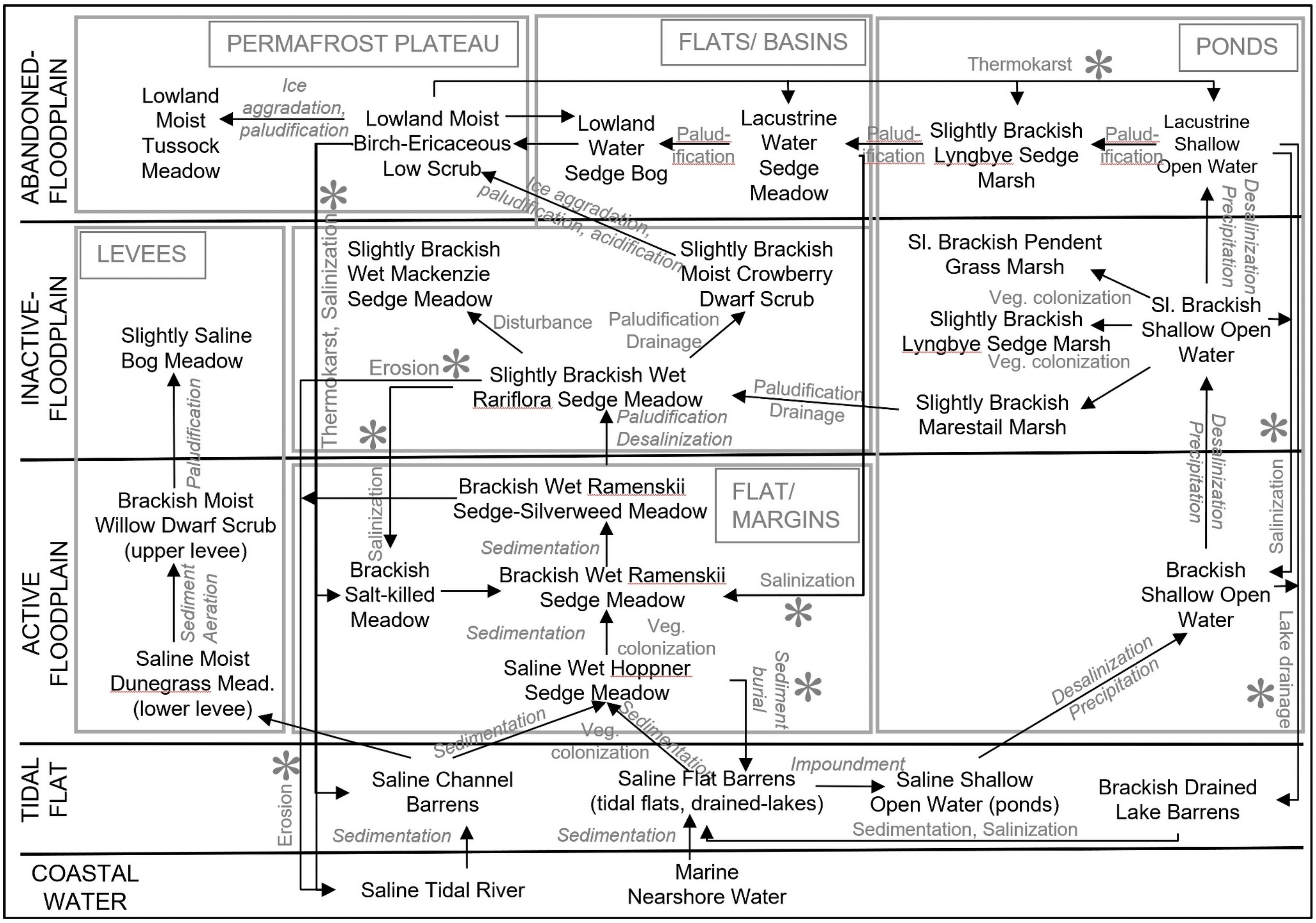

Figure 9. Pathways and biophysical drivers affecting the ecological transitions among ecotypes. Ecotypes are grouped by their associations with geomorphic environments (vertical stratification) and microtopography (horizontally grouped in gray boxes). Black arrows show the transitions among ecotypes, and the associated gray text describes the main drivers of the ecological shifts. The asterisks (*) indicate major factors that will drive changes associated with increase flooding, erosion, salinization, and thermokarst.

killed vegetation over the 1953–2015 period (Jorgenson et al., 2018), because historically salt-killed patches have been small and scattered, our field observations noted numerous small patches of Slightly Brackish Wet Rariflora Sedge Meadow that were killed by salinization from the 2005 storm (Figure 5) and small patches of salt-killed Lowland Moist Birch-Ericaceous Low Shrub on permafrost plateaus overridden by ex-Typhoon Merbok. We project that by 2050 overbank flooding on a monthly basis is highly likely to increase salinity levels above 8,000 μS/cm and kill salt-intolerant plants and affect most slightly brackish to non-brackish lacustrine and lowland ecotypes. Initially, nearly all of the Slightly Brackish Wet Rariflora Sedge Meadow (13.0% area in 2015, Table S3 in Supporting Information S1), Lacustrine Water Sedge Meadow (6.3%), and Lowland Water Sedge Bog (4.8%) are likely to transition to Brackish Wet Ramensky's Sedge-Silverweed Meadow, which already covered 7.3% of the area in 2015. In addition, Slightly Brackish Shallow Open Water (5.0%) and Lacustrine Shallow Open Water (13.3%) will become Brackish Shallow Open Water (already 2.5% in 2015). When including salinization after permafrost thaw and collapse (described below) and uncommon ecotypes, it is highly likely that altogether roughly 60% of the outer delta will be transformed by salinization. We have high confidence in projected large increases in Brackish Wet Sedge-Silverweed Meadow and Brackish Shallow Open Water, although it is uncertain as to timing (by 2050 or 2100) across the 30–80 km inland gradient. There is also some uncertainty as to whether flooding can extend as far as 80 km inland, but we expect that with a projected 0.7 m rise in sea level by 2100, that the height of large storm surges should persist overbank over the tidal cycle sufficiently long to push floodwaters across the entire outer delta.

