



Erosion of Coastal Beaches and Dunes During the Highest Water Level on Record in Southern Maine, USA

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Abstract As sea level rises, coastal water level records will continue to be broken, leading to increasing damage to coastal ecosystems, infrastructure, and communities. Maine, USA, experienced its highest water level ever recorded on January 13, 2024, just two days after another winter storm with an even higher storm surge on a smaller tide. These two storms destroyed a total of 28% of the dune area along four shorelines we mapped in southern Maine, documented with unoccupied aerial vehicle (UAV) photogrammetry. We found that 1) After the initial storm damage, only 10–50% of the dune volume lost in the storms recovered by the end of the growing season, nine months later. 2) Dunes offer greater stability for coastal sand as hardened infrastructure had greater losses during the storm and higher accretion after. 3) Beaches with southeasterly aspects, perpendicular to the storm winds, experienced 160% more normalized volume loss than beaches with easterly aspects. 4) Scraping and planting combined were 87–91% more effective in annual dune recovery than no action. Given no positive net dune recovery within 9 months after the storm, we suggest that restoration efforts like planting, scraping, and nourishment are needed to ensure dune longevity after record-breaking storm events.

Non-technical summary In January 2024, Maine experienced record-breaking sea levels during back-to-back winter storms, causing extensive coastal damage, especially to dunes. Dunes are important because they protect infrastructure, such as homes and roads, provide habitat for wildlife, and enhance the recreational value of beaches. We used drones to map dune and beach area and volume changes caused by these storms. Our findings show that 1) Dunes only recovered a portion of the sand lost nine months after the storms. 2) Dunes retained sand better than other structures, like hardened seawalls, which underwent more damage but gained back more sand afterward. 3) Beaches facing southeast (perpendicular to storm winds) lost much more sand compared to beaches facing east. 4) Beach scraping, moving sand from lower on the beach landwards towards dunes as a restoration method, and dune grass planting was much more successful than leaving the dunes to recover without intervention. Since dunes did not fully recover on their own after these powerful storms, we suggest that restoration efforts are necessary to keep dunes healthy in the future in order to continue protecting coastal areas and infrastructure from future storm damage.

1 Introduction

Approximately 600–700 million people globally live within 10 m of sea level, a number that is expected to increase to over a billion by 2050 (Oppenheimer et al., 2019). In the United States, 2.2 ± 0.25 million people lived within 1 m above sea level in 2020, an increase of 16% since 1990 (Titus, 2023). The east coast of the United States has been damaged by numerous hurricanes, and the northeast is annually hit by winter storms, including Nor'easters and other extratropical cyclones (Cuite et al., 2021). The intensity of these storms is expected to continue to increase with climate change, bringing costly economic, social, and environmental impacts (Whitehead et al., 2023). Large storms have reshaped coastlines around the world (George et al., 2021; Sigren et al., 2018; Houser et al., 2015), and

will continue to do so in the future. To prepare for this future, we need to understand how large storm events impact beaches, how they recover under a variety of circumstances, and which adaptation strategies are most effective in increasing resilience.

For millennia, coastal communities around the world have been forced to make a decision about life on the coast: retreat or adapt (Galili et al., 2019). These adaptations occur on a spectrum from purely natural solutions to hardened defenses and armoring to creative solutions such as raising buildings. In the United States, 14% of the total coastline is hardened, but Massachusetts, New Hampshire, and Maine have hardened their open coastline (i.e., direct exposure to the ocean) three times higher than the national average (Gittman et al., 2015). Hardened or armored shoreline infrastructure includes seawalls (Kraus and McDougal, 1996), riprap (Griggs, 2005), jetties, breakwaters (Komar, 2018), bulkheads (Gittman and Scyphers, 2017), and sea dikes (Scheres

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and Schüttrumpf, 2020). On the other end of the spectrum, purely natural shorelines consist of unaltered beaches and dunes, salt marshes, coastal bluffs, and bedrock. In between these two ends, humans have engineered nature-based solutions to mimic ecosystems such as constructed sand dunes (Magliocca et al., 2011), beach nourishment (de Schipper et al., 2021), artificial reefs (Fivash et al., 2021), and planted vegetation (Feagin et al., 2015). Beach nourishment entails importing sand and distributing it along the beach to replenish eroded areas. Scraping refers to redistributing existing sand from lower sections of the beach to the upper beach or dune area to build elevation. Planting involves establishing dune vegetation to stabilize upper beach sediment, reduce erosion, and promote potential long-term resilience. Implementing and repairing hardened infrastructure is often three to five times more costly than implementing more affordable nature-based solutions (Gonyo et al., 2023). Some property owners have even raised buildings above base flood elevation instead of, or in conjunction with, other adaptation efforts (Amini and Memari, 2021).

Coastal storms have destroyed infrastructure around the world. For example, Hurricane Sandy damaged large portions of the New Jersey coastline in 2012, especially areas that lacked dunes, have narrow beach widths (Barone et al., 2014), or were low elevation (Walling et al., 2016). Storms worldwide have been observed to damage beaches, including the dune and associated vegetation (Castelle et al., 2015; Anfuso et al., 2020; Maximiliano-Cordova et al., 2021). In Maine, the largest storm on record before 2024 was the 1978 blizzard, which caused extensive coastal damage to infrastructure and habitats (Kelley and Brothers, 2009). Understanding how these storms impact coastal communities is the best way to prepare the coastline to withstand these events and support coastal economies.

The coast of Maine has experienced approximately 0.2 m (7.5 to 8.0 in) of sea level rise since 1912 (Wake et al., 2019; Fernandez et al., 2020), with state-level plans to manage an additional 1.2 m (3.9 ft) by 2100 (Maine Climate Council, 2020). Dunes and beaches are particularly vulnerable to sea level rise as they serve as the first line of defense during storms (Sopkin et al., 2014). These systems are crucial, not only for protecting coastal infrastructure from erosion and flooding, but also for providing critical ecological services, including nesting sites for shorebirds such as piping plovers, *Charadrius melodus* (Barone et al., 2014; Horton and McKenzie, 2009). Long-term trends indicate variability in dune growth and erosion along Maine's beaches over the last 15 years, with particularly high-water levels in a 2018 storm (Slovinsky et al., 2022). These changes were primarily attributed to the type of coastline the beaches are adjacent to, such as seawalls, dunes, and rip rap. Major storm events, most commonly Nor'easters, can dramatically reshape the coastline, accounting for most of the annual or long-term changes on the beaches in merely a few hours (Hill et al., 2004).

Coastal Maine is a tide dominated system with southern Maine having a tidal range of 2.7 m (Kelley and Brothers, 2009). The 50th percentile average significant

wave height is 0.8 m and the maximum observed significant wave height was 9.6 m between 1982 and 2008 (NOAA buoy 44007 near Portland, Maine (ME)). Waves typically come from the south, but the largest waves, during winter storm events, typically come from the east-north-east (Kelley et al., 2005). The predominant current and longshore drift direction in the region is from north to south (Burkholder et al., 2024) but some bays exhibit currents from south to north, such as Saco Bay and are important for local sand budgets (Kelley et al., 2005). The Saco River, which enters the southern portion of Saco Bay, serves as the bay's primary sediment source, with sediment transported northward by local currents (Kelley et al., 2005). Saco Bay and areas to the south are predominantly sand near shore (depths less than 20 m) with muddy-sand, bedrock, and gravel making up deeper depths (Kelley et al., 2005).

