Are Salt Marsh Pools Suitable Sites for Restoration?

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Tidal marsh function and ecological integrity are influenced by an array of direct and indirect stressors. At the same time these marshes are responding to accelerated sea level rise. Alone or in interaction these stressors can contribute to marsh degradation and potentially reduce the resilience of marshes to sea level rise. Agencies and conservation organizations have acknowledged both the importance of marshes and the threat they face through the conservation and protection of marshes and, more recently, by investing in restoration.

In order to assess salt marsh condition and select appropriate restoration sites and strategies, it is first necessary to identify signs of marsh degradation and their causes. To do this, the impacts of direct alteration of marshes and associated hydrology must be assessed apart from climate change-driven sea level rise to understand the relative roles that direct human impacts and climate change play in marsh degradation. Only then can effective restoration projects be developed and implemented.

Ditching, impoundment, and tidal flow and range alterations can impact marsh condition and resilience, even in the absence of sea level rise. For example in Delaware Bay, more than half of the marshes were impounded and farmed (Smith et al. in review). Although most of the impounded areas are now subject to relatively unrestricted tidal flow, this former activity has resulted in present-day marshes that are lower in elevation than surrounding marshes that were never impounded. The elevation change has resulted in the loss of 10,000 acres of marsh. The remainder are struggling to keep pace with sea level rise while attempting to recover from farming-related elevation deficits. In this case, marsh deterioration is largely attributable to a direct human management impact rather than sea level rise.

While marsh farming was somewhat limited in extent in the Northeast, one author estimates that approximately 90% of all salt marshes in this region have been ditched (Bourn 1950). Ditching for mosquito control became widespread in the early 20th century and permanently changed the ecological character of marshes (e.g., Tiner 2013). Researchers are still grappling to understand its effect on marshes' capacity to keep pace with sea level rise. Nonetheless there is evidence that changes in hydrological function from ditching can potentially decrease marsh resilience to sea level rise (LeMay 2007).

Changes in tidal range resulting from channel deepening and shoreline hardening can also impact marsh condition. The deterioration of marshes in Jamaica Bay, New York is the result of dramatic increases in tidal range attributed to a variety of human actions (Swanson and Wilson 2008). The surface of the bay has decreased by more than 50% while the volume of the bay has increased by 350%. The tidal range has increased by 1.3 feet causing rapid loss of marshes that formed under a lower tidal range.

Each of these alterations can elicit symptoms of degradation. Like medical treatment, tidal restoration can treat the causes and/or the symptoms of degradation. Ideally the goal is to treat the root cause of degradation to achieve a lasting restoration outcome.

One feature of tidal marshes that may be misinterpreted as a symptom of degradation is the presence of marsh pools. This misinterpretation is be partly due to the fact that the genesis and geomorphic function of marsh pools have, until recently, been poorly understood (Harshberger 1916; Miller and Egler 1950; Redfield 1972; Wilson et al. 2009). In some settings pools are characteristic features of marshes with high ecological integrity, whereas in other settings they may represent marsh degradation from human impacts. These nuanced interpretations must be understood for practitioners to be effective in the efforts to manage and conserve tidal marshes. In this article we review research on the role of pools in both hydrologically altered and unaltered tidal marshes to aid marsh assessment determinations and restoration decision-making.

DYNAMIC MARSH POOLS

Tidal marsh pools are characteristic features of many tidal marshes that have never been ditched or impounded (Adamowicz and Roman 2005; Lathrop et al. 2000). An emerging body of literature has clarified our understanding of these features and demonstrates that tidal marsh pools

