Elevation, drainage, and spatially heterogeneous vulnerability of tidal marshes to sea level rise

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Abstract:

Marsh plants regulate marsh surface elevation through organic matter accumulation and sediment capturing, thus feedback loops and relationships between vegetation and marsh elevation form the basis of numerical models that estimate and predict marsh vulnerability to Sea Level Rise (SLR). However, with interior portions of shallow-sloping microtidal marshes suffering much more extensive inundation relative to edge marshes, it is necessary to identify factors in addition to elevation that create spatial heterogeneity in flood vulnerability. Here we studied the influence of drainage on vulnerability of the marsh interior and the marsh edge. Specifically, we compared the deviation of *in situ* observed hydrological metrics for surface (hydroperiod, daily inundation duration) and subsurface (soil saturation index, or SSI) soil levels of interior and edge marsh from expected values estimated using elevation and tidal regime alone. We further analyzed the bias that hydrological deviation introduced to marsh vulnerability estimation using growth response curves of typical marsh macrophytes to hydroperiod. We found that the water table fluctuation was attenuated from marsh edge to interior, which resulted in a higher sensitivity of interior marsh to elevation deficiency. At the brim of marsh collapse in the marsh interior, hydroperiod and SSI increased dramatically; they were 20-50% higher than at the same elevation at the marsh edge, which greatly reduces the window of opportunity for interior marsh plant communities to adapt to SLR. Our findings

demonstrate the importance of drainage in explaining spatial patterns in vulnerability across the marsh platform, which should be considered in future empirical studies and numerical simulations to develop practical tools for coastal management.

Key words:

Marsh stability; Drainage; Inundation; Groundwater; Plant dieback

Introduction

Marsh macrophytes regulate marsh elevation both through organic matter accumulation and sediment capture (Mudd et al. 2010, Baustian et al. 2012, Kirwan and Mudd 2012, Bouma et al. 2013). The long-term stability of marshes can be explained by interactions among sea level, marsh surface elevation, plant productivity, and sediment accretion, which interact to regulate marsh elevation in equilibrium with mean sea level (Baustian et al. 2012, Morris et al. 2013, Kirwan et al. 2016, Cahoon et al. 2019, FitzGerald and Hughes 2019, Cahoon et al. 2021).

The persistence of marsh ecosystems is thought to depend on the production of aboveground and belowground biomass by marsh plants, which can raise marsh surface elevation and avoid plant inundation caused by sea level rise (Morris et al. 2002, Kirwan and Guntenspergen 2012, Beckett et al. 2016, Gonneea et al. 2019). Specifically, marsh ecosystems will be stable in the face of sea level rise when marsh surface elevation is greater than the optimum for primary production, as an increase in sea level will stimulate primary production, leading to increased sedimentation and organic matter accretion. Otherwise, where surface elevation relative to sea level is lower than the optimum, the system will be unstable, as rising sea levels reduce primary production, leading to declines in mineral sedimentation and organic matter accretion, and further elevation loss (Morris et al. 2002). Therefore, the growth curve of marsh plants to varying elevation has been widely applied across entire marsh platforms in empirical studies (Morris et al. 2002, Baustian et al. 2012, Kirwan and Guntenspergen 2012, Voss et al. 2013, Kirwan and Guntenspergen 2015) and eco-geomorphologic models (Kirwan and Murray 2007, L. et al. 2010, Marani et al.

2013, Mariotti and Carr 2014, D'Alpaos and Marani 2016, Mariotti 2016, Duran Vinent et al. 2021) to estimate the stability of marsh platforms colonized by various macrophytes.

However, whether the hydrological stress experienced by marsh plant can be represented by elevation and tidal regime alone is still questionable, as hydrological conditions, especially groundwater dynamics can also be greatly influenced by distance from outlets such as tidal creeks and drainage conditions (Ursino et al. 2004, Van Putte et al. 2022, Xin et al. 2022). For example, in field studies, wave attenuation by marsh vegetation was observed as reduction in wave height over distance traveled (Möller et al. 2014, Stark et al. 2015). In addition, field observations and numerical simulations demonstrated that as the tide propagates toward the marsh interior, marsh subsurface hydrology is less responsive to tidal height, especially in interior marsh that is distant from tidal channels, which resulted in tide-induced water table fluctuations which attenuated from creek to marsh interior (Ursino et al. 2004, Cao et al. 2012a, Xin et al. 2013b, Byers and Chmura 2014, Xin et al. 2022). In addition, compared with creek banks, soil condition and vegetation in interior marsh is regulated more by rainfall and evapotranspiration than by tide (Xin et al. 2013a, Xin et al. 2017, Walker et al. 2019). These suggest the influence of elevation- and tidally-derived hydrological regimes weaken with increasing distance from tidal creeks, as the immediate effects of drainage diminish.

