

# Water Resources Research

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### Special Section:

Coastal hydrology and  
oceanography

### Key Points:

- Marshes reduce storm-surge induced surface and subsurface saltwater intrusion
- Reduced flood extent by marsh migration protects upland crop yield
- Marsh migration may provide financial benefits to farmers

### Supporting Information:

- Supplementary Information S1

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## Effects of Marsh Migration on Flooding, Saltwater Intrusion, and Crop Yield in Coastal Agricultural Land Subject to Storm Surge Inundation

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**Abstract** Low-lying coastlines are vulnerable to sea-level rise and storm surge salinization, threatening the sustainability of coastal farmland. Most crops are intolerant of salinity, and minimization of saltwater intrusion is critical to crop preservation. Coastal wetlands provide numerous ecosystem services, including attenuation of storm surges. However, most research studying coastal protection by marshes neglects consideration of subsurface salinization. Here, we use two-dimensional, variable-density, coupled surface-subsurface hydrological models to explore how coastal wetlands affect surface and subsurface salinization due to storm surges. We evaluate how marsh width, surge height, and upland slope impact the magnitude of saltwater intrusion and the effect of marsh migration into farmland on crop yield. Results suggest that along topographically low coastlines subject to storm surges, marsh migration into agricultural fields prolongs the use of fields landward of the marsh while also protecting groundwater quality. Under a storm surge height of 3.0 m above mean sea level or higher and terrestrial slope of 0.1%, marsh migration of 200 and 400 m protects agricultural yield landward of the marsh-farmland interface compared to scenarios without migration, despite the loss of arable land. Economic calculations show that the maintained yields with 200 m of marsh migration may benefit farmers financially. However, yields are not maintained with migration widths over 400 m or surge height under 3.0 m above mean sea level. Results highlight the environmental and economic benefits of marsh migration and the need for more robust compensation programs for landowners incorporating coastal wetland development as a management strategy.

**Plain Language Summary** Coastal wetlands are frequently the barrier between low-lying agricultural land and the ocean and thus are the lifeline for salt-intolerant crops, particularly during storm events when seas surge and rise several meters above normal conditions. However, sea level rise and erosion at the ocean's edge are causing marshes to shrink in size, particularly when marshes are not allowed to migrate landward—a critical mechanism through which marshes sustain land area in the face of global climate change. In this study, we use numerical models designed to represent a generalized marsh and agricultural field to explore how marsh migration into adjacent agricultural land impacts saltwater flooding and crop yield during storm events. Our work shows that along low-lying coastlines that experience large storm events, marsh migration into agricultural land can protect crop yield compared to scenarios without marsh migration, while also limiting saltwater contamination of the groundwater. However, along steeper coastlines and with smaller storm events, marsh migration does not benefit the farmer through maintained crop yield. Results suggest that marsh migration is an effective management strategy along topographically low coastlines subject to frequent storm surges and may financially benefit farmers in the short term and long term.

## 1. Introduction

The global threat of saltwater intrusion is accelerating due to anthropogenic and climatic influences. Saltwater intrusion is the landward movement of saltwater via surface and subsurface flow pathways. It occurs due to storm surge inundation on the order of hours to days; it also occurs due to sea-level rise (SLR) and groundwater withdrawals on the order of years to centuries. SLR-driven saltwater intrusion has received global attention for the current and future potential to compromise freshwater resources and alter ecosystem function (Michael et al., 2017; Werner & Simmons, 2009; Xiao et al., 2016, 2018). However, given the

current and projected increase in storm frequency and intensity (Goldenberg et al., 2001; Lin et al., 2019; Tebaldi et al., 2012; Vecchi et al., 2008), storm surges may have more acute impacts—driving salinization that contaminates freshwater resources, impairs coastal ecosystems, harms infrastructure, and renders agricultural land unusable on drastically shorter timescales (Anderson, 2002; Xiao et al., 2019). Therefore, creating coastlines and communities that are resilient to storm surge inundation is essential for short-term and long-term land use and community welfare.

Along coastlines worldwide, agricultural land is located within kilometers of the ocean. On the east coast of the United States, approximately 24% of the Albemarle-Pamlico Peninsula in North Carolina and 22% of land within 100 m of the Chesapeake Bay is agricultural (Bhattachan et al., 2018; Schieder et al., 2018). Saltwater intrusion can devastate agricultural productivity, as saltwater changes the soil chemistry of the farmland with negative consequences for crops that are not adapted to high salt concentrations. Already, the impacts of climate change are affecting coastal agricultural land. In Bangladesh, 3,000 km<sup>2</sup> of arable land was salinized (Khanom, 2016) and along the Chesapeake Bay, 400 km<sup>2</sup> of upland (including forest, urban, and agriculture) was converted to wetland (Schieder et al., 2018). In Virginia alone, 1.92 km<sup>2</sup> of agricultural land is lost annually to coastal wetlands (Fagherazzi et al., 2019; Titus et al., 2010)—likely a result of storm-induced and SLR-induced saltwater intrusion and soil saturation. These numbers are expected to increase in the coming century. For example, Kang et al. (2016) estimated that 951–1,377 km<sup>2</sup> of farmland in the Pearl River Delta, China will be compromised by storm events by 2030.

To reduce storm surge inundation and protect coastlines, often hard structures such as sea walls, dykes, and embankments are constructed. In recent years, however, ecological engineering, or green infrastructure, is increasingly being implemented as a coastal defense mechanism due to the longevity, natural evolution, and cobenefits of these ecologically based strategies (Temmerman et al., 2013). Green infrastructure includes oyster and coral reefs, seagrass and dune grass beds, and mangrove forests (Temmerman et al., 2013). Coastal wetlands, also referred to as tidal wetlands and marshes, are another form of green infrastructure that are particularly effective in dissipating wave energy and storm surges (Leonardi et al., 2018; Narayan et al., 2017). The dense marsh vegetation, which has high surface roughness or friction (i.e., Manning's  $n$ ) (Alizad et al., 2018; Sullivan et al., 2015), dissipates wave energy through enhanced drag from the vegetation canopy, counteracting the surging water (Möller & Spencer, 2002). For example, beyond 40 m of marsh, declines in wave height can reach 10–20% (Möller et al., 2014), and surge attenuation rates range from ~1.7 to 70 cm/km due to marsh presence (Stark et al., 2015; Wamsley et al., 2010). Thus, marsh width is important for flood mitigation (Stark et al., 2015).

The aforementioned studies focus on surface inundation and attenuation due to storm surges, which is important for protecting crops, infrastructure and human lives. However, research on saltwater infiltration and salinization of the unconfined aquifer due to coastal wetland storm surge attenuation is lacking yet critically important for the sustainability of coastal groundwater quality. Minimization of aquifer salinization has the potential to impact the long-term water quality of coastal freshwater aquifers (Yu et al., 2016), many of which are used for both domestic wells and crop irrigation (He & Andres, 2018). We hypothesize that the reduction in surge extent and thus flooded surface area due to the high vegetative friction of coastal wetlands may decrease the saltwater intrusion into the fresh groundwater. Therefore, the presence of coastal wetlands could impact crop yield in the short-term due to a decrease in flood extent and in the long-term due to maintained water quality of irrigation wells.

The above processes are dependent on the presence of coastal wetlands. Wetland width (perpendicular to the shoreline) is a function of both the terrestrial and ocean boundaries (Guimond et al., 2020b; Mariotti & Carr, 2014). Along the ocean boundary, wetlands are vulnerable to wave-driven erosion, and positive feedbacks exist where erosion increases wave fetch and, in turn, increases erosion (Mariotti & Carr, 2014; Mariotti & Fagherazzi, 2013). Along the terrestrial boundary, coastal wetlands respond to SLR by migrating landward as saltwater intrusion and/or elevated terrestrial water tables weaken neighboring ecosystem vegetation. The weakened upland ecosystem provides an avenue for marsh grasses to outcompete terrestrial species (Brinson et al., 1995; Guimond et al., 2020b; Kirwan et al., 2016). Observed migration rates vary from 0.5 to 2.1 m/yr (Hussein, 2009; Shieder et al., 2018), depending on topographic slope and upland land use (Alizad et al., 2016; Brinson et al., 1995; Feagin et al., 2010; Hussein, 2009; Raabe & Stumpf, 2016; Smith, 2013). For example, using Hydro-MEM, Alizad et al. (2016) showed that in Florida's Apalachicola

estuarine system marsh migration was governed by the topographic profile, limiting marsh migration to within a narrow coastal border.