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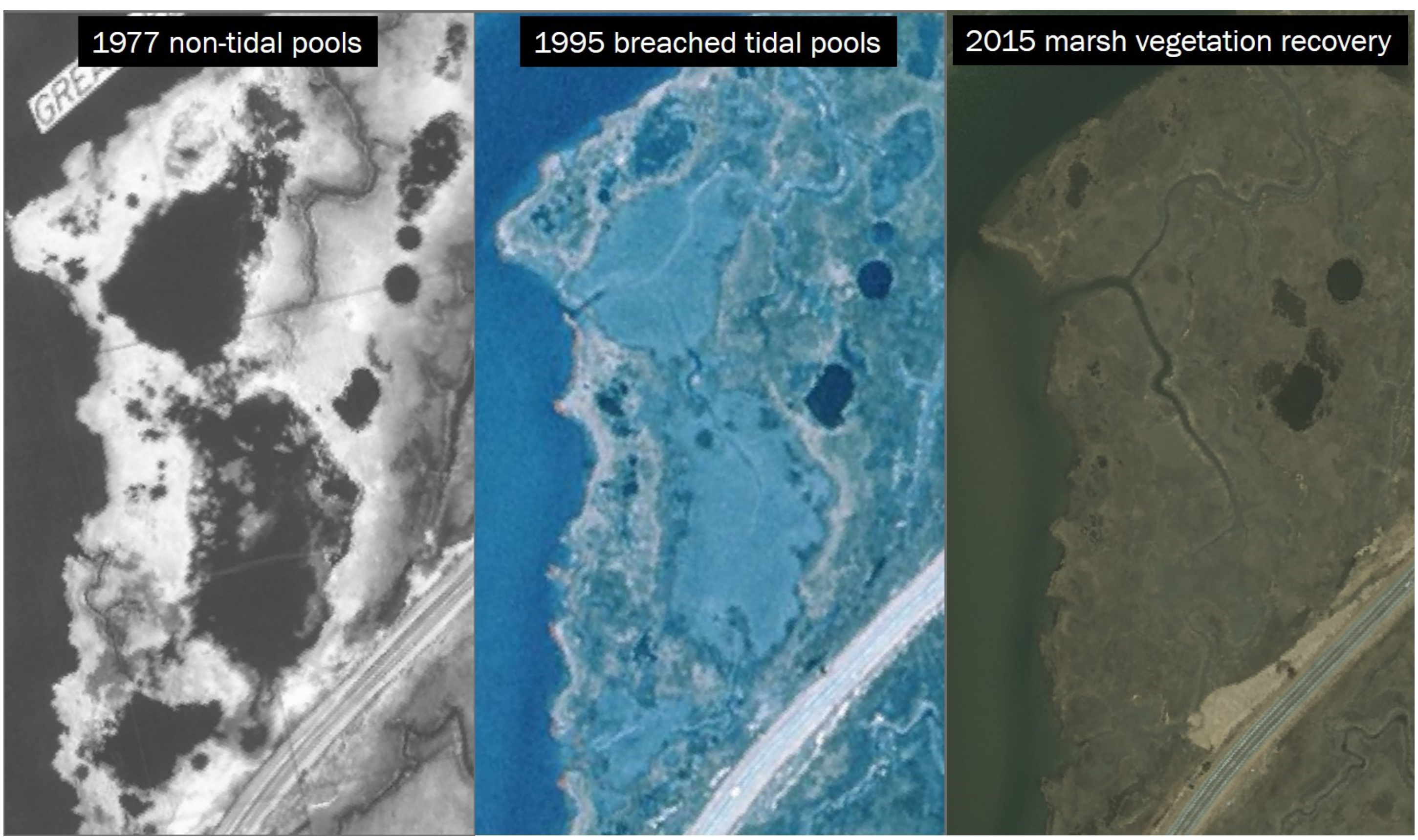
in some settings are part of a dynamic cyclical geomorphic process: pools form, expand, breach and revegetate over time (Mariotti 2016; Wilson et al. 2009, 2010, and 2014). Pools form in areas of poor drainage where a combination of waterlogging stress and low productivity produce nonvegetated patches that coalesce into pools (Wilson et al. 2014). Pools change in dimensions over time, typically expanding until their sides intersect with an adjacent tidal creek. At this point the pool becomes tidal with increased tidal action and sedimentation eventually promoting the return of vegetation to the former pool (Figure 1). The tall form of *Spartina alterniflora* is the first species to colonize the former pool because elevations are lower than the surrounding marsh surface. Over time, elevation increases because areas that are lower in the tidal prism experience more rapid accretion - sediment accretion rates in breached pools can be two to four times that of the surrounding marsh platform (Wilson et al. 2014).

