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ORIGINAL PAPER

"Waffle" pools in ditched salt marshes: assessment, potential causes, and management

Joseph A. M. Smith · Susan C. Adamowicz · Geoffrey M. Wilson · Ilia Rochlin

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Abstract Ditching is one of the most widespread forms of anthropogenic impact on tidal marshes but its effects remain poorly understood. Recently, the phenomenon of "waffle" pooling has been documented in ditched marshes, where a repeating pattern of shallow rectangular pools form in the marsh interior. While pools in unditched marsh may eventually revegetate, waffle pools appear to be a more permanent source of vegetation loss. This study assesses the factors influencing the distribution of waffle pools and other marsh pool types from Maine to Virginia using imagery and existing datasets. Waffle pools were most likely to occur where tidal range was less than 0.8 m, but they could also occur anywhere that tidal range was reduced by anthropogenic features. Unlike waffle pools, the presence of isolated and tidally-connected pools throughout the region was not influenced by tidal range, although both of these pool types were more likely to occur in unditched marshes with higher elevations relative to MSL. An analysis of change of New Jersey's and New York's marshes since 1970s confirmed that waffle pools are a recent phenomenon and that this process was responsible for 30–100% of all marsh interior vegetation loss in regions of the study area with tidal range below 0.8 m. Overall, interior marsh loss increased as tidal range decreased. Loss of marsh at edges due to erosion increased as the ratio of edge to marsh area increased. We propose that waffle pools are the product of long-term ditching impacts and that comprehensive strategies are needed that restore drainage networks, restore elevation and alleviate tidal restrictions. Since waffle pooled marshes often contain favorable salt marsh mosquito habitat, restoration efforts should integrate ecological approaches with mitigating public health concerns.

Keywords Salt marsh restoration · Hydrologic restoration · Tidal restriction · Ditching · Salt marsh change · Marsh pools · Mosquito control

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J. A. M. Smith (✉)
U.S. Fish and Wildlife Service, Edwin B. Forsythe National Wildlife Refuge, Galloway, NJ, USA
e-mail: smithjam@gmail.com

S. C. Adamowicz
U.S. Fish and Wildlife Service, Rachel Carson National Wildlife Refuge, Wells, ME, USA

G. M. Wilson
Bear Creek Wildlife Sanctuary, Saugus, MA, USA

I. Rochlin
Center for Vector Biology, Rutgers University, New Brunswick, NJ, USA

Introduction

Salt marshes are under increasing threat as the separate and interacting effects of sea level rise (Kirwan et al. 2010) and anthropogenic impacts (Bertness et al. 2002; Gedan et al. 2009; Adamowicz et al. 2020) mount at the global, regional and site level (Kirwan and Megonigal 2013). Human use of estuaries and their surroundings affect marsh condition and resilience to sea level rise by altering or disrupting natural geomorphic and biophysical processes. This can occur via direct (e.g. ditching, dredging, diking) or indirect actions (e.g. eutrophication) (Kennish 2001; Gedan et al. 2009; Kirwan and Megonigal 2013). When human impacts can be addressed at a given site through restoration and management, the marsh gains more resilience to other stressors, including sea level rise (Smith et al. 2017).

One of the most ubiquitous and visible forms of human impacts to marshes in the Northeast U.S. is ditching (Bourn and Cottam 1950)—a technique used to drain the marsh surface for agriculture and mosquito control. Despite the scale of the practice and potential scope of its impact, there is only limited information regarding how ditches affect marsh function and morphology (Tonjes 2013). Nonetheless the available research has revealed marked impacts on elevation, soil characteristics, and hydrology (LeMay 2007; Vincent et al. 2013a, b; Burdick et al. 2019).

A marsh degradation pattern recently observed in some ditched marshes areas are "waffle pools" (Adamowicz et al. 2020). These are pools that form in recurring patterns between parallel ditches, where often only a sliver of remnant vegetation remains along the ditch banks (Fig. 1A–D). While waffle pools are widespread in some areas, many parallel-ditched marshes exhibit no such pattern (Smith and Pellew 2021). Management interventions are being pursued to reverse waffle pool formation (Wigand et al. 2015), but a clear understanding of the conditions under which waffle pools form and the underlying mechanisms driving their formation has not yet been established.

In order to increase the resilience of salt marshes as global sea level rise accelerates, interventions are needed to restore function and resilience lost as a result of past management actions. A key limitation of the widespread implementation of such interventions is that the sheer variety of both physical settings and human impacts makes it difficult to identify a set of general strategies that can be broadly implemented (Waltham et al. 2021). Nonetheless, landscape-level analyses that explicitly examine the distribution of human impacts under a range of geomorphic and physical settings may help identify common patterns of degradation and their causes. This then sets the stage for the development of standard management strategies that can be applied under a specific set of circumstances such as tidal regime, tidal restrictions, anthropogenic impacts, degree of degradation, presence of invasive species, and landowner management objectives.

Essential elements of this approach are a clear understanding of the trajectory and nature of degradation over time and an understanding of the range of direct human impacts that have occurred at a site so that the association between past actions and current marsh condition can be established. Ideally, unaltered sites in similar geographic settings can serve as controls for parsing management impacts from the effects of sea level rise and the effects other regional processes. Here, we apply this approach to salt marshes of the Northeast U.S. to gain insights into the patterns of waffle pool distribution and their contribution to overall patterns of marsh change. We do this by (1) documenting the distribution of waffle pools and other interior open water in salt marshes along the Atlantic Coast from Maine to Virginia, (2) investigating patterns of association between interior open water with ditching, marsh elevation and tidal range and (3) conducting a detailed assessment of the contribution of waffle pools relative to other forms of salt marsh loss along a tidal range gradient along coastal New Jersey (NJ) and New York (NY) across a 50-year time interval.

We use our findings to explore potential mechanisms for waffle pool formation and to propose a management model for waffle pooled marshes that can be applied across the Northeast under specific contexts defined by landscape-level metrics. We illustrate examples of this management approach for individual marshes impacted by waffle pool formation and discuss complementary management strategies that enhance marsh longevity while addressing mosquito management goals (Rochlin et al. 2012a).