Identifying the deviation of *in situ* hydrological condition from elevation- and tidally- derived estimates is important, especially for interior marsh, as poorly-drained interior marsh in microtidal marshes has experienced the greatest habitat losses resulting from sea level rise, for example in the Mississippi Delta, Chesapeake Bay, and Venice Lagoon (D'Alpaos and Marani 2016, Kearney and Turner 2016, Smith et al. 2016, Mitchell et al. 2017, Ortiz et al. 2017, Schepers et al. 2017, Wang et al. 2021). Besides, an increasing body of empirical studies are applying the results of mesocosm experiments conducted in tidal creeks designed to test the effects of elevation relative to sea level (i.e. marsh organ experiments) without considering the spatial variation in drainage conditions that occur across a marsh platform (Kirwan

and Guntenspergen 2012, Adam Langley et al. 2013, Kirwan and Guntenspergen 2015, Janousek et al. 2016, Janousek et al. 2020, McLain et al. 2020, Payne et al. 2021). Furthermore, numerical models of marsh vulnerability to accelerated SLR seldom incorporate drainage conditions or subsurface hydrology into the current framework of a dynamic marsh surface elevation that is driven by the feedback between elevation, tide, plant growth and sediment deposition (Kirwan and Murray 2007, L. et al. 2010, Marani et al. 2013, Mariotti and Carr 2014, D'Alpaos and Marani 2016, Mariotti 2016, Duran Vinent et al. 2021).

Although some prior studies have noted the deficiency of overlooking heterogeneity in drainage conditions (Morris et al. 2013, Kirwan and Guntenspergen 2015, McLain et al. 2020, Van Putte et al. 2022), to our knowledge, no field studies have been conducted to quantify the deviation from elevation- and tidally- based estimations that can be attributed to spatial variation in drainage conditions. To address this, we selected two deteriorating marsh platforms in the Chesapeake Bay, United States. At each marsh, we monitored water levels and soil moisture in three different zones -- vegetated, plant dieback, and ponded -- interior marsh. For each zone, we estimated the difference between elevation- and tidally- derived hydrological regimes and *in situ* observations of hydroperiod, daily inundation duration, and soil aeration. We also analyzed the influence of hydroperiod deviation between *in situ* observations and elevation- and tidally- derived estimations on marsh stability using empirical growth response curves of typical marsh macrophytes from the region. By recognizing the effect of drainage on spatially variation in marsh stability, we hope to provide a resource for future studies and models of marsh stability, which are important and necessary tools for coastal management.

Study area

The Chesapeake Bay is one of the largest microtidal estuaries in the world, and has experienced increasing deterioration in recent decades (Kearney et al. 1988, Beckett et al. 2016). Within the Bay, we selected Deal Island (DI) and Farm Creek

Marsh (FCM), MD as study sites. These two marshes are in the early stages of transition from vegetated marsh to open pond (Walker et al. 2019, Qi et al. 2021). Areas in various states of deterioration can be found at both sites, but in general, deterioration at both sites is more apparent in marsh interiors, where drainage is poor and marsh accretion rates are lower compared with marsh edge (Walker et al. 2019, Qi et al. 2021).

Both DI and FCM are brackish marshes, but DI has a higher salinity range (7-15 ppt) than FCM (2-5 ppt) based on measurements in summer of 2019. Emergent vegetation in both marshes is typical of brackish marshes of the region, and includes grasses, sedges, and rushes of the species *Spartina patens*, *Distichlis spicata*, *Spartina alterniflora*, *Schoenoplectus americanus* and *Juncus roemarianus*. The dominant species is *S. alterniflora* in DI, and *S. americanus* in FCM, reflecting differences in salinity levels and the salinity tolerances of these two species. In DI, inundation stressed *S. alterniflora* colonize a spatially homogenous substrate of weak soil strength as a sparse meadow, whereas in deteriorating areas of FCM, *S. americanus* forms a heterogenous surface of hollows and hummocks.

At the marsh interior of each site, we selected three zones: vegetated, dieback, and pond, to capture the hydrological alteration along the trajectory of marsh deterioration. In DI, we monitored a tidal creek bank located 800 m from interior marsh as a reference point where the water table was likely to resemble an unrestricted tidal fluctuation. We did not instrument such a reference point at FCM because we found that the tidal creek water levels at FCM and DI were highly correlated. Therefore, we took hourly tidal height readings at Bishops Head station, MD from NOAA tide and current website, (Station ID: 8571421, https://tidesandcurrents.noaa.gov/stationhome.html?id=8571421) to represent tidal height at the local scale from FCM to DI. This Bishops Head station is 11 km southeast of FCM, and 12 km Northwest of DI.

<Fig. 1>

Methodology

In situ groundwater observation

At each site, three groundwater wells were installed in the vegetated zone, dieback zone, and pond, respectively, in April 2019 to monitor water table dynamics. In DI, a groundwater well was installed at a nearby tidal creeks (as shown in Fig. 1) in comparison with the interior part of the marsh.

Groundwater level data was collected at 15 min interval from May 2019 to March 2020 with HOBO water level loggers (U20L -04). Marsh surface elevation of each zone was measured within a 0.5 m radius from each groundwater well in May 2019 using a Trimble R8 Real Time Kinematic Global Positioning System (RTK-GPS) to reference water table data to the NAVD88 datum and to allow for comparison within and between sites. The flooding regime was estimated using tidal height data from the Bishops Head and *in situ* marsh elevation collected at each zone, as described above.

Hydrological metrics

We selected three metrics to represent surface inundation, daily inundation stress and soil aeration: 1) hydroperiod, 2) daily inundation duration, and 3) soil saturation index (SSI). Hydroperiod is the fraction of time marsh was flooded over the observation period. SSI is the fraction of the tidal period over which the soil remains fully saturated at a given depth, and SSI at depth=0.0 m is equivalent to the hydroperiod (Xin et al. 2010).

In situ hydrological metrics were calculated from observations of groundwater levels and marsh surface elevation. As a counterpart, estimated hydrological metrics was calculated from tidal height and marsh surface elevation. Comparison between in situ metrics and estimated metrics was conducted to analyze the hydrological bias caused by spatially dependent drainage.