Sedimentation will play a central role in how ecosystems on the outer delta respond to sea-level rise and storm flooding. The relatively high mean annual rate of surface accretion of 5.8 mm/yr on levees on active floodplains, based on mean total accumulation of 157.7 mm over 27 years (Figure 5), exceeds the recent rate of sea-level rise (4.2 mm/yr at Nome 1992−2021). As most sediment is deposited by large storms (Figure 5), we expect sedimentation rates to increase with increasing flooding frequency. The more rapid raising of levees next to the channels relative to more distal areas in the basins will likely lead to increased impoundment of water in the basins behind the levees. Already there are larger elevation differences between levees and basins on active floodplains near the coast than on inactive floodplains farther inland (Figure S6 in Supporting Information S1). In Brackish Wet Ramensk's Sedge-Silverweed Meadows (dominated by *Carex ramenskii*) that occur in the basins behind the small levees on active floodplains, surface accretion was 3.6 mm/yr (96.4 mm over 27 years), sufficient to maintain an equilibrium with sea-level rise. Thus, the productive and salt-tolerant Brackish Wet Ramensk's Sedge-Silverweed Meadows should easily persist. The future is less certain for Saline Hoppner Sedge Meadows that colonize the narrow upper margins of tidal flats and provide high-value forage for brant and other geese. While Hoppner Sedge (*Carex subspathacea*) is well adapted to saline soils and flooding, vegetation monitoring found numerous patches of this ecotype were buried by deep sediments (∼10 cm) from the 2005 flood, indicating this ecotype may be vulnerable to increased flooding and sedimentation. Follow-up inspection of three plots in 2023 found no substantial recovery of Hoppner Sedge in the plots since 2005. We did, however, observe new patches of Hoppner Sedge that had established in small patches where it was not previously present, due to both new colonization on mudflats and to the transformation of stands Ramensk's Sedge into the dwarf Hoppner Sedge morphology by heavy grazing (the two species are likely just different morphologies). This illustrates how animals, vegetation, and sedimentation interact in ways that could mitigate effects of sea-level rise. While we have high confidence that the ground surface of saline and brackish ecotypes on the active floodplain will keep up with sea-level rise, the relationship between storm magnitude and sediment deposition remains poorly understood.

In contrast, mean annual surface accretion in Slightly Brackish Wet Rariflora Sedge Meadows (dominated by *C. rariflora*) on inactive floodplains was only 1.4 mm/yr (mostly organics), one-third the rate of sea-level rise. We have not detected any sedimentation at monitoring sites on abandoned floodplain. This will likely lead to two main effects. First, with slower surface build up flooding frequency and salinization will increase with sea-level rise leading to a large shift toward Brackish Wet Ramensk's Sedge-Silverweed Meadows (described above). Second, the faster surface accretion of levees relative to the basins should also lead to increased water impoundment and development of extensive Brackish Shallow Open Water (described below). We expect sedimentation to remain negligible on inland areas even with increased flooding because most sediment is deposited in close proximity to river channels. A large uncertainty is how much future organic-matter accumulation in soils on inactive floodplains (Figure 6) can raise ground surfaces and thus reduce water impoundment.

Permafrost on the outer YKD is projected to thaw almost completely by 2050 from climate warming (Figure 8), leading to the collapse of the permafrost plateaus and lowering of the surface down to the level of the inactive floodplain. It is highly likely that this will cause a near total loss of Lowland Moist Birch-Ericaceous Low Scrub. During this process, development of thermokarst pits (Figure 7) will lead to an increase in impounded water, which provides positive feedback that increases heat gain (Jorgenson et al., 2010). This fragmentation of the permafrost plateaus by the pits will accelerate lateral degradation around the pits within the plateaus. Increasing storm flooding associated with sea-level rise and sea-ice loss, will lead to increasing salt-kill of vegetation along the permafrost margins leading to increased degradation (Figure 7). Together, these interactions will likely increase the rate of permafrost degradation beyond that predicted from climate alone. Lowland Moist Birch-Ericaceous Low Shrub will initially be replaced by Lacustrine Open Water, Lacustrine Water Sedge Meadow, Brackish Shallow Open Water, and Brackish Wet Rariflora Sedge Meadow depending on frequency. Brackish Wet Ramensk's Sedge-Silverweed Meadow and Brackish Shallow Open Water are likely to dominate as salinity increases with sea-level rise and storm flooding (Figure 9). Already, Lowland Moist Birch-Ericaceous Low Scrub on permafrost plateaus has decreased in areal extent from 24.5% in 1953 to 19.5% in 2015 due to permafrost thaw (Table S3 in Supporting Information S1). While we are highly confident that nearly all permafrost will be lost by 2050 in YKD there remains uncertainty as to the rate because of the interactions among fragmentation from internal pits, salt-killed effects along the margins, climate warming projections, and ecological feedbacks from water and vegetation growth. As most permafrost is tens of kilometers from the coastal fringe, there is also uncertainty as to how much Lowland Moist Birch-Ericaceous Low Shrub will be replaced by brackish versus fresh ecotypes, although by 2100 persistence of fresh ecotypes is highly unlikely.

