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Incorporating Measurements of Vertical Land Motion in Wetland Surface Elevation Change Analyses

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Abstract

We compared elevation trajectories from 14 rod surface elevation table (RSET) stations and 60 real-time kinematic (RTK) global positioning system (GPS) transects within the Blackwater National Wildlife Refuge (BNWR) from 2010–2013. The results were similar, 7.3 ± 0.9 (mean ± standard error; RSET) versus 6.2 ± 0.6 mm year^{-1} (RTK) ($P = 0.216$), and were greater than relative sea level rise (RSLR) computed at the nearest long-term tide station (3.9 ± 0.29 mm year^{-1}). Despite having shown elevation gain, these marshes continue to drown and convert to open water. Episodic, multi-day GPS measurements on geodetic control marks at BNWR between 2005 and 2023 revealed a substantial vertical land motion (VLM) signal. From 2005 to 2015, three reference marks used to control the 2010–2013 RTK study lost on average 6.0 ± 0.7 mm year^{-1}, corresponding to 80% and 94% of the elevation gain measured by the RSET and RTK techniques, respectively. The longer 18-year subsidence trend measured on one of these marks was lower, 3.9 ± 0.7 mm year^{-1}, highlighting important interannual variability. Wetland elevation change measurements need to account for VLM occurring below the reference marks used to measure elevation change. Estimates from the nearest long-term tide station may not be applicable to the wetland if the tide station is in a different geological setting. At BNWR, VLM was higher than the VLM at the Cambridge tide station, which helps explain why wetlands at BNWR are not keeping pace with RSLR despite the measured high rates of elevation gain.

Keywords

Wetland elevation
Sea level rise
Subsidence
Vertical land motion
SET
Real-time kinematic
GPS

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Supplementary Information

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Introduction

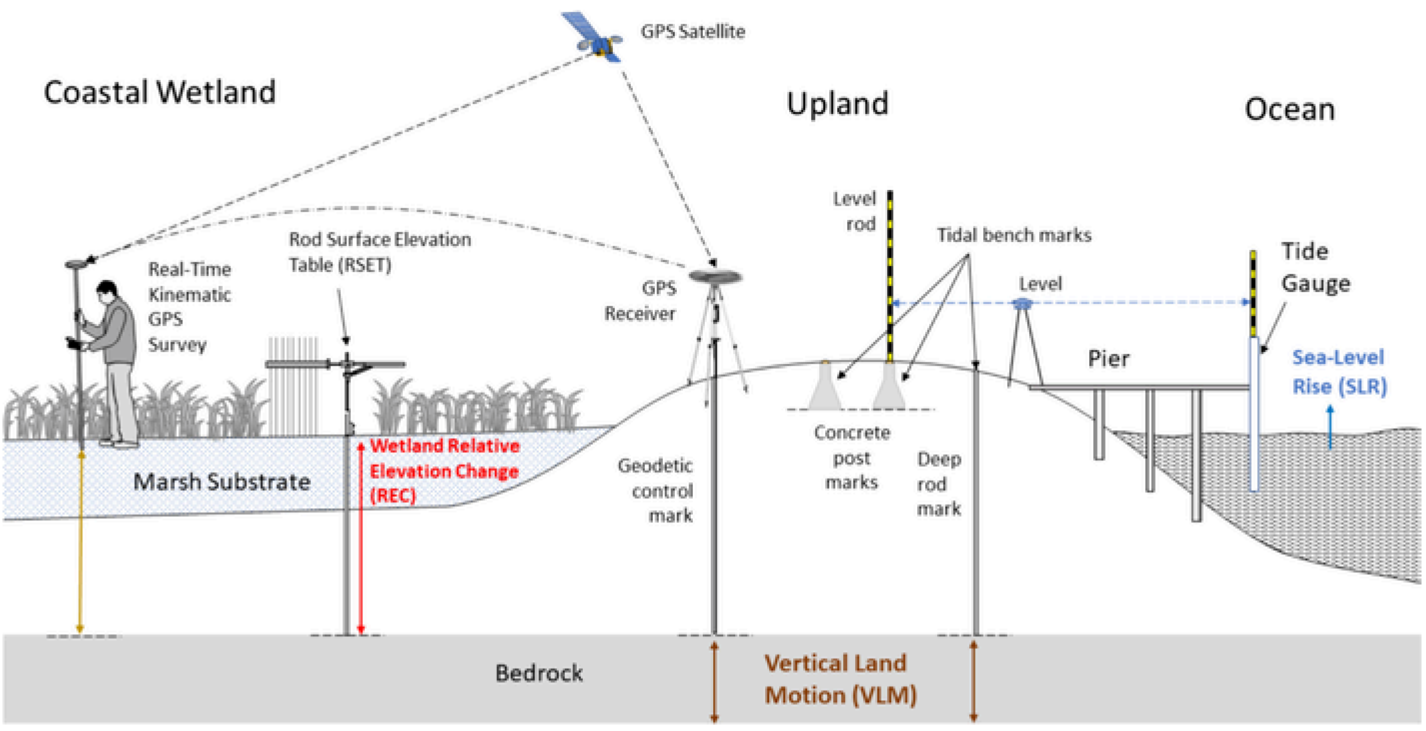
Coastal wetlands are restricted to a narrow elevation range in the intertidal zone (McKee and Patrick 1988) rendering them sensitive to changing sea levels if marsh soil elevation gain does not keep pace with global sea level rise (SLR). At the lower end of the elevation range, wetland plant species experience too much flooding, weaken, die, and can no longer keep the sediment intact resulting in soil erosion. Coastal wetlands exhibit robust processes of vertical growth, through a combination of surface sediment deposition and below-ground biomass accumulation (Cahoon et al. 1995, 2019, 2021; Morris et al. 2002). However, accelerating SLR, in combination with land subsidence and reduced sediment supplies (Weston 2014), means that many wetlands are vulnerable to inundation and loss (Ganju et al. 2015; Raposa et al. 2016). A result has been a considerable reduction in the size and distribution of coastal wetlands, especially along the U.S. Mid-Atlantic coast (e.g., Stevenson et al. 1985; Kearney et al. 2002; Weston 2014). Rates of global SLR are predicted to continue increasing into the future, threatening coastal wetland persistence and resilience, regardless of which emission scenario is realized (IPCC 2021). To plan for wetland sustainability in the face of these trends, natural resource managers need to know several key metrics, including the current elevation of their wetlands with respect to local water levels (tidal datums), and rates of wetland elevation change (Cahoon 2015; Hensel et al. 2023). **AQ1**