Influence of hydrological deviation on marsh vulnerability

To understand the deviation of *in situ* observations from estimations based solely on elevation and tidal fluctuations, and how these affect forecasts of marsh vulnerability to deterioration, we extracted growth response curves of typical

macrophytes to predicted and observed hydroperiods. Growth response curves were extracted from the literature, from studies using marsh organ experiments in sites on the Atlantic Coast of the United States. Growth response curves, including the ones used in this study, have been widely used to estimate and forecast marsh vulnerability to sea level rise.

We only adopted growth response curves that used plant biomass (aboveground or belowground) or biomass change relative to inundation duration. Some other response indicators were also used in relevant studies e.g. shoot/stem density, stem length, but these were less comparable across studies and could not be related to the hydrological metrics of interest in this study (Kirwan and Guntenspergen 2012, Adam Langley et al. 2013, Janousek et al. 2020).

Based on these criteria, three empirical studies were identified with the variables of interest for four out of five of the typical macrophytes (except *D. spicata*) at our study sites. Cumulatively, these studies contained 246 measurements of aboveground biomass and 178 measurements of belowground biomass. To synthesize, we normalized aboveground biomass and belowground biomass of a given species from each study separately with the equation of $x_n=[x_i - \min(x_i)]/[\max(x_i)-\min(x_i)]$. Then we merged the normalized data (with a range of [0~1]) from different studies to form a unified growth response curve. After a preliminary analysis, we found aboveground and belowground biomass response curves had similar shapes (Appendix S1: Fig. S1), therefore we merged the standardized aboveground biomass and belowground biomass into a uniform biomass response curve to inundation using quadratic regression.

<Table 1>

Results

Marsh elevation and hydrological series

In both sites, there was a difference in elevation of 0.22 m between healthy zones and ponds (dashed lines in Fig. 2). In DI, the elevation difference was similar between

vegetated zone to dieback zone and to pond, while elevation in FCM did not vary greatly between vegetated zone and dieback zone. However, there was a large elevation difference between the transition and dieback zones with ponds.

The water table at DI, which was monitored at the bank of tidal creek, was highly consistent with the tidal level measured at Bishops Head station (Fig, 2), and exhibited a tidal range of approximately 60 cm (Fig. 3). In the interior marsh, the water table levels at DI had a similar range of variability (20~30cm) as at FCM, but the daily variation at DI was muted compared to FCM (Fig. 3).

Within each site, interior marsh had smaller water table fluctuations but higher average water table height than nearby tidal creeks (Fig. 2~3), though there is slight difference in the distribution of water table across interior zones (Fig. 3).

<Fig. 2>

<Fig. 3>

Hydrological metrics deviation

The difference between in situ observed and estimated hydroperiod and SSI was small at the tidal creek but increased within interior marsh (Fig. 4). Estimated hydroperiod and SSI increased linearly with decreasing marsh surface elevation, while observed hydroperiod and SSI increased nonlinearly with increasing elevation and reached a maximum of 100% in several zones. Within any given zone, soil saturation index at depth was generally higher than hydroperiod other than where both reach a maximum of 100%. The deviation between estimated and in situ monitored hydroperiod reached a maximum of 50% at dieback zone, and is 22-33% at the pond and vegetated zones. In situ observed SSI at 0.1 m depth presented the greatest deviation (50%) from estimations from the dieback zone, and observed SSI at 0.2 m depth exhibited the greatest deviation from estimations of 40% in the vegetated zone.

<Fig. 4>

The distribution of daily inundation duration differed greatly between in situ observations and estimations. Estimated daily inundation durations averaged between 4 and 8 hrs in all zones for both sites, and increased slightly with the degree of interior

marsh deterioration (Fig. 5). Whereas measured observations showed that in the majority of observed days (65% in DI, and 30% in FCM), vegetated marsh zones were continuously inundated for the entire day, which almost never occurred in the estimation. For dieback zones and ponds, continuous inundation occurred on 100% of days in DI, and 75% and 100% of days, respectively, in FCM.

<Fig. 5>

Bias in marsh vulnerability estimation

Among the four macrophytes, only *S. americanus* showed a unimodal growth curve that peaked at intermediate daily durations of inundation; the other three species' performance decreased gradually with increasing hydroperiod. For vegetated zones of the marsh interior, the estimated hydroperiod (dashed green lines in Fig. 6) is 22%~26% lower than in situ observations (solid green lines in Fig. 6). Therefore, if species performance is estimated on the basis of elevation and tidal fluctuations alone, this results in an overestimation of plant performance by 10%-25%. This result in general overestimation of marsh plant resilience to sea level rise, especially for *S. americanus*, the dominant species at FCM. At FCM, for example, whereas the vegetated zone's elevation was estimated to be at the species' optimal performance level, based on these hydrologic corrections, it was actually within a suboptimal range.

In the dieback and pond zones of DI, the estimated hydroperiod indicated a suboptimal but non-lethal status for all species, but in situ hydrologic observations suggests a hydroperiod that no species could survive, which more accurately reflected the vegetation condition. Similar bias also happened in ponds of FCM, but not in dieback zones of FCM, because there was a smaller elevation difference between healthy and dieback areas.