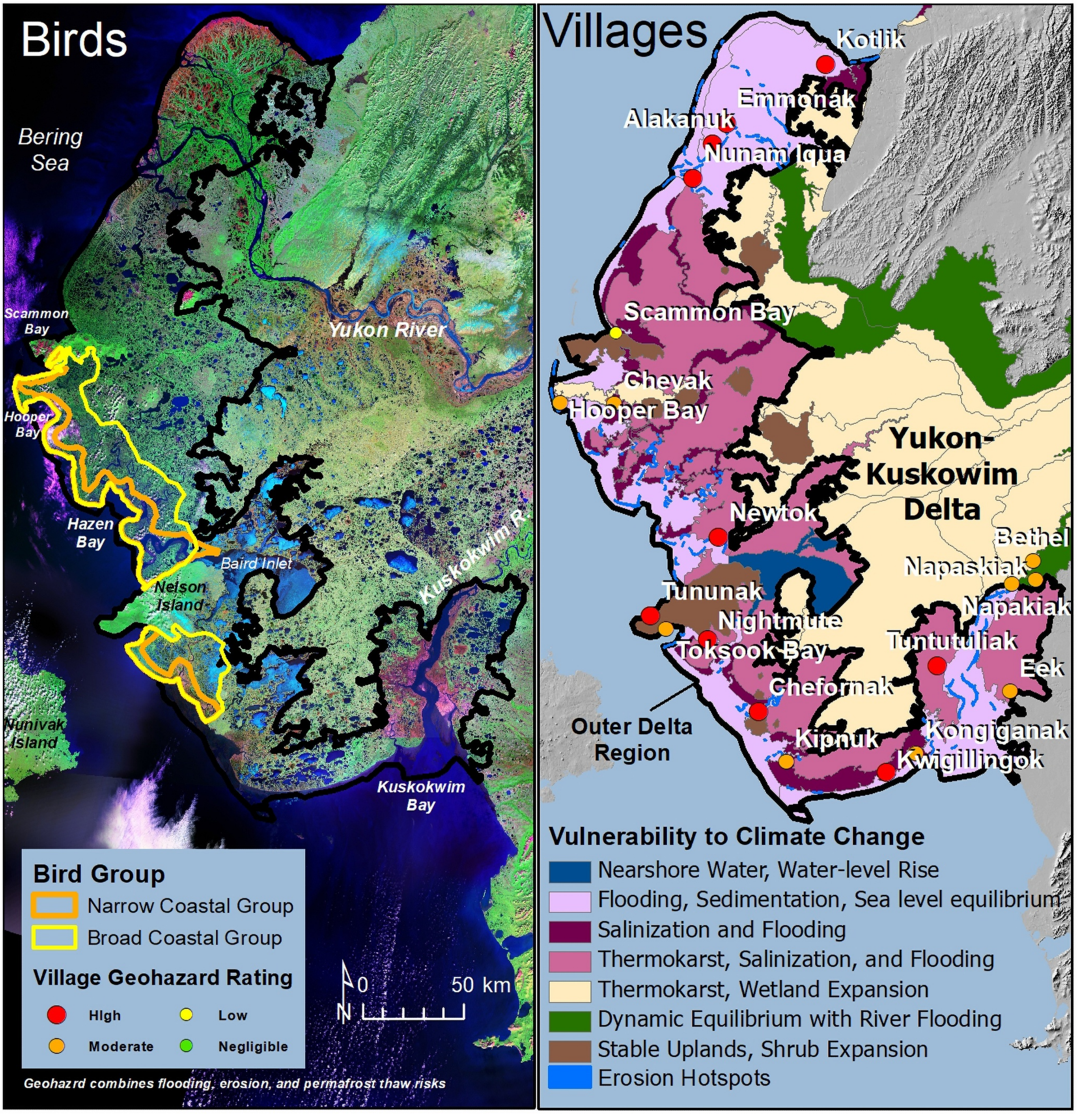

Figure 10. Maps of bird breeding areas (left), indigenous communities (right), and coastal landscapes (right) vulnerable to sea-level rise, storm-surge flooding, erosion, salinization, and thermokarst on the YKD. Bird breeding concentration areas (see text for species groupings) were generalized from published surveys (Gill & Handel, 1990; Lyons et al., 2024; Saalfeld et al., 2017; Sedinger et al., 1994). Erosion hotspots were derived from Macander et al. (2014) and the landscape vulnerability map was derived from Jorgenson and Roth (2010). The informal geohazard rating system averages the rankings for the potential risks of flooding, erosion, and permafrost thaw. Note coastal ecosystems are highly patchy, so boundaries of units are generalized for this small-scale mapping.

Channel migration is a major process that affected 5.2% of the area in the central delta from 1953 to 2015, with erosion (conversion of land to water) affecting 3.0% and deposition (conversion of water to land) affecting 2.2% (Table S5 in Supporting Information S1). Erosion hotspots associated with both channel and coastal erosion are shown in Figure 10. Ecotypes that are most likely to be affected by erosion are Brackish Ramensk's Sedge Meadow (1.2% of area in 2015, Table S3 in Supporting Information S1), Brackish Moist Willow Dwarf Scrub

(0.7%), and Saline Channel Barrens (2.5%) because they occur adjacent to tidal river channels. When eroded the vegetated ecotypes transition to Saline Tidal Rivers or Saline Channel Barrens. We expect this process to slightly increase with sea-level rise because of the additional water surging twice daily through the channels, although how the rate of erosion will change remains uncertain. Deposition along the channels to form new land results initially in the addition of Saline Channel Barrens and Saline Flat Barren (tidal flats).

Vegetation colonization of the barren margins of channels and tidal flats over time compensates for the loss of vegetation from channel migration and tidal flat expansion. Remote sensing showed that vegetation colonization was a major factor that affected 2.3% of the area (Table S5 in Supporting Information S1). The fringes of the barrens mostly transition to Saline Hoppner Sedge Meadow (1.0% of area in 2015) and Brackish Ramensk's Sedge Meadow (1.2%) near the outer coast, while inland Slightly Brackish Lyngbye Sedge Meadows (1.3%) develop. We are confident that colonization will continue at rates similar to the past because the ecotypes are well adapted to salinization and sedimentation. With increased flooding and salinization, however, we expect the inland channel barrens will become too saline for Slightly Brackish Lyngbye Sedge Meadows.

Lake drainage caused by channel migration and expansion of small tidal guts into basins has affected 1.5% of the area from 1953 to 2015, affecting Brackish Shallow Open Water (2.5% of area in 2015), Slightly Brackish Open Water (5.0%) and Lacustrine Open Water (13.3%, Tables S4 and S5 in Supporting Information S1). While drainage results in immediate barrens, the patterns of vegetation colonization in drained-lake basins are poorly known, although we have frequently observed Lacustrine Marestail Marsh and Slightly Brackish Wet Lyngbye Sedge Meadow in patches on exposed mud in slightly brackish basins. We project that the slightly brackish and lacustrine drained-lake basins will become increasingly saline and are likely to remain or become barren due to increasingly frequent inundation and salinization. How much waterbodies (totaling 20.8% of the area in 2015) will be tapped to form drained-lake basins, however, is highly uncertain and likely to be highly variable across the inland gradient.