The rod surface elevation table (RSET; Fig. 1) is a method used to assess the ability of wetlands to accrete vertically over time (e.g., Saintilan et al. 2022). The RSET technique relies on a deep rod mark construction made of 14-mm diameter, 122-cm long, stainless steel survey rods threaded together and driven into the substrate until refusal (Cahoon et al. 2002; Callaway et al. 2013; Lynch et al. 2015). In wetland settings, 12 to 24 m of the rod are typically able to be inserted. Although the length of rods inserted is known, the precise depth of the mark is unknown, as rods can bend when they hit obstructions (Lynch et al. 2015). At a given measurement epoch, an operator deploys the RSET instrument atop the RSET mark and measures the distance between the wetland soil surface and the horizontal arm of the RSET, recording to the nearest millimeter (Cahoon et al. 2002). Over time, these measurements enable the calculation of surface elevation change relative to the RSET mark. To emphasize that elevation change is measured relative to the in situ RSET mark, we follow the terminology of Doar and Luciano (2023) and use the term wetland relative elevation change (REC). The technique presumes that the RSET mark is stable within the wetland sediment matrix, which can be confirmed by repeated comparisons to a local vertical datum (Swales et al. 2016; Blum et al. 2021; Cahoon 2024). The RSET technique thereby measures REC above the base of the RSET mark, wherever that is in the sediment column (Cahoon 2015, 2024). The RSET technique, often paired with surface marker horizons to measure surface accretion, has revolutionized the understanding of wetland vertical processes (Webb et al. 2013; Saintilan et al. 2022).

Fig. 1

Conceptual diagram (not drawn to scale) showing different measurements of vertical change in a coastal setting (from right to left): a tide gauge measuring sea level rise (SLR) referenced via leveling to a network of upland tidal benchmarks; a geodetic control (deep rod) mark observed with GPS measuring vertical land motion (VLM; also shown is a radio transponder supporting real-time kinematic GPS); a rod surface elevation table, and a real-time kinematic GPS survey, both measuring wetland relative elevation change (REC).

Modified from Cahoon (2015, 2024)



Other techniques to measure REC have included leveling (Cain and Hensel 2018; Lynch et al. 2023), total station theodolites (Lynch et al. 2023), real-time kinematic (RTK) global positioning system (GPS) surveys, lidar surveys (Webb et al. 2013; MacKenzie et al. 2023), aerial imagery from drones (Kalacska et al. 2017), and InSAR (Da Lio et al. 2018). The vertical resolution of these techniques may vary; however, they all fundamentally rely on local geodetic control marks to localize the survey and compare elevation changes over time. An added benefit of GPS surveys is that they can be used to measure actual elevation with respect to a geometric reference frame (e.g., the International Terrestrial Reference frame of 2014, or ITRF2014; Altamimi et al. 2016) or an orthometric vertical datum (e.g., North American Vertical Datum of 1988, or ~~(~~NAVD 88~~,)~~ in the continental USA). Note that the same deep rod technology used by the RSET is used to establish deep rod geodetic control marks (Floyd 1978). Therefore, RSET marks and adjacent deep rod geodetic control marks can presumably both be anchored in the same underlying bedrock (Fig. 1).

To estimate wetland resiliency to accelerated SLR, scientists compare site-specific measurements of REC with the RSLR at well-established, long-term tide stations (e.g., Doar and Luciano 2023; Fig. 1). Long-term tide stations provide estimates of SLR relative to a local network of tidal benchmarks. If the land to which the tide station is referenced is itself undergoing vertical land motion (VLM), the resulting RSLR will include both SLR and VLM (Zervas et al. 2013). For this reason, we typically refer to long-term SLR at tide stations as RLSR because a tide station will always confound SLR with VLM. A presumption is often made that we can compare REC measured at a SET to RSLR at the nearest long-term tide station because both measurement types are referenced to a deep rod mark, presumably anchored in the same bedrock (Cahoon 2015, 2024; Doar and Luciano 2023). VLM can be measured directly via repeated GPS measurements (Swales et al. 2016; Doar and Luciano 2023; Fig. 1). In lieu of such direct measurements, scientists sometimes subtract the presumed global mean sea level trend from RSLR estimates at long-term tide stations to estimate VLM (e.g., Holdahl and Morrison 1974; Shinkle and Dokka 2004; Zervas et al. 2013). The presumption that we can compare REC to RSLR from the nearest tide stations warrants being tested. Although VLM can have broad, regional patterns, it is less well known to what extent local variations exist that can substantially modify the local VLM signal. For example, Swales et al. (2016) reported that VLM beneath SET rods in a mangrove forest in New Zealand was 2- to fivefold higher than VLM beneath a tide station located 10 km away. Similarly, Doar and Luciano (2023) measured rates of VLM at SET stations that were at least twice as high as the rate estimated from the nearest long-term tide station. Along the U.S. Mid-Atlantic coast, where this study was conducted, global isostatic adjustment (GIA) is causing regional subsidence as the forebulge beyond the former ice sheet margin collapses, leading to higher rates of RSLR (Snay et al. 2007; DeJong et al. 2015; Roy and Peltier 2015; Karegar et al. 2016; Pico et al. 2017). However, studies have reported localized subsidence hotspots in this region, presumably related to human activities such as groundwater withdrawals (Nelms and Moberg 2018; Ulizio 2021). This indicates that VLM may vary locally across the region.