Pools revegetate as long as their bed elevation is above the lower limit for marsh growth and/or if sediment deposition is greater than the rate of relative sea level rise (Mariotti 2016). Pool recovery can take between 10 and 100 years depending on the setting (Wilson et al. 2014).

Several lines of evidence demonstrate that pool formation and recovery can be a cyclical process in dynamic equilibrium that does not result in net marsh loss over time. Coring studies show that a given area of marsh has alternated between pool and vegetated marsh throughout the last thousand years (Wilson et al. 2009, 2010). Direct evidence from aerial photos also demonstrates this process over the course of decades (Mariotti 2016; Wilson et al. 2009, 2014). Modelling shows that pools in marshes with relatively high tidal range, high amounts of suspended sediment and surfaces above mean high water become revegetated marsh after breaching (Mariotti 2016). This model was validated in several regions in the eastern United States including Atlantic Coast tidal marshes near Cape May, New Jersey and Plum Island, Massachusetts, where the moderate tidal range and relative sea level rise allow for tidally breached pools to become vegetated marsh over time (Mariotti 2016). Pool formation and expansion typically occurs at elevations above mean high water in marshes with vegetated surfaces that are keeping pace vertically with relative sea level rise (Mariotti 2016). Thus the presence of pools on unaltered marshes is not necessarily a symptom, as some have interpreted it (Cavatorta et al. 2003;Hartig et

Figure 1. Depiction of pool dynamics at Nummy Island, Cape May County, NJ. Pools breached between 1977 and 1987. By 2015, extensive vegetation recovery has occurred. (Source Imagery New Jersey Geographic Information Network.)



al. 2002; Kelley et al. 1995; Smith 2009), of marsh degradation attributed to accelerated sea level rise.

