How old are marshes on the East Coast, USA? Complex patterns in wetland age within and among regions

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Key Points:

- Marshes largely formed after SLR slowed (after 4000 ybp). A second formation period occurred (~400 ybp), coinciding with land cover change.
- Studies that dated marshes to assess historic sea-level rise had an older and less varied age distribution than other studies.
- Coastal marshes are younger nearer the coast and in regions where land use change may have delivered large amounts of sediment to the coast.

Abstract

Sea-level dynamics, sediment availability and marine energy are critical drivers of coastal wetland formation and persistence, but their roles as continental-scale drivers remain unknown. We evaluated the timing and spatial variability of wetland formation from new and existing cores collected along the Atlantic and Gulf coasts of the United States. Most basal peat ages occurred after sea-level rise slowed (after ~4000 years before present), but predominance of sea-level rise studies may skew age estimates toward older sites. Near-coastal sites tended to be younger, indicating creation of wetlands through basin infilling and overwash events. Age distributions differed among regions, with younger wetlands in the Northeast and Southeast corresponding to European colonization and deforestation. Across all cores, wetland age correlated strongly with basal peat depth. Marsh age elucidates the complex interactions between sea-level rise, sediment supply and geomorphic setting in determining timing and location of marsh formation and future wetland persistence.

Plain Language Summary

Marshes, a type of coastal wetland, form under stable, slow rates of sea-level rise (SLR). Although many marshes along the East Coast of the United States formed after the most recent slowing of SLR (approximately 4000-6000 years ago), there is evidence that sediment erosion from colonial deforestation expanded marshes. This study uses sediment cores to determine when and where marshes formed to understand what drives modern marsh formation. We found that most marshes did form following SLR slowing after around 4000 years ago. We also found evidence of marshes forming during European colonization in the Northeastern and Southeastern United States. Finally, we found recent formation of marshes closest to the coast, possibly driven

by storm events and associated overwash. Through this study, we outline a novel way to easily determine marsh age and to better understand why marshes form through future research.

1 Introduction

Tidal marsh systems are geologically young and ephemeral, reliant on a source of sediment, relatively calm tectonics, and stable rates of sea-level rise (Day et al., 2011; Dokka et al., 2006; Kirwan et al., 2010; Reed, 1995). At the end of the last ice age, the Laurentide ice sheet melted and Greenland ice sheet reduced in size, increasing sea level rapidly (Carlson et al., 2008; Tarasov & Peltier, 2002). Current tidal marshes and complexes are thought to have formed as sea-level rise (SLR) slowed after the last ice age and about 4000-6000 years before present (ybp; Engelhart & Horton, 2012; Redfield, 1965), but to our knowledge no systematic assessment of marsh age has analyzed this history.

Sediment builds and maintains tidal marsh platforms (Day et al. 2011), and its availability is controlled by both upland supply and transport (and retention) along drainage networks. As SLR decelerated and wetlands established along the coast (Saintilan et al., 2020), sediment loads would have varied with watershed characteristics including catchment area, slope, and drainage network structure, as well as bedrock geology and glacial and climatic history (Bell & Laine, 1985; Gordon, 1979; Johnson & Fecko, 2008; Leopold et al., 1964; Meade, 1982; L. F. Phillips & Schumm, 1987; Sella et al., 2007). Sediment supply also reflects the balance of sediments and water from marine and inland sources (Braswell & Heffernan, 2019; Ganju et al., 2013; Yousefi Lalimi et al., 2020). Near coasts, storms can also impact landform stability and wetland dynamics (Cahoon, 2006; Davis, 1994; Leonardi et al., 2018).

These terrestrial and marine drivers may shape regional-, estuary- and local-scale formation and persistence of coastal wetlands.

Humans can promote or suppress wetland formation by mobilizing sediment and altering drainage networks (Syvitski et al., 2005; Walling, 2006; Weston, 2014). Deforestation, agricultural development, and erosion accompanied European colonization of eastern North America seaboard of the United States through the 17th-19th centuries (Cronon, 2003; Meade, 1982; Pfaff, 2000). The timing of this agricultural intensification is important for the fate of mobilized sediment. The resulting downstream pulse of sediment may have remained stored in fluvial networks (Trimble, 1999; Walter & Merritts, 2008), or was delivered to coasts where it increased marsh building (Gell et al., 2009; Kirwan et al., 2011; Tweel & Turner, 2012). Some studies have estimated that coastal sediment delivery could have dramatically increased marsh extents, as evidenced by significant expansion of marshes along the Mississippi River birdfoot delta (Tweel & Turner, 2012) and at Plum Island, MA (Kirwan et al., 2011). The degree of regional variation in this anthropogenic expansion and its potential drivers is uncertain.