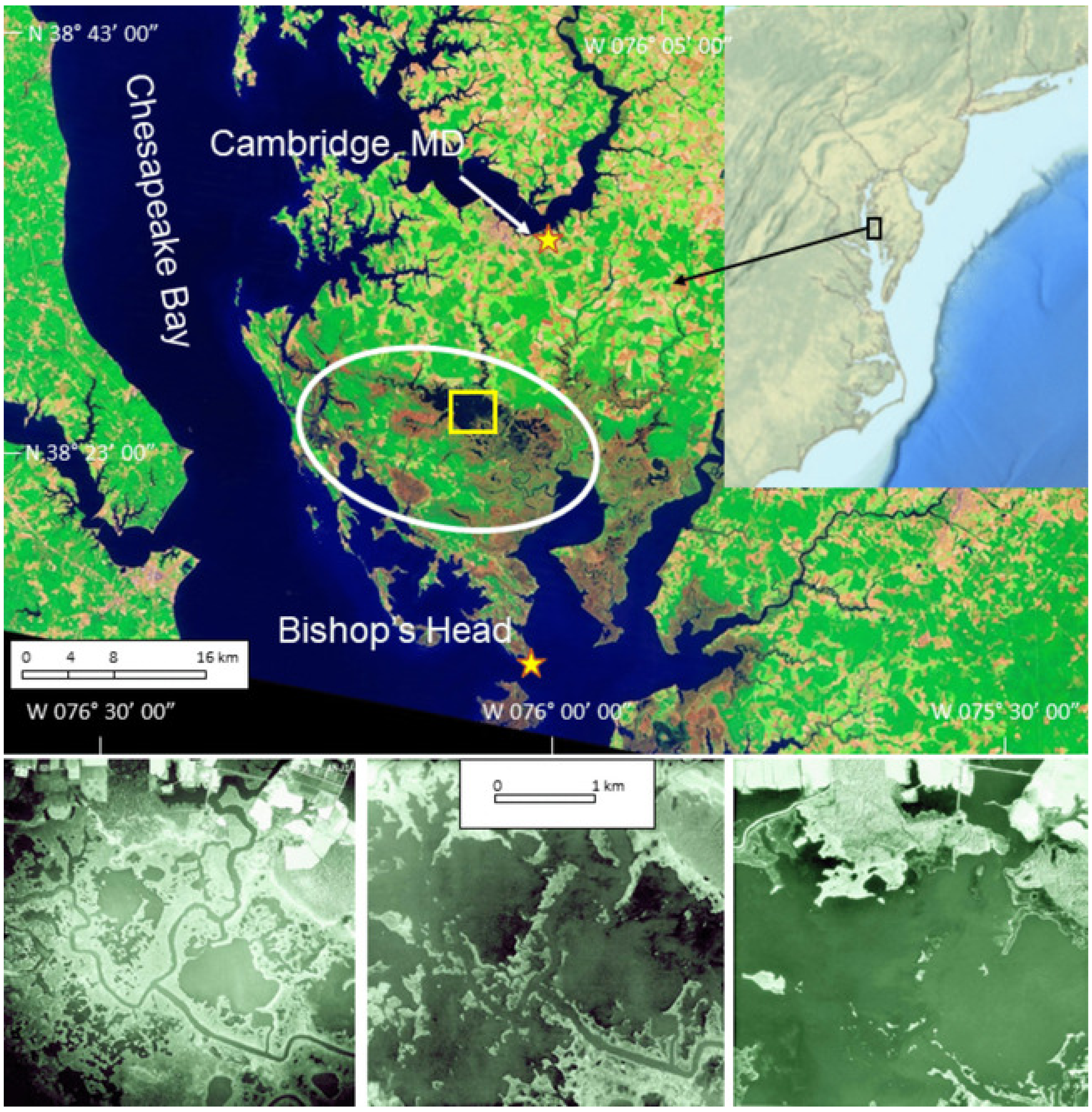
In this study, we tested two separate hypotheses: (1) whether REC as measured by the RTK GPS technique was similar to the rates measured over the same time interval using the RSET technique and (2) whether we could compare REC to RSLR at the nearest long-term tide station, when the tide station was not located at the wetland site. It was important to test the first hypothesis to ensure that estimates using one method or the other were not somehow biased. If both methods agreed, we could conclude that the rates of REC were a correct reflection of the vertical processes active in the broader wetland system. We tested the second hypothesis by analyzing repeated long, static, campaign-style GPS measurements on several geodetic control marks taken episodically over more than a decade to directly measure VLM. We then compared these measured rates of VLM to the computed rate of VLM at the nearest long-term tide station. It was important to test this second hypothesis given that many published studies investigating REC presume that these rates can be directly compared to RSLR at the nearest long-term tide station, assuming that VLM is essentially a regional process, not site-specific.

Site Description

The Blackwater National Wildlife Refuge (BNWR; N 38.4139, W − 76.0972 NAD83 (2011)) is a U.S. Fish and Wildlife Service refuge on the eastern shore of the Chesapeake Bay, south of the town of Cambridge, Maryland (Fig. 2). It was created in 1933 as a waterfowl sanctuary for birds migrating along the Atlantic Flyway and consists of over 11,000 ha of freshwater impoundments, brackish tidal wetlands, meadows, and lowland forests. Currently, the refuge contains about 3600 ha of wetlands, approximately one-third of the wetlands in the State of Maryland (Strain 2014). Natural marshes in and around the BNWR are brackish (about 2–5 ppt salinity; Stevenson et al. 1985), dominated by *Spartina alterniflora* along the marsh edge, with *Schoenoplectus americanus*, ~~and~~ *Spartina patens*, and *Distichlis spicata* dominating the interior marsh. This marsh type is typical of brackish marshes along the east coast of the USA (Cahoon et al. 2010).

Fig. 2

Map showing location of the Blackwater National Wildlife Refuge (N 38.4139, W − 76.0972 NAD83 (2011)) on Maryland's Eastern Shore, the approximate extent encircled in white on the top panel. The locations of the Cambridge and Bishop's head tide stations are shown as yellow stars. Bottom panel shows aerial imagery of Blackwater marshes in 1938 (left), 1974 (center), and 1989 (right). The approximate location of the bottom aerial imagery is indicated by the yellow box in the larger map. Bottom panel photo credits: FWS



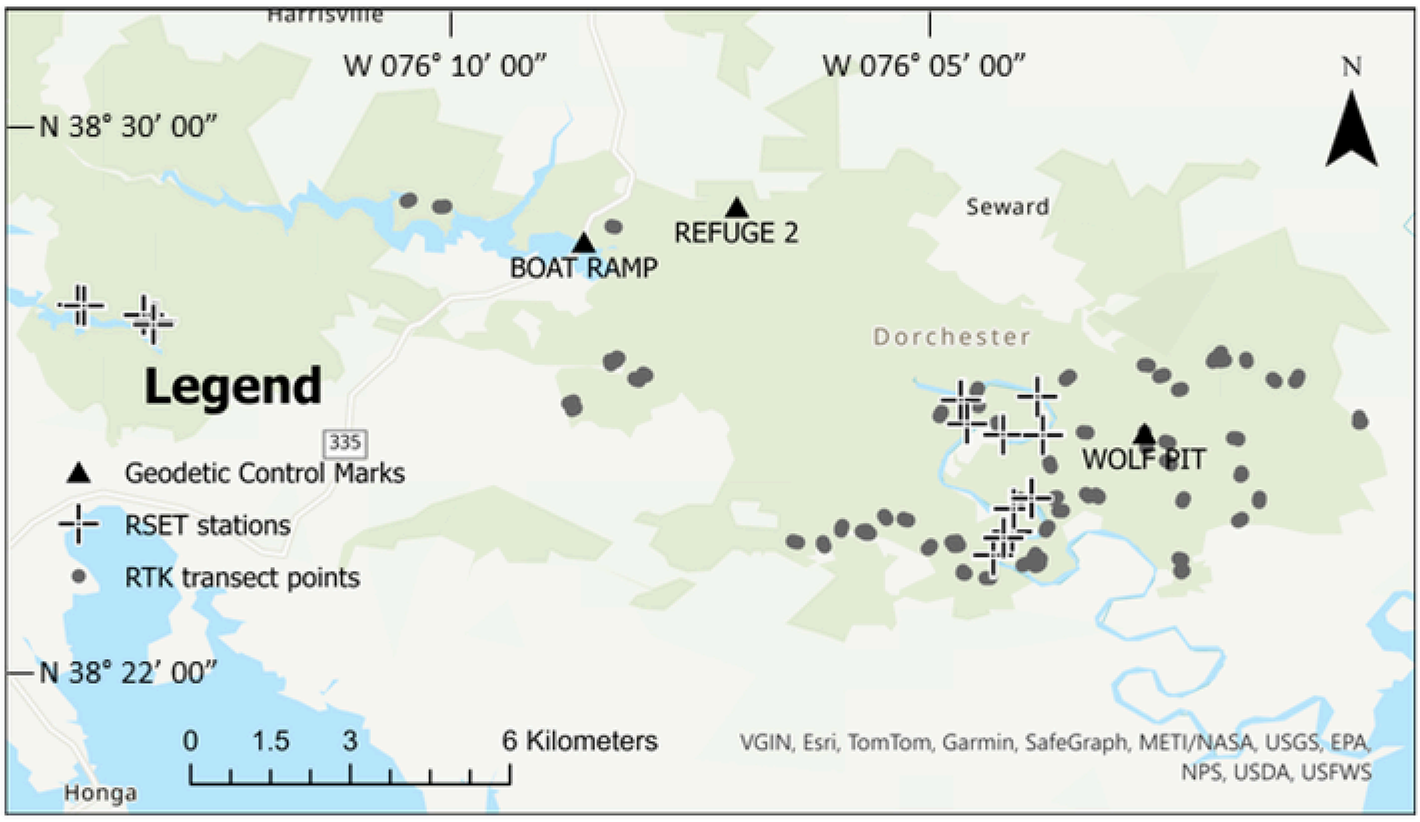
The wetlands in the interior of BNWR have been disappearing for many decades (Fig. 2; Stevenson et al. 1985). The refuge has been a prime example of the pattern of drowning interior marshes leading to the creation of small interior ponds, which increase in size, fuse with nearby ponds, and create megapools (e.g., Schepers et al. 2017; Himmelstein et al. 2021). The refuge is situated in a known regional subsidence hotspot (Holdahl and Morrison 1974; Sallenger et al. 2012; Eggleston and Pope 2013; DeJong et al. 2015; Love et al. 2016; Ohenhen et al. 2023), although evidence of localized subsidence within the refuge itself has been scanty. For years, refuge managers have facilitated research on the refuge aimed at discovering the processes resulting in such rapid wetland loss. Early studies pointed to a loss of sediment supply and altered hydrology due to road construction (e.g., Stevenson et al. 1985), but in the early 2000s, attention was focused on the traditional practice of controlled burning of the marsh (used in the nineteenth and early twentieth centuries in support of muskrat harvesting). A research project was established to test whether different return frequencies of controlled marsh burning promote vigorous wetland plant growth and enhance vertical accretion and elevation gain (Cahoon et al. 2010). The BNWR also enhanced the spatial extent of its monitoring of wetland elevations according to the burn regime throughout the refuge using single-base RTK (one base receiver controlling the RTK survey at any given moment in time). Over this same time period, the National Geodetic Survey (NGS) partnered with the U.S. Geological Survey (USGS) and the U.S. Fish and Wildlife Service (FWS) to run campaign-style GPS surveys in the region, which helped inform the VLM signal in this area.