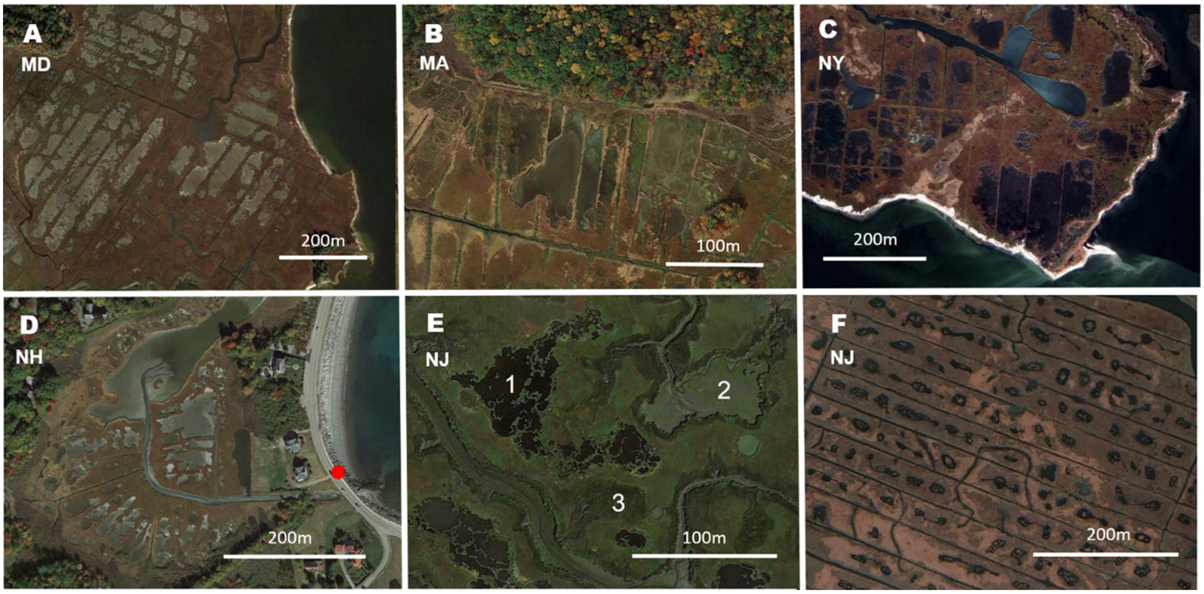

Fig. 1 Examples of interior open water features in northeastern and mid-Atlantic US salt marshes. **A–D** waffle pools. Panel D depicts a site where waffle pools are associated with a tidal restriction (marked with red dot). The marshes resemble a waffle, with cells formed by vegetated margins of grid ditches and filled with open water. **E** isolated (1), tidally-connected (2) and (3) revegetated pools in an unditched marsh, **F** OMWM, open marsh water management pools intentionally created for mosquito management. The two letter abbreviations indicate a state (*MD* Maryland, *MA* Massachusetts, *NY* New York, *NH* New Hampshire, *NJ* New Jersey). Source—Google Earth, earth.google.com/web

Methods

Regional analysis of marsh pool distribution

Across the northeast U.S. from Maine to the Atlantic coast of Virginia, we examined patterns of marsh pool presence and absence in relation to a range of explanatory variables. We divided this region into 10 contiguous zones, with zone boundaries occurring wherever a marked shift in tidal range (mean high water—mean low water) was apparent based on VDATUM (Parker et al. 2003), a regional spatial dataset of tidal datums (Fig. 2). Within each zone we generated 30 spatially-balanced (i.e. evenly-distributed) random points with a 1-km diameter circular buffer for a total of 300 sample circles. For each circle, we inspected time-series aerial imagery available via Google Earth to determine the presence or absence of tidally connected and isolated pools, pools created for open marsh water management (OMWM) and "waffle" pools. Isolated pools are open water areas with no direct connection to tidal channel network (Fig. 1E). Tidally-connected pools have channels entering them are usually at terminal location in the tidal channel network (Fig. 1E). We distinguished waffle pools from isolated pools by defining waffle pooling as a recurring pattern with at least 3 adjacent pools in occurring between a series of parallel ditches (Fig. 1A–D). OMWM pools for mosquito control take a variety of forms, but are typically isolated pools created in higher marsh areas that are often arranged in recurring patterns with shapes that are distinct from naturally-forming pools (Fig. 1F).

We also used imagery to identify tidal restrictions in sample areas by noting anthropogenic linear features such as roads and bridges and noting signs of restriction of channel width or channel bulges at linear features which suggest flow constriction (Crain et al. 2009). We validated relative tidal restriction density using an independent regional tidal restriction dataset (McGarigal et al. 2017). Additionally, for each sample circle, a local tidal range value (mean value for all dataset cells that intersected with the circle) was extracted from VDatum raster datasets (Parker et al. 2003). For marsh interior areas that did not overlap with the tidal range datasets, we measured the distance along the tidal channel network from the center of the circle to the closest point of the VDatum coverage and

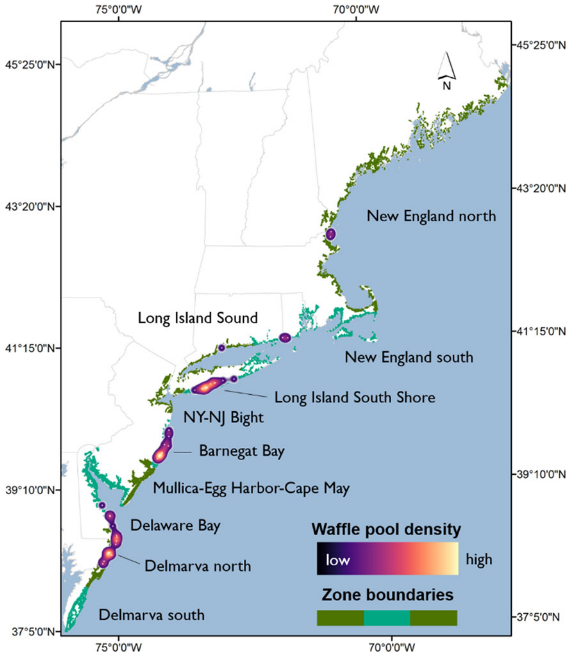

Fig. 2 Generalized map of waffle pool density. The extent of a regional analysis examining patterns of waffle pool presence in relation to tidal range, marsh elevation and ditching patterns. Hotspots or areas of high concentration of waffle pools are mapped. We note that this map is not intended to be comprehensive and waffle pools could occur in tidally-restricted marshes throughout the region. Seven zones for this study were delineated as contiguous regions with similar tidal range values

used that value. In these cases we anticipate that the tidal range value is overestimated because it tends to attenuate with increasing distances into the marsh interior (Dias et al. 2000).

We classified the marsh in each sample circle as unditched, intermittently ditched or parallel-ditched. Intermittent ditching is characterized by exhibiting a lower density of linear channels that do not have a regular pattern. These ditches may be associated with past management of marshes for agriculture (Smith et al. 2017), facilitating drainage of uplands, or navigation. Parallel-ditched (aka "grid-ditched") marshes have regularly-spaced ditches that were typically created as part of mosquito control efforts in the early twentieth century (Crain et al. 2009). These drainage patterns often overlay prior agricultural alterations (Adamowicz et al. 2020). We considered a marsh was parallel ditched where there was a series of at least 5 parallel ditches within the sample circle. For parallel ditched marshes, we measured the spacing of three ditch pairs and used the average as a covariate in subsequent analyses. It is possible that in some cases apparently unditched marshes may have had a history of ditching, for example a marsh historically impounded for agriculture which experienced dike breaching decades ago may have since experienced the formation of sinuous tidal channels (Weinstein et al. 2000).

Finally, to determine total marsh area in sample circles and the proportion of marsh area above or below MHHW, we clipped a regional spatial dataset of marsh area and elevation to our sample circles (Correll et al. 2018). This layer used local elevation (3 m resolution National Elevation Dataset) and 29 distinct tidal datums from Maine to Virginia to determine marsh zones occurring above and below MHHW. We used an additional regional dataset (McGarigal et al. 2017) to further clip marsh features to eliminate errors of commission where upland was classified as marsh in Correll (2018).