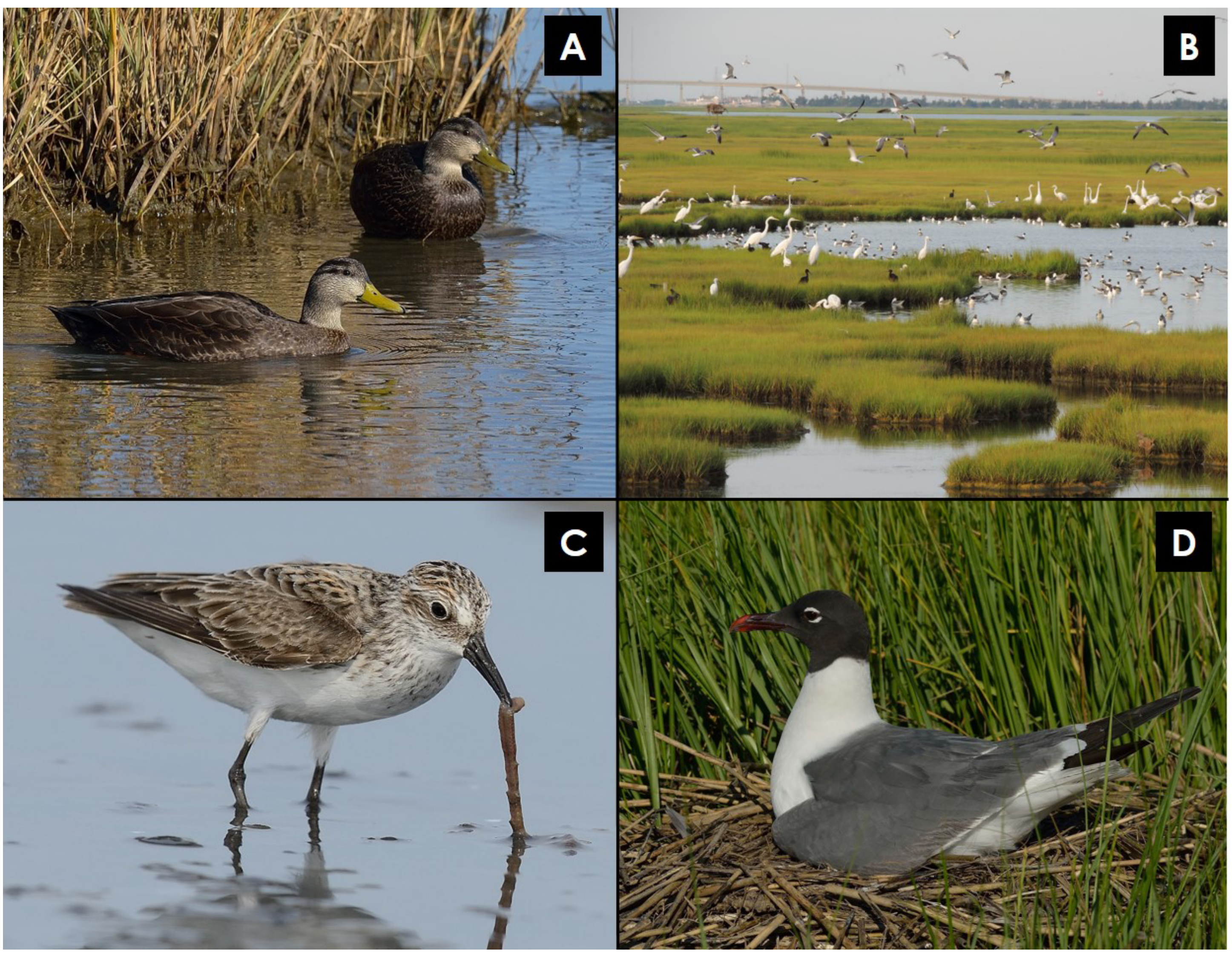
DYNAMICS DRIVE HABITAT DIVERSITY

Marsh pools are important habitat for a wide range of tidal marsh vertebrates. Significantly greater numbers of wading birds, shorebirds and terns use marshes with pools than marshes without them (Clarke et al. 1984). Spectacular congregations of herons and egrets along with terns and gulls occur in tidal marsh pools where the birds feed on small fish throughout the summer and fall (Master 1992).

Bird species diversity and abundance on marshes is directly related to pool area (Erwin et al. 1991). Pools offer feeding opportunities on submerged aquatic vegetation, fish, worms, mollusks and insect larvae (Erwin 1996). Pool habitats are unique in that they exist at a high elevation on the marsh platform and thus provide aquatic habitat at all tide stages.

Waterfowl are attracted to the unique feeding opportunities in pools (Stewart 1962), the most notable being the presence of widgeongrass (*Ruppia maritima*) (Bourn 1950; Miller and Egler 1950). Widgeongrass, a cosmopolitan species used by waterfowl throughout the world, is one of the most common plant foods for overwintering black ducks (Eichholz et al. 2010). This plant is very sensitive to wave action and currents and therefore finds suitable growing conditions in the still waters of small tidal marsh pools. These pools also have high numbers of snails, another important food for wintering black duck (Heck et al. 1995). Not surprisingly, black ducks show preferential habitat selection for tidal marsh pools (Morton et al. 1989). Erwin

FIGURE 2. A. Waterfowl feed in both breached and unbreached pools (American black duck); B. marsh pools are used extensively by wading birds (mixed species feeding aggregation of great egret, snowy egret, glossy ibis and laughing gull); C. breached pools provide shorebird feeding habitat (semipalmated sandpiper); D. revegetating pools after breaching provide high-quality nesting habitat for colonial gulls and terns (laughing gull). (Photos A, C and D courtesy of ©M.J. Kilpatrick. Photo B courtesy of ©J. Smith.)