Generally, marshes are bordered by coastal forests, urban development, or agriculture. Urban development, including manicured lawns and infrastructure (i.e., seawalls, roads, etc.) inhibits marsh migration into upland areas. Marsh migration into coastal forests has occurred, yet a series of failures and feedbacks are required with respect to tree growth and regeneration before migration can occur (Brinson et al., 1995; Kirwan et al., 2007; Kirwan & Gedan, 2019). In contrast, agricultural land may provide an ideal location for marsh migration, with low topographic slopes and minimal anthropogenic or vegetative barriers (Gedan et al.). Farmer resistance to marsh migration due to a loss of potentially arable land and income makes agricultural uplands effectively anthropogenic barriers. However, at some point productivity declines are great enough that the farmland is abandoned and a unique assemblage of plants are left to colonize (Gedan & Fernández-Pascual, 2019; Tully et al., 2019).

In this study, we use hydrological models with coupled surface and subsurface flow regimes and density-dependent fluid flow to explore how marsh migration into farmland impacts both surface and subsurface saltwater intrusion due to storm surges. This study is the first of its kind to not only capture marsh-induced surge dissipation through overland flow but to also capture changes in the volume of subsurface salinization. Results provide critical insight into coastal wetland impacts on aquifer water quality and coastal water resource sustainability—a frequently overlooked benefit of coastal wetlands. Results are put into the context of crop yield to identify short-term and long-term strategies for sustainable agriculture and aquifers amid climate change and potential marsh migration.

## 2. Methods

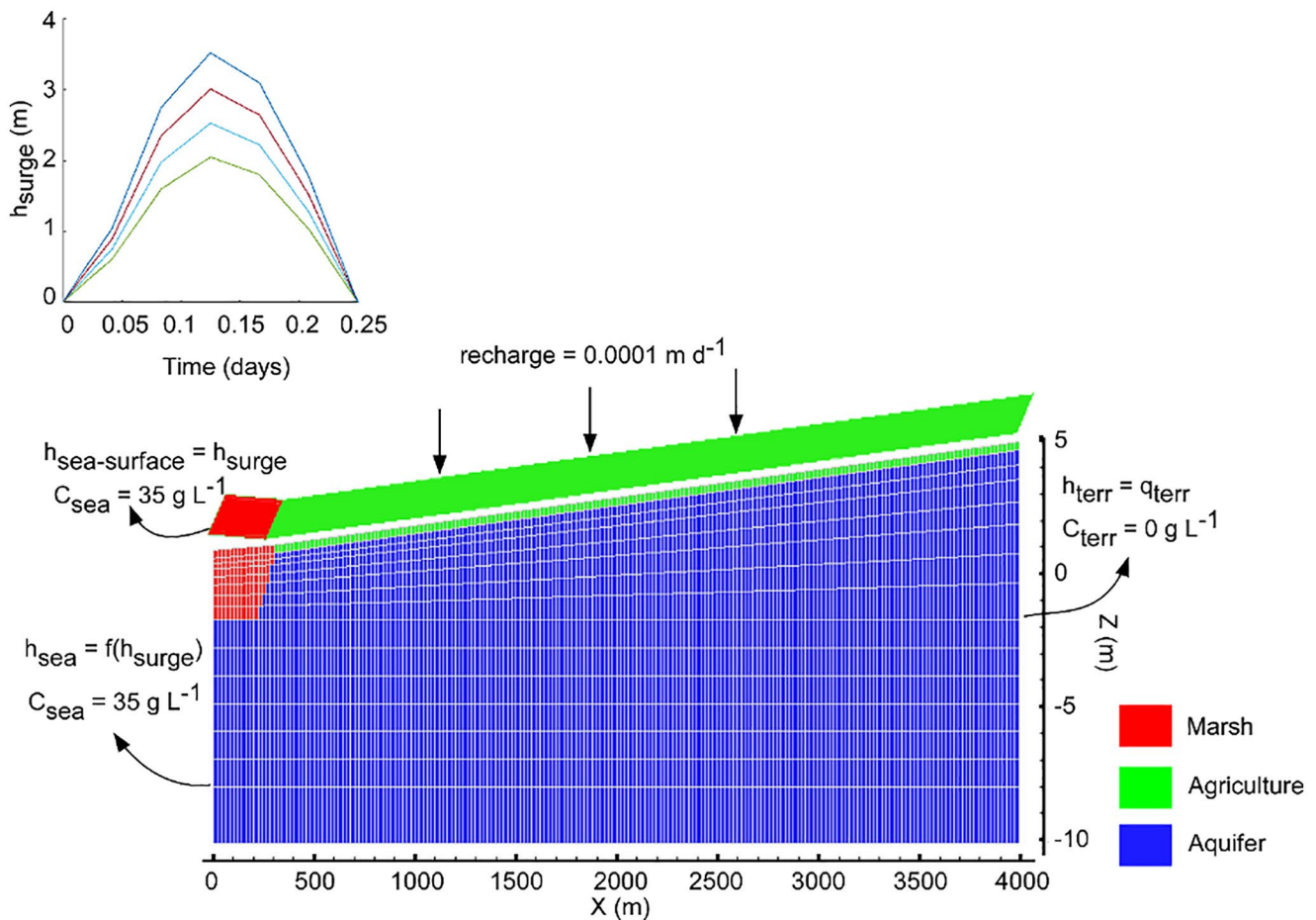
### 2.1. HydroGeoSphere

Two-dimensional (2D) hydrological models were developed using the surface water and groundwater modeling software *HydroGeoSphere* (Therrien et al., 2006). *HydroGeoSphere* is ideal for simulations of storm surge inundation due to incorporation of both variably saturated conditions and density-dependent fluid flow, and thus has been used for various flood modeling studies (e.g., Yang et al., 2013, 2015; Yu et al., 2016) and tidal marsh studies (Guimond et al., 2020b; Moffett et al., 2012; Zhang et al., 2014). *HydroGeoSphere* is particularly unique due to its ability to simultaneously simulate surface water dynamics and groundwater flow. Two-dimensional surface water flow was simulated using Manning's equation and the diffusion-wave approximation of the Saint Venant equation. Three-dimensional, variably saturated subsurface flow was simulated with Richards equation (Therrien et al., 2006). Darcy's Law was used to compute the fluid exchange between the surface and subsurface domains (i.e., infiltration). Density-dependent salt transport was solved using the advection-diffusion-dispersion equation in both surface and subsurface flow regimes. Model theory and numerical implementation are more thoroughly explained in Therrien et al. (2006).

### 2.2. Model Domain, Parameters, Boundary Conditions, and Simulation Approach

The 2D, finite difference model domain was 4,000 m long ( $x$ ) and extended to a depth of 10 m below sea level ( $z$ ; Figure 1). The grid discretization was 20 m in the  $x$  direction and was variably discretized in the  $z$  direction (Figure 1). The depth of the top cell of the model was 30 cm across the entire domain to represent the root zone. There are seven layers of proportional depth between the top cell and  $-2$  m, followed by 1 m layers from  $-2$  to  $-8$  m. The last layer was 2 m deep from  $-8$  to  $-10$  m.

The model domain was designed to represent a generalized coast-marsh-upland transect along a topographically low coastline. Given the large-scale focus on surface and subsurface saltwater intrusion, generalized models rooted in site-specific data were used in this study. These simplified models enable systematic understanding of the mechanisms and controls impacting the magnitude and extent of saltwater intrusion that can be obscured by the unique features of a site-specific study. Through these simplified models, we are able to isolate the impacts of marsh width and terrestrial slope on saltwater intrusion. Coastal wetland zones were represented by a low slope (0.06%) and were on the seaward side of the model domain. Agricultural areas were represented by slightly higher slopes (0.1–0.4%), representative of slopes found along the



**Figure 1.** Two-dimensional, surface and subsurface model domain, zone distribution, and boundary conditions. Insert shows height and duration of four storm surge scenarios.