For analyses of isolated, tidally-breached and waffle pool presence/absence, we used a binary logistic model in a generalized estimating equation that accounted for spatial clustering by specifying sample points within each zone as repeated measures with an independent correlation structure. For isolated and tidally-breached pools, predictor variables included ditching presence, total marsh acres in sample circle, the percent of marsh that was below MHHW, tidal range and an interaction between low marsh percentage and ditching status. For waffle pools and OMWM pools, we constrained the dataset to include only grid-ditched marshes, included the same predictor variables as above, with average ditch spacing as an additional variable. The analyses were conducted in SPSS v26 (IBM Corp 2016). We conducted follow-up analyses where appropriate to estimate threshold values along continuous variables that determined the presence or absence of different pool types using a standard logistic regression with an additional parameter that modelled a disjoined slope at a hypothesized changepoint via the MCP package (Lindeløv 2020) available for program R (R Core Team 2020). For all analyses, if two random sample areas overlapped, we omitted one from the analysis. We also omitted any areas with no tidal marsh evident and those where the marsh was managed as an impoundment.

Estuary-scale analyses of marsh change

New Jersey study area

The New Jersey study area comprised an approximately 99,000 ha of salt marsh from Cape May to the northern extent of Barnegat Bay (Fig. 3). The study area was defined based on National Wetlands Inventory (NWI) maps (Wilen and Bates 1995) classified as "Estuarine and Marine Wetland" or "Estuarine and Marine Deepwater" for New Jersey's Atlantic coast tidal marshes that occur between highly-developed barrier islands and the mainland. As described below, we characterize all change within this footprint, but note that we do not estimate marsh expansion beyond the NWI footprint via marsh migration. Extensive unditched areas of marsh occur in some areas, along with regions that are ditched. Ditching in the study area occurred in most cases prior to 1930s and was associated with historic farming and/or mosquito control activities. Some of the ditched areas are overlain with the more recent practice of Open Marsh Water Management which occurred during the late twentieth century (Meredith et al. 1985a; Wolfe 1996).

We used 1970 NJ Wetlands basemaps which are 1:24,000 scale black and white aerial photos with tidal

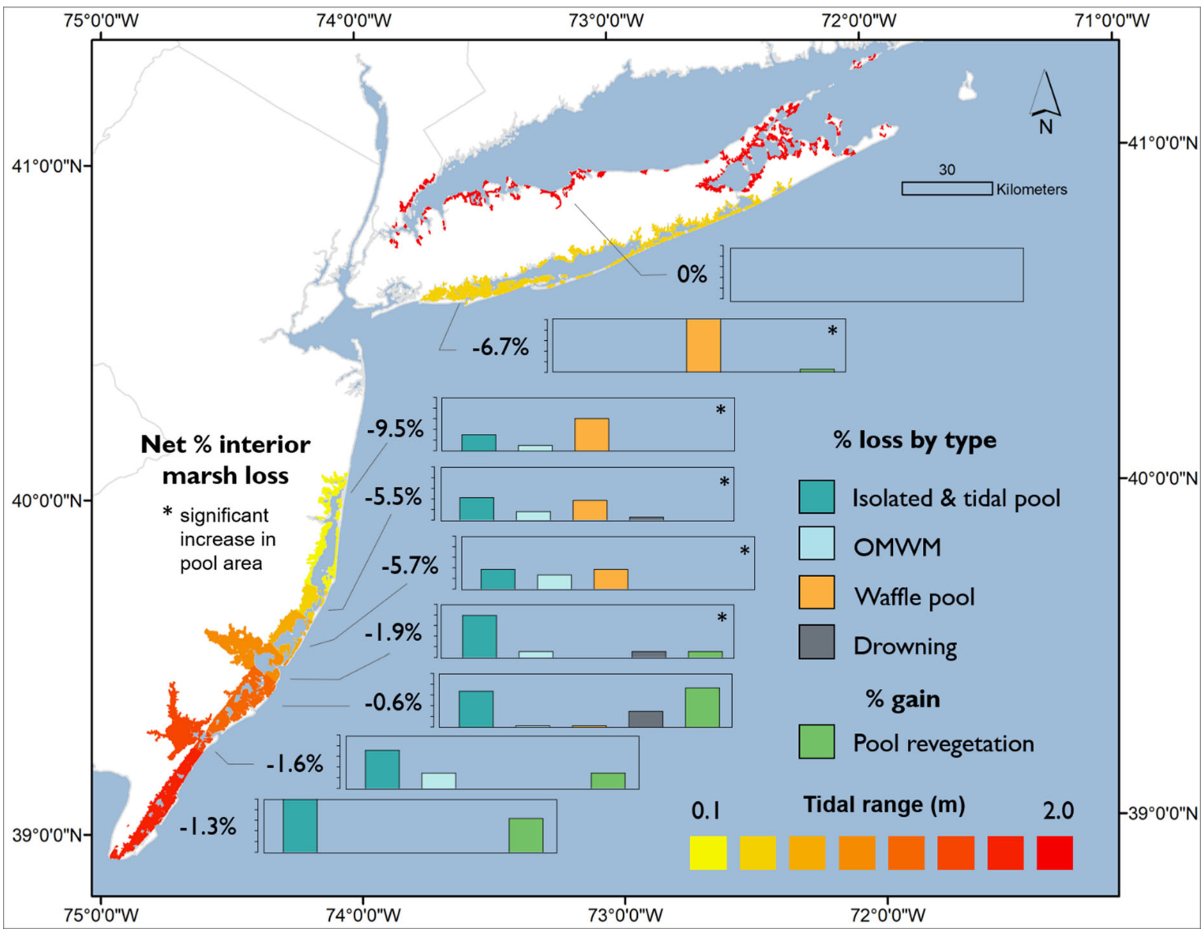

Fig. 3 Summary of interior marsh change patterns along the NJ and Long Island, NY coasts between 1970–74 and 2015–17. Net interior marsh loss is displayed to the left of graphs with pointers linking values to the corresponding study region. The percent contribution to this net loss (summing to 100%) of different types of open water are depicted in bar graphs. Isolated and tidally-connected pools, OMWM pools and waffle pools are described in the text. We define drowning as areas that converted from low marsh to open water without well-defined pool outlines. Pool revegetation is when a pool location in 1970–74 was vegetated in 2015–17. Each zone is delineated via a color scale that corresponds with tidal range values. See table S6 for additional details of change analysis

marsh plant species delineations (Brown 1978) superimposed on them as the baseline for comparison with the present marsh extent. The 1970 baseline is notable in that from this point forward there was little direct filling and development of coastal wetlands in the study area. The 1970 basemaps were supplemented by1977 NJ tidelands maps (NJ Office of Information Technology 1977) to verify classifications when there was uncertainty due to image quality or misalignment. For the present time frame, we used 2017 true-color growing season imagery (NJ Office of Information Technology 2017) to classify vegetation and 2015 orthoimagery, 0.3 m pixel resolution aerial photography (NJ Office of Information Technology 2015) to confirm water cover classifications.