Materials and Methods

We obtained wetland REC data from 14 wetland rod surface elevation table (RSET) sampling stations within BNWR (Fig. 3). Twelve of the stations had been established as part of the experimental prescribed burning framework (Cahoon et al. 2010). That framework is not the direct focus of this paper (the authors had found no differences in wetland vertical dynamics among the different burn treatments). Rather, the salient characteristic was that the 12 RSET stations were distributed across the study site in 2006 (Fig. 3) and sampling was conducted through 2013. We used REC data from 2010–2013 that overlapped with the GPS surveys. We obtained additional data from 2 more RSET stations that were part of a broader SET monitoring network along the Atlantic Coast and were located near the 12 burn treatment RSETs (Saintilan et al. 2022). We measured REC once a year at all 14 RSET stations from 2010–2013. The RSET data can be found at https://doi.org/10.5066/P13LEPNQ . Linear regressions were computed at the pin level and averaged to the SET sampling station level (Lynch et al. 2015).

Fig. 3

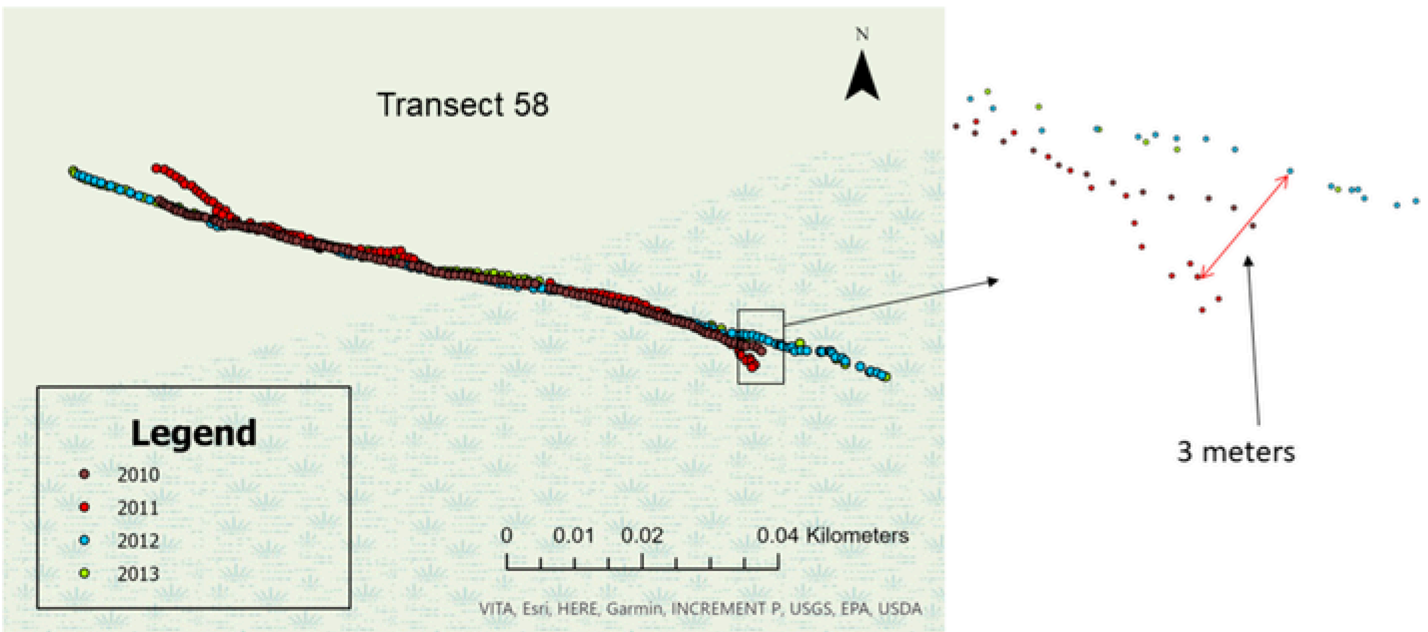
Locations of real-time kinematic (RTK) transects (gray circles denote individual sampling locations along the transects), rod surface elevation table (RSET) sampling stations (black crosses), and geodetic control marks (black triangles) around the center of the Blackwater National Wildlife Refuge. Coordinates for all points are given in Supplemental Information. Map created using ArcGIS Pro