To determine how climatic, geomorphic and anthropogenic drivers impact wetland formation, we analyzed an extensive data set of new and published coastal tidal marsh basal ages, from coastal areas spanning local and regional gradients of upland and marine influence. We classified each core by physical location, region, and study objectives to address the questions: 1) When did tidal marshes form? 2) Where is historical deforestation and colonization correlated with wetland formation? This study expands the spatial scale of previous studies, extending regional and site-specific wetland formation projects over a continental coastline.

2 Materials and Methods

2.1 Core Database

To understand the spatial patterns of wetland formation, we collected literature that reported dating evidence (mainly radiocarbon) from basal layers of tidal wetlands or salt marshes. We searched for literature in the Web of Science (Web of Science Core Collection) using combinations of the keywords “marsh”, “age”, “dating”, and “radiocarbon”. Studies along the Atlantic and Gulf coasts that clearly dated core samples at or near the basal peat layer were included in this study, regardless of study aims. With each date in the study, we recorded study objectives (sea level or other), depth of sample, region, and various other descriptors of each core (Supplemental Methods, Supplemental Database).

2.2 Field Study – Site Description and Core Collection

To characterize local spatial variability in wetland age and more directly evaluate the role of riverine and marine influence, we collected 97 cores across 5 sites (Supplemental Methods; Table S1): 2 pairs of riverine- and marine-dominated wetlands (Ogeechee River, GA and Cape Romain, SC; Cape Fear River, NC and Masonboro Island, NC) and a fifth site (Barnstable Harbor, MA) that we paired with Plum Island, MA, where a previous study had intensively sampled basal peat age and core depth (Kirwan et al., 2011). As in that study, we dated basal peat in a subset of cores, and determined the period of formation on the basis of regional depth-age relationships.

To distribute samples within each site, we researched the history of wetland areas in each site, delineated marsh polygons from the National Wetlands Inventory (U.S. Fish and Wildlife, 2014), and assigned random points within each area (ArcGIS 10.5). We used a Russian peat corer with extension rods (Aquatic Research Instruments) to collect 5 cm diameter, 50 cm long half-moon core sections. Sediment cores were collected to 10 cm past the basal peat layer or to

point of refusal. We visually inspected and described any major stratigraphy during coring and photographed each section in the field. Cores were stowed in cold coolers and transported back to the laboratory (Grainger River Center, Duke University, NC), where they were stored at 4°C until analysis.

Field Study – Laboratory Analysis

We analyzed bulk density and percent organic matter (Supplemental Methods). Along each core, we determined where the basal peat layer or formation of the marsh occurred based on these factors: where the organic matter rose above 10% by mass (moving up from the bottom of the core), refusal during coring, or core description (basal peat layer described in field)(Belknap & Kraft, 1977). Four cores spanning the range of depths at each site (8 amongst two regions of the Cape Fear site) were chosen for radiocarbon dating (24 cores total), based on the clarity of the basal peat layer from organic matter content or field description and distance from other radiocarbon dated cores. Samples were prepared (Supplemental Methods), and shipped to the National Ocean Sciences Accelerator Mass Spectrometry Facility at Woods Hole Oceanographic Institution for standard acid-base-acid pretreatment and radiocarbon analysis. We determined the calendar age of each sample using OxCal software (OxCal v4.3) calibrated with chronological models (Table S2). We chose the IntCal13 curve to determine the calibrated radiocarbon date within confidence intervals (Reimer et al., 2013).

2.3 Age-Depth Relationships

We used age-depth relationships to estimate the date of formation for undated cores at each of our 6 intensive sites. We pooled our own measurements with published cores to find regional age depth-relationships as characterized by linear relationships between log-transformed depth and basal peat age. From these relationships, we estimated age and its 95% confidence

interval for each undated core. We then assigned each core to an age category (pre- or post-European settlement) based on whether estimated ages were greater or less than 400 ybp; the few cores with confidence intervals that overlapped 400 ybp were classified as uncertain. This binning allowed us to assess regional patterns in wetland age while minimizing the influence of uncertainty around age estimates.

2.4 Analysis

We used multiple measures of marine and upland influence to determine how geomorphic setting affects the initiation and persistence of coastal wetlands. We used distance from the ocean as both a proxy of both potential frequency of storm overwash events and as a potential mediator of upland vs. marine sediment supply (Supplemental Methods). Although we recognize that geomorphic setting is more complex across the coastline than these proxies illustrate, our data synthesis approach does not allow for the detailed differentiation between geomorphic settings due to time constraints and scientific bias. To determine the comparative influence of watershed and estuary on each wetland, we used river:tide ratio (RTR; Braswell & Heffernan, 2019), which compares the annual volumes of river runoff and tidal inflows into an estuary (Supplemental Methods). We used Mclust package (version 5.2.3; R 3.4) to assess modality of the age distributions across several variables, specifically to determine if there was a younger mode of marsh formation by region, distance from coast, or RTR.