New York study area

The New York study area comprised salt marshes of mesotidal Long Island sound (approx. 900 ha) and microtidal Long Island south shore (mainly South Oyster Bay, Great South Bay, Patchogue Bay, Moriches Bay and Shinnecock Bay, approx. 2,245 ha). Salt marsh data were collected and processed for Long Island Tidal Wetlands Trends Analysis, a joint effort by interstate, state, and non-profit agencies and organizations (Cameron Engineering and Associates 2015). This project generated shapefiles delineating salt marsh vegetation that are available upon request from New England Interstate Water Pollution Control Commission (NEIWPCC). The wetland boundaries for the base year, 1974, were established via manual image interpretation of color-infrared imagery and using the official New York State 1974 wetland boundaries. The second or "present time" shapefile delineated tidal wetland vegetation via automated image classification based on either 2005 or 2008 color-infrared NYS imagery. This was done to preserve uniform marsh land cover classification scheme. However, for the purpose of this study, the "present time" salt marsh delineation was updated using 2016 NYS color orthophotographs (https://gis.ny.gov/gateway/mg/webserv/). The updated analysis captured the marsh land area conversion to open water (either bay or internal) and beach area at the marsh edges.

Tidal marsh change analysis

We estimated marsh area for two time periods using point cover estimation (NJ in1970 and 2017; NY in 1974 and 2016). We generated spatially-balanced random points (Theobald et al. 2007) across the study area (10,000 for NJ, 1000 for each of the two estuaries in NY) to estimate both historic and present marsh cover. At each point we classified cover for historic and recent time frames (Karl et al. 2014) according to the following categories: vegetated marsh (low, high, brackish, or *Phragmites australis*), unvegetated or misclassified areas (upland, developed, dredge spoil, or bare) and the following water classifications: tidal channels (creeks and ditches), open water/beach, and pools ("waffle" pools in the marsh interior). This approach allows for estimation of cover at two points in time as well as the capacity to estimate patterns of change and stability among classes (Pontius et al. 2004).

Pool categories included interior isolated pools without tidal creek connection (retaining water at low tide), interior pools connected to tidal creeks, OMWM pools and "waffle pools". Several cover classes characterized marsh change between the two time intervals. These included marsh conversion to open water distinguished as "edge erosion" at bay edges, "creek expansion" which documented widening of tidal channels, marsh aggradation where open water became marsh and "spoil recovery" where historic spoil placement had revegetated. Large confined dredge spoil mounds placed on marshes to elevations above the high tide line were not included in the analysis area. For each point we also noted its proximity to ditching and classified a point as occurring in a ditched marsh if it was within 100 m of a ditch.

To estimate error around land cover percentages, we bootstrapped cover class frequency data with 1000 sampling iterations (Scheiner 1998). For categorical analyses of differences among land cover patterns based on point classification frequencies, we used Fisher's exact Chi Square Test with Bonferroni correction for multiple comparisons (Rice 1989). We present results as area derived from percent cover estimates of the study area.

We used VDatum (Parker et al. 2003) to determine the tidal range value at each random point that fell in open water. We then used normal mixture analysis to subset the data into zones representing a gradient in tidal range. This resulted in the delineation of 7 zones for NJ and 2 zones for NY (Fig. 3). All marsh change data were summarized across these zones for analysis. For New Jersey, in each tidal range zone, we further calculated the ratio of open water edge density to 1970s marsh area to characterize cumulative exposure of marsh edge to wave action. We calculated edge by converting NWI polygons to line features representing the edge of marsh and water. Then we manually excluded all edges that were developed, those associated with tidal channels in the marsh interior and any primary channels that were less than 30 m wide.

Results

Regional analyses of pool distribution

Region-wide, the majority of marshes sampled (77% ± 2.0 SE, n = 256) had intermittent or extensive parallel ditching. All sampled areas in southern New England and Long Island were ditched. Virginia's eastern shore had the least amount of ditching, with 82.7% (± 7.1% SE) of sampled areas apparently unditched (Table S1). With the exception of this region of Virginia, parallel ditching was present in all zones, ranging from 12 to64% of sample sites. Ditch spacing ranged from 7 to 95 m and averaged 34.8 ± 1.4 m. It did not vary by tidal range ($R^2 = 0.34$, DF = 1, F = 4.3, p = 0.072). Tidal restrictions were encountered in all zones in this study except the NJ Atlantic Coast and the Eastern shore of Virginia (Table S1). However, a more comprehensive regional assessment found restrictions in all regions (McGarigal et al. 2017).

Across the northeastern U.S., marsh pools were composed of isolated and tidally-connected pools. Both these forms were more likely to be encountered in marshes with no ditching evident (Fig. 4a and Tables S2, S3) and both were also more likely to be present on higher elevation marshes (i.e. where the proportion of marsh below MHHW in the sample was low, Fig. 4b). For unditched sampling locations, isolated pools occurred in marshes that had a mean of 75.5% ± 0.61 SE of marsh area above MHHW which was greater than that of unditched sites without isolated pools that had a mean of 35.6% ± 0.55 SE of marsh above MHHW (F = 23.5, df = 1, p < 0.001).

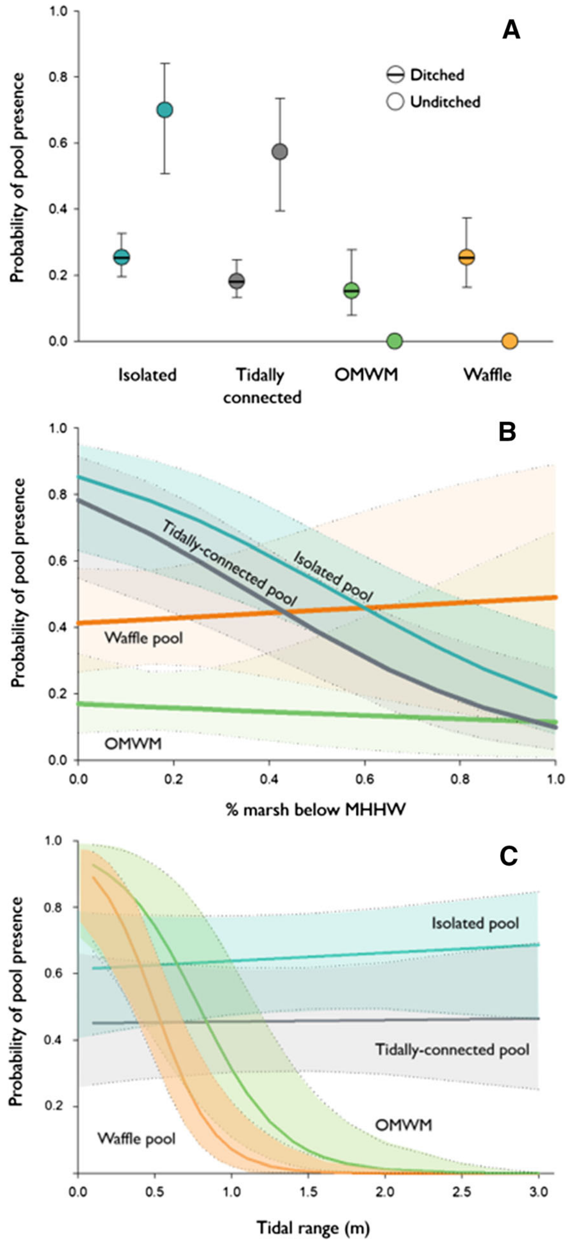

Fig. 4 Regional analysis of open water features in the marsh interior. Open water in the marsh interior is primarily composed of isolated or tidally connected pools, waffle pools, and open marsh water management features (OMWM). The three panels show probability of open water feature presence as a function of **A** in ditched vs. unditched marshes (mean ± 95% CI) **B** proportion of low marsh (shaded area 95% CI) **C** tidal range (shaded area 95% CI)

Similarly, unditched locations with tidally-breached pools had a mean of 69.6% ± 0.54 SE of marsh area above MHHW which was greater than that of unditched sites without isolated pools which a mean of 28.8% ± 0.63 SE of marsh above MHHW ($F = 24.4$, $df = 1$, $p < 0.001$). Tidal range did not influence the presence of pools when controlling for these other factors (Fig. 4c).