(2006) suggests that the prospect of fewer pools could be detrimental to wintering black ducks.

Breached pools provide mudflat habitat that is exposed for a longer period of time compared with adjacent tidal creeks and mudflats. At least ten species of shorebirds use breached pools as alternate feeding habitats, particularly when tides cover other intertidal areas (Erwin et al. 2006).

Beyond birds, marsh pools are important for fish production and overwintering (MacKenzie and Dionne 2008; Smith and Able 1994). One study suggested that the majority of mummichog (*Fundulus heteroclitus*) in marshes move into tidal marsh pools during winter because marsh pools maintain warmer water temperatures (Smith and Able 1994).

Pool revegetation dynamics also may have an underappreciated role for tidal marsh nesting birds. Laughing gulls and terns select nest sites in taller grass above mean high water (Bongiorno 1970); nests in taller grass have a reduced probability of flooding (Montevecchi 1978). Nest sites that are less exposed to wind and tidal action are less likely to wash away (Montevecchi 1978). Gulls (Montevecchi 1978) and terns (Burger and Lesser 1978) build nests upon wrack that collects among tall grass in the higher parts of the marsh. These nest habitat descriptions suggest the conditions created by a revegetating pool, where tall *Spartina alterniflora* grows adjacent to higher elevations in the marsh interior. The only other tall *Spartina alterniflora* in these marshes exists along creek channels which is more limited in extent and is exposed to greater wave and tidal action.

FIGURE 3. Combination of ditching and open marsh water management, West Creek, Ocean County NJ. Tidal range, 0.61 m. (Source Imagery © Google Earth.)

FIGURE 4. Marsh ponding between ditches, Great River, Suffolk County, NY. Hydrological restoration is planned at this site. Tidal range, 0.34 m. (Source Imagery © Google Earth.)

Considering the importance of pools as wildlife habitat and the geomorphic process that perpetuates cyclical pool dynamics, we conclude that this process is a key driver of habitat diversity in tidal marshes. The dynamic successional process of pool formation, breaching and recovery maintains a diversity of habitats used by different species at different times. In summary, these include:

1. Intact pools are important feeding habitat for ducks (particularly for dabbling species that seek out *Ruppia*), wading birds, terns and gulls and serve as roosting habitat for shorebirds.
2. Breached pools are also foraging habitat for the above species and most importantly provide mudflat habitat for feeding shorebirds that is the only available habitat at higher tide stages when mudflats in creeks and sounds are inundated.
3. Revegetating pools are used by colonial nesting gulls and terns that preferentially choose nest sites in these tall grass areas.

MARSH POOLS IN HYDROLOGICALLY ALTERED MARSHES – A SIGN OF DEGRADATION?

The research evidence presented above makes it clear that pools are not necessarily a sign of degradation in tidal marshes that have never been the subject of direct human alteration. However, it is important to make the distinction between pools in marshes that have never been directly altered and those that have been hydrologically altered by ditching and open marsh water management.

Pools on altered marshes take two forms: those created intentionally during open marsh water management activities (Figure 3) and those that have formed and expanded over time between ditches (Figure 4). The impact of hydrological alterations on marsh function and resilience to sea level rise is poorly understood (Elsey-Quirk and Adamowicz 2016). Preliminary evidence suggests that the rates of vertical accretion in these marshes may be lower than surrounding unaltered marsh (LeMay 2007) and that natural pond dynamics cease when these hydrological alterations are made (Wilson et al. 2014). In marshes subject to microtidal regimes, interior ponding between ditches is not displaying the same cyclical dynamics of pools in unaltered marshes. The combination of low accretion rates associated with low tidal amplitude (Kirwan and Guntenspergen 2010), altered hydrological function and sediment availability may be contributing to continuous expansion of pools in these areas while limiting the potential for tidal breaching that could lead to revegetation.