Delaware-Maryland-Virginia (Delmarva) coastline and other low-lying coastlines such as the Gulf Coast and parts of southeast Asia (Jelgersma et al., 1993). Surface properties were designated with different parameters for marsh and agricultural land (Table 1). Marsh overland flow properties incorporated relatively high Manning's roughness ( $n$ ) compared to the agricultural fields, which had a slightly lower  $n$  due to a lower stem density (Chow, 1959; Table 1). The subsurface domain was divided into marsh, loam, and aquifer units (Table 1). The marsh zone was further divided into (1) formerly established marsh (termed here *front marsh*) and (2) migrating marsh (transgressing into former agricultural field; Figure 2). The depth of the front marsh reflects depths of low permeability, mud-rich and silt-rich sediments found along the East Coast of the United States (Gardner & Porter, 2001; Hughes, 2016; Ward et al., 2008). The hydraulic conductivity ( $K$ ) of the marsh was 0.01 m/day based on Guimond et al. (2020a). The loam unit captured the root zone (top 30 cm) of the model domain and had a  $K$  of 1.1 m/day (Carsel & Parrish, 1988). The aquifer unit encompassed the rest of the model domain and had a  $K$  of 47 m/day, characteristic of a sandy coastal aquifer based on the Delaware Geological Survey geophysical well log database. The unsaturated properties were also varied based on the subsurface unit (Table 1).

Boundary conditions were prescribed along the seaward boundary, upland boundary, and to the surface domain (Figure 1). The bottom of the domain was a no-flow boundary, representing the top of a confining layer. The seawater boundary condition in the surface domain ( $h_{\text{sea-surface}}$ ) was a specified head boundary condition, originating at mean sea level (0 m) and increasing up to the storm surge height and back down (inset, Figure 1). This approach assumes a hydrostatic column of water that continuously thickens during the surge. In the subsurface, the specified head seawater boundary ( $h_{\text{sea}}$ ) was a function of the surge height (Yu et al., 2016). The seawater concentration in the surface and subsurface domains was held constant at 35

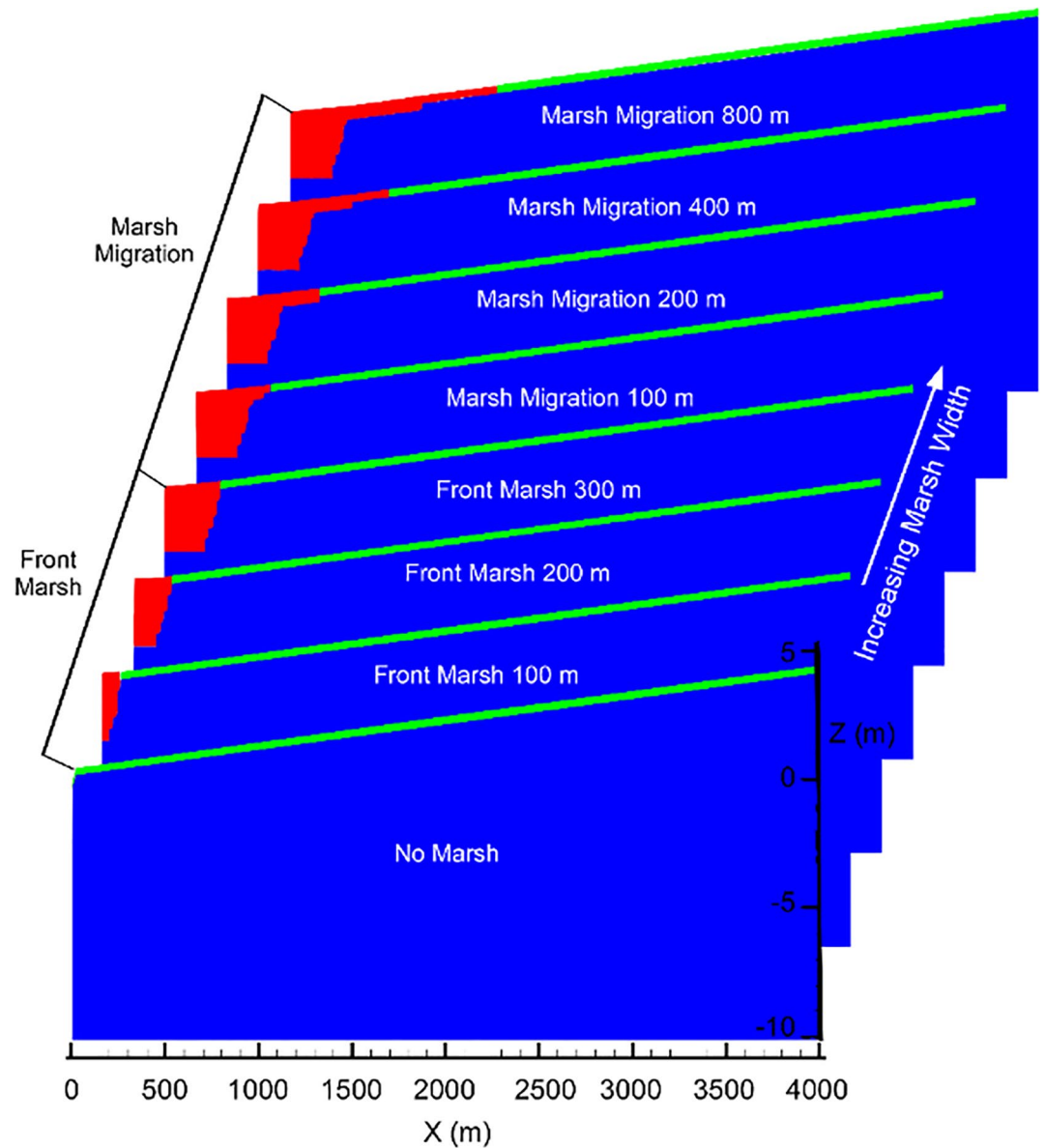
**Table 1**  
*Surface and Subsurface Parameter Values for Model Simulations*

Parameter	Value			Source
	Marsh	Agriculture	Aquifer	
	<i>Porous Media</i>			
Hydraulic conductivity ( $\text{m d}^{-1}$ )	0.01 <sup>1</sup>	1.1 <sup>2</sup>	47 <sup>3</sup>	<sup>1</sup> Guimond et al. (2020), <sup>2</sup> Carsel and Parrish (1988), <sup>3</sup> DGS geophysical log database
Porosity	0.3	0.35	0.4	Carsel and Parrish (1988)
Longitudinal dispersivity (m)	50	50	50	Gelhar et al. (1992)
Transverse dispersivity (m)	5	5	5	Gelhar et al. (1992)
Vertical transverse dispersivity (m)	5	5	5	Gelhar et al. (1992)
Van Genuchten $\alpha$ ( $\text{m}^{-1}$ )	5.9	7.5	14.5	Carsel and Parrish (1988)
Van Genuchten $\beta$	1.48	1.89	2.68	Carsel and Parrish (1988)
Residual saturation	0.100	0.065	0.045	Carsel and Parrish (1988)
	<i>Overland Flow</i>			
Manning roughness coefficient ( $\text{d m}^{-1/3}$ )	$7 \times 10^{-6}$ <sup>1,2</sup>	$2 \times 10^{-6}$ <sup>1</sup>		<sup>1</sup> Arcement and Schneider (1984), <sup>2</sup> Sullivan et al. (2015)
Obstruction storage height (m)	0.04	0.04		
Rill storage height (m)	0.01	0.01		
	<i>General</i>			
Freshwater density ( $\text{kg m}^{-3}$ )	1,000			
Seawater density ( $\text{kg m}^{-3}$ )	1,025			
Freshwater concentration ( $\text{g L}^{-1}$ )	0			
Seawater concentration ( $\text{g L}^{-1}$ )	35			

ppt. Recharge was a constant specified flux to the surface domain of 0.0001 m/day, which accounts for both precipitation and evapotranspiration.

The upland boundary condition was a specified flux boundary with a concentration of 0 ppt. The terrestrial flux ( $q_{\text{terr}}$ ) for the upland boundary was assessed based on the average flux from steady state simulations. For steady-state simulations, the surface seawater level boundary condition was a specified head boundary condition held at mean sea level (0 m), and the subsurface seawater boundary condition was a function of the mean sea level. The upland boundary condition in the subsurface was a specified head boundary condition equivalent to 60% of the topographic elevation at the upland boundary in order to maintain a topography-dependent unsaturated zone. Thus, fluxes varied between scenarios with different topographic elevations. The terrestrial flux acquired from the steady-state simulations varied from 0.0175 to 0.183 m/day. Recharge to the surface domain was the same for both steady-state and transient simulations. Transient simulations were started from the steady-state distribution of heads and salinities, using the average terrestrial flux.