Waffle pools occurred throughout the region exclusively (and by definition) in parallel ditched marshes, with 10% ± 1.8 SE of all sampled areas affected (Table S1). The highest concentrations (Fig. 2) occurred in southern New England (8.3 ± 8.3%), the south shore of Long Island (32.0 ± 9.5%), Barnegat Bay NJ (26.9 ± 8.9%) and northern Delmarva (26.9 ± 8.8%). Logistic regression analysis indicated that the only significant variable influencing the presence or absence of waffle pools was tidal range (Table S4), where decreasing tidal range predicts an increasing probability of waffle pool presence (Fig. 4c). We noted three observations which were outliers where waffle pools occurred where tidal range was greater. All three sites were associated with tidal restrictions and were excluded from further analysis. Binomial changepoint analysis identified a tidal range threshold of 0.82 m (95% CI 0.61–1.1, Figure S1) with the probability of waffle pool formation sharply increasing below this threshold (Fig. 4c). OWMM features were most concentrated in the Barnegat Bay region of New Jersey (Table S1) and, like waffle pools, these pools were more likely to be encountered in the most microtidal areas (Fig. 4c and Table S5).

Estuary-scale patterns of marsh change

Our analysis of marsh change since 1970 in New Jersey and Long Island revealed that the magnitude of interior marsh loss via conversion to pools increased as tidal range decreased ($R^2 = 0.78$, $F = 23.1$, $df = 1$, $p = 0.0020$, Fig. 5a). Net interior loss was lower where tidal range was highest in part because a portion of interior loss was offset when tidally-breached pools revegetated (Fig. 2 and Supplemental Table S6). We observed no pool revegetation in regions with tidal range below 1.0 m and all of these zones experienced significant loss of interior vegetated marsh (Fig. 2 and Supplemental Table S6).

In New Jersey there were approximately 40 ha of waffle pool coverage in 1970 which expanded to 200 ha by 2017. Waffle pools were absent from Long Island in the 1970s. Overall waffle pool development and expansion over the 40–50 year period since 1970 accounts for 24% (36–100% range across zones, Fig. 2) of the total interior marsh loss in the three zones comprising Barnegat Bay, and close to 100% of interior marsh loss on the south shore of Long Island.

For marsh loss at the edge, there was no relationship with tidal range ($R^2 = 0.01$, $F = 0.007$, $df = 1$, $p = 0.93$). In this case, regions with a higher ratio of edge to marsh area experienced a greater magnitude of marsh loss to open water or conversion to beach habitat ($R^2 = 0.70$, $F = 11.9$, $df = 1$, $p = 0.018$, Fig. 5b). Marsh edge losses were statistically significant in all study areas (Supplemental Table S2).

Discussion

Our results illustrate the extent, impact, and trajectory of waffle pools in salt marshes of the Northeast and identify key factors associated with their occurrence. Unlike other pool types, which occurred primarily in unditched marshes at higher elevations across all tidal ranges, waffle pools are almost invariably associated with parallel ditch networks where, predominantly, tidal range did not exceed 0.8 m (95% CI 0.61–1.1). An important exception, exhibited by several areas that were outliers in our analysis, is that tidal restrictions can also induce waffle pool formation upstream from the tidal restrictions in regions with an otherwise large tidal range (CMA Engineers 2018). This suggests that anthropogenic alterations in any setting that reduce tidal amplitude in a grid ditched system have the potential to induce pool formation.

Change analyses at the estuary level in NJ and NY indicated that waffle pools are a recent and likely increasing phenomenon that is one of the largest contributors to vegetation loss in the marsh interior. Depending on the region, between 36 and 100% of the interior marsh loss to open water in microtidal marshes could be attributed to waffle pool formation. In contrast, where tidal range was greater than 0.8 m, marshes experienced little net change in pool area because pool formation and expansion was offset by vegetation recovery in tidally-breached pools (Smith and Pellew 2021). Unlike interior patterns of loss, marsh loss via edge erosion was unrelated to tidal range and was instead associated with edge exposure, i.e. a higher ratio of edge to marsh area led to higher amount edge erosion as a result of wave exposure (Leonardi et al. 2016). Overall, edge erosion was the

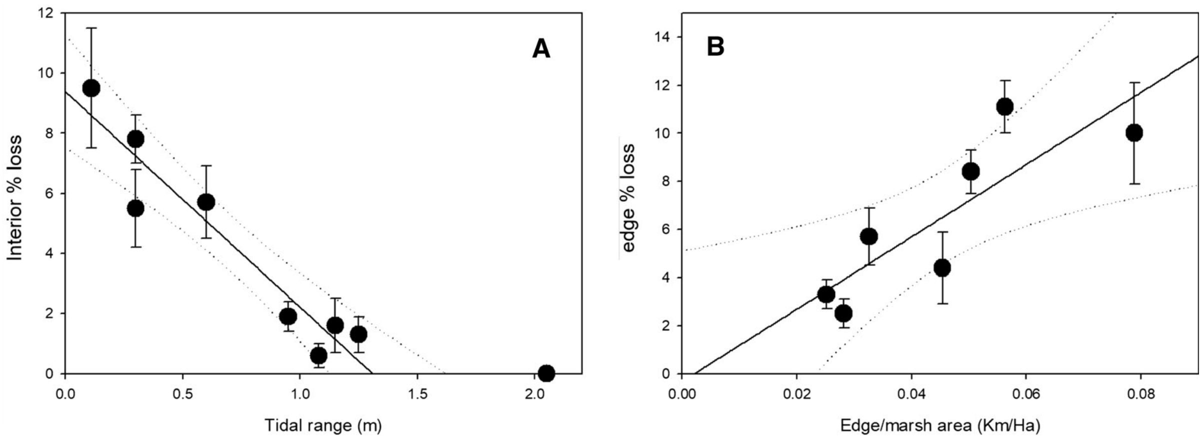

Fig. 5 Marsh loss in the interior and the edges of the salt marshes. Loss was defined as the proportion of sampling points that converted from marsh area to open water (or beach in case of edge loss) between 1970 and 2017. **A** Interior loss was mostly due to open water features such as waffle pools and it increased with lower tidal range, **B** the vegetated marsh edge was lost to bay and beach formation and increased as the edge/marsh area ratio increased (i.e. smaller marshes with a lot of exposed edge experienced larger losses). Error bars represent uncertainty around the area estimate (SE). Solid lines are linear regression models with 95% confidence intervals represented by dotted lines

greatest contributor to marsh loss in NJ/NY estuaries, accounting for 2%–20% of overall loss since 1970.