3 Results

Most of the 387 cores (from 43 papers) in our literature database (see Table S4) had marsh initiation dates in the millennia following the slowing of sea-level rise (literature - mean: 2450±90 SE (standard error) ybp; median: 2166 ybp), but varying geomorphic drivers and biases

159 from the literature affect patterns in age distribution. Among all dated cores (field plus
160 literature), the age ranged from 0 ybp to 10,819 ybp (Figure 1; database - *n*: 411, mean: 2767±98
161 SE ybp; median: 2591 ybp). Sea-level rise studies dominated the literature of tidal marsh
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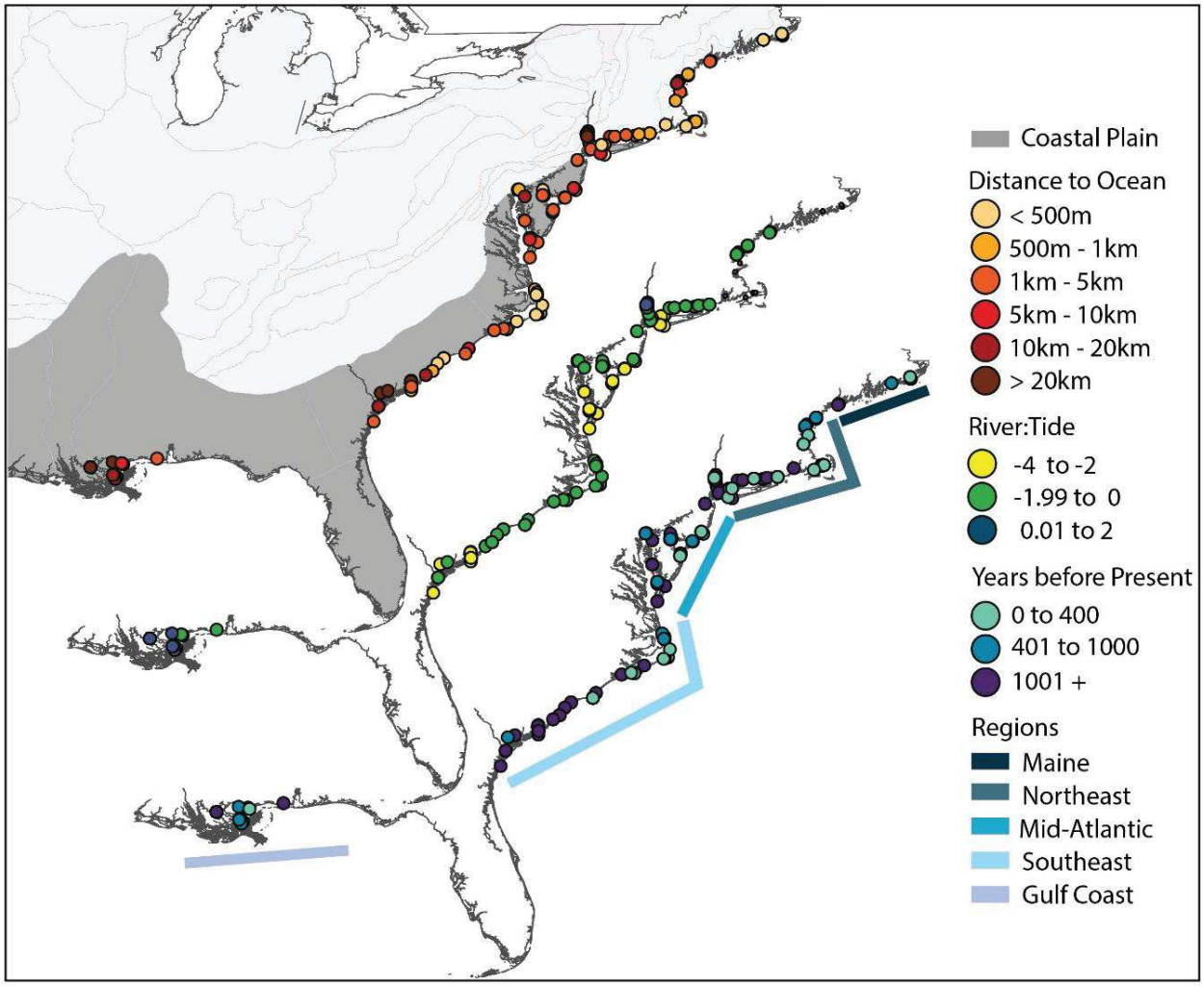