Transient simulations included four front marsh simulations (0, 100, 200, 300 m) and four migration simulations (100, 200, 400, 800 m). Each front marsh scenario (100–300 m) was run alone as well as with each marsh migration scenario. For example, front marsh widths and marsh migration scenarios with 300 m of front marsh are shown in Figure 2. Unless otherwise noted, the figures and text in this manuscript depict the simulations shown in Figure 2 given the similarity in results between 100, 200, and 300 m front marsh simulations. Simulation results are displayed based on total marsh width (0–1100 m), where 400–1100 m is marsh migration atop formerly agricultural land. However, results are discussed in terms of total marsh width as well as width of front marsh (0–300 m) and migrated marsh (0–800 m), noting that the simulation with 0 m of migrated marsh width is equivalent to the simulation with 300 m of front marsh.



**Figure 2.** Model zonation scenarios with an increase in front marsh and marsh migration. Red is marsh and green is agricultural land. Figures highlight difference in marsh depth between front marsh and migrated marsh.

Front marsh was distinguished as formerly established wetland and thus was deeper than the migrating marsh. The marsh depth in the marsh migration scenarios was shallower due to a shorter time period for soil development. For each domain, four storm surge scenarios were simulated (2.0, 2.5, 3.0, 3.5 m above mean sea level (0 m); Figure 1). Note, the mean higher high water (MHHW) or the marsh-agriculture transition in the model domain is 0.7 m, and thus, relative to MHHW, storm surge scenarios were 1.3, 1.8, 2.3, and 2.8 m. Surge water levels were based on present-day 10-, 50-, and 100-year storm surge heights experienced along the United States Atlantic and Gulf Coasts and projected future surge heights (Lin et al., 2019; Marsooli et al., 2019). For example, along the Atlantic Coast of the United States, 10-year storm surge heights range from 0.89 to 1.52 m, and 50-year storm surge heights range from 1.13 to 2.07 m (Lin et al., 2019). Along the Gulf Coast of the United States, 10 year storm surge heights can reach up to 2.72 m (Needham et al., 2012). However, these numbers are rapidly changing. While present-day (1980–2005) 100-year surge heights range from 0.27 to 4.3 m along the Atlantic and Gulf coasts of the United States, climatological-hydrodynamic models suggest these heights will become annual events in some areas within approximately the next 50 years (Marsooli et al., 2019), posing a

serious threat to coastal agriculture. In addition to varying marsh width, migration extent, and surge height, simulations were run for five upland slope scenarios (0.1%, 0.15%, 0.2%, 0.3%, 0.4%) based around the average topographic slope of the Atlantic Coastal Plain (Clark et al., 1912) but also representative of topographically low coastlines globally. In total, 320 transient simulations were run.

### 2.3. Salinization Assessment Criteria

The output of the model simulations was analyzed using four assessment criteria (Yu et al., 2016): (1) maximum flood extent, (2) saltwater infiltration, (3) maximum salinized volume, and (4) salinity-dependent crop yield. The *maximum flood extent* is calculated as the maximum landward extent that water with salt concentration above 1.255 g/L intrudes via overland flow beyond the front marsh. 1.255 g/L is the approximate salinity at which corn is negatively influenced by salt content (Butcher et al., 2018). From these results, the change in flood extent relative to the no front marsh and no marsh migration scenarios can be calculated in addition to the salinized agricultural area. *Saltwater infiltration* is the total volume of water infiltrated from the surface domain into the subsurface domain with salt concentration greater than 0.5 g/L, the U.S. Environmental Protection Agency drinking water standard (EPA, 2009). The *maximum salinized volume* is the maximum volume of the subsurface domain with salt concentrations above 0.5 g/L within 20 days of the storm surge event. Volumes are reported per m length of coastline.

The *salinity-dependent crop yield* was calculated using crop-specific relative yield and actual yields from the mid-Atlantic. The mid-Atlantic was used as a reference due to the data availability in coastal farmland. The crop-specific relative yield in the agriculturally defined regions of the model domain was calculated based on the average root zone salinity (top 30 cm of sediment) using the modified discount response function (van Genuchten & Gupta, 1993) for corn and soybeans (Steppuhn et al., 2005). Corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) were used in this study, as they are two of the four major global cash crops (Tanji & Kielen, 2002) and prevalent in coastal regions of the United States. Corn and soybean are moderately sensitive and moderately tolerant to salinity, respectively (Tanji & Kielen, 2002). Calculations were based on the simulated root zone salinity 1 week after the storm surge occurred, allowing time for short-term plant response to salinity to occur and long-term plant response to salinity to begin (Munns & Termaat, 1986; Munns & Tester, 2008). Relative yields were converted to actual yields based on Maryland and Delaware's 2019 average corn and soybean yield (10,106 kg/ha and 3,060 kg/ha, respectively; USDA-NASS Quickstats, 2019) to arrive at the *salinity-dependent crop yield*. Crop yields for front marsh scenarios (0–300 m) were normalized to the same area of agricultural land (3,700 m).