We were unable to quantify sediment supply across our study which is another important determinant of marsh persistence (Ladd et al. 2019) and pool dynamics (Mariotti 2016). Available data from the Barnegat Bay, NJ (Defne et al. 2020) suggests that this parameter likely varies widely throughout the region we studied. Patterns in Barnegat Bay (Defne et al. 2020) indicate that suspended sediment declines from the bay edge to the marsh interior (a 4 km distance in some places). In some regions of the bay there is a clear pattern of a greater prevalence of waffle pools in the deep interior of marshes. The greater sediment supply near the bay edge may help reduce the likelihood of waffle pool formation as eroded edges redistribute sediment to the adjacent marsh surface (Leonardi et al. 2018). In addition to a lower sediment supply, interior marshes also experience a decreasing tidal range along this edge to interior gradient as tidal energy dissipates across a vast unmaintained ditch network.

Our findings of increased interior marsh loss where tidal range is narrowest support the increasing recognition that microtidal marshes have the greatest vulnerability to sea level rise as well as to other perturbations that alter tidal hydrology (Kearney and Turner 2016; Vinent et al. 2019; Donatelli et al. 2020). By definition, microtidal regions have less potential elevation capital (Cahoon et al. 2019) because the elevation range that can support vegetation growth declines with tidal range (Kearney and Turner 2016). Minimal sediment import due to ebb-dominated tidal dynamics (Friedrichs and Perry 2001) means that marsh accretion is dependent on organic processes (Turner et al. 2002) and thus the optimum elevation to maximize accretion falls into an even narrower range, particularly for *Spartina patens* which comprises a large proportion of marsh area in these systems (Kirwan and Guntenspergen 2012). We found few, if any, unditched extreme microtidal marshes (< 1.0 m range) in the Northeast U.S. salt marshes. Microtidal marshes typically have lower drainage density relative to mesotidal marshes (Friedrichs and Perry 2001; Zhou et al. 2014), but we found that ditch spacing across the Northeast does not vary according to tidal range. Thus, the relative impact of ditching on hydrology may be greater in microtidal marshes.

Given that waffle pool formation occurs exclusively in marshes that have been hydrologically altered by ditching (or ditching and tidal restriction combined), there is a clear opportunity to pursue management intended to reverse these impacts. This management is essential for the conservation of several tidal marsh-dependent species including salt marsh sparrow and Eastern black rail. For example, one of the greatest population densities of salt marsh sparrows overlaps with a hot spot of waffle pool distribution in New Jersey (Wiest et al. 2016). Prior to degradation from waffle pools, these microtidal marshes in many cases had extensive areas of infrequently-flooded *Spartina patens* marsh that is used for nesting by these two species (Gjerdrum et al. 2005; Kern 2015; Watts 2016; Roberts et al. 2017).

Potential causes

Our findings make clear that waffle pool formation is associated with microtidal parallel-ditched marshes and that it is a relatively recent and ongoing phenomenon. The mechanism of waffle pool formation needs to be understood in order to improve the design and outcomes of projects focused on reversing these patterns. Based on the results of this study and a review of existing literature, we propose that waffle pool formation is caused by drainage alterations from ditching via a multi-decadal, two-stage process (Fig. 6). This consists of (1) a drying phase initiated by increased marsh platform drainage from ditching that leads to elevation deficits and (2) a subsequent rewetting phase when ditch maintenance ceases and channel siltation, along with sea level rise, increase the amount of water held by the marsh.

The intended purposed of ditching was to lower the water table (Tonjes 2013) and drain surface pools (Smith 1907; Bourn and Cottam 1950). This leads to a drier marsh surface (Fig. 6B) due to increased seepage discharge at ditch margins (Gardner 2005) and increased proportion of the tidal prism contained by ditches. These effects are confirmed by observations of vegetation community shifts toward species adapted to high marsh elevations (Bourn and Cottam 1950). This altered hydrology can leave areas of the marsh at a position in the tidal frame that is above the optimum range for below-ground biomass production (Kirwan and Guntenspergen 2012) which is the primary contributor to accretion in microtidal marshes (Craft et al. 1993). Depending on the new position in the tidal frame imposed by ditching, organic accretion rates can slow and/or existing peat can oxidize (Portnoy 1999) which can lead to elevation deficits over time (LeMay 2007; Burdick et al. 2019).

The pronounced elevation differential apparent between ditch edges and the interior (LeMay 2007) isdue to past-placement of ditch spoils in some locations. But this differential is also likely due to more rapid rates of accretion compared with the interior due to more favorable hydrological conditions (Gardner 2005). Higher ditch margins in turn may reduce flooding frequency of the interior marsh and likewise prevent drainage of the interior after high water events. Such extremes in moisture can disrupt organic accretion and/or trigger vegetation dieback. For example, a growing season drought during a neap tide cycle can cause salinity build up (McKee et al. 2004) and acid sulfate production via oxidation which lowers pH dramatically (Linthurst and Seneca 1980). With subsequent spring tide events these interior areas may then more likely to retain water where vegetation has died back. The resulting increase in the zone of saturation through the root zone leads to additional vegetation dieback and further expansion of pools (Watson et al. 2016; Adamowicz et al. 2020). If the water in pools evaporates, this then exposes the unvegetated platform to further desiccation and oxidation (Miller and Egler 1950). Such a wetting and drying cycle may be the basis for formation of pools in other settings as well at higher marsh elevations (Smith and Pellew 2021).

The second proposed component of waffle pool formation, the rewetting phase (Fig. 6C), is not necessarily a prerequisite for waffle pool formation, but contributes to its likelihood because it shifts the water table upward, so that marsh platforms with an elevation deficit (due to ditching) are at a lower relative position in the tidal frame. Given accumulated elevation deficits, this can result in areas of the marsh platform that are too low to support vegetation growth or shifts in vegetation communities toward species adapted to more frequent flooding. We suggest that this second phase is a component of waffle pool formation because our results indicate that the appearance of the pools coincided with a widespread shift in management practices that ended routine maintenance of parallel ditches. This resulted in widespread sedimentation (Corman et al. 2012) and bank-slumping (Mariotti et al. 2016) that shallowed and blocked ditches. This reduction in drainage efficiency of ditched networks can impound water in some areas (Corman and Roman 2011) and reduces seepage discharge along channel edges (Gardner 2005) which raises the water table and creates increasingly favorable conditions for waffle pool formation in interior areas where elevation has been lost. Another management practice, ditch plugging, can produce similar patterns (Vincent et al. 2013a).