In 2010, FWS established a set of sixty 60-m transects across two different fire frequency treatments: 1–1.5 years and > 1.5 years. In comparison to the SET study, these transects included a much broader spatial sampling of the refuge (Fig. 3). At 10-m intervals along each transect, FWS staff collected RTK-derived positions and heights, as well as vegetation and disturbance data. RTK thresholds included a minimum of 3-min occupations with position dilution of precision (PDOP) ≤ 2.0, residual mean square error (RMS) ≤ 0.01 m, and ≥ 7 satellites in view. The sampling design was based on a power analysis with the goal of being able to discern a 1–2 cm change in elevation over a 5–10-year period. The geodetic control marks within the BNWR used for the RTK base stations had official positions and heights published on National Geodetic Survey Datasheets (https://geodesy.noaa.gov/datasheets/index.shtml). The RTK base stations provided local positional control for the RTK survey (Henning 2014). Procedures included the deployment of a static GPS antenna and receiver on the "base station" geodetic control mark for the duration of the RTK survey. The base station broadcasted positional correctors in real time based on the difference between the known coordinates (and height) at the base and the instantaneous computation of the position (and height) from the simultaneous GPS satellite observations at the base. The rover would receive the positional correctors and use them to correct the coordinates (and height) of the rover deployed along the wetland transects. For this reason, measurements of elevation using RTK were always made with respect to the elevation of the base station. The coordinates of these geodetic control marks (base stations) had been established in 2005 as a result of a regional GPS height modernization campaign in Dorchester County, Maryland, so the positions were relatively recent at that time (2010). The height modernization campaign had followed procedures outlined in Zilkoski et al. (2008). FWS surveyed the 60 transects each summer (June and July) for 4 years (2010–2013). The base stations selected were the marks "Boat Ramp" (permanent ID or PID DH8203 on NGS dDatasheets), "Refuge 2" (PID HV8917), and "Wolf Pit" (PID DH8215). The base stations were all stainless steel deep rod marks encased in greased sleeves (Floyd 1978) and had very open sky views to ensure excellent satellite data reception. Because of variability in the paths of the RTK transects over time (Fig. 4), we averaged elevations over each transect within each measurement event (Supplementary Information 1). We then compared the average elevations within each transect over time.

Fig. 4

Map showing horizontal deviation of repeated real-time kinematic (RTK) transects over time (transect #58 shown). Each color represents the course of a different annual transect. The maximum horizontal deviation among different years' trajectories was about 3 m (right panel). Coordinates for all points are given in Supplemental Information. Map created using ArcGIS Pro



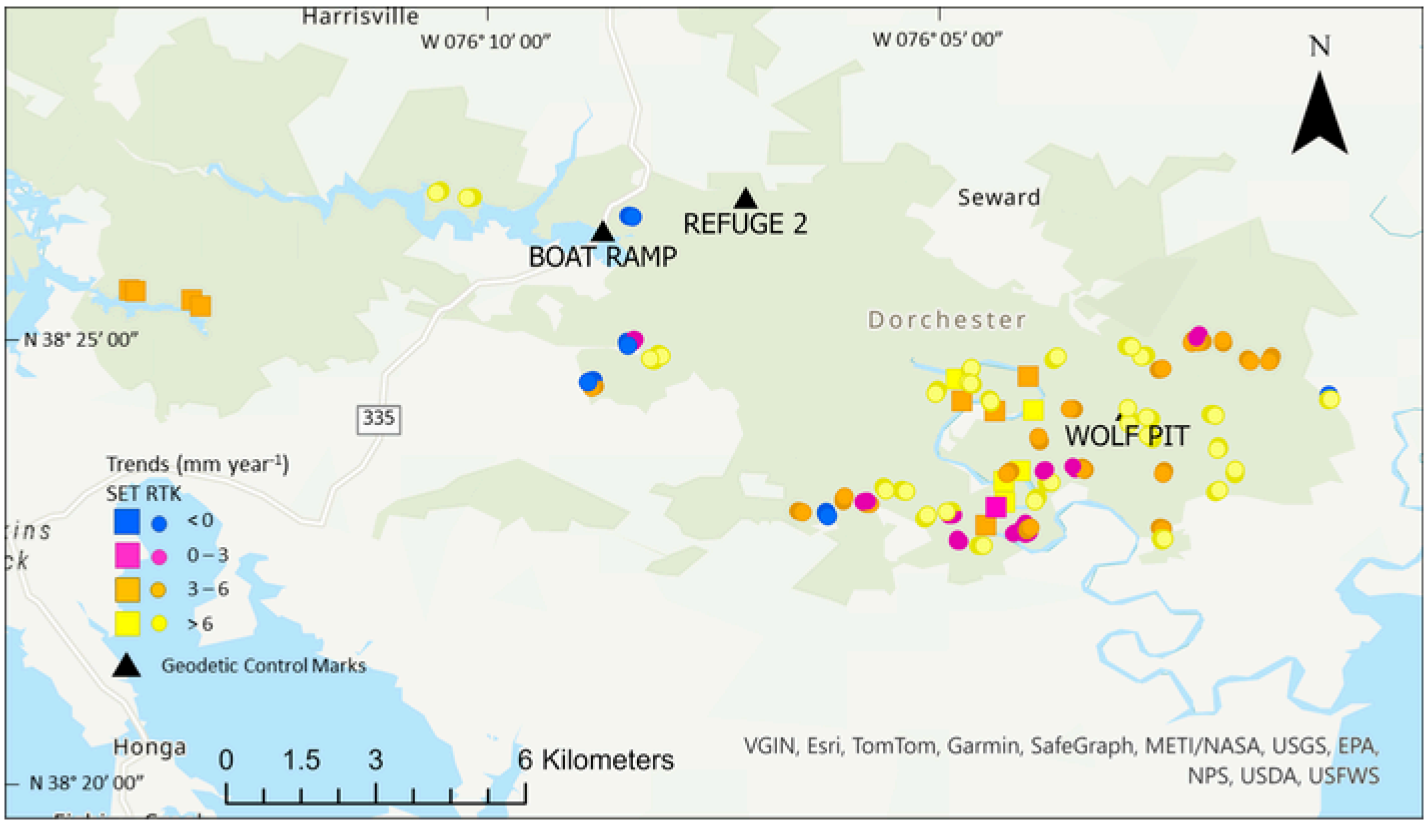
In June 2015, we re-determined the positions of the three geodetic control marks used in the RTK survey in a smaller campaign-style, static GPS survey to determine if their heights had changed since the original 2005 survey. Equipment included GPS antennas with calibrated antenna reference points (https://geodesy.noaa.gov/ANTCAL/) and calibrated, fixed-height GPS tripods. We obtained three observation sessions, spanning a total of 41–61 h across the 3 marks. In July 2017, and then in October 2019–2023, larger regional GPS campaigns included a minimum of three 24-h observation sessions per year on the mark "Refuge 2" (HV8917). Occupations typically lasted 5–7 days (Troia et al. 2022). We analyzed the GPS data from all these surveys using the NGS OPUS Projects web tool (https://geodesy.noaa.gov/OPUS-Projects/OpusProjects.shtml) to run the least squares network adjustments (Gillins and Eddy 2017). The original 2005 GPS data were also reprocessed in OPUS Projects using a similar network design and constraints as the 2015 analysis. For more details on the survey and post-processing, refer to Supplementary Information 2. We analyzed the resulting 18-year trend in ellipsoid heights, expressed with respect to the ITRF2014 reference frame, using weighted least squares regression (weighed for the standard deviation of each height measurement) in the SPSS software for Windows version 29.0 (IBM 2022).