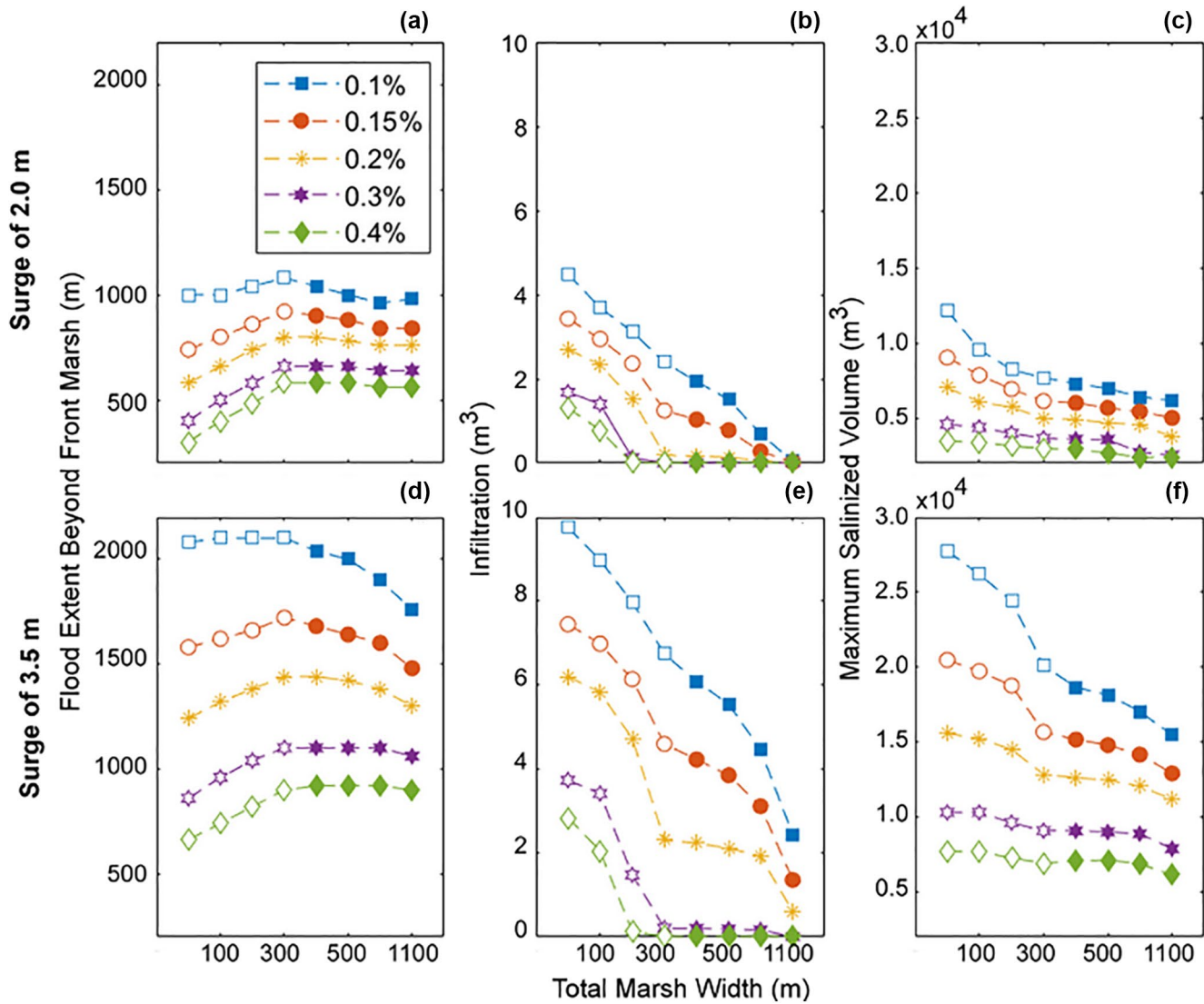
### 2.4. Economic Calculations

To put yields in the context of farmers' finances, the maximum revenue gained and lost during years with storm events was calculated. Calculations were based on crop yields from scenarios with 200 m of marsh migration and used the average price of corn and soybeans (\$0.17 and \$0.30 per kg, respectively; USDA-NASS Quickstats, 2019). Input and production costs were also considered in financial calculations given that marsh migration decreases the area of arable land as well as the area of farmland that is cultivated. In the state of Maryland, it cost approximately \$1,394 to cultivate a hectare of corn and \$898 to cultivate a hectare of soybeans, including the \$242 per year for the estimated cost of land (University of Maryland Extension). Cultivation calculations excluded the estimated \$242 per year for the cost of land, assuming that farmers still pay for land even when marsh migration has occurred. We note that the calculated input cost saved is a maximum, since there are some fixed costs which would not scale with area cultivated and will differ based on the magnitude of marsh migration. Calculations also considered financial incentives from wetland development programs, such as the Conservation Reserve Enhancement Program which provides farmers annual payments of 200% land rental costs per year.

## 3. Results

### 3.1. Maximum Flood Extent

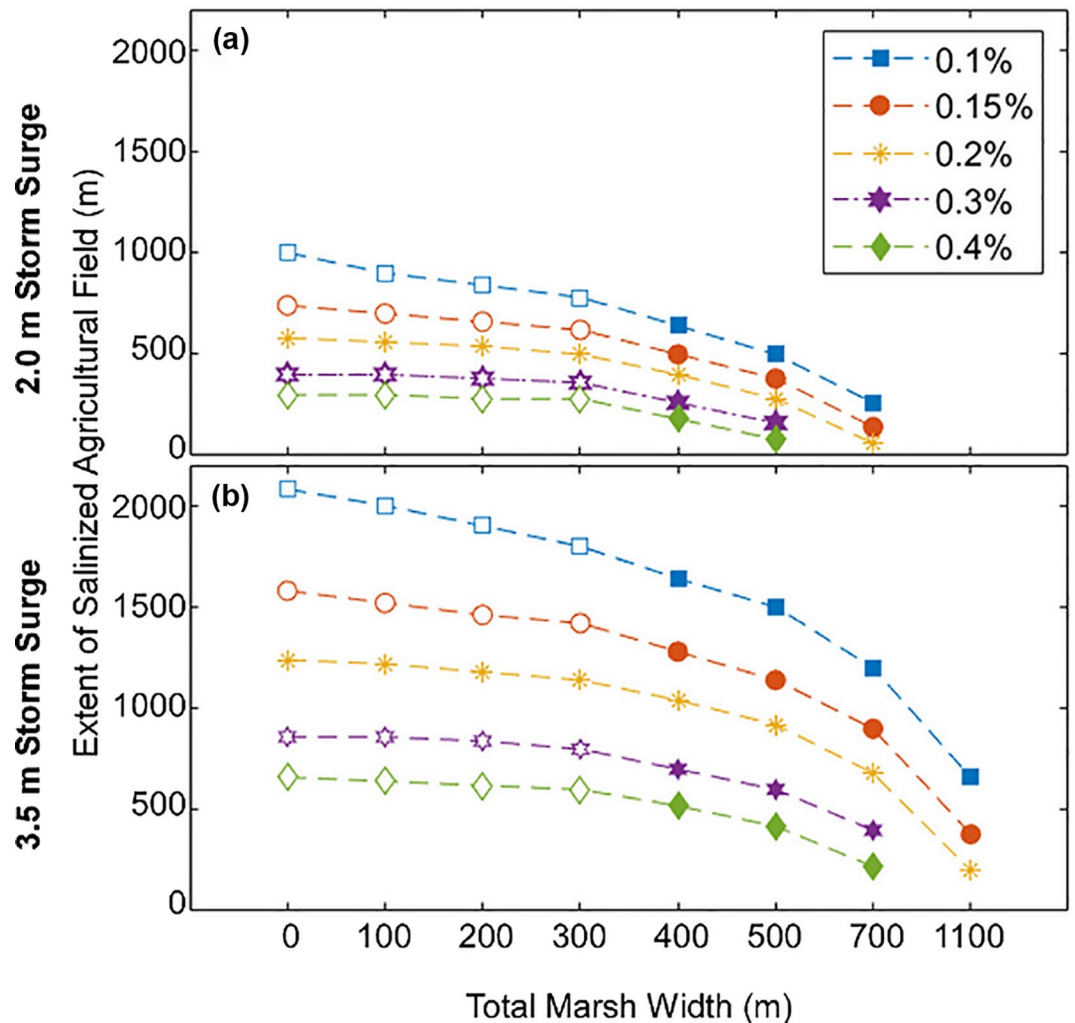
Increased marsh width or upland slope reduced flooding, whereas increased surge height increased flooding (Figures 3 and S1). The reduced flood extent with increasing marsh width reduced the extent of salinized



**Figure 3.** Flood extent beyond front marsh (a), (d), total infiltration (b), (e), and maximum salinized volume (c), (f) with total marsh width for 2 and 3.5 m storm surges. Colors indicate topographic slope (%). Front marsh simulations are depicted by open markers and marsh migration simulations are depicted by closed markers. Plots highlight increase in saltwater intrusion with lower slopes and higher storm surges.

agricultural field (Figure 3) and was greatest for scenarios with lower upland slopes (i.e., 0.1–0.2%) and higher storm surges (Figure 4). For example, for an upland slope of 0.1% and surge height of 3.5 m above mean sea level, the flood extent was reduced from 2,080 m without front marsh to 1,800 m with 300 m of front marsh, a surge dissipation of 280 m. The surge was further reduced to 1,460 m with 1,100 m of marsh (i.e., 800 m of marsh migration; Figure 4). In contrast, for an upland slope of 0.4% and surge of 3.5 m above mean sea level, the flood extent was reduced only 60 m with 300 m of front marsh and did not decrease further with marsh migration. However, scenarios with higher upland slopes experienced less flooding overall, such that in scenarios with 0.3% and 0.4% upland slope and low storm surges, no agricultural land was salinized (Figure 3), suggesting unfavorable conditions for marsh migration.

Flood extent was not impacted by variability in front marsh width but the total marsh width overall. For example, for a given total marsh width, the flood extent beyond the front marsh is nearly always equal no matter the fraction of total marsh that is front marsh (Figure S2). However, for a given marsh migration scenario, simulations with more front marsh will have less flooding due to a greater total marsh width (Figure S2).