Therefore, plant performance and marsh resilience in the vegetated zones of interior marsh was overestimated for all species when elevation and tidally-derived hydrologic regimes were used

<Fig. 6>

Discussion

Tide station data was a good match to tidal creek water levels. However, within the marsh platform, as the tide propagates over and through the peat matrix into marsh interior, tide-induced water table fluctuations are greatly attenuated. Due to the narrow fluctuation of the water table in interior marsh zones, even minor elevation change can greatly shift the hydroperiod and period of soil saturation. These dynamics are poorly captured when estimated using tidal height and marsh elevation. As a result of the underestimation of hydroperiod and soil saturation in deteriorating microtidal marshes, we have also underestimated the vulnerability of interior marsh to sea level rise by applying elevation and tide-derived hydrological regimes to the whole marsh platform.

Effect of elevation and drainage on hydrological regime

A decrease in the water table fluctuations in response to reduced drainage in interior marshes has been previously observed in field investigations and numerical simulations (Ursino et al. 2004, Cao et al. 2012a, Cao et al. 2012b, Byers and Chmura 2014, O'Connor and Moffett 2015). However, most observations were only conducted for days and focus on transient asynchronization in groundwater table at different distance from tidal creek, and seldom were further interpreted or upscaled to inform difference in vegetation performance and marsh vulnerability between marsh edge and marsh interior. With a year-long observation, we found estimates by elevation and tidal height understimate hydroperiod in interior marsh by 25% ~ 50% (Fig. 4a). Rather, this reduction in the tidal fluctuation in interior marsh is also greatly influenced by dampening (by friction or water spreading) as tide propagates across the marsh (Stark et al. 2015, Xin et al. 2022).

The difference in the fluctuation of the water table between marsh exterior and interior marsh creates a divergent response in hydroperiod and SSI to elevation variation (Fig. 4). At Deal Island, for example, there was little fluctuation at all in the groundwater table within interior marsh (Fig. 3). Let’s take an ideally occasion at Deal Island that we can find marsh points with elevation ranging from 0 to 0.7 m in marsh exterior zone and marsh interior zone We then assume marsh points within each zone shared the same groundwater level as but differed in elevation. Finally we can calculate the hydroperiod and SSI under different elevation levels at each section

(Fig. 7). We can found that when elevation drops from 0.36 m to 0.15 m, there is a sharp increase in the hydroperiod in marsh interior (88% increase) relative to the marsh creek bank (30% increase) (Fig.7). Interestingly, the hydroperiod and the SSI in interior marsh is underestimated at the left side of the intersections of the curves, whereas it is overestimated, albeit to a lesser degree, at the right side of the intersections, indicating that at very high elevations of marsh, soils may be more drained and less frequently inundated than expected (Fig. 7). Given that we observed that deteriorated marsh stages are lower in elevation and peat collapse can be develop fast following vegetation death (Day et al. 2011), we expect that elevation loss during marsh deterioration means that the estimation of hydroperiod based on elevation can quickly become out of date, and distort the true experience of plants in these deteriorating microtidal marshes. Therefore, it is important to recognize the range of water table fluctuations in interior marsh in order to better predict the plant response within interior marshes and its feedbacks to marsh elevation gain and loss. Elevation loss in interior marshes leads to pond expansion and habitat loss.

<Fig. 7>

Spatially heterogeneous marsh vulnerability

In many studies (D'Alpaos and Marani 2016, Ortiz et al. 2017, Schepers et al. 2017), the higher vulnerability of interior marsh is attributed to a lower accretion rate in marsh interiors than at marsh edges (Kirwan et al. 2016). Our study suggests that the higher inundation at the surface and saturation of the subsurface layer in interior marshes, which is caused by poor drainage, should be a more direct factor. The high frequency of saturation and inundation reduces belowground biomass production, often before aboveground biomass reductions are observed (Turner et al. (2004), meaning that these effects can be easily missed in monitoring efforts. This might explain the shallow subsidence rates observed in the Chesapeake Bay, where accretion rates in interior marshes can be much higher than the rate of sea level rise, as high as 9-15 mm/yr, yet marsh surface elevation has decreased 1.8 ± 2.7 mm/yr on average, and this occurred before any evidence of plant dieback was observed (Beckett et al.

2016).

This deficiency of using elevation as the sole indicator of marsh stability, and the importance of drainage in understanding spatial heterogeneity in marsh vulnerability has been reported in prior studies. For example, Kirwan and Guntenspergen (2015) reported that *S. americanus* produced 2-4 times greater aboveground biomass in marsh organs than at the equivalent elevations in its natural habitat of interior marsh. Similarly, drainage associated with creek banks facilitated seedling survival and marsh stability in microtidal or macro marshes (Liu et al. 2020, Cao 2021). Therefore, it is necessary to consider spatial heterogeneity in drainage in future studies of marsh vulnerability and risk.

Besides overall higher vulnerability of interior marsh than marsh edge, the higher sensitivity of hydroperiod to a narrow range of elevation in interior marsh makes deterioration occur more quickly and with less warning than at more exterior locations. It may also leave interior marshes less resilient to minor disturbances because only a trivial loss of relative elevation, of about 15 cm in this study, can create a disproportional increase in hydroperiod that can greatly change the growing conditions and cause plant mortality or prevent recovery (Raposa et al. 2017, Watson et al. 2017, Qi et al. 2021). From this aspect, microtidal systems are much more vulnerable to sea level rise effects than meso- and macrotidal systems (Kirwan and Guntenspergen 2010, D'Alpaos et al. 2012).