Historically, winter storms in Maine have caused the most damage to the coastline, particularly Nor'easters, which bring strong northeasterly winds and typically snow (Zielinski, 2002). In recent years, however, storms have increasingly tracked farther inland, resulting in more rain than snow and southeasterly winds that can produce even higher storm surges (Picard et al., 2023). On January 9–10 and 13, 2024, Maine experienced consecutive record-breaking winter storms, leading to a federal disaster declaration. Although this increasingly common storm pattern is not yet well studied, the tracks of the January 10th and 13th storms followed more inland routes compared to the typical coastal or offshore paths (Townsend et al., 2006). Due to the high astronomical tide in addition to storm surge on January 13th, the Portland, Maine tide gauge (NOAA 8418150), recorded the highest water level ever observed at 1.4 m above mean high water (MHW). On January 10th, high tide at Camp Ellis (Saco, Maine) occurred at 09:24 AM (GMT-4) with an expected height of 0.23 m above mean high water (MHW). However, the observed high water reached 1.26 m MHW, implying a storm surge of 1.03 m. Wind data from the Portland International Jetport (located 18–30 km north of the study area) showed winds from the W and SW, with speed averaging 7.4 m/s and gusting to 24.0 m/s. Wave data from the National Data Buoy Center in Portland reports maximum wave height on January 10th to be 7.0 m, with a period of 11.43 seconds, recorded at 11:10 AM. On January 13th, high tide at Camp Ellis occurred at 12:12 AM with an expected height of 0.51 m above MHW. The observed high water reached 1.58 m MHW, indicating a storm surge of 1.07 m. Winds were more varied, coming from directions between ENE and W, averaging 7.2 m/s and gusting to 21 m/s. The maximum wave height reached 6.6 m, with a period of 10.0 seconds, recorded at 17:40 PM. During the storms, the highest frequency winds were from the WSW, ranging from 3.6 to 8.6 m/s. The pair of storms caused \$70.3 million in damage to public infrastructure, according to Maine's federal disaster request, with at least tens of millions more in damage to private property.

Our study aimed to understand the impact of the January storms on dune volume and the subsequent recovery of these systems over the following year. Specifically, we sought to quantify the changes in dune vol-

ume across four dune and beach systems in Southern Maine: Saco beaches (Bayview, Ferry, and Camp Ellis), Hills Beach, Fortunes Beach, and Goose Rocks Beach (GRB; Fig. 1; Table 1). By using these beaches as case studies, we aim to understand the short-term dynamics of dune erosion and recovery to gain insights into the resilience of coastal systems as weather events intensify: 1. Examine dune morphology response pre and post winter storm. 2. How does initial damage and recovery compare between coastline types, such as sea walls, riprap, and natural dune? 3. How does initial damage and recovery compare between beach aspect and presence of offshore structure? 4. Are restoration efforts such as planting and scraping effective in dune volume recovery?

2 Methods and Data

2.1 Study Area

Saco, Hills, Fortunes, and Goose Rock beaches were examined in this study due to the close proximity and ease of data collection. These beaches offer a wide range of adaptation strategies and infrastructure, which help us better understand storm impacts on coastal systems and communities (Table 1). These beaches are primarily frequented by seasonal visitors, with some year-round residents. All of these beaches have been heavily engineered to safeguard back dune residential developments. What we refer to as Fortunes Rocks Beach includes the eastern, central, and western segments of beach, commonly known as Biddeford Pool, Middle Beach, and Fortunes Rocks Beach, respectively. Pre-storm observation data for Saco and Hills beach were not obtained in this study. As a result, we rely on aerial imagery from Maine Orthoimagery collected in 2021 as a pre-storm baseline, even though two years had passed, this is the best dataset available and there were no major storms between the 2021 observation and our post-storm UAV flights, although natural processes such as aeolian deposition and beach rotation may have influenced the dunes and beach during that period. Because of this, we only provide dune area analysis for Saco and Hills Beaches and do not have data to conduct a dune or beach volume analysis (see Table S1 for UAV flight details and imagery dates). The fall (September) digital surface model (DSM) for Goose Rocks Beach could not coregister to the pre-storm DSM due to warping of imagery during processing, so we combined the storm damage (change from pre-storm to post-storm) and the recovery period (change from post-storm to fall) to obtain net change at Goose Rocks Beach. For net volume change at all other beaches, we coregistered the fall DSM to the pre-storm DSM and generated a differenced DSM.

2.2 Data collection and processing

Photographs of the dunes and beaches were collected using a DJI Mavic 3E UAV equipped with real-time kinematics (RTK) during low tides and daylight hours. We received RTK corrections from either the Gorham, Maine CORS stations or our own custom base station

in Biddeford, Maine based on availability as both stations experienced down time. Both resulted in positional uncertainties of less than 5 cm, even though we did not use any ground control because we are focused on relative, not absolute, accuracy. Surveys were collected at approximately low tide and each point in the survey was captured in at least 9 photographs. Beaches were surveyed in December and early January, one to two months before the January 9–10th and 13th storms, as the baseline pre-storm dataset. Beaches were surveyed again from February to April, one to three months after the storms. Final surveys were completed again in September, nine months after the storms, as the recovery period. The specific times and dates of surveys are reported in Table S1, with information on tidal height, survey horizontal accuracy, and pixel resolution. The photos collected from these surveys were processed in Agisoft Metashape Professional (Version 2.0.3). In this photogrammetry software, the photos were aligned to create a point cloud, which was then used to generate orthomosaic imagery and DSMs of the dunes and beaches. Because the flights included parts of the ocean and swash zone, we created masks for subsequent analysis to exclude these areas.

2.3 Data analysis

To quantify change in dune area at each beach, we digitized polygons of dune extent based on orthomosaic images from photogrammetry surveys in QGIS software (Version 3.4) (Table S1; see data availability). The vegetation on the dunes was categorized and sectorized by density to distinguish between primary, densely vegetated dunes (primary dune) and sparse, patchy vegetated dunes (sparse dune) during analysis. In the months following the January storms, a new category for planted dune area was added. We calculated the average retreat of dunes from their seaward extent of vegetation, and conversely the average length of vegetation recovery seaward, by dividing the difference in area by the shoreline length of dunes. Area changes were normalized by the length of each beach to allow for direct comparison between beaches.