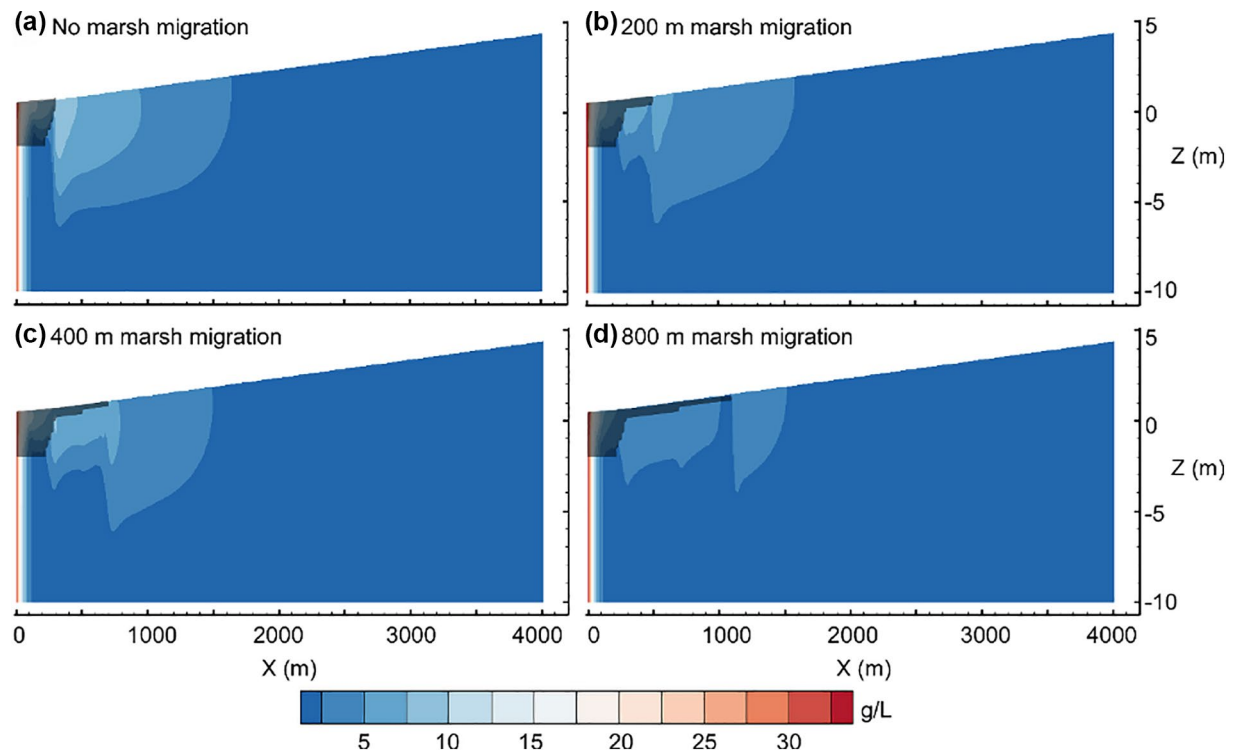


**Figure 4.** The extent of salinized agricultural field for all front marsh (open markers) and marsh migration (closed markers) scenarios. Colors indicate topographic slope. Results are shown for storm surge scenarios of 2.0 m (a) and 3.5 m (b).

### 3.2. Saltwater Infiltration and Salinized Volume

The quantity of saltwater infiltrating from the surface domain into the subsurface domain decreased with an increase in marsh width and land slope and increased with an increase in surge magnitude (Figure 4). The reduction in infiltration with marsh width is likely a result of the reduced surge extent, suggesting that salinization is diminished when marshes are allowed to migrate. For example, for scenarios with 0.1% slope, infiltration decreased from  $4.5 \text{ m}^3$  with no front marsh to  $2.5 \text{ m}^3$  with 300 m of front marsh, then decreased to  $0.04 \text{ m}^3$  with 1,100 m of total marsh under the same slope and surge height (Figure 4). The magnitude of saltwater infiltration was minimized when the surge did not extend beyond the marsh, as seen in scenarios with higher slope and lower surge magnitude (Figure 3 and S1). The salinized volume showed similar patterns to saltwater infiltration, decreasing with an increase in marsh width and upland slope and increasing with storm surge height (Figures 3, 5, and S1), further highlighting the reduction in subsurface saltwater intrusion with increased marsh width.

Front marsh width impacted the maximum salinized volume, particularly for simulations with low slopes and high surges (Figure S2). For each marsh migration scenario, simulations with a greater front marsh had a smaller salinized volume. This difference is greater in low slope scenarios. Similarly, simulations with larger front marsh showed a smaller salinized volume compared to simulations with the same total marsh



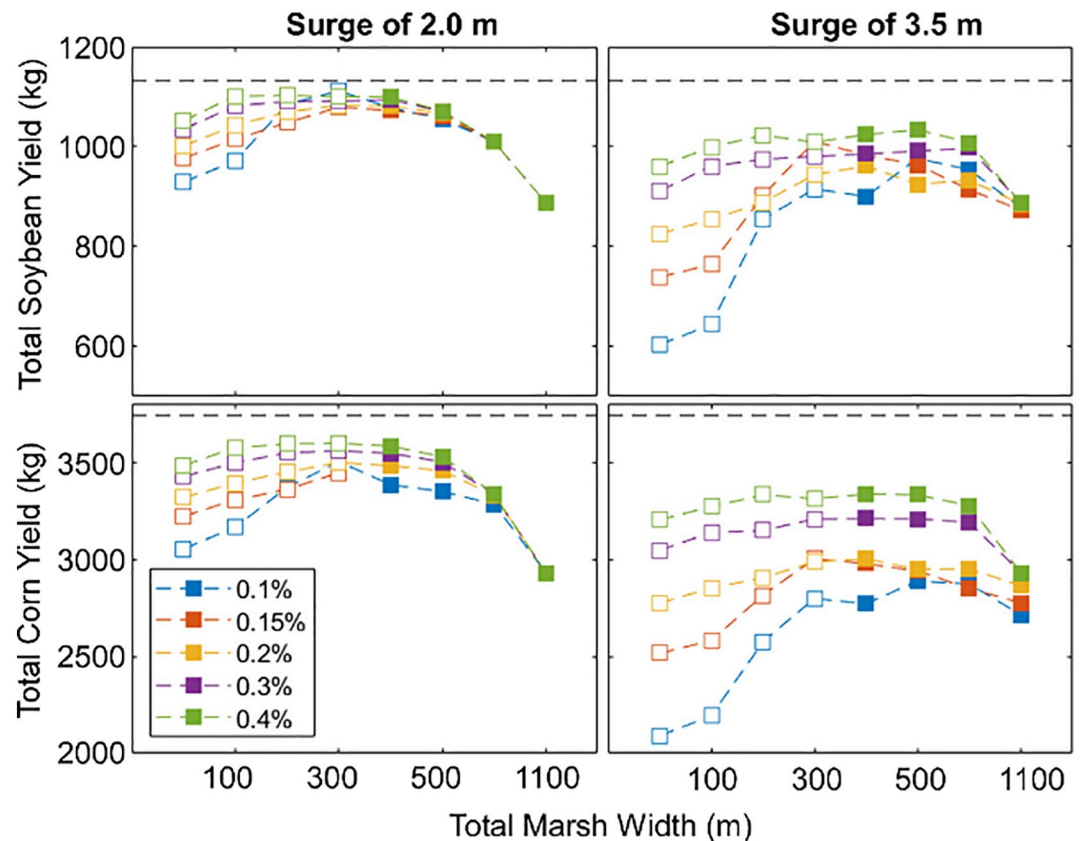
**Figure 5.** Volume salinized 7 days after the storm surge for scenarios with 0.1% topographic slope, 3.5 m surge, 300 m of front marsh, and (a) no marsh migration, (b) 200 m of marsh migration, (c) 400 m of marsh migration, and (d) 800 m of marsh migration. Marsh zone overlays salinity plots.

width but smaller front marsh (Figure S2). This is likely due to a greater extent of the thicker, less permeable marsh sediment of the front marsh.

### 3.3. Salinity-dependent Corn and Soybean Yield

While corn and soybean yields were less than average annual conditions (10,106 kg/ha and 3,060 kg/ha, respectively) for all slope and marsh scenarios under a storm event, the yield loss was lower for higher slopes and lower storm surge heights (Figure 5). In general, corn and soybean yield decreased with an increase in storm surge height and increased with an increase in upland slope. Yield declines occurred across the inundated upland (i.e., agricultural field) but were greatest near the marsh-cropland boundary where salinities were highest (Figure 6). For most surge and slope scenarios, an increase in the front marsh width increased the corn and soybean yield relative to no front marsh scenarios (i.e., 0 m total marsh) when normalized to the same area of upland (3,700 m; Figure 5). Increases in crop yield due to front marsh presence were greatest for lower upland slopes (i.e., less than 0.3%). For example, for a 2 m surge and 0.1% slope, the soybean yield increased from 929 kg/m coastline with no front marsh to 1,112 kg/m coastline with 300 m of front marsh out of a potential 1,132 kg/m coastline. In comparison, with a surge of 2 m and a slope of 0.4%, the soybean yields only increased from 1,052 kg/m coastline with no front marsh to 1,100 kg/m coastline with 300 m front marsh.