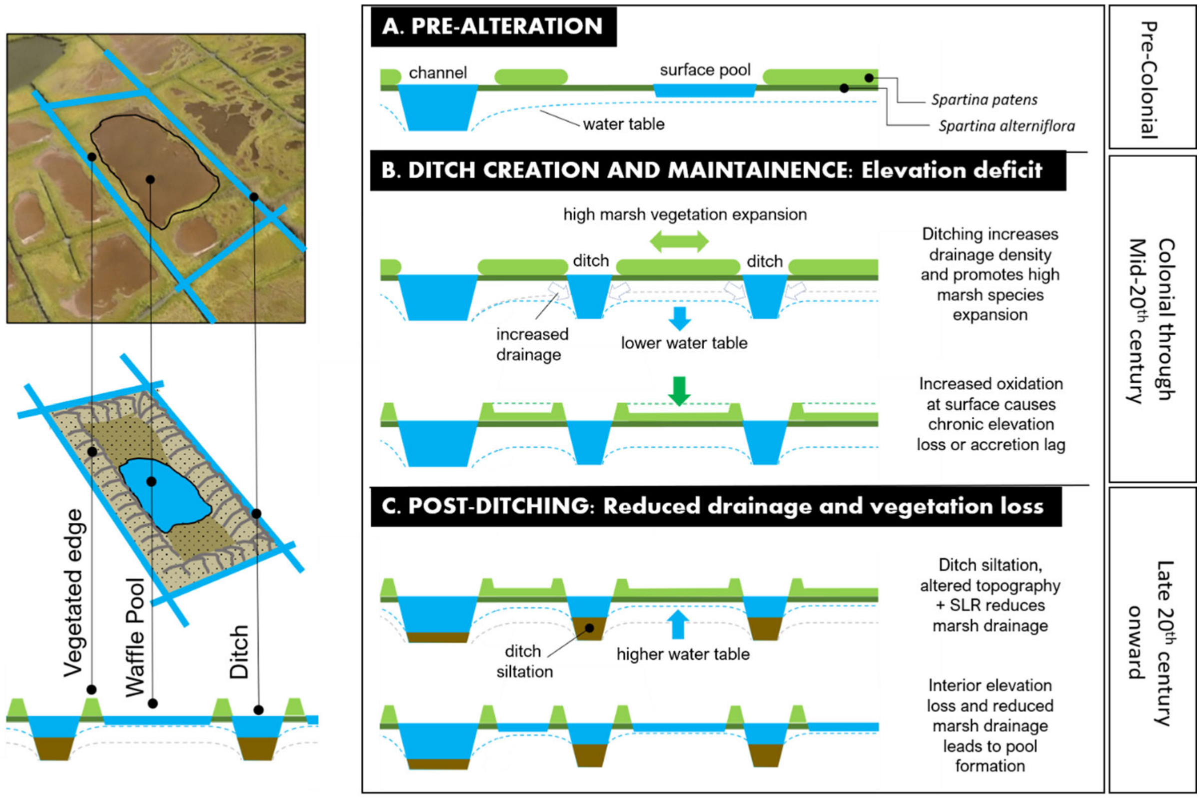

Fig. 6 Proposed mechanism for waffle pool formation. **A** Salt marsh hydrology and elevation at equilibrium. **B** Historic marsh management for agriculture and mosquito control focused on draining marshes using ditches. Surface pool extent was reduced and high marsh plant cover expanded in some settings. Ditches and/or tidal restrictions lowered the water table and exposed the marsh surface to greater oxidation. This caused decomposition of accumulated peat and/or a slowing of organic accretion rates that resulted in elevation loss over decades after ditches were created. Resulting elevation differentials between channel margins and the interior (along with spoils placed along ditch margins) affect surface water flooding and drainage which exposes the interior to greater extremes of wet and dry conditions. **C** In the latter part of the twentieth century efforts to maintain ditched networks lapsed as mosquito control techniques evolved. Along with sea level rise, widespread siltation of ditches raises the water table and drives shifts from vegetated marsh to open water or vegetation community shifts from high marsh to low marsh species in areas with elevation deficits. Ditch plugging and opening of tidal restrictions can also induce or exacerbate such patterns

Once ditches were created, managers recognized the need to maintain them because otherwise siltation would prevent them from adequately conveying water (Leslie 1926). As the practice of mosquito control evolved over course of the twentieth century, ditches were no longer considered an essential element for mosquito management (Wolfe et al. 2021). An observation common among mosquito control managers is that the waffle pool phenomenon began to appear when ditch-cleaning ceased (Dominick Ninivaggi pers. comm). It is plausible that proper management and upkeep of grid-ditched network would have slowed down waffle pool development, however, such degree of attention is beyond the capabilities of most if not all mosquito control districts.

Tidal restrictions are an accidental experiment where waffle pooling is induced by a management intervention that artificially reduced tidal flow. Restrictions lower water levels and induce elevation deficits in the same manner described above, with marsh platforms following the zone of saturation downward (Portnoy 1999). Likewise later ditch siltation in these areas reduces drainage and increases water table height which enhances the likelihood of waffle pool formation. Furthermore, if tidal restrictions are opened up to increase tidal flow, there will be additional impacts to the marsh due to increased water levels.

One limitation to elucidating the mechanism of pool formation is that the process is not well understood in any tidal marsh setting (Perillo 2019). In addition, there are only a few tracts which can serve as comparable control sites for distinguishing the impact of ditching and other alterations from that of sea level rise (Smith and Pellew 2021). Under these circumstances, it cannot be ruled out that runaway pool expansion (Mariotti 2016) would occur regardless of ditching (Schepers et al. 2017). In addition, given that pools are typical features in unditched marshes around the world (Perillo 2019), some pool formation might be expected as the maintenance of ditched networks has become less frequent and marsh geomorphology trends toward a new equilibrium (Wilson et al. 2014; Burns et al. 2021).

Ditching-induced elevation deficits are likely to occur regardless of tidal range (Mariotti et al. 2020a), but because of the narrow elevation range at which vegetation can grow in extreme microtidal marshes, the consequences are more pronounced. In settings with a greater tidal range, marsh elevations deficits compared to unditched regions may still be apparent (LeMay 2007; Mariotti et al. 2020b) with corresponding vegetation community shifts toward those adapted to more regular tidal flooding.

Management

Based on our findings that waffle pools are a recent and ongoing phenomenon and that they are likely a product of both past and current hydrological alterations, we propose that this issue is one of the most urgent to address in tidal marshes of the Northeast and mid-Atlantic United States. Immediate management interventions can help prevent further expansion of pools and stabilize vegetated marshes at risk of converting to waffle pools in the future. Our results, discussion and management experience to this point lead us to propose three interventions to reverse waffle pooling that can be pursued individually or in concert depending on the setting.

Comprehensively restore hydrology

Comprehensive restoration of the tidal channel network is the most critical component of preventing, halting and reversing the trend of waffle pool formation. The goal is to achieve a balanced tidal channel network that is appropriate given a site's existing elevation, tidal hydrology and freshwater inflows. The outcome of this approach is a relatively stable surface and subsurface tidal hydrology that maximizes the organic accretion potential of a marsh. In practice, channel densities are reduced by revegetating a portion of the ditch network (Fig. 7) either through direct filling (Rochlin et al. 2012a; Cardno ENTRIX 2013) or through treatments that accelerate passive sedimentation of ditches (Burdick et al. 2019). Remaining channels are carefully selected to serve as primary conduits for tidal flow. These primary channels subsequently experience greater current velocities that helps prevent siltation and the need for maintenance.