Given data availability, we calculated volume changes for four beaches: Bayview and Camp Ellis (Saco coast), Fortunes, and Goose Rocks Beach. To analyze changes in dune volume, we first coregistered (Nuth and Kääb, 2011) the pre-storm, post-storm, and recovery period DSMs, to ensure horizontal and vertical alignment. We differenced the DSMs to identify relative height changes during three time periods: storm damage (pre-storm to post-storm), recovery (post-storm to fall), and net (pre-storm to fall). This process allowed us to identify areas where the dunes had either lost or gained elevation and compute the associated volume change. Polygons were grouped by their vegetation type: beach upper, beach lower, primary dune, and sparse dune. Beach upper is the landward side of the beach and beach lower is the seaward side of the beach, separated by the berm edge. Polygons were also grouped by their coastline types, or the structure backing the beach: dune, none, seawall, and riprap. None refers to a beach that is backed im-

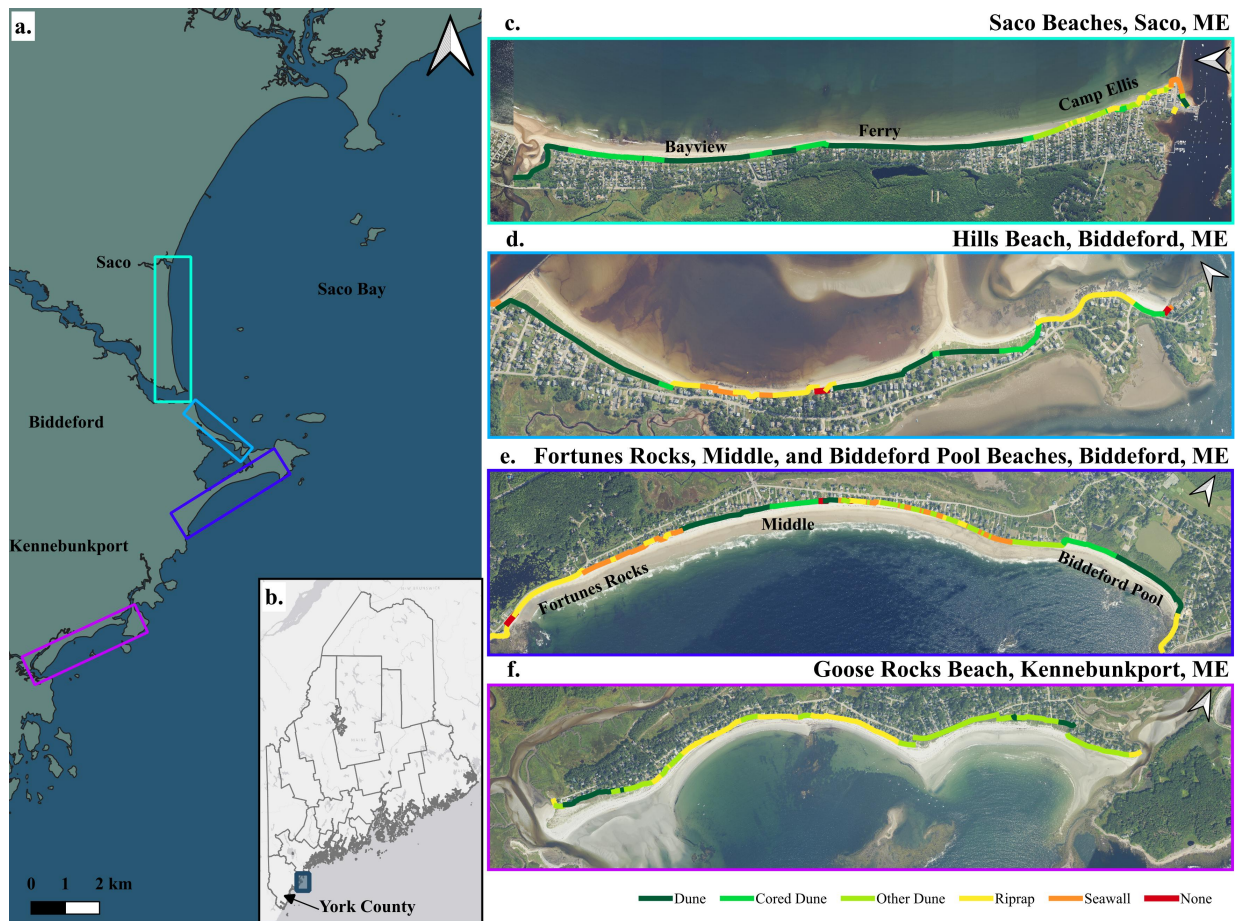


Figure 1 Location of beaches surveyed in this study with National Agriculture Imaging Program imagery from 25th Jul 2023, 10th Aug 2023, 23rd Aug 2023. a) shows the greater region of these beaches in southern Maine. b) shows location of study within Maine. c–f) show Saco, Hills, Fortunes, and Goose Rocks Beaches, respectively. In c), the jetty at Camp Ellis can be viewed on the southernmost side (far right). Lines on beaches show coastline protection type and categorized dunes by structure. Cored dune type indicates dunes that have grown over a seawall or riprap.

mediately by houses or other infrastructure, not dune, seawall, or riprap. Volume changes were normalized by the length of each beach to allow for direct comparison between beaches.

We created average beach profiles for each survey period by digitizing the top of the nearshore zone (low water line), the top of the subaerial zone (the seaward extent of dunes, seawalls, and rip rap), and the top of the backshore zone (the landward extent of these structures; see [Riazi et al., 2022](#) for definitions). We created lines perpendicular to the backshore line, spaced 5 m apart, extending to the waterline where our data ends. These lines were turned into a series of points sampled every 1 m, each assigned a coastline type attribute based on imagery (dunes, seawall, or rip rap) to record the elevation from DSMs for each survey date. We then calculated the mean and standard deviation of elevation across the beach, generating average profiles categorized by coastline type (dunes, seawalls, rip rap, none) for each survey period.

2.4 Uncertainty analysis

Uncertainty in area calculations originate in the digitizer accuracy and the resolution of imagery ([Crowell et al., 1991](#); [Fletcher et al., 2003](#); [Burns et al., 2021](#)). Digitizer accuracy (D), is the measure of the interpretation of varying imagery and the ability of the digitizer to con-

sistently identify and digitize the extent of dune vegetation. Digitizer accuracy may be impacted by imagery quality, shadows, and seasonal variation in vegetation. Therefore, digitizer accuracy was calculated for each time period of imagery at each beach. Three randomly selected dunes on each beach were digitized 10 times for each date of imagery (pre-storm, post-storm, and recovery; [Burns et al., 2021](#)). The mean and standard deviation of area was calculated for each of the 10 replicates. Mean polygon size was then correlated to variation, and a regression equation was generated to estimate digitizer accuracy. We combine this with the resolution of the imagery (pixel size) to estimate total uncertainty (U) in area calculations as they are random and uncorrelated. To calculate this uncertainty, the square root of the sum of the two sources, digitizer accuracy (D) and pixel resolution (P), was taken following equation 1 ([Crowell et al., 1991](#); [Fletcher et al., 2003](#); [Burns et al., 2021](#)).

$$U = \pm\sqrt{(D^2 + P^2)} \quad (1)$$

Uncertainty in the volume analysis arose from vertical offset of stable terrain during DSM coregistration, which was calculated for each set of differenced DSMs and ranged from 0.3 to 5 cm across all beaches. To account for this in the volume calculations, we multiplied the area of each digitized dune polygon by this

Table 1 Characteristics of the four beach systems focused on in this study including the length of the shoreline, beach facing in cardinal directions, and mean and standard error for azimuth degrees of transects perpendicular to each beach along the full length of the beaches. Percent of shoreline by length of dunes, seawall, riprap, and other shoreline types are also reported.