Results

Relative elevation change of the wetland surface averaged over the 14 RSET sampling stations included in this study was 7.3 ± 0.9 mm year^{-1} (mean ± standard error; $P = 0.04$). Relative elevation change averaged across the 60 RTK transects was 6.2 ± 0.6 mm year^{-1} ($P < 0.0001$). The average SET trend was only slightly higher than the RTK trend ($P = 0.216$). Elevation gain and a few instances of elevation loss did not appear to follow any specific geographic trend (Fig. 5).

Fig. 5

Map showing wetland relative elevation change (REC) trends across the Blackwater National Wildlife Refuge for 2010–2013, according to two independent datasets: squares represent surface elevation table (SET) sampling stations; circles represent individual data points along real-time kinematic (RTK) transects. Black triangles represent the geodetic control marks. Map created using ArcGIS Pro



The elevations of the three geodetic control marks used in the RTK survey declined between 2005 and 2015 (Table 1). Change in elevation was not very different among the three marks ($P \geq 0.16$). When the average elevation loss across the three geodetic control marks (− 6.0 ± 0.8 mm year^{-1}) was added to the SET and RTK results, a very different image of net elevation change was seen (Fig. 6). Adjusted for this average rate of subsidence, the average REC trend from the RSET sampling stations was now 1.3 ± 1.6 mm year^{-1} (compared to zero, $P = 0.50$), and the corresponding adjusted rate for the RTK data was 0.3 ± 0.7 mm year^{-1} (compared to zero, $P = 0.73$). The entire 18-year VLM time series (2005–2022) for the geodetic control mark Refuge 2 showed elevation loss as well as important interannual variability. The largest elevation loss occurred between 2005 and 2015 (Fig. 7). The overall trend for VLM at Refuge 2 over the entire 18-year period was − 3.9 ± 0.7 mm year^{-1} ($P < 0.001$).

Table 1

Ellipsoid heights (expressed with respect to the International Terrestrial Reference frame of 2014 reference frame) along with standard errors (± SE) at the three geodetic control marks observed at the Blackwater National Wildlife Refuge from the 2005 and 2015 GPS surveys. The table also provides computed height differences and the corresponding annual rates of change. Please refer to Supplementary Materials 2 for more information on the GPS data analysis

Mark name, permanent ID (PID)	Boat Ramp, DH8203	Refuge 2, HV8917	Wolf Pit, DH8215
Ellipsoid height September 2005 (m)	−35.462 ± 0.006	−35.304 ± 0.006	−36.399 ± 0.006
Ellipsoid height June 2015 (m)	−35.505 ± 0.003	−35.365 ± 0.003	−36.468 ± 0.003
Height differences 2005–2015 (m)	−0.043 ± 0.007	−0.061 ± 0.007	−0.069 ± 0.007
P-value for *T*-test comparison to zero	$P = 0.099$	$P = 0.070$	$P = 0.062$
Annual elevation change rate (mm year^{-1})	−4.4 ± 0.7	−6.5 ± 0.7	−7.1 ± 0.7

Fig. 6

Map showing wetland relative elevation change (REC) trends across the Blackwater National Wildlife Refuge for 2010–2013, according to two independent datasets: squares represent surface elevation table (SET) sampling stations; circles represent individual data points along real-time kinematic (RTK) transects. Black triangles represent the geodetic control marks. The figure is similar to Fig. 5, but the rates of REC are now corrected for a − 6.0 mm year^{-1} rate of vertical land motion (VLM) (subsidence). The estimate of VLM is based on the average elevation change across three geodetic control marks from 2005 to 2015. Map created using ArcGIS Pro