Water-level changes from water impoundment and lake expansion affected 0.5% of the area from 1953 to 2015 due mostly to Slightly Brackish Rariflora Sedge Meadow changing to Slightly Brackish Open Water (Tables S4 and S5 in Supporting Information S1). While uncommon in the past, this will likely accelerate with sea-level rise and buildup of levees. With increased water depths we expect that the ponds will lose their abundant islands due to increased water impoundment, and thus, eliminate an important nesting habitat. Yet the evolution of these basins is uncertain because of the interaction among flooding frequency, levee buildup, tidal-gut expansion and lake drainage. Even the formation and evolution of lakes in the past is poorly understood as they transition from being mostly absent on barren tidal flats to becoming widespread small ponds with highly irregular shorelines and abundant islands on inactive floodplains, to large rounded ponds with even shorelines on abandoned floodplains. Thus, the rate and extent of transition from meadows to open water, and possibly to barren flats subject to frequent tidal flooding remains highly uncertain.

Paludification caused by the organic infilling (soil and emergent plants) of along the margins of Lacustrine Shallow Open Water (13.3% of area in 2025, Table S3 in Supporting Information S1) is a relatively minor driver of landscape change (0.5% from 1953 to 2015, Table S5 in Supporting Information S1) in the inland portions of the outer delta (Table S5 in Supporting Information S1). Sphagnum mosses are major contributors to infilling along pond margins and are highly sensitive to salinity. With increased flooding and salinization, paludification is highly likely to be eliminated as a change driver by 2050. We are uncertain, however, as to whether salinization will extend to the inland margins of the outer delta region by that date.

Together, the ecosystem changes are highly likely to lead to a radical transformation of the delta with nearly total loss of Lowland Moist Birch-Ericaceous Low Scrub (~20% area in 2015), and widespread conversion of lacustrine, lowland, and slightly brackish meadows and bogs (totaling ~28%) and open water ecotypes (totaling ~18%) from salinization by 2100. These will be replaced by the expansion of saline and brackish vegetation (from ~12% in 2015), open water (~11%), and tidal barrens (~11%). In a broader concept, we envision that over the course of 100 years or more, the outer coast is likely to shift toward a system of barrier islands along the coastline and a dendritic network of emergent levees inland that help maintain productive saline and brackish ecotypes supported by abundant sedimentation. Inland areas are likely to transition to shallow lagoon systems and tidally flooded barrens in deepening basins behind slowly building levees along the tidal rivers and small guts. While there are many uncertainties on how inland portions of the outer coast region will evolve, increased tidal and storm-surge flooding, salinization, differential sedimentation rates, and permafrost thaw are inevitable, leading to major ecosystem shifts across roughly 70% of the region by 2100.

To project landscape-level changes across the region, we used the mapping of ecological landscapes (co-varying associations of ecotypes) done for the YKD (Jorgenson et al., 2010) to spatially extrapolate the vulnerability of coastal ecosystems to sea-level rise, storm flooding, salinization, and permafrost degradation (Figure 10). In this regionalization, we project the active floodplain with frequent sedimentation will maintain dynamic equilibrium with sea-level rise, affecting 11,229 km^2 (34% of outer delta region, 32,759 km^2). The inactive floodplain with marine, alluvial, and organic soil materials and slightly brackish ecotypes will be vulnerable to increased flooding and salinization, affecting 3,443 km^2 (10% of outer delta). The abandoned delta floodplain with permafrost plateaus and freshwater ecosystems will be vulnerable to flooding, salinization, and thermokarst, affecting 14,435 km^2 (44% of outer delta). The modern delta of the Yukon River in the northern portion of the outer delta, however, will mostly remain in dynamic equilibrium with river flooding and sedimentation, although sea-level rise will increase flooding. Nearshore water within the outer delta (1,074 km^2, 3%) will be affected solely by sea-level rise. Note that there are small inclusions of upland areas within the outer delta region that are not subject to flooding and salinization (2,144 km^2, 7%). When considering the inner delta study region (34,525 km^2), the upriver floodplains of the modern Yukon and Kuskokwim Rivers will remain in dynamic equilibrium with river flooding unaffected by sea-level rise (24% of inner delta). Upland areas with thaw-stable surfaces (2%) will be subject to shrub expansion (Frost et al., 2021) and lowland ice-rich areas will be subject to thermokarst and wetland expansion (74%).

3.3. Vulnerability of Bird Populations

The YKD is a globally significant breeding ground and staging area for a wide variety of waterbirds. Here we focus on the likely effects of climate change on habitats for a subset of birds for which a significant portion of their populations rely on the YKD, and grouped the birds into broad and narrow coastal groups with differing distribution and habitat-use. The narrow coastal bird group includes black brant, common eider, black turnstone, semipalmated sandpiper, dunlin, and red phalarope, which mainly use ecotypes associated with tidal flats and saline and brackish ecotypes on active floodplains. The broader coastal group includes the greater white-fronted goose, emperor goose, cackling goose, spectacled eider, tundra swan, western sandpiper, rock sandpiper, bar-tailed godwit, red-necked phalarope, black-bellied plover, and ruddy turnstone, which use slightly brackish, lacustrine, and lowland ecotypes on inactive and abandoned floodplains, but also overlap with the narrow coastal group (Lyons et al., 2024). Below we briefly summarize the status and trends for these key birds, and then evaluate how our projected biophysical changes described above could affect their nesting and foraging habitats.