| Beach Name | Shoreline Length (m) | Beach Facing | Mean Azimuth (Degrees north) | Standard Error | % Dune | % Seawall | % Riprap | % Other |
|-------------|----------------------|--------------|------------------------------|----------------|--------|-----------|----------|---------|
| Bayview | 1,420 | East | 90.2 | 0.13 | 65.2 | 34.8 | 0.0 | 0.0 |
| Saco Coast | 4,210 | East | 87.5 | 0.28 | 35.0 | 9.2 | 30.7 | 25.1 |
| Camp Ellis | 1,230 | East | 82.8 | 0.87 | 28.3 | 24.8 | 27.7 | 19.2 |
| Hills Beach | 2,190 | Northeast | 53.9 | 1.31 | 50.3 | 5.0 | 37.5 | 7.2 |
| Fortunes | 2,550 | Southeast | 147.6 | 0.42 | 20.2 | 27.7 | 40.1 | 12.1 |
| Goose Rocks | 3,150 | Southeast | 148.8 | 0.38 | 11.4 | 3.4 | 62.2 | 23.1 |

vertical offset, representing our uncertainty. Seasonal changes of dune vegetation caused bias in recovery and total damage differences. On average, the transition from dormant to active dune vegetation inflated measured volume change by approximately 15 cm in height across dune polygons. This effect is due to photogrammetry capturing the top or side of vegetation rather than the ground surface when comparing pre-storm and fall surveys. We corrected for this bias by removing 15 cm of height from dune polygons in the recovery and total damage periods. While 15 cm was the average vegetation height, which was accounted for in our bias correction, some vegetation varied above and below this value. To account for this variability in vegetation height, we increased vertical uncertainty to 10 cm across the entire dataset, doubling the largest coregistration uncertainty and representing one standard deviation of vegetation height change.

3 Results

3.1 Dune Area Change

The four shorelines we studied, Saco, Hills, Fortunes, and Goose Rocks Beaches, experienced a loss of 28% of total dune area during the initial storm damage of January 2024. There was a total $54,000 \pm 4,300 \text{ m}^2$ of dune area lost, with an average retreat of 5.78 m perpendicular to the coast. Fortunes saw the greatest loss of total dune area with a 46% loss of area, with other beaches ranging from 7–40% (Table 2).

Area loss of natural dunes on the four shorelines ranged from 9–46% (mean 22%). Dune cored by seawalls and riprap ranged from 5–59% (mean 28%) and were typically greater losses than non-cored dunes (Data S1). Beaches with easterly aspects in Saco Bay experienced smaller losses to all dunes, ranging from 1.25 ± 0.41 to $4.23 \pm 0.53 \text{ m}^2/\text{m}$ of beach whereas beaches with a southeasterly aspect experienced losses from 5.97 ± 0.22 to $8.40 \pm 0.15 \text{ m}^2/\text{m}$ (Figure S1).

Across all beaches in the survey, we found a 19% increase in dune area during the recovery period and a normalized length increase of 2.94 m across all beaches. The area of dunes along the four beaches reached 86% of the pre-storm area by the fall, with 13% of the recovery being planted ($6,382 \text{ m}^2$) and 87% non-planted vegetation. Planting efforts and natural recovery of dune area along Fortunes Beach from post-storm to the fall resulted in an increase of 36% of dune area, but there

was still a net loss of dune area compared to pre-storm area.

We observed a decrease in the proportion of primary dune vegetation immediately post-storm at all beaches, with a remaining net loss at 4 out of 6 beaches after the recovery period. At Fortunes, the pre-storm proportion of primary dune area to sparse dune area was 7:1, which decreased to 4:1 post-storm and remained in the fall. Across all beaches except Bayview, we observed a net loss in the primary dune area.

3.2 Volume Change

Fortunes and Goose Rocks Beaches experienced similar losses in normalized volume during the initial storm damage, directly before and after the storms, whereas Bayview had much smaller losses (Table 2; Fig. 2b). Camp Ellis had the largest normalized dune losses but also had the most limited dune area. During the recovery period, from after the storms to fall 2024, Bayview, Fortunes, and Goose Rocks had large gains in volume to the entire beach-dune system while Camp Ellis had minimal volume recovery. The net volume change from pre-storm to fall showed a loss at all beaches except Fortunes; however, Fortunes still experienced a net loss in dune volume. The majority of dune loss at each beach occurred primarily along the seaward edge of the dunes. Over nine months of recovery, net losses remained at all beaches along the seaward edges of the dunes. On the beach faces, we primarily observed volume loss in the upper portion of the beach during the initial storm damage, followed by a large gain to the upper beach during the recovery period (Fig. 3). Of the dune volume (both primary and sparse) lost during the initial storm damage, only 10 – 50% dune volume recovered through the growing season, nine months after the storms (Table 2). Fortunes Beach had the most extensive dune planting and beach scraping during the recovery period. Areas with both planting and scraping recovered 87–91% more volume than comparable areas that did not undergo restoration efforts. However, we do not have sufficient data to quantify the impact of beach nourishment or to separate the effects of planting and scraping, as these efforts were not implemented independently on these beaches during our study period.

At all beaches, during the initial storm damage, there was a loss of primary and sparse dunes as well as sandy beach face with a volume gain during the recovery period for each vegetation type. At Fortunes Beach, there