For marsh migration scenarios up to 400 m (i.e., 700 m total marsh), crop yields varied on average less than 80 kg compared to no marsh migration scenarios (i.e., 300 m of total marsh), despite a reduction in the extent of arable land. For scenarios with 0.1% slope and 3.0 m storm surge and above, the crop yield even increased with marsh migration compared to no marsh migration (Figure 5). For example, under scenarios with 0.1% slope and 3.0 m storm surge height, corn yield increased from 2,946 kg/m coastline with no marsh migration (i.e., 300 m total marsh) to 3,031 kg/m coastline with 200 m of marsh migration (i.e., 500 m total marsh); soybean yield increased from 936 kg/m coastline to 987 kg/m coastline under the same surge height and marsh migration width (Figure 5). In contrast, under low storm surge scenarios (i.e., 2.0 m), corn and



**Figure 6.** Total corn and soybean yield (kg) per m of coastline for all slope scenarios and lowest (2.0 m) and highest (3.5 m) storm surge scenarios. Results show all front marsh (open marker) and marsh migration (closed marker) scenarios. The black dashed line is the total potential yield per m of coastline without marsh migration or a storm event. Colors indicate topographic slope (%).

soybean yields decreased with marsh migration relative to the no marsh migration scenario (i.e., 300 m total marsh). The maximum decline in soybean yield was approximately 102 kg/m coastline between scenarios with no marsh migration and scenarios with 400 m marsh migration; the maximum decline in corn yield was 262 kg/m coastline. With 800 m of marsh migration (i.e., 1,100 m of total marsh), corn and soybean yields decreased for all surge and slope scenarios, as the crops preserved through a decrease in flood extent could not compensate for the loss of agricultural land to marsh migration.

### 3.4. Economic Impacts of Marsh Migration

The reduction in saltwater intrusion due to marsh migration and, in turn, protected yield has the potential to benefit farmers financially when compared to scenarios without marsh migration. Economic calculations show that marsh migration can protect up to \$7,565 of revenue or decrease up to  $-\$13,090$  of revenue per year for a 500 m shore parallel parcel relative to no marsh migration (Table 2). To put these amounts into perspective, under ideal conditions without storm events or marsh migration, farmers would earn approximately \$17,180 per year for the 200 m by 500 m shore parallel patch of land, assuming storms or high tide events have not already begun to impact yield, under the scenarios and assumptions in this study. For soybeans, protected revenue amounts to \$9,150 per storm event year or a revenue loss of  $-\$8,400$ , compared to the \$9,181 earned under ideal, nonstorm conditions. However, when taking into consideration the decreased input costs by not cultivating the land, farmers may save up to a total of \$19,081 per year or lose  $-\$1,574$  per year for a 500 m shore parallel corn field with 200 m of marsh migration during storm event years; for a 500 m shore parallel soybean field, savings range from \$15,707 to  $-\$1,843$  with 200 m marsh migration relative to storm scenarios without marsh migration (Table 2).

**Table 2**  
*Economic Calculations Based on Corn and Soybean Yield Changes Due to Storm Surge Salinization*

	Corn		Soy	
	Max gain	Max loss	Max gain	Max loss
Change in crop yield (kg) <sup>a</sup>	44,500	-77,000	30,500	-28,000
Average crop price per kg (\$)	0.17		0.30	
Change in revenue (\$) <sup>a</sup>	7,565	-13,090	9,150	-8,400
Cultivation costs (\$) <sup>b</sup>	11,515		6,557	
Total savings and loses including cultivation costs (\$) <sup>a</sup>	19,081	-1,574	15,707	-1,843
Potential revenue from federal CREP program (\$)	4,843		4,843	
Total savings with federal payment (\$)	23,924	3,269	20,550	3,000

Calculations highlight the potential financial benefit to farmers of allowing marsh migration into agricultural fields.  
<sup>a</sup>Relative to storm scenarios without marsh migration. <sup>b</sup>Excludes land rental costs.

There are potential sources of revenue in place for coastal wetland development, such as the CREP's annual payments of 200% land rental costs per year. Considering CREP's payment, for 200 m of wetland development along a 500 m field, CREP will pay the landowner \$4,843, assuming land rental is equivalent to \$242 per ha (University of Maryland Extension). When added to the potential financial benefit of maintaining crop yield, the compensation for conversion of agricultural land to wetland may approach or exceed that of a productive field and may further benefit farmer finances during storm event years (Table 2).

#### 4. Discussion

Along coastlines worldwide, land owners and managers, including farmers, are increasingly facing the question of how to best manage coastal land subject to saltwater intrusion. The management decisions of farmers are particularly critical as these decisions impact short-term and long-term financial stability of individuals and regions. To date, agricultural land management strategies include installing water control structures (White & Kaplan, 2017), shifting crops to more salt-resilient varieties (Ventura et al., 2015), enrolling land in easements, or, in some cases, abandoning land completely (Tully et al., 2019).

Land management requires decisions about both management strategy and timing of implementation, which are based on short-term and long-term costs and benefits. For example, if a farmer decides to shift to crops that are more salt tolerant due to yield reductions, the long-term profit from this shift must outweigh short-term costs required to change crops (e.g., new farm equipment) (Tully et al., 2019). The timing of this shift is also important. If the shift in crops is made too late with respect to the timescale of saltwater intrusion, the land will not be productive for long enough to outweigh the initial investments. This study identifies a strategy for coastal agricultural land management that may maintain the short-term productivity of agricultural land while also maintaining the short-term and long-term water quality of coastal unconfined aquifers: marsh migration into marsh-adjacent agricultural land. Additionally, this strategy provides societal benefits such as carbon sequestration and water filtration.

##### 4.1. Marsh Migration as a Management Strategy to Maintain Crop Yield

As sea-level rises, marshes naturally migrate into the upland areas (Kirwan et al., 2016). Along the Chesapeake Bay, nearly 100,000 acres (400 km<sup>2</sup>) of upland were naturally converted to wetland at an average rate of 0.49 m/yr and as high as 2.1 m/yr (Schieder et al., 2018). Agricultural land provides an ideal setting for marsh migration due to the low topographic elevation and minimal anthropogenic or vegetative barriers. However, the continuation of mowing and cultivation of marginal agricultural land halts marsh migration, as the perceived economic losses due to conversion of agricultural land to coastal wetland are large (Fagherazzi et al., 2019). Whereas inundation scenarios for long-term SLR may be catastrophic (Epanchin-Niell

et al., 2018), marsh migration may enhance the short-term resilience of farmland subject to storm surge flooding, which can compromise agricultural land well before the impacts of SLR. Simulations in this study show that marsh migration into agricultural land reduces saltwater intrusion in the land that has not undergone marsh migration. This translates into maintained crop yield relative to no marsh migration scenarios despite the loss in agricultural land under a range of slope, surge, and migration scenarios.

As marshes migrate into farmland, the arable land is replaced by ecologically dense wetland with abundant ecosystem services including storm surge dissipation. The dense vegetation of coastal wetlands increases the surface roughness and frictional forces resisting water traveling over them (Möller et al., 2002). Our simulations showed that this increase in roughness can decrease storm surge-induced flooding into coastal agricultural land. The change in flood extent is greater for shallower topographic slopes and larger storm surges (Figure 4), highlighting the efficacy of marsh migration as an adaptation strategy along topographically low coastlines subject to storms. The lower change in flood extent in scenarios with higher topographic slopes (i.e., 0.3%, 0.4%) suggests that marsh migration may not be as beneficial in these regions.

The decrease in flood extent with marsh width has implications for crop yield. By diminishing the flood extent, less agricultural land is salinized, which results in maintained productivity across a greater area of the farmland compared to scenarios without front marsh or marsh migration. In some scenarios, the reduction in salinization and in turn minimized decline in crop yield compensates for the decrease in farmland due to marsh migration, enabling crop yield to be maintained between no marsh and most marsh migration scenarios (e.g., 0–400 m) when large storm events occur. However, for some scenarios, the decrease in salinization extent does not compensate for the loss in agricultural land, resulting in declines in total crop yield compared to scenarios without marsh migration (Figure 5). This is evident in scenarios with high topographic slopes (0.3% and 0.4%) and low storm surges (2.0 and 2.5 m), where the surge does not extend beyond the marsh. In these scenarios, marsh migration is not a favorable management decision with respect to maintained crop yield.

#### 4.2. Importance of Marsh Migration for Coastal Water Quality

Whereas the decline in flood extent due to coastal wetlands is known, most studies focus on storm surge inundation through overland flow models and surface analyses, neglecting the impact of storm surges and marsh migration on the water quality of surficial aquifers (Möller et al., 2014; Stark et al., 2015; Wamsley et al., 2010). Through the use of coupled surface-subsurface and variable-density fluid flow models, we are able to show that not only does marsh migration reduce coastal flooding, it also reduces the magnitude of saltwater infiltration into the unconfined aquifer and, in turn, contamination of fresh groundwater with salt (Figures 4 and 6). A reduction in flood extent decreases the area over which infiltration can occur and thus as marsh width increases and flood extent decreases, the volume of salinized aquifer also decreases.