The status and trends vary among these key birds. Black brant nests have declined by nearly half from 1992 to 2017 (Wilson, 2018). During 1985−2014, greater white-fronted, cackling, and emperor geese populations increased (Fischer et al., 2018), although recent evidence indicates cackling geese and emperor geese populations have been declining since ∼2015. The threatened spectacled eider population (∼6,000 during 2010–2014) remains very low. The recently estimated breeding populations on the YKD of western sandpiper population (3.5 million birds), Pacific flyway population of dunlin (704,000), the tschuktschorum race of the rock sandpiper (105,000), black turnstones (142,000), and bar-tailed godwits (114,000), comprise the large majority of these populations in Alaska (Lyons et al., 2024). In addition, the global population of bristle-thighed curlews (10,000) and 75% of the Alaskan red knot population (22,000) use the YKD during migration (Alaska-Shorebird-Group, 2019).

Habitats used by the narrow and broad coastal groups will be differentially affected by the effects of sea-level rise, flood-frequency changes, salinization and permafrost thaw (Figure 8). Habitats used by the narrow coastal bird group are likely to persist because surface accretion is in rough equilibrium with sea-level rise. Tidal flats and early successional habitats on active floodplains are likely to expand, at least in the short term, to the benefit of the bird species in the narrow coastal group. With the elevated surface, spring nesting by birds is unlikely to be affected by monthly high tides (spring tides) and early summer storm surges are rare. For the broad coastal group that predominantly nests on the inactive and abandoned floodplains, sea-level rise likely will significantly impact nesting success because surface accretion will be insufficient to keep up with sea-level rise. Nesting, however, could shift to other areas. By 2050, high tides will routinely flood the inactive floodplain for 10 s of kms inland on a biweekly to monthly basis (Figure 4). By 2100, we envision most of the inactive floodplains will become tidally affected, shallow estuarine waterbodies, with the active floodplains on the outer coast functioning more like a barrier island system.

Lakes on the delta have abundant small islands, which evolved from the initial microtopography on the earlier tidal flats, provide nesting sites for many waterbirds that are more difficult for predators to access. We project that these islands will mostly disappear due to sea-level rise as water levels increase in the basins behind the accreting levees. The broader coastal group, particularly cackling geese, that heavily rely on these islands for nesting and protection from predators are likely to be significantly affected.

Inland salinization will dramatically increase from more frequent tidal flooding and storm surges. This will have the greatest effect on the broader coastal group that is more dependent on freshwater, particularly during brood rearing. For young ducklings of spectacled (*Somateria fischeri*) and Steller's (*Polysticta stelleri*) eiders, water salinity >6 ppt (~10,600 μS/cm) is acutely toxic (Hollmen et al., 2023). They, as well as many other species, are able to breed in saline environments, however, because they have access to freshwater in nearby elevated areas, such as permafrost plateaus, or can utilize rainwater. Within a few decades, however, biweekly tidal flooding caused by sea-level rise, along with collapse of permafrost plateaus with freshwater ponds, will eliminate access to freshwater ponds within 10's of kilometers of the coast. This change is likely to severely reduce the ability of eiders to successfully fledge young.

Permafrost thaw likely will lead to the collapse of most permafrost plateaus on the abandoned floodplain by 2050. Permafrost plateaus are dominated by Lowland Moist Birch-Ericaceous Low Scrub (~20 of area in 2015), which supports numerous berry-bearing plants that provide forage to birds, including crowberry (*Empetrum nigrum*), blueberry (*Vaccinium uliginosum*), cranberry (*Vaccinium vitis-idaea*), and cloudberry (*Rubus chamaemorus*). Thus, this vegetation provides high-value foraging habitat for emperor, cackling, and white-fronted geese (Babcock & Ely, 1994; Sedinger & Raveling, 1984), as well as bristle-thighed curlews (*Numenius tahitiensis*), whimbrels (Numenius phaeopus), and Hudsonian godwits (Limosa haemastica) (Lyons et al., 2024).

While these ecological transitions will significantly alter the availability of high-value habitats on the YKD, predation, disease, the ability of geese to modify their own habitats, and changes in migration and wintering grounds, remain other key factors affecting bird populations. Brant and cackling geese are highly vulnerable to nest predation by arctic foxes (Sedinger et al., 2016); large-scale nest failures in brant due to arctic fox predation have occurred multiple times per decade since about 1980. Subsistence harvest and fall hunting along their flyways also contribute to geese and shorebird mortality (Naves et al., 2019). In recent years, disease, especially avian influenza, has reduced both survival and breeding propensity of geese on the YKD (Ely et al., 2013). Populations also are greatly affected by habitat changes, climate change, and wildlife management strategies in their winter grounds.

Diminished bird populations during or following years of high mortality or nesting failure lead to complex interactions among geese grazing, sedimentation, and vegetation availability. Grazing by geese establishes and maintains grazing lawns by converting a tall form of Ramensk's Sedge into grazing lawns with higher forage quality (Person et al., 2003), which is required for growth by both emperor geese and brant (Schmutz & Laing, 2002; Sedinger et al., 2001). In addition, geese remove substantial biomass and enhance the rate of nutrient turnover (Ruess et al., 2019), reducing the accumulation of organic matter that facilitates the transition from active to inactive floodplain (Jorgenson & Ely, 2001). Years of high nest failure leave a lasting legacy of declining growth rates of goslings (Lohman et al., 2019), with lower growth rates resulting in lower first-year survival and recruitment into the breeding population (Sedinger & Chelgren, 2007). Sedimentation from large storms also interacts by providing nutrient input, knocking down accumulating plant litter that shades plants and reduces photosynthesis, and smothering diminutive plants, such as Hoppner sedge. Thus, the aerial extent of grazing lawns exists in a dynamic balance between losses from sedimentation and creation through grazing by geese. We foresee that more intense grazing under a warming climate may be required to maintain grazing lawns sufficient to support viable populations of brant and emperor geese on the YKD. This could be particularly important for areas where Brackish Wet Ramensk's Sedge-Silverweed Meadow replaces Slightly Brackish Wet Rariflora Sedge Meadow due to salinization. Implications of reduced grazing by geese for geomorphological dynamics due to sea-level rise also remain unclear.