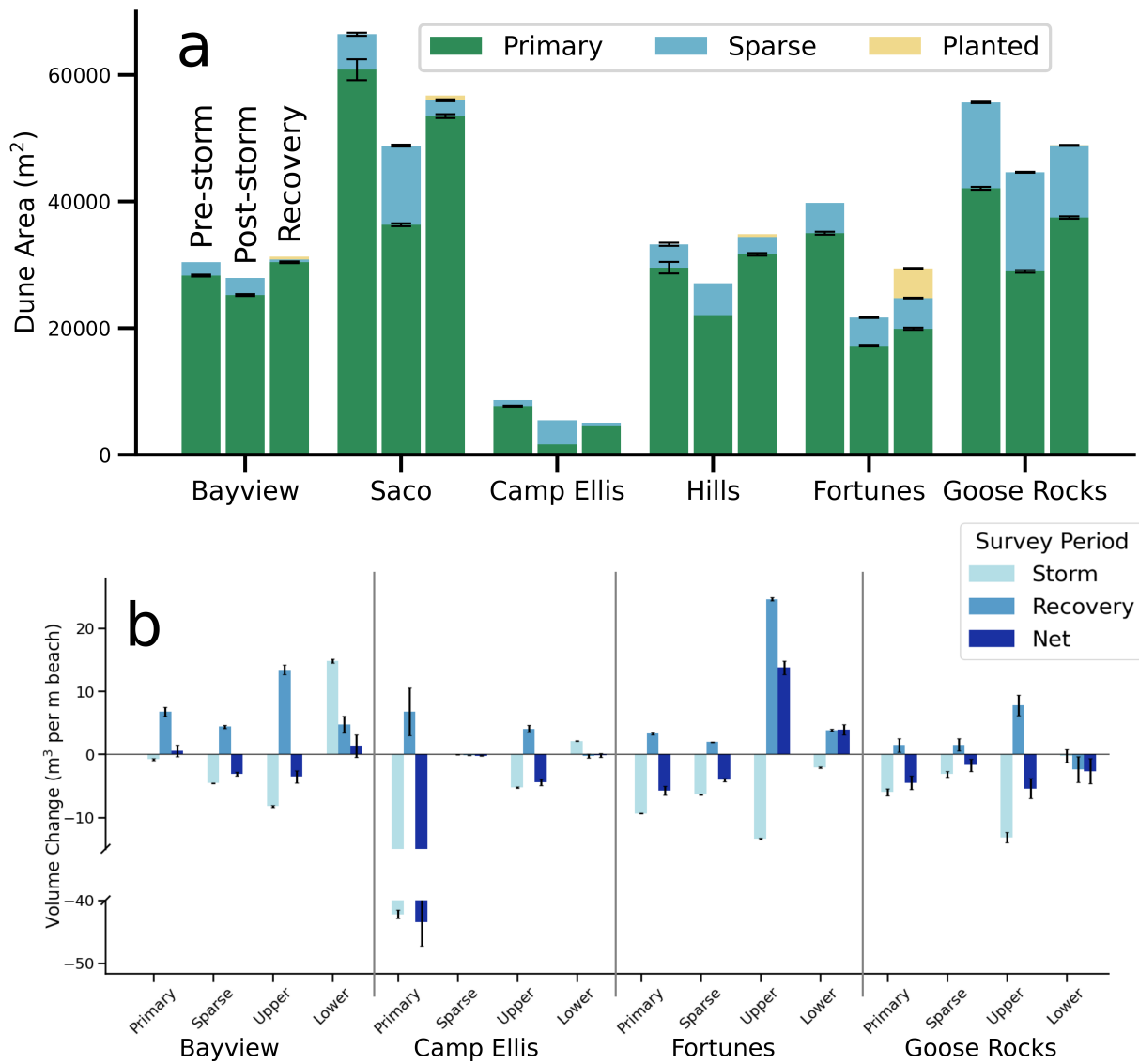


Figure 2 Annual change in dune area (six beaches) and volume change (four beaches). a) Pre-storm, post-storm, and recovered dune area (m²), separated by vegetation type: primary (green), sparse (blue), and planted/restoration (yellow). Error bars are displayed if the uncertainty is greater than 300 m². b) normalized volume change (m³/m of beach) of primary and sparse dune and upper and lower beach for each survey period storm (from before to after the storm; light blue), recovery (from after the storm to the fall; medium blue), and net (from before the storm to the fall; dark blue). Lower beach was below the winter berm and upper beach was landward, above the winter berm. Error bars represent uncertainty.

was an overall net gain in volume to the beach-dune system over the recovery period (Table 2). However, that gain was primarily driven by an increase in sandy beach volume, which varies widely seasonally and has been impacted by beach scraping and nourishment. Overall, 93% of the recovery at Fortunes is accounted for on the beaches, leaving the dunes at a net loss in volume. Bayview, Camp Ellis, and Goose Rocks Beach did not experience enough recovery to offset losses, resulting in a total net loss across the beach areas and dunes, ranging from -7.4 to 0.9 (± 3.4) m³/m, with Camp Ellis experiencing a net loss of -43.3 ± 3.8 m³/m to its dunes despite 16% recovery of initial damage (Fig. 2b).

During the storms, all coastline types experienced a similar loss in average height, ranging from -0.13 to -0.35 (± 0.02) m/m of beach length, except for Bayview, which experienced a slight increase in height of 0.11 ± 0.01 m/m of beach length along coastline backed by dunes. At Bayview and Fortunes Beaches, from post-

storm to the fall, there was an increase in height along all four coastline types. At Camp Ellis and Goose Rocks Beach, however, there was only a slight increase in the average height of beach backed by dunes whereas beach backed by seawall, riprap, and none had negligible changes in average height (Fig. 4). The average net change in height per beach length for coastline backed by both dune and riprap was -0.05 ± 0.04 m/m of coastline, and coastline backed by seawall was -0.01 ± 0.04 m/m of coastline, within the limit of detection. Although the net damage to coastlines backed by seawalls and riprap was less than or equal to that of coastlines backed by dunes, the height variation of initial damage to fall recovery for coastlines backed by dunes, seawall, and none was 0.57 m/m, 0.89 m/m, and 1.04 m/m (all ± 0.6), respectively. This indicates that there is less variation in height along coastlines backed by dunes from before the storms to the fall (Data S2).

Table 2 Total changes in dunes by area (m²) and changes in both beach and dune volume (m³) by coastline over time with total change in dune area and volume and normalized change by shoreline length (area: m²/m, volume: m³/m).

| Beach Name | | Storm Damage (Pre-storm to Post-storm) | | Recovery (Post-storm to Fall) | | Net (Pre-storm to Fall) | |
|-------------|--------------------------|--|-------------|-------------------------------|------------|-------------------------|------------|
| | | Total | Normalized | Total | Normalized | Total | Normalized |
| Bayview | Volume (m ³) | 5,500 ± 900 | 3.9 ± 0.6 | 39,000 ± 3,700 | 27.5 ± 2.6 | 1,200 ± 5,000 | 0.9 ± 3.4 |
| | Area (m ²) | -2,200 ± 200 | -1.2 ± 0.1 | 3,000 ± 200 | 1.7 ± 0.1 | 900 ± 200 | 0.5 ± 0.1 |
| Camp Ellis | Volume (m ³) | -3,700 ± 100 | -3.1 ± 0.1 | 3,000 ± 600 | 2.5 ± 0.5 | -3,400 ± 600 | -2.8 ± 0.5 |
| | Area (m ²) | -3,100 ± 100 | -2.5 ± 0.1 | -400 ± 80 | -0.3 ± 0.1 | -3,500 ± 100 | -2.9 ± 0.1 |
| Saco Coast | Volume (m ³) | - | - | - | - | - | - |
| | Area (m ²) | -16,000 ± 2,000 | -4.2 ± 0.5 | 6,400 ± 500 | 1.7 ± 0.1 | -9,700 ± 2,000 | -2.5 ± 0.5 |
| Hills | Volume (m ³) | - | - | - | - | - | - |
| | Area (m ²) | -6,200 ± 1,200 | -4.5 ± 0.8 | 7,800 ± 300 | 5.7 ± 0.2 | 1,600 ± 1,200 | 1.2 ± 0.9 |
| Fortunes | Volume (m ³) | -67,000 ± 700 | -19.7 ± 0.2 | 100,000 ± 1,500 | 31.0 ± 0.4 | 56,000 ± 7,300 | 16.2 ± 2.1 |
| | Area (m ²) | -18,100 ± 300 | -8.4 ± 0.2 | 7,800 ± 300 | 3.6 ± 0.2 | -10,300 ± 300 | -4.8 ± 0.1 |
| Goose Rocks | Volume (m ³) | -55,000 ± 6,200 | -17.0 ± 1.9 | 31,000 ± 12,000 | 9.6 ± 3.9 | -23,700 ± 12,500 | -7.4 ± 2.9 |
| | Area (m ²) | -12,500 ± 500 | -6.0 ± 0.2 | 5,700 ± 400 | 2.7 ± 0.2 | -6,800 ± 400 | -3.2 ± 0.2 |