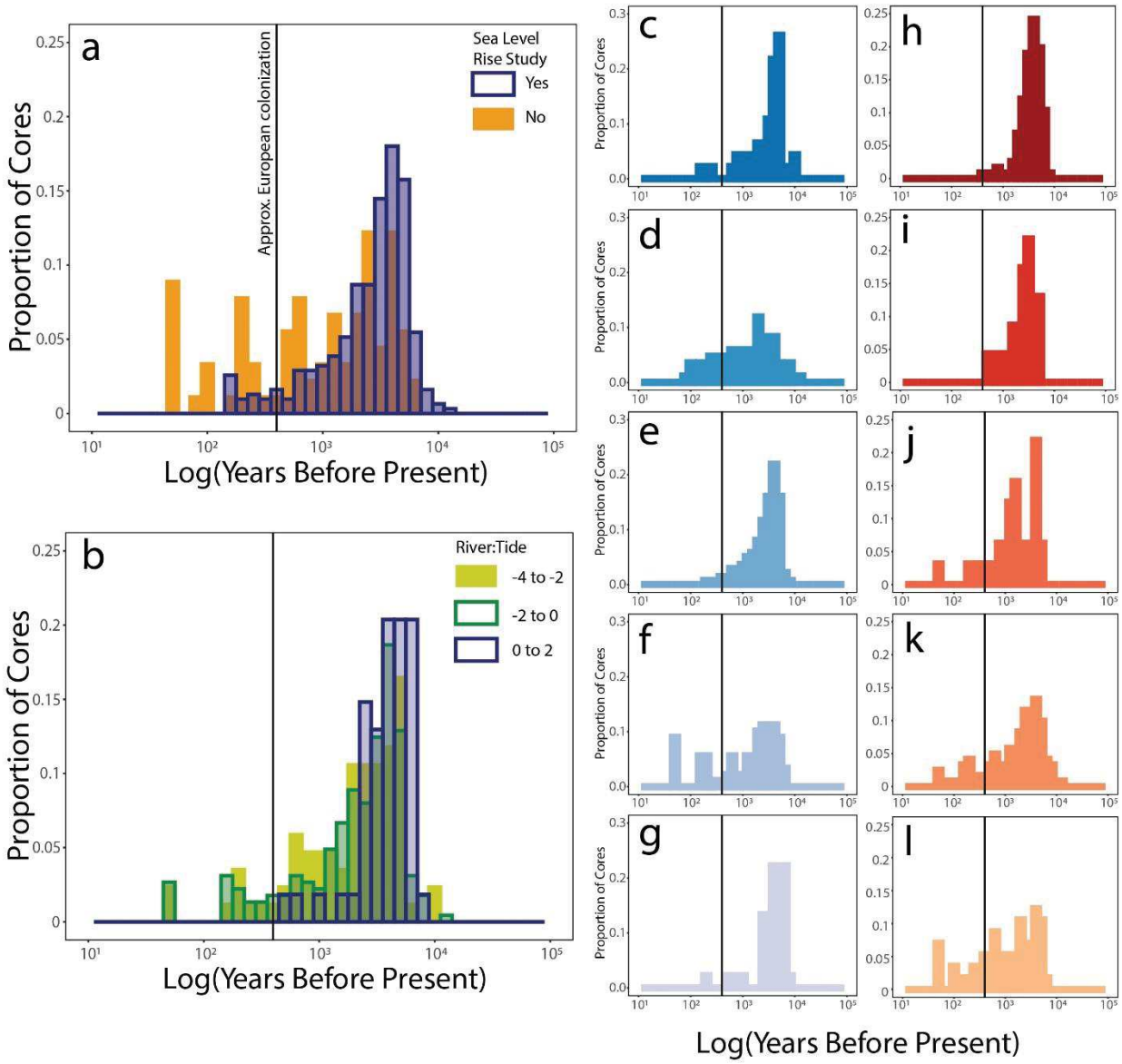
Figure 1. Our core database covered literature with radiocarbon dates along the Atlantic and Gulf coasts of the United States. These regions had heterogeneous drivers of wetland formation resulting in varying marsh ages. The map displays proxies for the various drivers used in the remainder of the paper (river:tide ratio, distance to the coast, region), as well as the dependent variable, wetland age in years before present.

ages (Figure 2a). Of the 387 database cores, 314 (approximately 81%) are associated with studies that had objectives related to geologic records of past sea level. These cores are predominately older, after the deceleration of SLR in the Holocene (Figure 2a; mean: 3111±110 SE ybp; median: 3101 ybp). The remainder (73 cores; approximately 19%) come from studies that addressed marsh natural history, rather than sea level. These cores spanned a wider distribution and had no clear mode (Figure 2a; mean: 1955±199 SE ybp, median: 1721 ybp).

Wetlands closer to the coast had more young cores and a wider range of wetland ages (Figures 2h-1, 3, S1) than cores further inland. Cores that were further from the coast (moving up river or up sound) had a narrow distribution of ages (Figures 2h, 3; Greater than 20 km from ocean; *n*: 116, mean: 3778 ± 134 SE ybp, median: 3776 ybp), with older dates than cores that occur close to the coast (Figures 2k, 3; between 0.5 and 1 km from the ocean; *n*: 60, mean: 1901 ±228 SE ybp, median: 1401 ybp).