At Deal Island and many other sites, plant displacement in interior marshes has been observed prior to pond formation and expansion (Raposa et al. 2017, Watson et al. 2017, Qi et al. 2021). Additionally, mortality of flood intolerant species, such as *S. patens* and *D. spicata*, occurred before colonization and replacement by flood tolerant species, such as *S. americanus* and *J. roemerianus* (Fig. 8). The elevation range of *S. americanus* is only a scant 4 to 5 cm lower than *S. patens* (Holmquist et al. 2021), despite a large difference in flood tolerance (Fig. 7, and Qi et al. 2021). It is likely that the steep response curve of hydroperiod and elevation in interior marshes didn't given sufficient window of opportunity for displacement to be accomplished, i.e. after preexisting plant die off and elevation loss, the hydroperiod has already shifted

outside the appropriate range of subsequent plant species before the latter can establish. Therefore, understanding the elevation building capacity and flood tolerance of different plant assemblages could improve predictions of the elevation trajectory in deteriorating marshes (Kelleway et al. 2017).

<Fig. 8>

Achieving more accurate estimation of interior marsh

The deteriorating marshes selected for this study were located within the range of elevation where elevation and tidally-based estimates severely underestimate hydroperiod and SSI (Fig. 7). This is consistent with observations of rapid vegetation displacement and pond expansion at these same sites over the past decade (Taylor et al. 2020, Qi et al. 2021). Based on the relationship between observed hydroperiod and elevation, we predict that marsh vulnerability may be overestimated for interior marsh areas at higher-elevation or with greater elevation capital. This provides a hypothesis that can be tested in future studies.

Current numeric models that simulate marsh vulnerability to sea level rise are based on geomorphological drivers such as elevation, tidal range, and distance from surface water features. In general, subsurface flow and its interaction with surface flow are not incorporated in these models (Kirwan and Murray 2007, L. et al. 2010, Marani et al. 2013, Mariotti and Carr 2014, D'Alpaos and Marani 2016, Mariotti 2016, Duran Vinent et al. 2021). We urge future modeling studies to consider more than surface elevation of the marsh platform, but also to incorporate subsurface hydrological processes in order to more accurately reflect the hydrological stress on marsh plants and the feedbacks to marsh platform integrity. In this way, the estimates of marsh vulnerability and tools for marsh conservation and restoration can improve.

Empirical studies can also better incorporate additional measurements to represent the factors influencing the drainage condition of a marsh. We recommend considering the distance from tidal creeks and soil permeability in study designs and monitoring efforts. These factors can be used to establish regression functions between tidal and groundwater fluctuations to improve data interpretation and interpret spatial variability in marsh plant performance, ponding, and ecosystem

deterioration in microtidal marshes.

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Table 1 Data sources of synthesized growth response curves of typical macrophytes to inundation duration.

Species	Growth response indicators
S. americanus	live aboveground biomass (AGB), live belowground biomass (BGB), root to shoot ratio[a]
S. patens	live AGB, live BGB, root to shoot ratio[a]; AGB, BGB[b]
S. alterniflora	AGB , BGB [b]; Total AGB, Live AGB, Total shoot density, End-of-season BGB[c]
J. roemerianus	total AGB, Live AGB, total shoot density, end-of-season BGB[c]

[a]Kirwan and Guntenspergen (2015)- Blackwater and Transquaking River, Maryland.

[b]Snedden et al. (2015)- Middle Breton Sound and lower Breton Sound, Louisiana.

[c]Voss et al. (2013)- Pine Knoll Shores and Lola, North Carolina.

Figure legends

Fig. 1 a) Location of the two study sites within the Chesapeake Bay. Shallow groundwater wells were located in the vegetated, dieback, and pond zones at each site: b) Farm Creek Marsh (FCM) and c) Deal Island (DI).

Fig. 2 Groundwater table (solid lines) and surface elevation (dashed lines) of different zones (color coded) of deteriorating marshes at DI (a) and FCM (b) (Datum: NAVD 1988). At DI, 'tidal creek' means nearest tidal creek to interior deteriorating marshes of DI (Fig. 1c), and at FCM, it represents tidal height at Bishops Head station.

Fig. 3 Groundwater level at marsh interiors (vegetated zone, dieback zone, pond) was distributed within a narrow height range compared to tidal creeks at both marsh sites (a-DI; b-FCM). Similar to Fig. 2, tidal creek in a) means nearby tidal creek in DI, and tidal creek in b) means Bishops Head station.

Fig. 4 Comparison of soil saturation index (SSI) at soil depth of 0 m (a, $SSI_{0.0}$, equivalent to the hydroperiod), 0.1 m (b, $SSI_{0.1}$) and 0.2 m (c, $SSI_{0.2}$) between in situ observations (blue) and estimations (red) derived from elevation and tidal height. TC-tidal creek; PD-pond; DB-dieback zone, VG-vegetated zone. The response curve of hydroperiod and SSI to elevation in interior marsh was fitted with logistic

regression, and results of tidal creek in DI was marked separately with *.

Fig. 5 Comparison of the distribution of daily inundation duration between observations and estimations from elevation and tidal height.

Fig. 6 Growth response curves of typical macrophytes to hydroperiod was generated from empirical data (Voss et al. 2013, Kirwan and Guntenspergen 2015, Snedden et al. 2015). The difference in hydroperiod estimated using elevation and tidally-based method (dashed lines) and in situ observations (solid lines) are also displayed for each marsh zone. Colors indicate the vegetated zone (green), the dieback zone (orange), and the pond (blue) for Deal Island (DI, left) and Farm Creek Marsh (FCM, right column).