Table 1

Quotes From Local Residents Indicative of Their Observations of Environmental Changes Associated With Sea-Ice Loss, Storms, Flooding, Erosion, Thermokarst, and Resulting Changes in Vegetation, Bird Populations, and Subsistence Activities (From Fienup-Riordan and Rearden (2012) and CEC Elders Gathering, November 2022)

The tuaq (shore-fast ice) *used to be very thick, and it froze as much as six miles from shore. Nowadays our ocean doesn''t freeze far from shore, and our tuaq and rivers become unsuitable for hunting because they are too thin and dangerous.* John Phillip Sr., Kongiganak
They say the ocean is always changing and doesn''t stay the same. That''s why they say the ocean cannot be learned. After the tide comes up, when the tide goes out, it changes. —Paul Tunuchuk, Chefornak
The tides too, they're higher than normal. The water level is so high that when we get south winds even some of the boats, where we usually store and put up the boats, while water is rising, the water gets into the boats. So that's one of the observations that I have noticed. —Simeon John, Toksook Bay, November 2022
Today it floods more often. In the past it flooded in fall only once in a while, covering our muddy lowland. This past fall it flooded and covered the land three times when it was wind down there. John Phillip Sr., Kongiganak, December 2005, after large storm
During this time there are many floods in my village: Tuntutuliak and Kipnuk are experiencing more and more floods these days. John Phillip Sr., Kongiganak, December 2005
The old villages of Cevv''arneq and Arayakcaarmiut that used to be situated on high ground have sunk down. And inland around the hills, many allngignat (tundra islands) *have sunk and become scarce. The melting land is obvious.* Paul John, Toksook Bay
It is obvious through those (hills sinking) that the ice underground is melting. One day, when (the hills) sink and the land becomes level, it will become thin again. Nick Andrew, Marshall
Some lakes that were once filled with water are now empty, as they have a means of draining probably due to the melting. They begin to refer to them as nanvallret (dry lake-beds) when they empty and different grasses start to grow in them. Paul John, Tooksok Bay
Towards the end of the summer, we get more rains. And the natural timing used to be like towards the end of July, right after in the early August, the cloudberries would be ripe at that time. But now, the berries are ready to be picked, even while we're in the middle of our fishing season in July. And that's not the norm. Simeon John, Toksook Bay, November 2022
November or late October right after it froze we heard swans. They're around later, and they come earlier, in April. Francis Thompson, St. Mary's, November 2022

Note. Additional observations are available at the online Yup'ik Atlas (https://eloka-arctic.org/communities/yupik/atlas/index.html).

3.4. Vulnerability of Indigenous Communities

3.4.1. Local Observations of Ecological Changes

Local residents are keen observers of their environment and provide a robust oral tradition relating knowledge of cultural continuity and environmental change on the YKD (Ambrose et al., 2014; Fienup-Riordan & Rearden, 2014) (Table 1). Because of travel and hunting on the land and Bering Sea, local knowledge of the interactions of ever changing ocean conditions (*imarpik elitaituq*), tides (e.g., *ancarneq* for outgoing and *taqcarneq* for incoming tides), sea ice (e.g., *elliquan* for newly frozen shore-fast ice and *manialkuut* for rough ice pushed on shore by tides), and storms (e.g., *cayukaulluni* for weather suddenly turning bad) are much more granular, and the vocabulary much more comprehensive and nuanced, than those obtained from scientific remote sensing and field monitoring. Similarly, specialized terms have been used to describe changes to the coastal landscape and interactions among land and water due to storm surges (*ulerpak*, for large swell or flood), erosion (*ussneq*, for caved-in riverbank), and permafrost thaw. Here we provide some selected observations from local residents to illustrate that the changes in biophysical drivers of ecosystem and landscape change that we have documented are consistent with what locals have observed and known about for decades.

The potential impacts to indigenous peoples and communities from climate change on the YKD are numerous. The recent ex-Typhoon Merbok destroyed many boats and field equipment that villagers rely on for their subsistence activities, and also the associated power outages led to spoilage of meat and fish stored in freezers (Schwing, 2022a, 2022b). Salinization of drinking water ponds at subsistence camps has led to the increasing need to haul freshwater out to field camps. The ongoing collapse of permafrost plateaus is leading to the loss of habitat for cloudberry and crowberry, essential components of local diets (Herman-Mercer et al., 2020). Sea-ice retreat and instability, coastal erosion, and storms all contribute to impeding hunting seals and walrus (Green et al., 2021). Later freeze up and earlier breakup has contributed to more hazardous travel on tidal rivers that already present unique challenges from shifting ice and open leads (Fienup-Riordan & Rearden, 2012). The greatest impact, though, has been the damage to housing, property, and village infrastructure from erosion, flooding, and permafrost thaw (Denali Commission, 2019).

Yupiit and Cupiit originally were nomadic, with only seasonal camps and infrastructure. Hence small groups could respond to storm surges by vacating temporary camps. However, federal funding for infrastructure, principally schools, promoted the aggregation of small indigenous groups into villages that were situated predominantly along the coast. During the early stages of village development there was little assessment of environmental hazards. This concentration of infrastructure into fewer villages has led to increased vulnerability to coastal erosion, storm flooding, and permafrost thaw.

3.4.2. Adapting to Change

In testimony before Congress in 2004, the U.S. Government Accountability Office identified that 183 of 213 villages in Alaska experience some level of flooding and erosion (GAO, 2009), and that one village on the YKD (Newtok) and three in other coastal regions (Kivalina, Koyukuk and Shishmaref) were developing plans to relocate. Since then, there have been increasing efforts by local and regional native organizations, state agencies, and the Federal Government to assess the risks of flooding, erosion, and permafrost thaw, and to develop mitigation strategies to address the threats. Detailed threat assessments of flooding and erosion recently have been prepared for most coastal communities in the region (Buzard, Overbeck, et al., 2021; Overbeck et al., 2020; USACE, 2009), aided by collaborative community-based monitoring efforts (https://dggs.alaska.gov/hazards/coastal/monitoring.html). In addition, most communities have had geotechnical soils and permafrost investigations in support of infrastructure planning, such as at Emmonak (Drage et al., 1981) and Cherfornak (Grarek, 1999). In 2019, a study of 187 communities found 29 faced a high threat from erosion, 38 faced a high threat from flooding and 35 faced a high threat from thawing permafrost (Denali Commission, 2019). A recent erosion exposure assessment by the Alaska Division of Geological and Geophysical Surveys documented shoreline changes, forecast 60 years of erosion, and estimated the cost of infrastructure in the erosion forecast area along Alaska's coast (Buzard, Turner, et al., 2021). Of the 48 communities along western and northern Alaska that were evaluated, 11 of the most vulnerable villages are on the YKD (Figure 10) and comprise 80% of the total estimated cost of infrastructure replacement.