Our proxy for inland sediment, RTR, also elucidated timing of wetland formation. Cores with a larger RTR (more riverine water volume than estuarine volume), have a narrower distribution and older mean and median age than cores that have lower RTR (Figure 2b, S1; Log(RTR) = 0 to 2; *n*: 34, mean: 4819± 233 SE ybp, median: 4736 ybp). As river to tide ratio decreases (towards more marine influence), the distribution widens and contains younger dates of formation (Figure 2b; Log(RTR) = -4 to -2; *n*: 109, mean: 2292± 193 SE ybp, median: 1662 ybp). Our data points to sites with less river influence have younger marshes than sites with more river influence.

The distribution of core age differs among regions (Figures 1, 2c-g, S1), but all regions had the highest abundance of cores between 2500-3000 ybp (All dated cores; *n*: 411; mean: 2767±98 SE ybp; median: 2591 ybp; Figure 2c-g). Based on BIC and ICL scores, the distribution of ages across all regions is best described by 2 clusters or modes of



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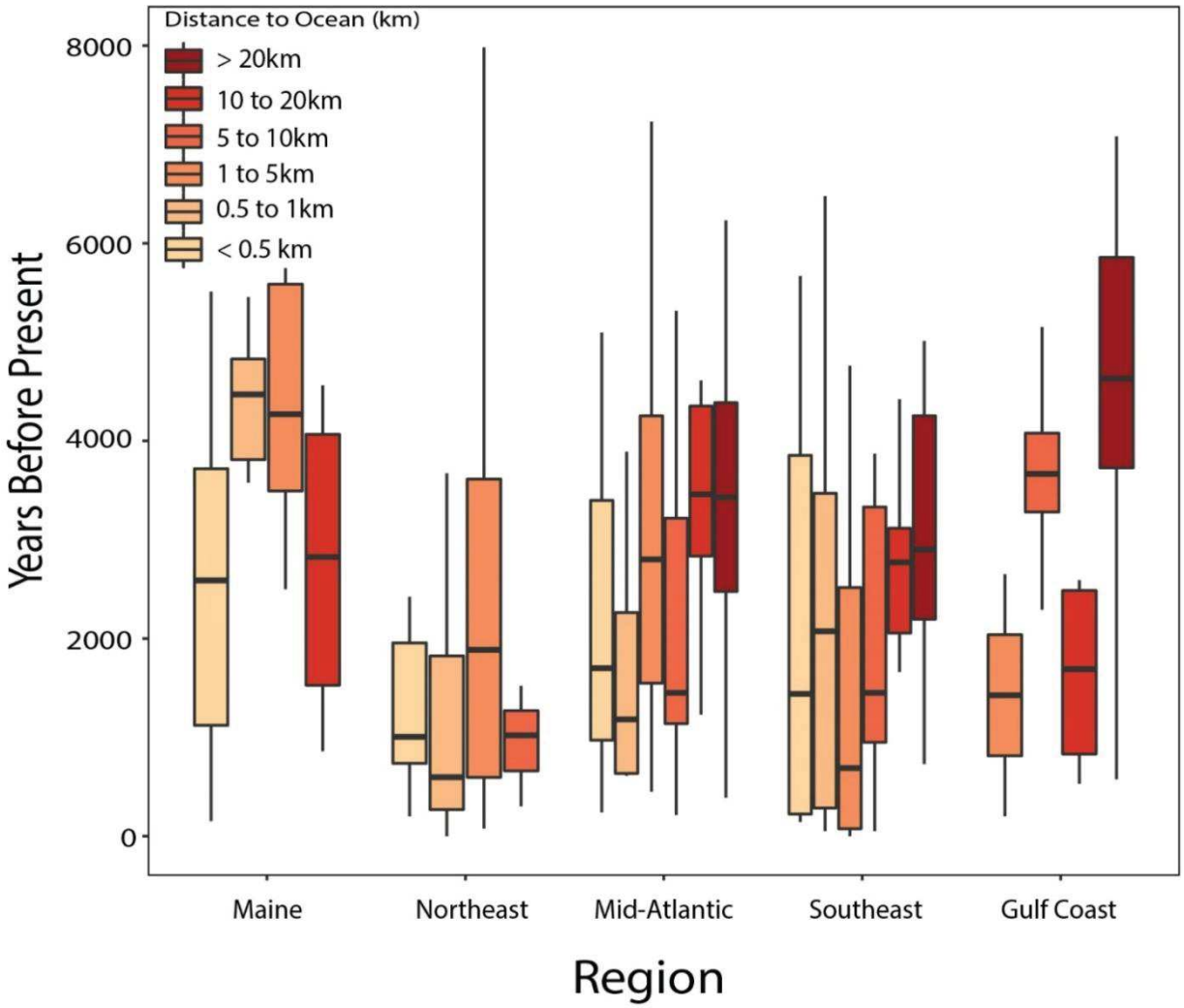
194 **Figure 2.** Sea-level rise studies dominated our core database, with older dates of formation than
195 studies with other objectives (a). These studies (blue histogram) skewed our database towards
196 older cores with longer records, as seen in this distribution of wetland ages by study objectives.
197 Timing of wetland formation varied with River:Tide Ratio (RTR), as a proxy for the relative
198 influence of the watershed to the estuary. Wetlands with higher RTR typically formed earlier and
199 have less variability than wetlands with low RTR (b). Regionally, wetlands formed at different
200 times, with the Northeast and Southeast having younger wetlands than other regions (c- Maine,
201 d- Northeast, e- Mid-Atlantic, f- Southeast, g- Gulf Coast). Wetland age varied with distance to
202 the ocean (decreasing downward through panels), as a proxy for marine and storm impacts and
203 basin infilling, with wetlands closer to the coast having younger mean age (h- > 20km, i- 10km
204 to 20km, j- 5km to 10km, k- 1km to 500m, l- < 500m). On all panels, vertical black line
205 represents approximate time of European colonization.