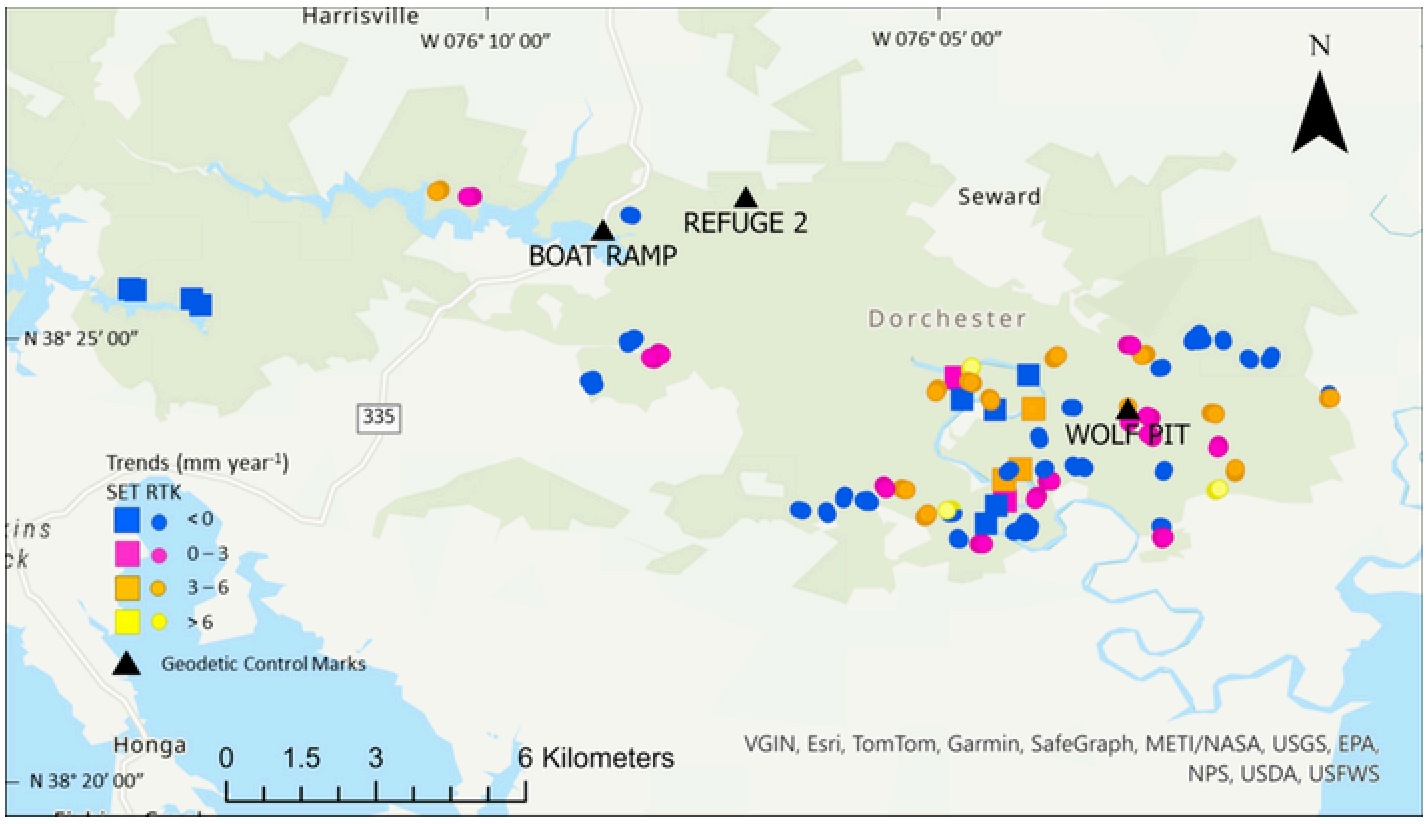
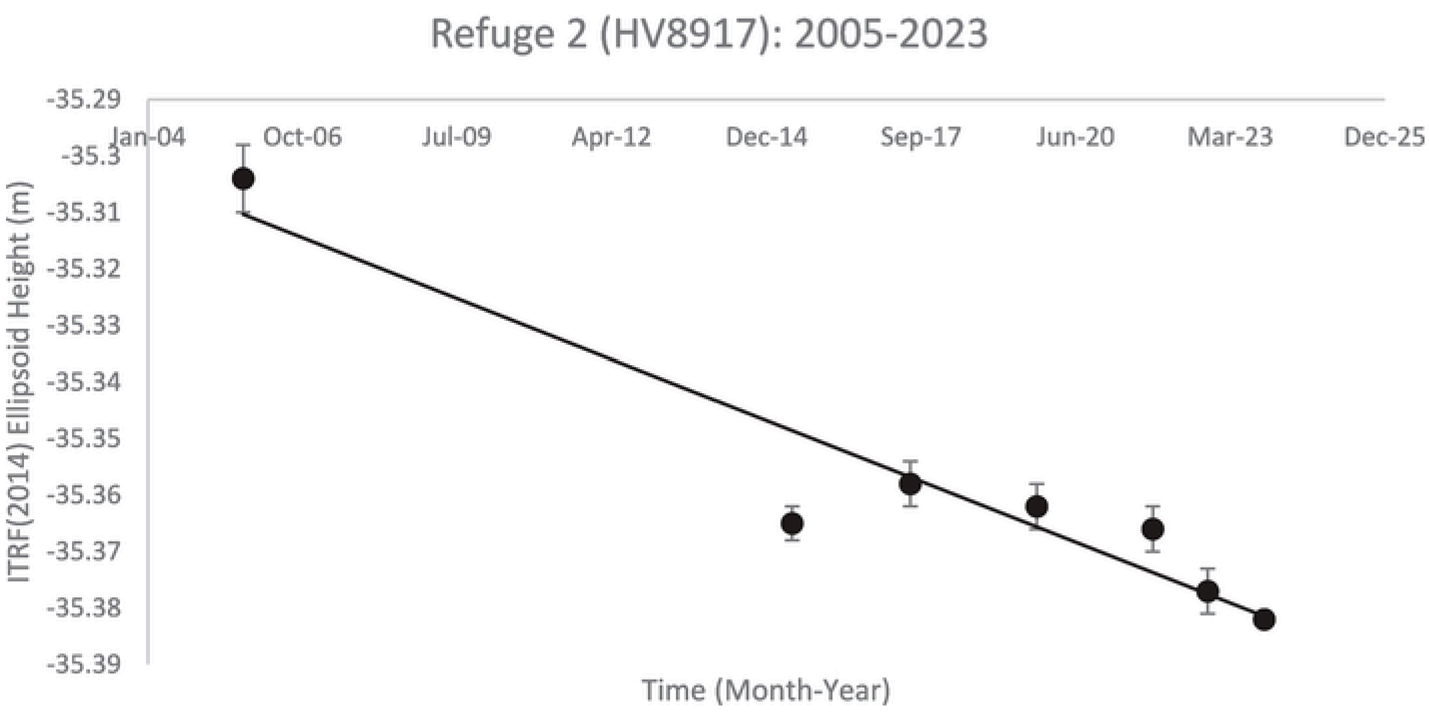


Fig. 7

Ellipsoid height measurements based on global positioning system (GPS) at the geodetic control mark "Refuge 2" (the mark used as the base station for the corresponding real-time kinematic [RTK] survey) from 2005 to 202~~2~~3. The straight line corresponds to the simple linear regression through the data (− 3.9 ± 0.7 standard error [SE] mm year.$^{-1}$)



Discussion

The SET and RTK elevation change datasets used in this study were completely independent and showed no difference in elevation gain (7.3 ± 0.9 mm year^{-1} versus 6.2 ± 0.6 mm year^{-1}, respectively, $P = 0.216$). This is consistent with recent studies, including Lynch et al. 2023, which also showed no differences between SET and RTK-based wetland elevation trajectories in a Mid-Atlantic saltmarsh over a 6-year period. Although the RSET technique has proven itself to be capable of measuring millimeter-scale wetland REC (Webb et al. 2013), the RTK technique is still not widely used for this purpose. Averaging over a large number of permanent transects appeared to be a valid technique to both reduce the error inherent in RTK measurements but also to deal with the lack of consistency in returning to the exact same points on the marsh surface over time. Vertical error for any one RTK-derived point may be at the 2–12-cm level (Henning 2014); however, repeatability can be at the sub-centimeter level (Matori et al. 2008). No formal vertical error assessment was conducted for the RTK survey, although the protocols followed called for no more than 2 cm bias from the known, published height of the geodetic control marks used as checkpoints for the survey. Despite the intrinsic error of RTK data, the large volume of data collected resulted in trends detectable at the millimeter scale within 4 years of measurements.

The elevation gain measured across the marshes at BNWR by the SET and RTK techniques appears to be at odds with the documented pattern of wetland loss (Schepers et al. 2017; Himmelstein et al. 2021). One way of explaining the conundrum has been to presume that the sediments being deposited on the marshes are not "new" sediments being brought into the system but are rather sediments from marshes currently being eroded (Cahoon et al. 2010). Essentially, the marshes are feeding on themselves, accreting vertically at high rates (Ganju et al. 2015), but the overall trend for the Blackwater coastal wetland landscape continues to be wetland loss. Why are rapidly accreting remnant marshes still showing signs of drowning? We partially explain this by subtracting the subsidence measured at the geodetic control marks (2005–2015) from the RSET and RTK elevation results. The corrected elevation gain rates of 1.3 and 0.3 mm year^{-1} (RSET and RTK, respectively), when compared to the nearby long-term tide station trend of RSLR (3.9 mm year^{-1}) or even the decorrelated long-term oceanographic SLR trend at the same tide station (2.0 mm year^{-1}, computed from Zervas et al. 2013), demonstrate that wetland REC is not keeping pace with local sea level rise.