The widespread and severe damage caused by ex-Typhoon Merbok in September 2022 again highlighted the urgency of the plight of villages in western Alaska among the press, politicians, and agencies (Telford, 2022). Ex-Typhoon Merbok caused flooding and damage along ∼1,500 km of coastline, raised water levels at Nome to a peak of 2.91 m on 17 September 2022, and affected 37 villages, including 14 villages on the YKD (Figure 11). Storm advisories were extensively broadcast before the storm and post-storm damage assessments, including field photography, acquisition of satellite and drone imagery, and surveys of high-water marks were done at 26 villages soon afterward (Horen et al., 2022). On 17 September Governor Dunleavy issued a disaster declaration and on 23 September, President Biden issued a federal major disaster declaration. Electrical utility workers, tribal health organizations, American Red Cross, Alaska Department of Transportation, Coast Guard, and other organizations responded within days.

Due to the flat coastal terrain, many of the villages on the YKD are among those identified as having combined threats from flooding, erosion, and permafrost thaw. In our assessment, we slightly revised the threat rankings (1-high to 3-low) of the Denali Commission for villages on the outer YKD, based on more recent detailed threat assessments (Buzard, Overbeck, et al., 2021), and calculated an overall geohazard rating based on the average of the threat rankings. Integrating the combined threats into a single index helps better identify villages where land settlement from permafrost thaw will increase risks of coastal flooding. We identified 10 villages potentially at high risk, seven villages at moderate risk, and only one village at low risk (Figure 10). Two villages just outside of the outer delta also were classified as moderate risk.

In response to these threats, there have been increasing efforts to mitigate the impacts on the YKD. Newtok residents have been planning to relocate since the 1990s, and between 1996 and 2012, local, state, and federal governmental entities have spent more than $27 million on technical assessments and design for a relocation to higher ground at Mertarvik (Newtok Planning Group, 2011; Schwing, 2023). But the process is agonizingly slow; the first erosion assessment for Newtok was done in 1984 (Woodward-Clyde Consultants, 1984). The U.S. Army Corps of Engineers (USACE) and the Natural Resources Conservation Service, USDA (NRCS) administer key programs for constructing flooding and erosion control projects. Some past efforts by the USACE on the YKD include erosion control at Emmonak since 1998 and Bethel since 1985 (https://www.poa.usace.army.mil). In 2022, the Department of the Interior allocated $25 M for Newtok and $15 M for Napakiak for relocation efforts