Fig. 7 There is a divergent response of hydroperiod (a) and soil saturation index at 0.1 m depth (b) to elevation change in tidal creeks (red) and interior marshes (blue) at Deal Island. Asterisks indicate the observed result in interior marsh, these levels were used to validate the simulated result (filled circles).

Fig. 8 Dieback of *S. patens* and *D. spicata* before being displaced by more flood tolerant species, such as *S. americanus* (a) or *J. roemerianus* (b) in interior marsh of Deal Island.

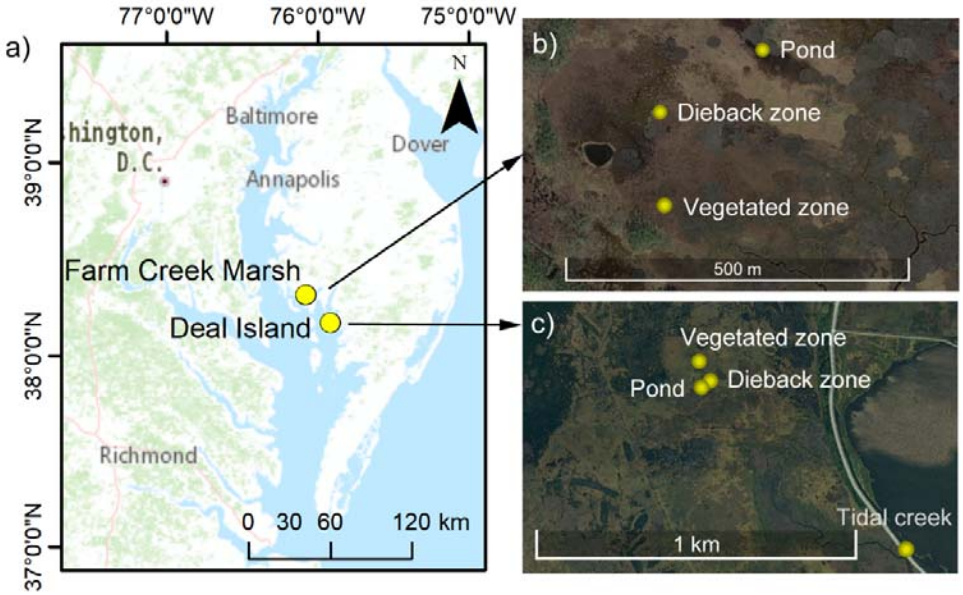
a)
77°0'0"W
76°0'0"W
75°0'0"W
39°0'0"N
38°0'0"N
37°0'0"N
N
hington,
D.C.
Baltimore
Annapolis
Dover
Farm Creek Marsh
Deal Island
Richmond
0 30 60 120 km
b)
Pond
Dieback zone
Vegetated zone
500 m
c)
Vegetated zone
Pond
Dieback zone
Tidal creek
1 km

Fig. 1

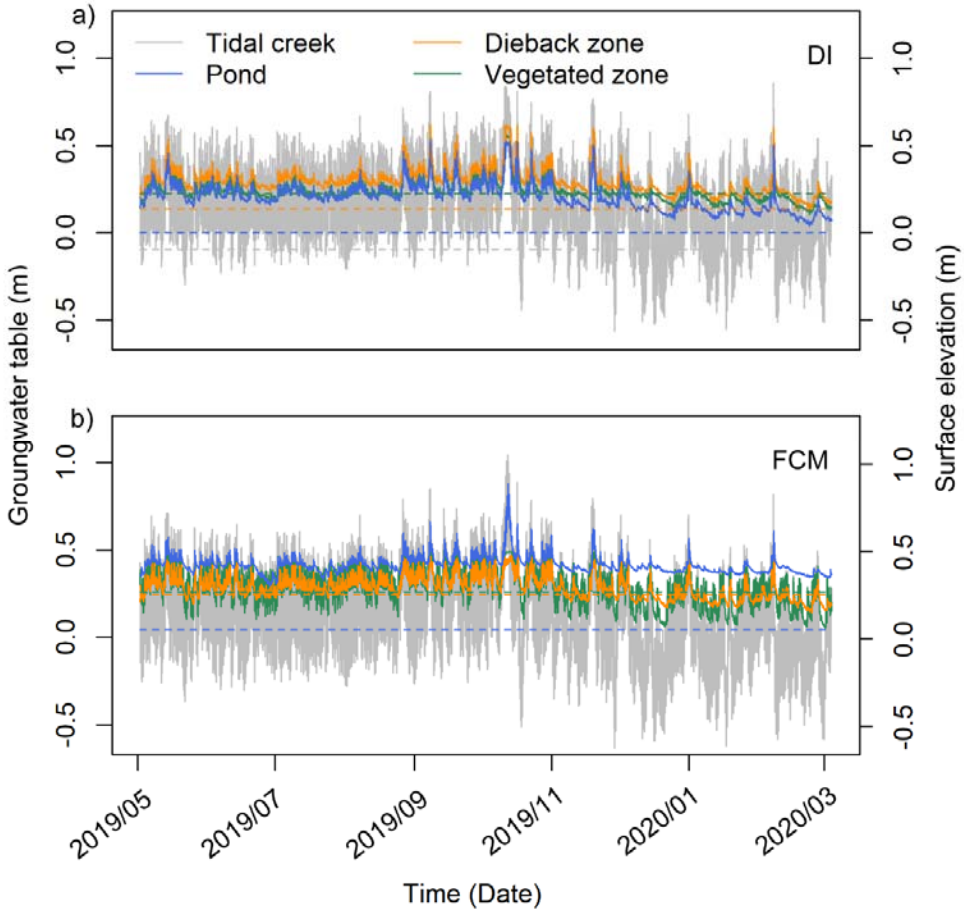
a)
Tidal creek
Pond
Dieback zone
Vegetated zone
DI
b)
FCM
Groungwater table (m)
Surface elevation (m)
1.0
0.5
0.0
-0.5
2019/05
2019/07
2019/09
2019/11
2020/01
2020/03
Time (Date)