Wetland elevation trends are often compared to RSLR from the nearest long-term tide station to determine if elevation gain is keeping up with changes in sea level (Cahoon 2015; Feher et al. 2022; Doar and Luciano 2023). At least 30 years of continuous water level data are needed to have a robust estimate of sea level change that is not biased by seasonal and interannual patterns of variability (Zervas et al. 2013). Long-term water level records account for both the underlying hydrologic signal (e.g., global sea level rise, in addition to local influences of salinity, currents) and local VLM (Snay et al. 2007; Zervas et al. 2013). However, such long-term data records are usually associated with cities and ports, not necessarily coastal wetlands. Although recent monitoring programs have recommended deploying water level recorders at wetland sites (Cahoon 2015; Hensel et al. 2023), such data will not provide an accurate estimate of long-term sea level trends over the short term. For this reason, researchers still resort to estimating RSLR at their wetland settings using the nearest long-term tide station, presuming that the deep VLM signal will be the same between both locations (Cahoon et al. 2015, Doar and Luciano 2023).

The subsidence we measured by GPS over the 18 years at Refuge 2 (3.9 mm year^{-1}) is consistent with DeJong et al.'s (2015) findings of subsidence at BNWR, although their estimate of subsidence, averaged over the entire twentieth century, was lower, around 1.6 mm year^{-1}. DeJong et al. (2015) used a suite of sedimentary dating techniques to describe the stratigraphy at 70 boreholes within BNWR. Other published rates on GIA-induced subsidence in the mid-Atlantic are similar (1.3 to 4.0 mm year^{-1}, Boon et al. 2010; 1.7 mm year^{-1}, Engelhart et al. 2009). DeJong et al. (2015) explain that BNWR is underlain by Pleistocene deposits of varying thicknesses due to glacial-interglacial cycles leading to localized river incision and aggradation and the formation of paleochannel systems. Differential compaction and subsidence of these paleochannels could help explain the rates of subsidence measured at BNWR. However, DeJong et al. (2015) also noted that this would not be limited to BNWR.

It remains unclear how far the subsidence rates measured at BNWR extend regionally. Zervas et al. (2013) estimate VLM at the Cambridge tide station (station 8-571-892) to be − 1.9 mm year^{-1}. Of course, the long-term RSLR trend at Cambridge itself may be biased downwards due to the lower rate of SLR in the earlier part of the twentieth century (Dangendorf et al. 2017). Using publicly available monthly mean sea levels from the Cambridge tide station (https://tidesandcurrents.noaa.gov/waterlevels.html?id=8571892), we calculate the latest 30-year RSLR trend from the tide station to be 5.3 ± 0.3 mm year^{-1} (1994–2023). However, the corresponding global mean SLR over that time period would be 3 mm year^{-1} (Dangendorf et al. 2017), so the resulting 30-year estimate of VLM at the tide station would be only − 2.3 mm year^{-1}, similar to the earlier estimate. These estimates are all less than the rates we measured at BNWR. Swales et al. (2016) reported similar findings in their measurement of deep subsidence using repeated GPS campaigns in New Zealand. Deep subsidence rates at the RSET marks within a mangrove wetland were 2- to fivefold higher than rates recorded at the nearby tide gauge located 10 km away. Similarly, Doar and Luciano (2023) measured subsidence rates that were at least twice as high as those estimated at the nearest long-term tide station. These findings across different geographies and wetland settings underscore the importance of measuring VLM within the wetland itself to ensure reliable estimates of RSLR to which the wetlands would be responding.

The Bishop's head tide station is a relatively recent installation that lies about 20 km to the southeast of the study area in BNWR (Fig. 2). The station was established in 2005 and is therefore too recent to provide a reliable long-term sea level trend (https://tidesandcurrents.noaa.gov/stationhome.html?id=8571421). However, the data from 2005 to 2023 reveal a 7.3 ± 1.2 mm year^{-1} trend in RSLR (compared to zero, $P < 0.0001$; Supplementary Information 3). Over the same time period (2005–2023), the linear trend in RSLR at the Cambridge tide station was 6.0 ± 1.2 mm year^{-1}, $P < 0.0001$, indicating an approximately − 1.3 mm year^{-1} change in VLM between Cambridge and Bishop's head. If the long-term VLM at the Cambridge gauge is − 1.9 mm year^{-1}, this ~~indicates~~suggests that the long-term VLM at Bishop's head may be around − 3.2 mm year^{-1}, which is close to our estimate of − 3.9 mm year^{-1} from the 18-year GPS-derived VLM trend at Refuge 2. Recent data from Ohenhen et al. (2023) suggest that rates as high as − 4 mm year^{-1} may exist at the southern end of BNWR. All of this reinforces the contention that the BNWR wetlands are in a different VLM environment compared to the Cambridge tide station.

The GPS techniques used in this study included several efforts to minimize vertical errors including using calibrated 2-m, fixed-height GPS tripods, occupying marks for multiple 24-h observation sessions, and using analytic procedures to estimate atmospheric errors and ensure comparability over time. As shown in Swales et al.'s (2016) study, adherence to similar rigorous techniques can yield robust estimates of VLM at deep rod marks. Although we have formal error estimates for the least squares–adjusted ellipsoid heights, we do not have similar estimates for the height differences. Instead, we inflated the error estimate by computing the square root of the sum of squared error. The actual error estimates are expected to be somewhat less. Regardless, our computed height differences are different at $P = 0.1$. Swales et al. (2016) measured rapid subsidence at the actual SET marks in mangrove forests in New Zealand (7.9–9.4 mm year^{-1}). In our study, we measured VLM at the three upland geodetic control marks, and our estimates were of similar magnitude to those of Swales et al. (2016). Our estimates of VLM provide important information on processes leading to elevation loss that was not captured by either the SET or the RTK techniques, nor the nearest long-term tide station. Da Lio et al. (2018) also showed that REC measured by SETs were overestimates compared to InSAR measurements of the natural reflectors scattered throughout the wetlands. These results indicate that satellite-based measurements of elevation change with respect to a geometric reference frame would need to be incorporated into ground-based measurements of REC.

Conclusions

The results of this study indicate that the contribution of deep subsidence to VLM at BNWR may be important in driving the historical wetland loss in this area. Relying on the nearest long-term tide station to estimate RSLR and compare that to wetland elevation change rates may be inaccurate if the tide station is in a different VLM environment compared to the wetlands. For this reason, studies of wetland elevation change using techniques such as RSET or RTK could also consider measurements of the vertical motion of the corresponding reference marks to ensure a complete picture of wetland vertical dynamics. Episodic, multi-day GNSS campaign surveys are excellent techniques to estimate coastal VLM and can provide critical data to understand the mechanisms leading to wetland vertical dynamics.

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Supplementary Information

Below is the link to the electronic supplementary material.

Supplementary file1 (DOCX 344 KB)

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