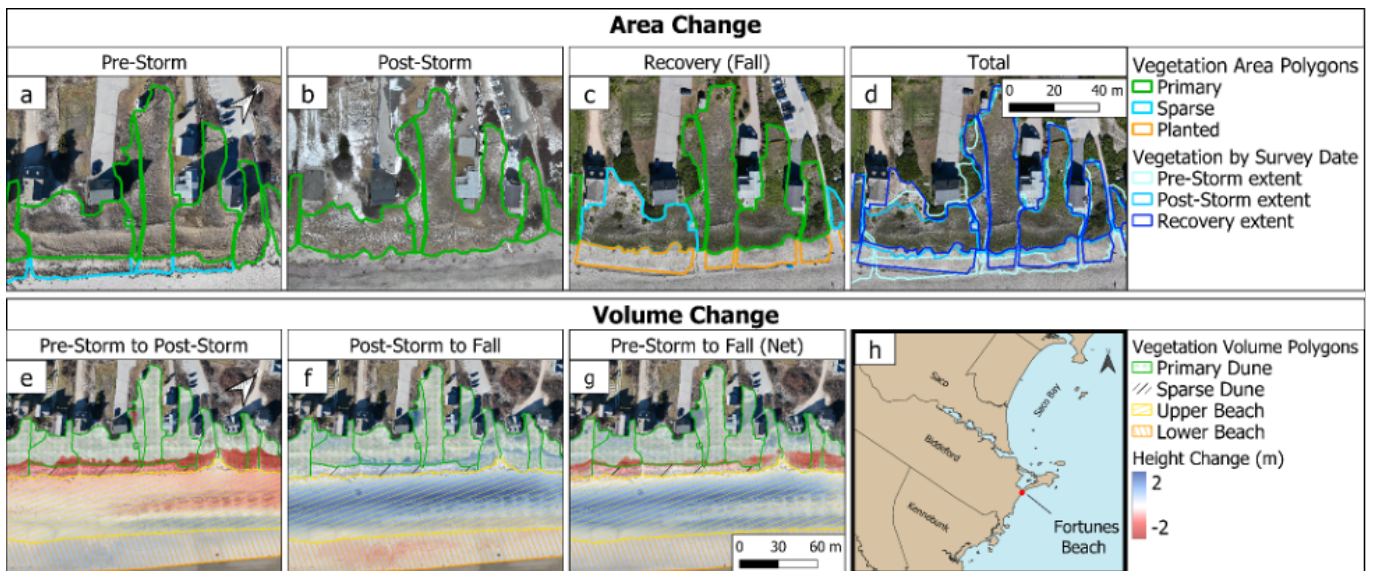


Figure 3 Fortunes Beach dune area and volume change. a) Extent of dune areas pre-storm (date: 4th Jan 2024), b) post-storm (date: 22nd Feb 2024), c) in the fall after annual recovery (date: 8th Sep 2024), and d) total change in dune extent on imagery from c. e-g) Differenced DSMs for each time period used to derive volumes associated with the plot and date above it. Red indicates erosion, contributing to volume loss within the vegetation volume polygons. Blue indicates deposition, contributing to volume gain within the vegetation volume polygons. White indicates the limit of detection from ±0.1 m h) Location of map frames within Fortunes Beach and our study area.

4 Discussion

Natural coastlines, such as dunes, provide an area where storm surge, tidal forces, and wave energy can dissipate and be absorbed, reducing storm damage (Barone et al., 2014). During the 2024 storms, dunes were eroded, particularly along their seaward edges, and initially lost 28% of their area and experienced net losses to dune volume on each beach after recovery. It is well documented that hardened coastlines such as seawalls and riprap are more susceptible to erosion than dunes, especially during intense storms like hurricanes, given direct wave exposure (Olivera et al., 2024; Walling et al., 2016). Since hardened coastlines reflect wave energy, it is difficult for sand to accumulate at the base after it has been removed, resulting in net volume loss,

especially along upper beach faces (Beuzen et al., 2018). This is consistent with our observations that the upper beaches, particularly along coastline backed by seawalls and riprap experienced 60–97% greater initial volume erosion per meter of beach than upper beaches backed by dune, likely because the hardened structure concentrated erosive forces onto the upper beach (Data S2). Along with this, the profile height of coastline backed by seawalls and riprap fluctuated 0.14 – 0.32 m greater than coastline backed by dune throughout the storm and recovery periods (Fig. 3). This suggests that dunes offer a superior and stable form of coastal protection in that they are able to maintain more sand during storm events. Future work should collect data on the relative property damage behind these different coastal defenses, which is likely of primary concern to coastal

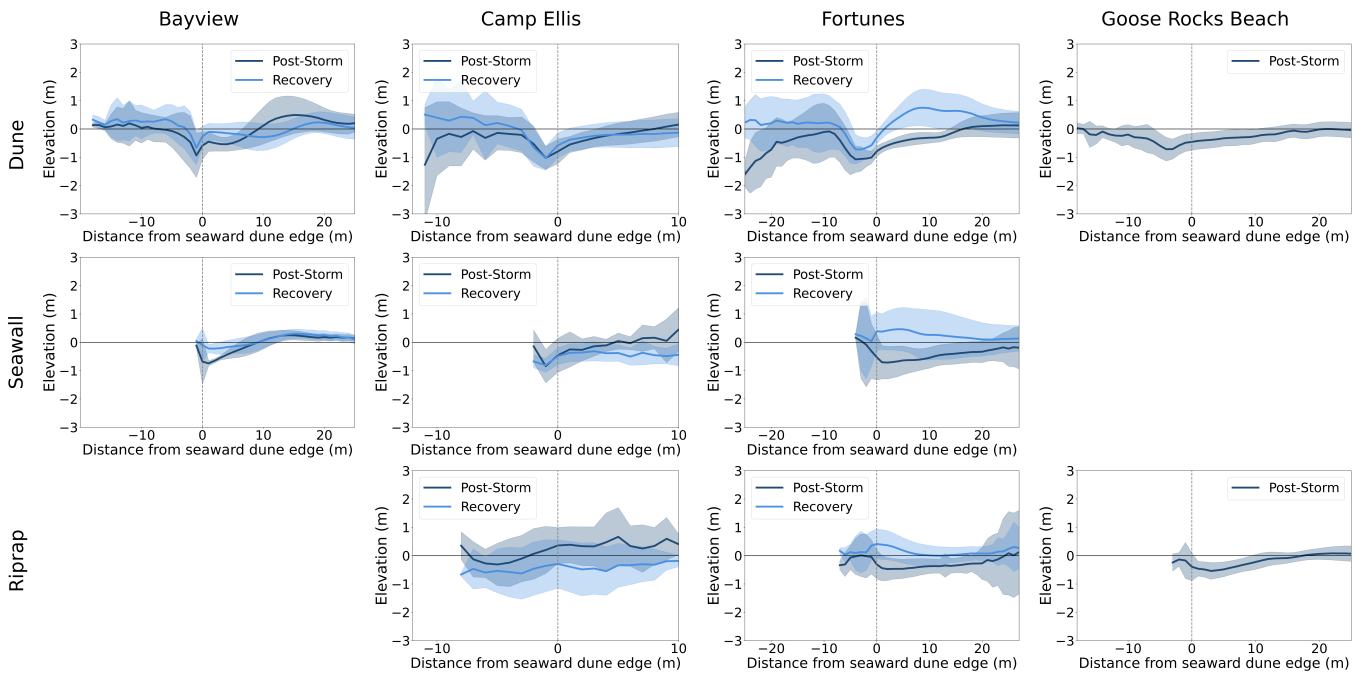


Figure 4 Average beach profiles of four beaches separated by type of coastline backing the beach (i.e. dune, seawall, and riprap) derived from coregistered DSMs. The post-storm line (dark blue), collected directly after January storms, indicates vertical change from the pre-storm profile. The recovery line (light blue), collected in the fall, indicates vertical change from the pre-storm profile to the fall recovery period. Lines represent average elevations for each beach position calculated from perpendicular cross sections along each beach. A distance of 0 meters marks the seaward extent of dune vegetation; negative distances extend landward across the backdune, while positive distances extend seaward toward the ocean. Shaded regions around the lines indicate one standard deviation for each average beach profile.

property owners.