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207 **Figure 3.** Regional trends in age reflect differences in marine influence and basin infilling. Here we consider core age by region (x-
208 axis) and distance to the coast (darker red is farthest from the coast). Cores were younger within 500 meters from the ocean. We found
209 cores were older with distance from the ocean (particularly in the Mid-Atlantic and Southeast), pointing to sediment delivery from
210 rivers as an important driver of wetland formation.

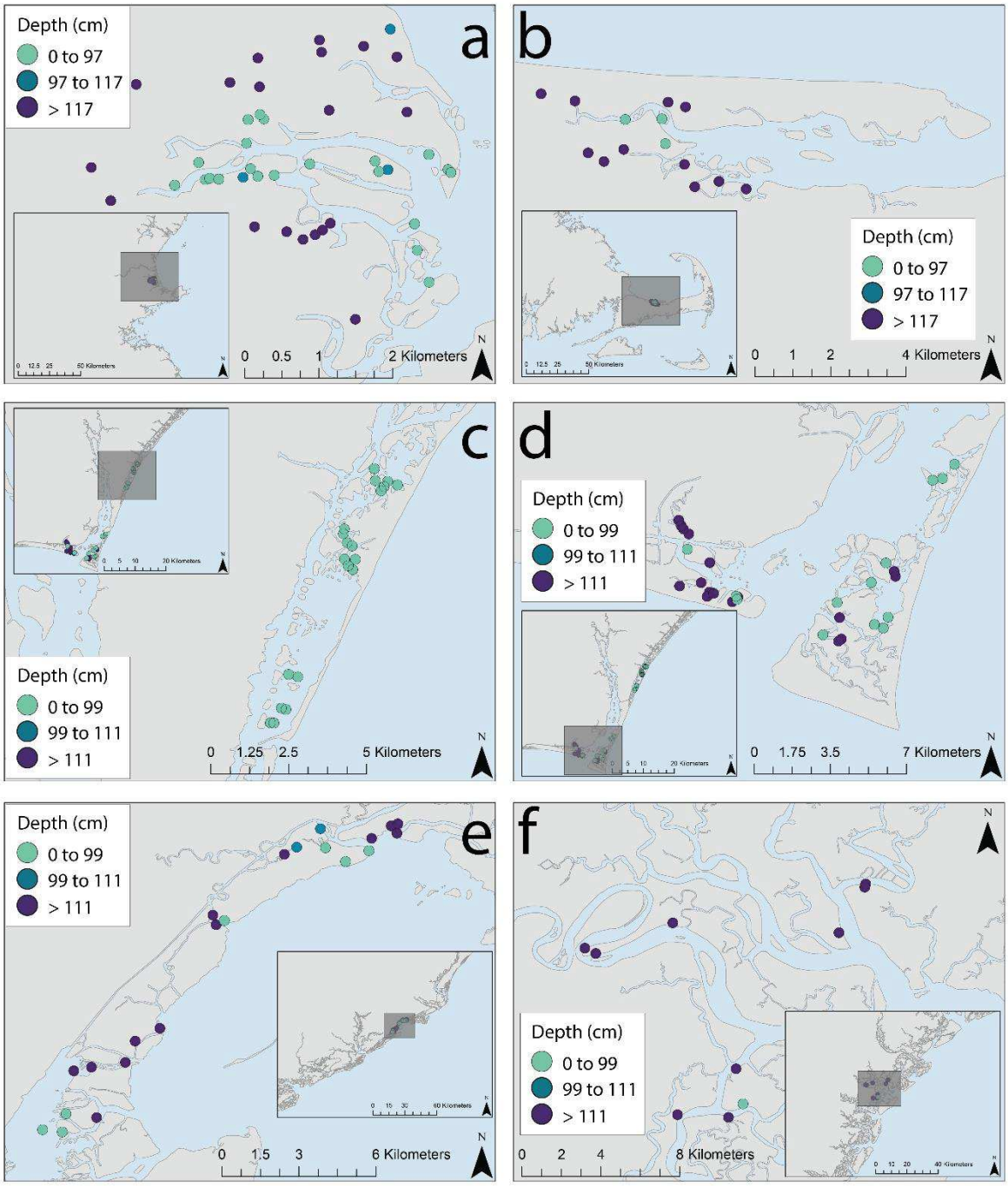

Figure 4. Our field data show variability in depth by region, landform, and distance to the ocean. The field sites were arrayed by a gradient of upland influence and by region. Our Massachusetts site, Barnstable Harbor (b) was paired with data from Kirwan et al. (2011; a) at Plum Island. The North Carolina pairs compared a barrier island system, Masonboro Island (c), to large river system, Cape Fear River (d). We paired Bulls Bay at Cape Romaine NWR (e) with the mouth of the Ogeechee River in Georgia (f). Regionally, North Carolina and Massachusetts displayed more variation than Georgia/South Carolina, which had less young (shallow) cores based on our regional fits and depth binning.

unequal variance (Mclust version 5.2.3; R 3.4; using all dates greater than 0). We find an older mode of the distribution (*n*: 274, mean: 3829 ± 94 SE ybp, median: 3660 ybp) and a smaller mode of younger cores (*n*: 128, mean: 701 ± 43 SE ybp, median: 615.5 ybp). We found that the Northeast Atlantic coast has a younger and wider distribution of wetland ages, best described by one, normal mode (*n*: 84, mean: 2065 ± 239 SE ybp, median: 1446 ybp). The Southeastern Atlantic coast also reflected this trend, albeit with a better fit of seven modes of equal variance (Oldest two modes: *n*: 33, Mean: 4079 ± 175 SE ybp, Median: 4114 ybp; Youngest two modes: *n*: 20, Mean: 133 ± 17 SE ybp, Median: 145 ybp). Other regions were also best described by two or more modes, but either had extremely small young modes ($n = < 5$) or the youngest mode had ages > 400 ybp.

Age-depth relationships by region were sufficiently strong to differentiate wetland initiation as before or after European colonization (Figure 4, Table S3). Explanatory power of depth as a predictor of age varied from 0.61 to 0.7 across regions, with slopes (after log-log transformation) ranging from 0.83 to 1.9 (Table S3). We repeated the above analyses using the all the cores, including our field cores dated by regional age-depth relationships. These results reflect similar trends and drivers, particularly a secondary younger peak of wetland formation (Supplemental Text S2; Figure S1). We do find that the age-depth estimated cores added younger cores and more information to data poor areas such as the Southeast (Figure S1). In addition, these cores add resolution to the dating in our field sites, allowing for the determination of age patterns in heterogeneous areas (Figure 4). Although unconventional, these cores complement the results found by the database alone.