In locations where ditches have intact levees or where waffle pools areas are otherwise isolated from a channel network, shallow, narrow channels known as runnels (Hulsman et al. 1989; Wigand et al. 2015) can be excavated to provide surface drainage sufficient to allow vegetation recovery as long as interior elevations remain within the growth range of salt marsh plants (see Supplemental Figure S2 for details). However, runnels need to be an element of the broader hydrological restoration design described above in order to achieve the overall the goal of stabilizing water table hydrology across an entire site.

Select waffle pool remnants can be converted to smaller, deeper pools in marsh interior areas to provide additional drainage and serve as habitat for fish and wildlife (Erwin et al. 1991, 1994; Roman et al. 2002; Raposa 2008; Rochlin et al. 2012b; Smith and Niles 2016), including those that feed on mosquito larvae such as *Fundulus heteroclitus* (Meredith et al. 1985b; Wolfe 1996; Rochlin et al. 2009). Accordingly, restoration designs should not aim at complete elimination of pools, but at incorporating some of these hydrological features into a plan that enables long-term solutions for improved marsh resilience and mosquito control.

Recover elevation lost from subsidence

Ditching and the process of waffle pool formation has shifted large areas salt marsh to a lower position in the tidal frame. Hydrological restoration can restart elevation building processes as vegetation recovers in

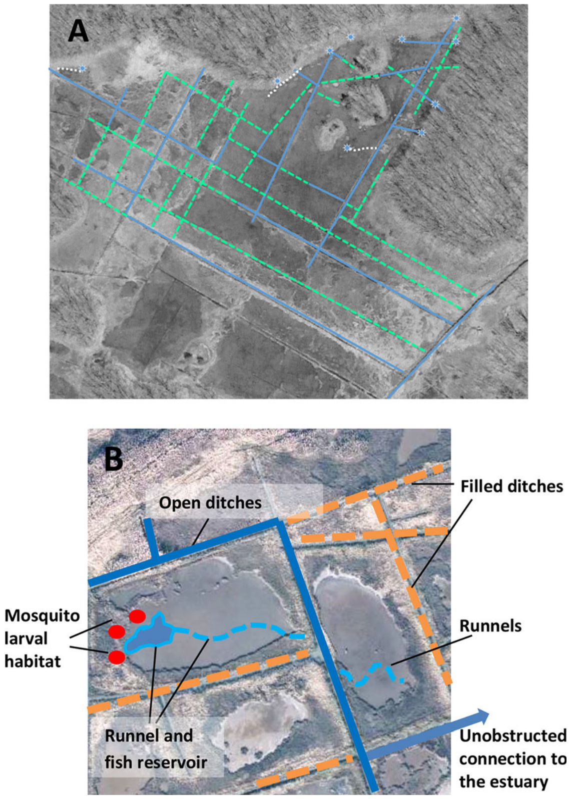

Fig. 7 Waffle pool mitigation using integrated marsh management. **A** Proposed hydrological restoration at a site in Ipswich, MA impaired by advanced waffle pool degradation. Both blue and dashed green lines signify the existing ditch network. Blue lines represent channels that will remain open as the primary tidal channel network. Dashed green lines denote secondary, less dominant channels that should be revegetated. White dotted lines are runnels connecting to the mosquito production areas (blue dots). **B** Conceptual representation of waffle pool mitigation project. The grid ditched network is broken up by completely filling select ditches (light brown dashed line) and leaving open primary tidal channels (dark blue line). Runnels, or shallow meandering connectors serve to break through levees and drain waffle ponds (light blue dashed line). Some runnels serve a dual purpose of draining waffle ponds and connecting the remaining channel network to fish reservoirs (dark blue area with light blue border). The latter are placed within mosquito larval habitat to support refuge for killifish that provide biological control of mosquito larvae. The marsh connection to the estuary and the tidal exchange are re-established, gradually if warranted. Base image: Google Earth 2018, earth.google.com/web, true color image converted to black and white

former waffle pools and accretion resumes (Burdick et al. 2019; Adamowicz et al. 2020). Using careful adjustment to water table levels/zone of saturation and marsh vegetation, accretion rates can be optimized, primarily through belowground biomass production (Kirwan and Guntenspergen 2012). Nonetheless, there will be cases where waffle pool base elevations are too low in the tidal frame to allow for vegetation recovery. In such cases, sediment addition, either from dredged or upland sources, could be used to recover lost elevation (Ford et al. 1999) as part of an overall restoration strategy that includes hydrological restoration. Sediment addition may also be necessary to restore *Spartina patens* habitat for nesting birds. A key technical challenge is that the sediment needs to be distributed very thinly across large areas with minimal impact to existing marsh function and morphology so that it integrates rather than interferes with the process of hydrological restoration. An additional concern is that increasing elevation using dredge material, particularly if high marsh is the goal, risks oxidizing sulfidic dredged soils which can produce sulfuric acid and release heavy metals that are toxic to plants and animals and set back the recovery trajectory of a site (Demas et al. 2004).

Address anthropogenic features such as bridges and culverts that restrict tidal amplitude.

In many cases waffle pool formation is associated with tidal restrictions caused by impoundments, culverts and bridges that create or exacerbate microtidal conditions. This increases the site's vulnerability to any subsequent perturbations, including accelerated sea level rise (Kearney and Turner 2016; Vinent et al. 2019). Removing tidal restrictions is an important strategy for increasing the resilience of tidal marshes, but before restrictions are removed it is critical to address prior marsh degradation. Marsh elevation and hydrology first need to be assessed and restored to conditions that are appropriate for the increased tidal influx resulting from tidal restriction removal to avoid further marsh degradation. A case in point is the site illustrated in Fig. 7A, which experienced exacerbation of waffle pooling after a restricting culvert was replaced in order to allow more complete tidal exchange. The resulting flow inundated the marsh surface. This precipitated the formation of waffle pools because elevation loss due to subsidence was not addressed prior to increasing tidal flow.

Conclusions

The landscape-level analyses of waffle pool distribution and patterns of marsh change presented here have revealed consistent patterns across the Northeast United States. Rather than solely an artifact of sea level rise, degradation from waffle pools appears primarily to be the result of anthropogenic alterations of hydrology via ditching and/or tidal restrictions. This understanding helps advance restoration practice toward a clear strategy to address waffle pools across a broad geography. Although some of the tactics necessary to restore marshes with waffle pools are well-established, using them in concert is a new approach and there are few published examples to draw upon (see Adamowicz et al. 2020 for case studies). Additional research which applies theory and models of tidal marsh geomorphic evolution in landscapes impacted by ditching and tidal restrictions can help practitioners better understand underlying mechanisms of degradation as well as improve restoration designs and predictions of project outcomes. Rigorous adaptive management that employs well-considered monitoring that feeds back into project adjustments, in turn, will help improve restoration outcomes and future project designs. Communities of practice using collaborative learning (Maher et al., this issue) are well-poised to successfully address these complex and multi-scale challenges of increasing the persistence of microtidal marshes through restoration.

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