Fig. 2

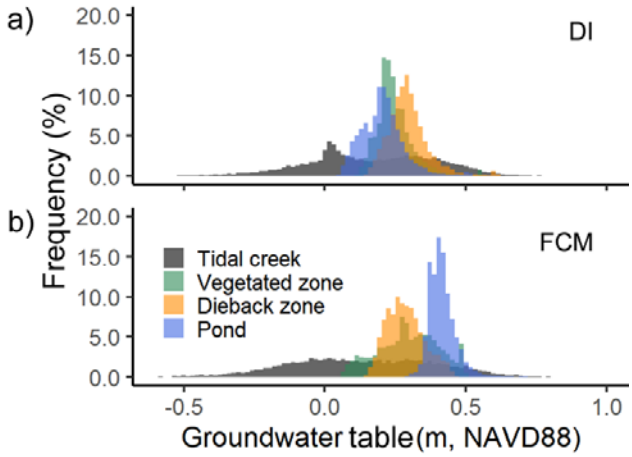
a)
DI
b)
FCM
Frequency (%)
20.0
15.0
10.0
5.0
0.0
Tidal creek
Vegetated zone
Dieback zone
Pond
-0.5
0.0
0.5
1.0
Groundwater table (m, NAVD88)

Fig. 3

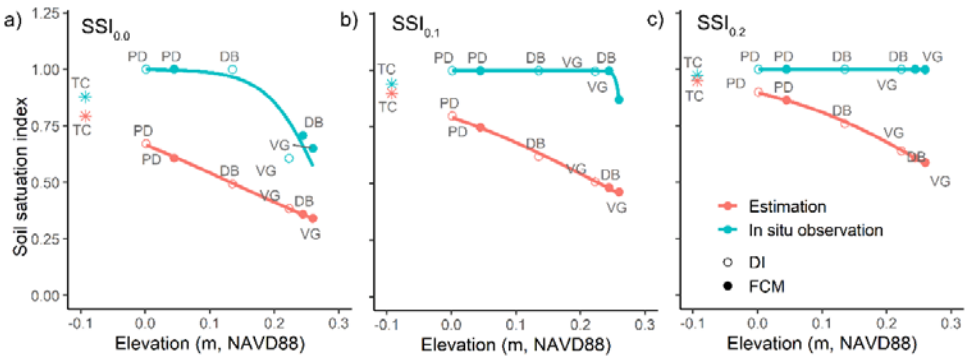
a)
SSI0.0
b)
SSI0.1
c)
SSI0.2
Soil satuation index
Elevation (m, NAVD88)
Estimation
In situ observation
DI
FCM
PD
DB
VG
TC

Fig. 4

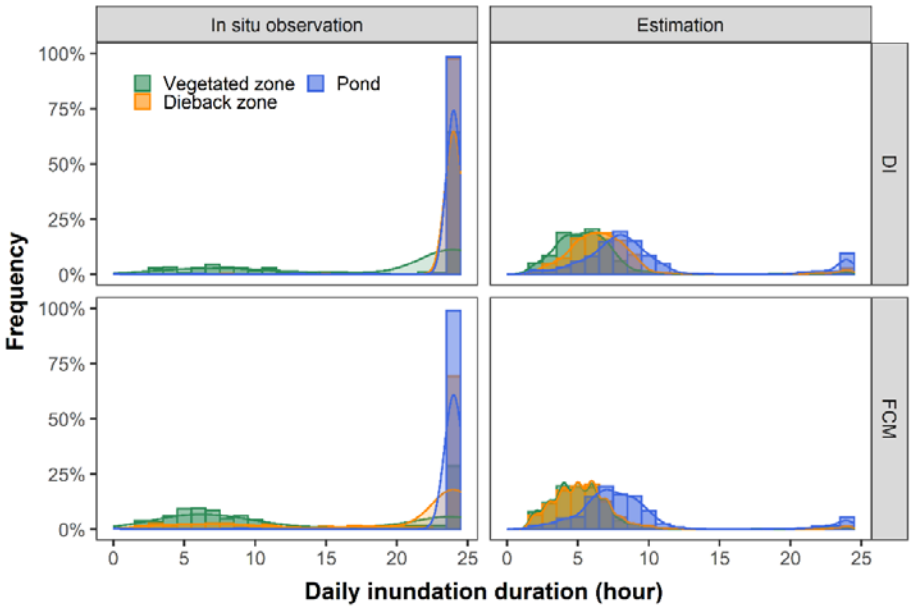
In situ observation
Estimation
Vegetated zone
Pond
Dieback zone
DI
FCM
Frequency
100%
75%
50%
25%
0%
0
5
10
15
20
25
Daily inundation duration (hour)