5 Discussion

Our results provide the first continental coastline scale synthesis of evidence that the main, first-order driver of coastal marsh formation is the rate of SLR. After the disintegration of the Laurentide ice sheet (Carlson et al., 2008) and the stabilization of the Greenland ice sheet, melt water to the ocean slackened, decreasing the rate of SLR (Tarasov & Peltier, 2002). Although the timing of these events is not well constrained (Engelhart & Horton, 2012; Gehrels, 2010), it is generally agreed that the rate of SLR slowed between 4000-6000 ybp (Engelhart & Horton, 2012). The decrease in the rate of SLR likely varied within this window across regions along the coast based on local conditions. Our results confirm that most wetlands in our core database and field study formed after this window (Mean: 2450 ybp). This finding supports previous work showing that tidal marshes are unable to form and persist under periods of great sea-level change (such as transitions in glacial-interglacial cycles), which limits adequate sedimentation and macrophyte survival (Kirwan et al., 2010; Marani et al., 2010; Morris et al., 2002; Saintilan et al., 2020). Although we do find a peak of wetland formation, there is much variation in the date of formation regionally and across all cores. This finding is consistent with both regional variation in the rate SLR and differences in timescales of wetland formation due to basin and watershed morphology.

Age distributions of marshes varied as a function of upland or riverine influence, as measured by RTR (ratio of annual river discharge to tidal estuary volume). Although there are many drivers of wetlands (e.g. vegetation feedbacks; Marani et al., 2010; Morris et al., 2002), sediment supply is a major control of marsh platforms (Bouma et al., 2016; D'Alpaos et al., 2012; Yousefi Lalimi et al., 2020). Cores from sites with a higher RTR formed earlier and varied less in age than sites with a lower RTR (Figure 2b). Areas with higher RTR should have greater sediment delivery and build elevation faster, and therefore those areas are more likely to have a

date that corresponds with the deceleration of SLR. Areas with lower RTR may take longer to develop wetlands due to sediment limitation. Our results support this hypothesis and, furthermore, are consistent with the finding that high RTR areas also support greater abundance of wetlands (Braswell & Heffernan, 2019).