Simulated wave flumes suggest that dune cored by hardened structures respond similarly to natural dunes until erosion has exposed the underlying structure, which then responds as the underlying structure with more intense and concentrated wave uprush and downrush (Kobayashi and Kim, 2017). Our observations indicate that dunes cored by seawall and riprap experienced 6% higher initial area loss compared to natural dunes. At Fortunes beach, the seawall cored dune areas were exposed after the overlying sandy dune and vegetation eroded, which thereafter likely caused that section of beach to behave similarly to beach backed by seawalls, resulting in greater erosion along cored dune beach, although it likely offered protection to the remaining dune fragments. Expectedly, during recovery, the area of cored dune vegetation returned at a slower rate than non-cored dune areas with non-cored dunes recovering 150% greater dune area than cored dunes. Cored dune recovery was likely slower because the underlying hard structures (e.g., seawalls) were exposed after the storms, limiting the natural accumulation of sand and inhibiting vegetation recolonization, though we lack data on post-storm sediment transport, deposition patterns, and nearshore bathymetry.

Fortunes and Goose Rocks Beach have similar southeasterly aspects and are not within Saco Bay (Fig. 1; Figure S1). Notably, a physical difference between these two beaches is the presence of offshore bedrock protrusions at Goose Rocks Beach, likely buffering the coastline from waves. Both beaches experienced similar total volume losses initially after the storms between -17 and $-19.7 \pm 1.9 \text{ m}^3/\text{m}$. The proportion of that volume loss on

beach area, primary dune, and sparse dune were also similar at both beaches (Fig. 2). During the recovery period, both beaches had similar dune recovery at $5 \pm 1.1 \text{ m}^3/\text{m}$; however, out of the entire system, dune and beach face, Fortunes had a 136% greater recovery volume gain than Goose Rocks Beach. Goose Rocks Beach had a net loss from before the storm to the fall whereas Fortunes had a gain, which was primarily driven by increased volume of the upper beach. The offshore rock outcroppings at Goose Rocks Beach are primarily on the west side, where we observed $-14.2 \pm 1.9 \text{ m}^3/\text{m}$ of volume loss during the storm, while the east side more than double, at $-32.7 \pm 1.9 \text{ m}^3/\text{m}$. While we initially hypothesized that the offshore rocks at Goose Rocks Beach provided a buffer against storm erosion, the beach experienced a volume loss similar to that of Fortunes Beach, which lacks offshore rocks but has a comparable aspect. Although we do not have data on offshore sediment transport, Fortunes and Goose Rocks Beach have similar closure depths offshore (Fig. 5). Due to Goose Rocks Beach’s isolation by rock outcroppings and partial embayment, we hypothesize that Goose Rocks Beach may be less integrated into the onshore-offshore sediment transport cycle, making it difficult for sediment to exit and enter the immediate bay and replenish the beach and dunes.

The dunes at Camp Ellis Beach lost more sand on a normalized basis during the observed storm period compared to the other studied beaches. We observed $42.2 \pm 0.6 \text{ m}^3/\text{m}$ of dune volume loss at Camp Ellis, which never fully recovered by fall (Fig. 2b). We hypothesize that this is due to the jetties and riprap infrastructure that surrounds these dunes. Since the construction of

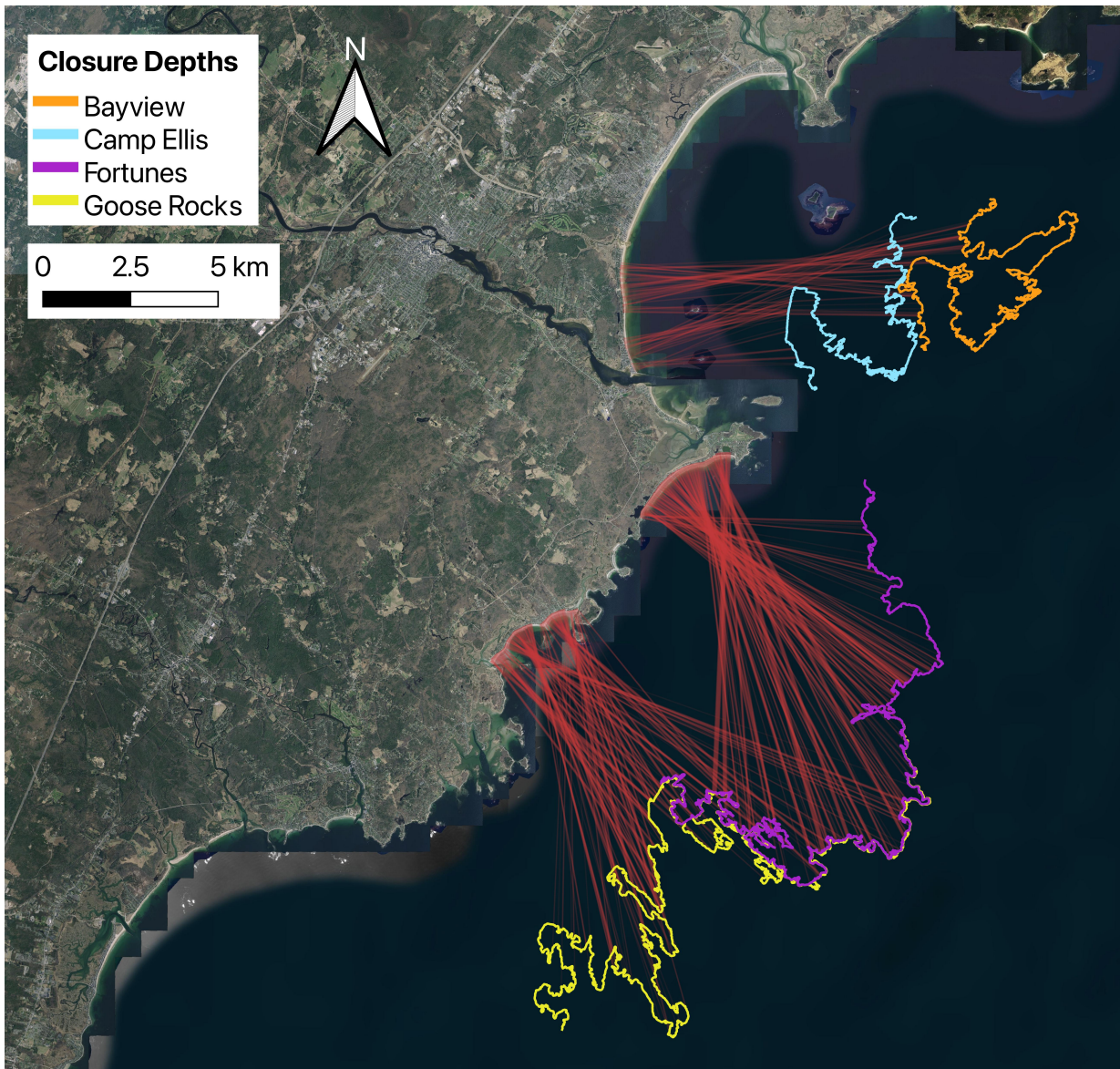


Figure 5 Mean closure depths and their respective distances to our study sites. Bayview and Camp Ellis, in Saco Bay, had closure depths of 11.63 m and 9.51 m, respectively. Fortunes Rock had a closure depth of 15.68 m, and Goose Rocks had a closure depth of 15.82 m (all depths in meters below NAVD88). Sample lines were generated 5 m apart perpendicular to the beach and clipped with closure depth contours derived from BlueTopo bathymetric data from NOAA.