Minimizing salinization of unconfined aquifers is critical for both domestic and agricultural water usage. For example, most domestic and irrigation wells along the Delaware coast withdraw water from the unconfined aquifer (He & Andres, 2018). Contamination of domestic wells for irrigation can be costly to landowners and in some cases, irreversible. The use of saline water for irrigation can increase saltwater intrusion in space and time and further impair crop yield (Letey et al., 1985). Whereas the effect of one storm surge on salinization may not be huge, multiple surges over time can have compounding effects, causing persistent water quality damage (Anderson, 2002). The tipping point at which aquifers are no longer usable is a function of the size and frequency of storm event and flushing time of the aquifer (Yu, 2010), which can take up to tens of years to flush (Holding & Allen, 2015; Vithanage et al., 2012). Thus, by allowing marsh to migrate, this tipping point is higher, prolonging the use of the freshwater aquifer in the short-term and long-term.

#### 4.3. Importance of Maintaining Front Marsh

While management strategies are important and necessary, our simulations also highlight the importance of preserving marshes in front of agricultural fields. In general, the change in flood extent shows the largest changes with wider front marsh (Figure 4), suggesting that the greatest declines in storm surge occur due

to front marsh presence. Front marsh width also impacts the subsurface salinized volume. For a given total marsh width, simulations with a greater front marsh see less subsurface salinization when compared to scenarios with the same total marsh but less front marsh (Figure S2). Front marsh is particularly valuable to crop production, as maintaining healthy front marsh does not require farmers to sacrifice agricultural land. As shown in Figure 5, corn and soybean yields increased with front marsh width. However, SLR and depleted sediment supplies to estuaries decrease a tidal wetland's ability to vertically accrete at the same pace as SLR, enhancing wetland vulnerability to drowning. Thus, this work highlights the importance of managing lands to promote maintenance of front marsh width not only for the preservation of ecosystem services but also for the short-term and long-term sustainability of coastal agricultural land and water resources.

#### 4.4. Impacts on Nutrient Dynamics and Potential for Alternative Revenue

Coastal wetlands offer numerous services in addition to storm surge dissipation including water filtration and carbon sequestration (Barbier et al., 2011). Coastal wetland surface and subsurface nutrient removal processes (Brin et al., 2010; Mitsch & Gosselink, 2008; Nordstrom & Roman, 1996) are particularly important in coastal agricultural zones where fertilizers and pesticides can runoff into estuaries causing widespread eutrophication (Boesch et al., 2001; Kemp et al., 2005). Because of the large-scale and critical nature of this issue, programs exist to compensate landowners for implementing strategies to reduce nutrient loads to the Chesapeake Bay, including development of wetlands in marginal agricultural land (Council, 2000) (see: <https://www.nrcs.usda.gov>; Allen, 2005; [http://www.mdnutrienttrading.com/docs/Phase%20II-A\\_Crdt%20Generation.pdf](http://www.mdnutrienttrading.com/docs/Phase%20II-A_Crdt%20Generation.pdf) and Stephenson et al., 2016). These programs are designed to pay farmers to restore wetland habitats, although each initiative has a different payment approach and eligibility requirement. For example, Gewin (2019) noted that one program offers a one-time payment of \$4000–\$5000, whereas another program offers annual payments equivalent to 200% of the rental payment for the land (see: <https://www.fsa.usda.gov>). Similarly, coastal wetlands are hotspots of carbon sequestration (McLeod et al., 2011), and thus marsh migration has the potential to receive credits through the voluntary carbon markets (Freedman et al., 2009; Hansen, 2009).

However, the incentives discussed above do not necessarily compensate farmers for personal, cultural, and financial ties to the land, nor do they compensate farmers to the extent that scientists' value coastal wetlands. For example, de Groot et al. (2012) valued coastal wetlands at a median value of \$12,163 per hectare per year, which far exceeds the average revenue gained per hectare of farmland (Fagherazzi et al., 2019) or compensation by the aforementioned programs. The value of coastal wetlands is based in part on their ability to protect coastlines from storm surge inundation. Since 2012, the four largest tropical cyclones have caused approximately \$330 billion dollars of damage (NOAA, 2018), yet the presence of wetlands has minimized this number. During Hurricane Sandy, the presence of wetlands protected \$625 million in flood damage (Narayan et al., 2017). Given the projected increase in storm surge frequency and intensity (Goldenberg et al., 2001; Vecchi et al., 2008), new programs and financial structures that are founded on science-based strategies to maintain crop yield and benefit present and future communities need to be developed. New programs should recognize the multifaceted benefits of wetland creation or restoration to society, such as groundwater protection, in order to further encourage wetland creation and adequately compensate farmers. Whereas this study is a simple modeling analysis, results show that conversion of agricultural land to wetland may maintain or enhance crop yield when land is subject to storm surge inundation, putting wetland creation in the context of maintained crop yield and illustrating the potential promise of this strategy. This study also provides foundational information for land managers needing to make site-specific implementation decisions.

#### 4.5. Model Simplifications and Additional Considerations

Whereas the use of generalized models in this study enables targeted analysis of marsh width on saltwater intrusion, this method accrues assumptions and limitations. Models assume that there is no microscale or macroscale topography. While we know that macroscale topography impacts saltwater intrusion (Yu et al., 2016), the generalized models used in this study isolate the impact of marsh width (front and migration

width) on surface and subsurface salinization. Similarly, the unit-specific proscribed roughness values (i.e., marsh, agriculture) prevent models from capturing microscale topography and roughness variations. Additional limitations include homogeneous zonal properties in the surface and subsurface and constant recharge. Simulations also assume that marsh migration can occur. We acknowledge that marsh migration is complex and that this assumption neglects factors such as ponding, tidal range, morphology, species-specific friction coefficients, and topographic variations. Future studies focused on the feasibility and timescales of marsh migration should consider coupling hydrogeological, geomorphological, and ecological processes. Given the shallow water table elevations across topographically low coastlines and increasingly frequent inundation due to storm events, marsh establishment is a reasonable assumption for most scenarios in this study. Additionally, we recognize that marsh migration affects elevation and in turn species distribution, processes which are not incorporated in this study. By removing these complexities, we are better able to generate new understanding of system controls that enables land managers to develop science-based management strategies based on their site-specific conditions. However, these factors should be considered for implementation of marsh migration strategies.

These simulations and quantification of yield assume a storm surge will occur at least annually. If a storm event, and subsequent saltwater intrusion, does not occur, the agricultural and water quality benefits do not necessarily outweigh the loss of land to marsh migration. However, it is important to note that numerous ecosystem benefits still occur (e.g., nutrient filtration). While the US Atlantic and Gulf coasts are not currently experiencing annual storm surge events, models suggest that the combination of SLR and climatic change could cause 100-year flood events to occur annually in New England and Mid-Atlantic regions (Marsooli et al., 2019). Therefore, conversion to wetland may become increasingly important for crop preservation. Additionally, marsh migration may also protect coastal agricultural land from “sunny-day” or high tide flood events, which have the potential to flood agricultural land multiple times per year (Sweet et al., 2018).

## 5. Conclusion

Coastal agricultural land is threatened by SLR and storm-surge inundation. While some initiatives are in place to encourage farmers to convert marginal farmland to wetland for nutrient mitigation and duck habitat creation, there is a lack of science-based information on the impacts of marsh migration into coastal agricultural land. Here we show how marsh migration into agricultural land decreases flood extent, saltwater infiltration, and aquifer salinization—changes that are most pronounced in scenarios with lower terrestrial slopes and higher storm surges. The decrease in saltwater intrusion with marsh migration enabled corn and soybean yields to be maintained relative to no marsh migration in scenarios with low topographic slopes, surge heights of 3.0 m or higher, and migration widths up to 400 m, despite the loss of land available for cultivation. At the same time, the decrease in flood extent minimized saltwater intrusion into the unconfined aquifer, enhancing preservation of coastal groundwater quality. Therefore, despite the loss in agricultural land, farmers along topographically low coastlines (<0.3%) benefit from marsh migration through reduced surface and subsurface saltwater intrusion and may also qualify for compensation through wetland creation initiatives or ecosystem service-based compensation. Along coastlines with topographically higher slopes (0.3% or greater), marsh migration is not a favorable management strategy for the conditions considered in this study. More studies are needed to provide scientific-based decisions to enhance the sustainability of coastal agricultural land, including issues such as saturated soil extent and duration.

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