Our results support the hypothesis that "resetting events," such as intense storms, shape wetland age distributions, particularly along the back of barrier islands in lagoonal systems (500 meters away from coast; Figures 2h-l, 3). We found more, younger cores in sites closest to the coast and a wider distribution of age. Washover fans from storms can initiate wetland creation by increasing elevation in back barrier areas to a level that supports vegetation (Davis, 1994; Osgood & Zieman, 1993). These fans are variable in space and time, depending on storm intensity and geomorphology of the barrier, leading to variability in age along landforms close to the coast (Donnelly et al., 2004; Morton & Sallenger, 2003).

Basin infilling, where the areas of the estuary closest to the mouth of the river fill with sediment first (Roy, 1994), can also create a gradient of wetland ages from the river to the coastline (Gell et al., 2009; Redfield, 1972). We found support for this hypothesis in that sites furthest from the coast, mostly within large estuaries such as Chesapeake Bay, had less variable formation dates and more cores that dated from around the time of the slowing of SLR (Figures 2h-l, 3). We found additional substantiation for this result in the field data from places like Cape Fear River, NC and Plum Island, MA where variability in date of formation and younger ages of cores occurred close to the coast (Figure 2h-l, 3).

Through the interaction of agricultural erosion, geomorphic setting, and infrastructure, we find that the regional history of agriculture could impact the formation of wetlands along the Northeastern seaboard and barrier islands systems of the Southeastern United States. We

289 determined that the Northeastern region of the Atlantic coast (Figures 2d, 3) had some younger
290 dates that correspond with timing of European agricultural expansion (Klein Goldewijk et al.,
291 2010, 2011; Foster et al., 1998). Humans both increase and reduce the amount of sediment
292 reaching the ocean through deforestation and erosion of agriculture and damming or impounding
293 rivers (Syvitski et al., 2005). Erosion was particularly intense in the Southeastern piedmont
294 (Trimble, 1974), yet the large coastal plain and piedmont region likely trapped much of this
295 sediment in floodplains, making transport to the coast slow or negligible at relevant time scales
296 (J. D. Phillips, 1991, 1995; J. D. Phillips et al., 1993; Trimble, 1977; Walter & Merritts, 2008).
297 The short or non-existent coastal plain and smaller drainage networks could contribute in
298 efficient transport of sediment to the coast in the Northeast (Gordon, 1979; Kirwan et al., 2011).
299 This region also experienced peak agricultural earlier, before the creation of major dams (Foster
300 et al., 1998). Although some of the sediment was certainly trapped behind mill dams (Walter &
301 Merritts, 2008), the geomorphic setting of this region may have contributed to sediment reaching
302 the coast. Based on our results, we propose that pulses of anthropogenic sediment from erosion
303 happened earlier and in more connected drainage networks than in other regions, creating
304 younger wetlands and expanding marsh complexes (Figures 2d, 3). Although more evidence is
305 needed to determine if this is a true signal of regional wetland expansion, or an artifact of studies
306 in our database, it does compliment previous studies that have found evidence of wetland
307 expansion after European colonization and land-use change (Hilgartner & Brush, 2006; Kirwan
308 et al., 2011; Mattheus et al., 2009; Tweel & Turner, 2012). This finding points to a regional
309 expansion of wetlands post-colonial period where sediment was easily conveyed to the ocean
310 and not stored in the floodplain or behind a dam.

Understanding the influence of watershed and marine drivers on wetland formation is imperative for predicting their future persistence under lower sediment regimes, high rates of SLR, intense coastal storms, and anthropogenic stressors. Our findings on the timing and conditions of formation help elucidate two previously debated mechanisms of marsh persistence. First, recently formed marshes point to the importance of sediment in growing and maintaining marshes. With declining sediment loads (Falcini et al., 2012; Syvitski et al., 2005; Weston, 2014), marshes may contract back to a low sediment, pre-colonial deforestation state (Kirwan et al., 2011). Old, Holocene marshes, formed during periods of slow rates of SLR, highlight the importance of SLR in marsh formation and persistence (Crosby et al., 2016; Törnqvist et al., 2020) and complementing recent findings on the connection of mangrove formation to SLR (Saintilan et al., 2020) . Our study integrates these perspectives, emphasizing that marsh age is tied to the interactions between SLR and sediment supply. Mismatches between the conditions of formation (higher sediment supply and lower rate of SLR) and the current environment is likely to influence how marshes respond to future stressors. Through understanding marsh age, we reveal the drivers of marsh persistence including geomorphic setting, terrestrial and marine sediment supply, and barrier island dynamics.

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336

337 **Data Availability**

338 Datasets for this research are included in this paper's supplementary information files and on
339 Harvard Dataverse (Radiocarbon Dates: https://doi.org/10.7910/DVN/KDXIRN; Marsh Age
340 Literature Database: https://doi.org/10.7910/DVN/GHK8AS). Please see supplemental reference
341 file and excel file of data used in the core database.

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