Fig. 5

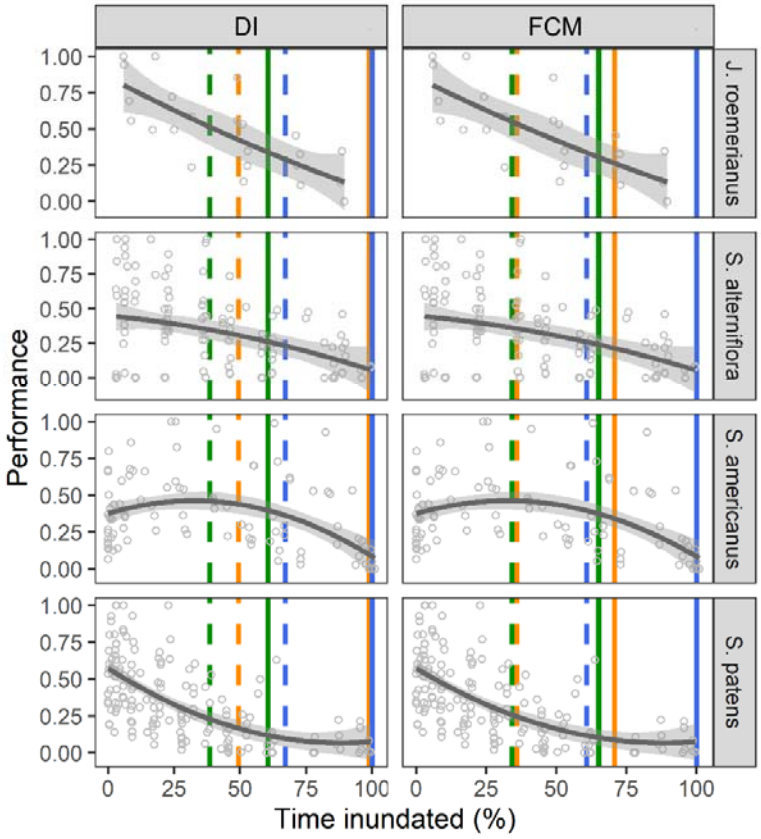
DI
FCM
J. roemerianus
S. alterniflora
S. americanus
S. patens
Performance
1.00
0.75
0.50
0.25
0.00
0
25
50
75
100
Time inundated (%)

Fig. 6

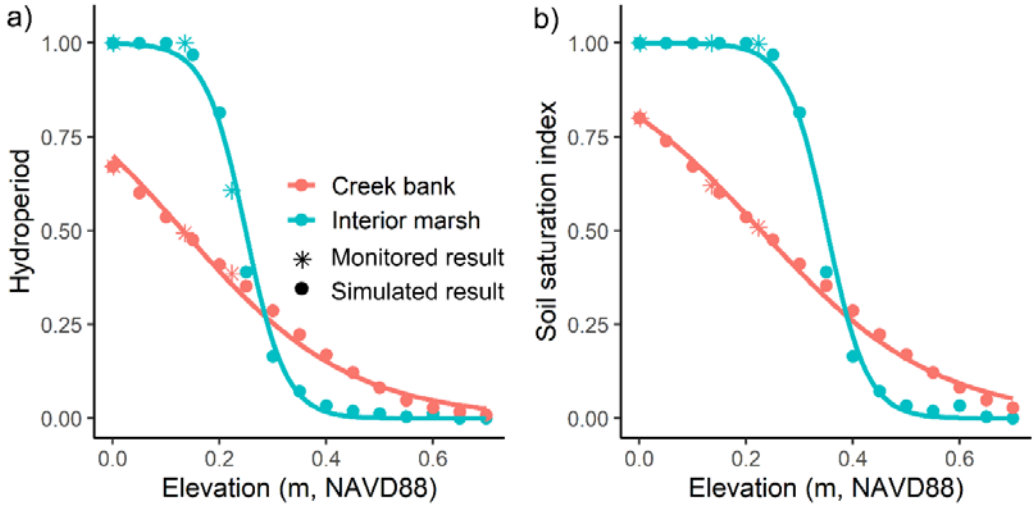
a)
b)
Hydroperiod
Soil saturation index
1.00
0.75
0.50
0.25
0.00
0.0
0.2
0.4
0.6
Elevation (m, NAVD88)
Creek bank
Interior marsh
Monitored result
Simulated result

Fig. 7

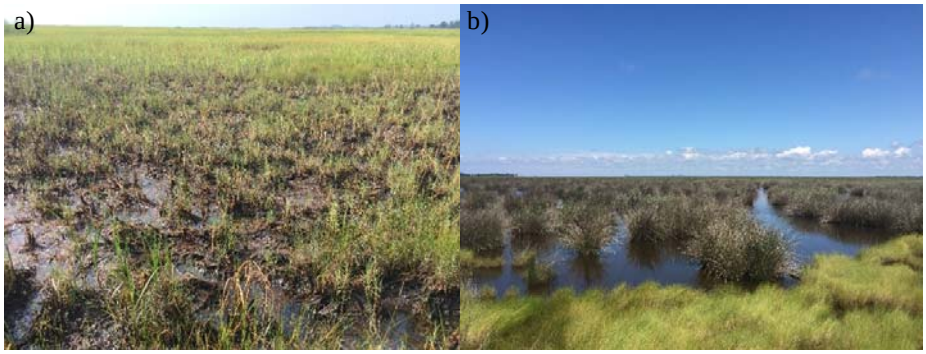

Fig. 8