the north jetty at Camp Ellis in 1866, followed by the addition of another jetty at the south end of the Saco River in 1897, both of which were lengthened and raised throughout the 20th century (Fig. 1c), it is suggested that wave energy has been concentrated on the Camp Ellis coastline, causing coastline retreat of around 100 m and resulting in the loss of over 30 homes (USACOE, 1992; Kelley et al., 2005; Kelley and Brothers, 2009). This long-term erosion of Camp Ellis is further evidenced by accretion to the north at Pine Point in Scarborough, Maine as the sand migrates north (Kelley et al., 2005). Energy concentration on the Camp Ellis coastline by the jetties could be an explanation for the much higher rate of erosion we observed. To compensate for this erosion, the City of Saco has attempted numerous times to ge-engineer the beach with sand and other measures (Personnel communications, City of Saco), and a planned spur jetting by the US Army Corp of Engineers, extending 230 m (750 ft) perpendicular from the existing Saco

River jetty, could slow erosion. Given that Camp Ellis has long been cut off by the jetties from its main sediment source, the Saco River (Kelley et al., 2005), and we do not observe an annual recovery of beaches or dunes, the City of Saco may potentially need to continue periodic nourishment to maintain the beach.

Dunes have a natural recovery mechanism, where vegetation traps windblown sand, promoting deposition and vertical accretion (Costas et al., 2024). In addition to this natural recovery, various human-led restoration efforts, including dune grass planting/adding nutrients, beach scraping, and beach nourishment, are commonly employed (Morton et al., 2025; Moore et al., 2020; Johnston et al., 2023; Wells and McNinch, 1991). Beach nourishment, in particular, is known to have many positive effects on dune restoration and especially on beaches backed by seawalls that subsequently have difficulty accumulating sand (Olivera et al., 2024; Tiede et al., 2024; Johnston et al., 2023). Fortunes Beach had

the most extensive planting and scraping efforts of all the sites in our study and had some areas that did not receive restoration. This makes it an ideal location to assess the efficacy of restoration techniques. The planting at Fortunes took place in the spring, which allowed us to observe recovery over the course of a single growing season, from immediately after the storm to the fall. Our findings showed that dune areas with both planting and scraping recovered 87–91% more height compared to areas with no restoration efforts. We observed that the upper beach with scraping recovered 0.14 m less sand than the upper beach without scraping. This indicates that sand removed from the upper beach and placed on the dunes during the scraping process does negatively impact the beach, although it has substantial benefits to the dunes behind it. We additionally find that the entire beach width consisting of planted dune, upper, and lower beach saw an average height gain of 0.51 m during the recovery period while beach width without planting saw an average height gain of 0.55 m, suggesting that scraping and planting is less effective in capturing sand on the beach. However, our results show that scraping is effective at incorporating sand into dunes by making sand immediately available for incorporation into the dune system and can quickly bolster coastal protections, which is more affordable for property owners to implement with the benefit it yields.

Future work should focus on sand moving from the lower beach into near shore areas during storms, where it would take much longer to return and become available for incorporation back into the beach and dune system (Fig. 5). Given that we only present about nine months of post-storm data here, more long-term observations are needed to understand how the beach and dune system respond to planting and scraping over years and multiple storm events. Restoration efforts will continue to be important in the future with the increasing frequency and severity of storms (Picard et al., 2023), especially given that we did not observe positive net recovery of dune area or volume during our study period. Though some beach faces had positive recovery by fall, they are more prone to large fluctuations of sand, especially during intense storms, as we document here. Beach scraping and dune planting, which were 90% more effective for the dune than no action, is one strategy to support the recovery and longevity of dunes and stability of beach faces as record-breaking storms, similar to those that occurred in January of 2024, continue and become more frequent.

Because the storms of January 9–10 and 13th, 2024, tracked further south than typical winter storms (Zielinski, 2002; Picard et al., 2023; Townsend et al., 2006), winds from these storms were out of the southeast rather than the northeast, making winds perpendicular to Fortunes and Goose Rocks Beaches, which have a southeast aspect (Figure S1). Our results further indicate more erosive forces present on Fortunes and Goose Rocks Beach as these southeast facing beaches underwent 18–22% higher normalized volume losses than east facing beaches during the storms (Fig. 2b). If storms continue to track further south as has been documented in recent years, beaches in Maine, particularly with a

southeast aspect, may be more at risk of volume loss during intense winter storms, increasing the vulnerability of the coastline.

5 Conclusions

The winter storms that hit Maine in January 2024 caused substantial damage to the state's coastal dunes and beaches, with a record high water level resulting from coinciding storm surge, waves, and astronomical high tide. Across four shorelines in southern Maine dune area loss ranged from 18–45%, with the greatest impact at Fortunes Beach, where natural dunes lost 46% of their area. Dune volume recovery was limited to only 10–50% of the initial storm damage. Despite restoration efforts, including dune grass planting and beach scraping, vegetation regrowth was sparse, and most beaches experienced a net loss of dune area and volume over nine months of recovery. Though coastline backed by hardened structures, particularly seawalls, retained more sand volume during the recovery period than coastline backed by dunes, they also underwent greater initial volume losses than coastline backed by dune. Though dunes were more stable during the storm and recovery period, seawalls, riprap, and cored dunes should only be removed where dunes can be effectively built and maintained. Our results, less than one year after the storm, suggest that beach scraping and dune planting are effective strategies, as they were 90% more effective in building dune height than no action. Although, additional observations are needed to quantify the long-term efficacy of scraping and planting and extend the dataset into shallow depths. Beaches with a southeasterly aspect experienced greater volume loss compared to other beaches, likely due to storm winds coming from the southeast. Given that we did not observe a positive net recovery of dune area or volume, restoration efforts may be essential for the recovery, longevity, and stability of dunes and beach faces, especially as record-breaking storms, like those in January 2024, are expected to track further south and become more frequent.

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Land Recognition

We recognize that our work was completed from an institution located on the traditional and unceded lands of

the Wabanaki.

Data and Codes Availability

All dune polygons, ortho imagery, and digital elevation models are made freely available here: DeWater, Katelyn; Pittsley, Matthew; Birchem, Johanna; Ellis, Ruth; Janik, Tyler; Merrill, Paige-Marie; and Kochtitzky, William, "Erosion of Coastal Beaches and Dunes During the Highest Water Level on Record in Southern Maine, USA (Data Files)" (2025). Geographic Information Systems Data Projects. 3. https://dune.une.edu/gis_data/3.

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Conflict of Interest Disclosure

The authors have no competing interests.

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Declaration on Artificial Intelligence Use

The authors declare that no generative artificial intelligence was used in the writing of this manuscript.

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