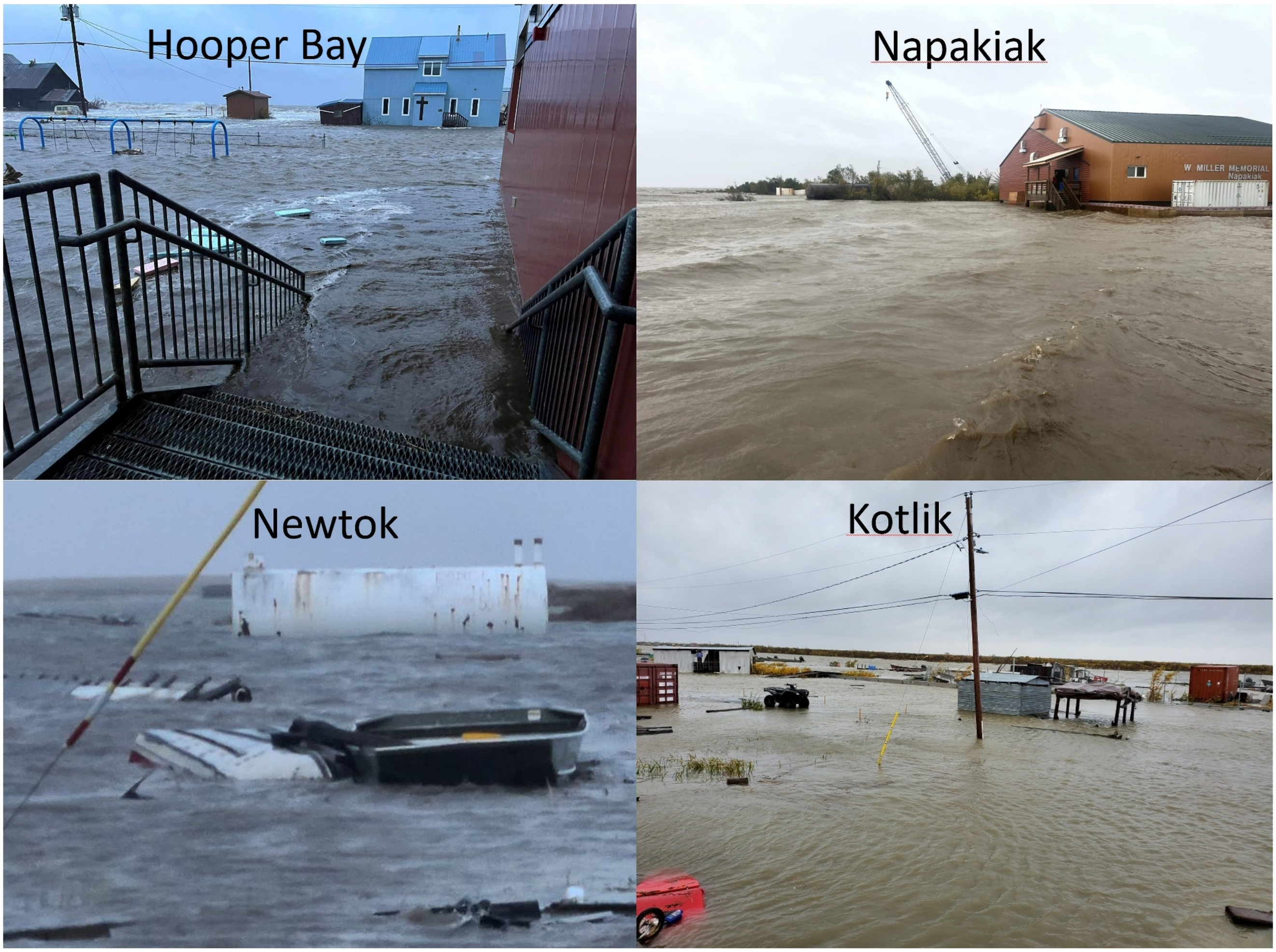

Figure 11. Storm surge flooding of Hooper Bay (photo by KYUK News), Napakiak (Bethany Hale), Newtok (Bruno Chakuchin), and Kotlik (photographer unknown, Alaska Division Geological and Geophysical Surveys) on 17 September 2022 from ex-Typhoon Merbok.

(Schwing, 2023). Also in 2022, the NRCS received $40 million over 5 years for efforts under the Emergency Watershed Protection program to help for 18 Alaskan communities with erosion control and relocation (Ebertz, 2022). Communities on the outer YKD that already are approved for funding include Kotlik, Alakanuk, Kwigillingok, Napakiak, Hooper Bay, Tuntutuliak, and Tununak.

When measures for prevention, minimization or mitigation of flooding and erosion have been determined to be technically and financially infeasible, village relocation is usually the best option. Options for villages on the YKD can include relocation to a new site, a nearby village, or to the regional center at Bethel, (ASCG, 2004). Evaluating relocation options typically has been directed by community organizations based on local surveys, with assistance from state and federal agencies, and consultants (Newtok Planning Group, 2011). During planning for Newtok's relocation, two village, five regional, eight state, and 10 federal entities participated. Based on Newtok's experience there is a strong community desire to relocate residents to a new nearby site and thus maintain the culture and societal connections of the residents.

The requirements for relocating a village are enormous, however, including the need for site surveying, gravel sources, roads, airports, water and sewer facilities, solid waste landfills, power generation and distribution, schools, communication facilities, health clinics, community buildings, and new housing (Newtok Planning Group, 2011). While the initial estimate to relocate Newtok alone was ~$100 million, other estimates ran as high as $300 million. The cost for relocating 10 villages at high risk will likely total billions of dollars. This will require a huge societal effort. While there are dozens of federal and state agencies with applicable grant or assistance programs to help with various aspects of hazard mitigation or relocation, the financial obligations are daunting.

Currently, there is no designated State or Federal agency with overall responsibility for addressing the relocation needs of Alaskan communities affected by flooding, erosion, and permafrost collapse.

4. Conclusion

Coastal tundra ecosystems, wildlife and indigenous communities on the YKD are highly vulnerable to sea-level rise, sea-ice loss on the Bering Sea, storm flooding, bank erosion, and the collapse of the ground surface from permafrost thaw. These drivers interact in non-linear ways involving sea-ice extent, frequency and timing of storm flooding, salinization, sedimentation and organic-matter accumulation, surface compaction, plant damage and vegetation shifts, and permafrost thaw. We developed a conceptual model of how interactions in these factors over decadal time scales will lead to the widespread transformation of coastal ecosystems within this century, but the changes vary by landscape. For example, projected decreases in sea ice during the fall season of increased storminess will lead to increased flooding and salinization, vegetation damage and permafrost collapse, and thus loss of ecosystems important for berry production for bird foraging and local harvesting. The permafrost plateaus also have been essential for village infrastructure and subsistence camps. We project the active-delta floodplain with frequent sedimentation will maintain dynamic equilibrium with sea-level rise, the inactive floodplain with infrequent flooding and low sedimentation rates will be vulnerable to increased flooding and salinization that will transform the landscape toward more saline and brackish ecosystems, and the abandoned delta floodplain with permafrost plateaus will be vulnerable to thermokarst, salinization and flooding that will radically shift freshwater ecosystems toward brackish ecosystems. We project that roughly 70% of ecosystems on the outer delta will be transformed during this century. This will greatly affect bird nesting and foraging habitats, with both winners and losers. Already, 10 of 18 Yup'ik communities on the outer delta have severe flooding, erosion and permafrost thaw problems and are facing relocation of their low-lying villages. While there are dozens of federal and state agencies with applicable grant or assistance programs to help with various aspects of hazard mitigation or relocation, the financial obligations are daunting. The consequences of adapting to this changing landscape are enormous and will require a huge societal effort.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data used in this report are publicly available. Data on past relative sea-level rise and water-levels at Nome (station 9468756) were obtained from NOAA (https://tidesandcurrents.noaa.gov/sltrends/). Data on the global average historical rates and projections on future RSL at Nome were obtained from NASA (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool?). Median monthly extents of sea ice were obtained from the National Snow and Ice Data Center (https://noaadata.apps.nsidc.org/NOAA/G02135/north/monthly/shapefiles/shp_median/). Data for storm track analysis used the extratropical storm track data set available at the University of Manitoba (Crawford et al., 2021). Data from our environmental monitoring network are available from the Arctic Data Center, including the tide gauge database (Jorgenson, 2025a), water and sediment database (Jorgenson, 2025b) and the soils database with tables for site information, soil stratigraphy, radiocarbon data, and vegetation cover (Jorgenson & Kanevskiy, 2025). The airborne lidar imagery is available at ADGGS (https://elevation.alaska.gov/). The thermal modeling data of permafrost are available at SNAP (https://uaf-snap.org/project/permafrost-dynamics-modeling-in-alaska-using-a-high-spatial-resolution-dataset/).

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