Ditching drains natural marsh pools, changes soil pore water levels, modifies accretion, and alters plant communities. One study that compared ditched marshes to those with natural hydrology found that natural marshes had consistently higher elevation compared with ditched marsh (LeMay 2007). Increasing ditch density was correlated with decreasing elevation. These elevation differences corresponded with dramatic differences in hydrology between ditched and natural marsh. In ditched areas, interior marsh flooded first and stayed flooded longer while in marshes with natural hydrology, the marsh interior only flooded after water topped creek banks. Despite longer periods of inundation, ditched sites did not receive more sediment deposition than sites with natural hydrology. Overall the lowered elevations may be due to reduced organic matter accumulation, plus increased sediment trapping in ditches and/or increased sediment export from the marsh surface.

Ditches are sinks for sediment accumulation that might otherwise be deposited on the marsh surface (Corman et al. 2012). Ditched areas also have longer pore-water retention in the rooting zone, lower soil bulk density and lower mineral content (Vincent et al. 2013*a*). Compared with marsh areas adjacent to natural creeks, ditched marshes have significantly less plant cover and significantly more plant species associated with poor drainage conditions (Vincent et al. 2013*b*). Siltation and narrowing of ditches that prevents proper drainage can further drive marsh interior degradation (Vincent et al. 2013*a*). This pattern has been observed in Rhode Island marshes where interior marsh ponding was associated with blocked ditches (Watson et al. 2016).

All of these patterns may be exacerbated or attenuated with varying tidal range. It is well-established that microtidal regions have the greatest lags in vertical accretion with respect to sea level rise (Kirwan and Guntenspergen 2010). Any impact that ditching has on a marsh's resilience to sea level rise may therefore be more exaggerated in microtidal areas.

With the hypothesis that ditching is the ultimate cause of runaway pool expansion in ditched marshes, restoring natural hydrology to marshes affected by ditching (in conjunction with sediment application where necessary) may allow for the return of natural pool dynamics, increase habitat diversity, and ultimately improve resilience to sea level rise. On the other hand, restoration projects that counter runaway pool expansion by filling these pools with dredged sediment without restoring hydrology may be treating a symptom rather than the cause of degradation.

A FRAMEWORK FOR INTERPRETING MARSH POOLS.

Some observers have interpreted pool formation, expansion and pool breaching as signs of sea level rise-induced marsh degradation and permanent marsh loss (Cavatorta et al. 2003; Hartig et al. 2002; Kelley et al. 1995; Smith 2009). But, as reviewed here, more recent research cautions against broadly applying this interpretation to all marsh pools. Mariotti (2016) and Wilson et al. (2014) provide new insights to better understand the relationship between pools and the condition of the marshes they occupy. Determining whether pools represent permanent marsh loss depends on past human impacts, marsh elevation, suspended sediment concentration and tidal range.

Using the framework proposed by Mariotti (2016), pools occur in unditched marshes under three general regimes: marsh drowning, pond collapse, and pond recovery. Each regime is determined by varying levels of relative sea level rise (RSLR), tidal range and sediment supply. Marsh drowning, when the vegetated marsh platform does not keep pace with relative sea level rise (Morris et al. 2002), has occurred in only a few regions (Mariotti 2016) and is associated with either altered tidal ranges (Swanson and Wilson 2008), unusually high rates of subsidence (DeLaune et al. 1994) and/or settings with very narrow tidal amplitude (Kirwan et al. 2016).

Pond collapse, when the vegetated marsh platform keeps pace with relative sea level rise, but pool platforms do not, occurs in settings with narrow tidal range and low suspended sediment supply. In these situations pools continue to expand after breaching and do not experience vegetation recovery. An example of this regime are the marshes surrounding the Blackwater River, Maryland (Schepers et al. 2016)

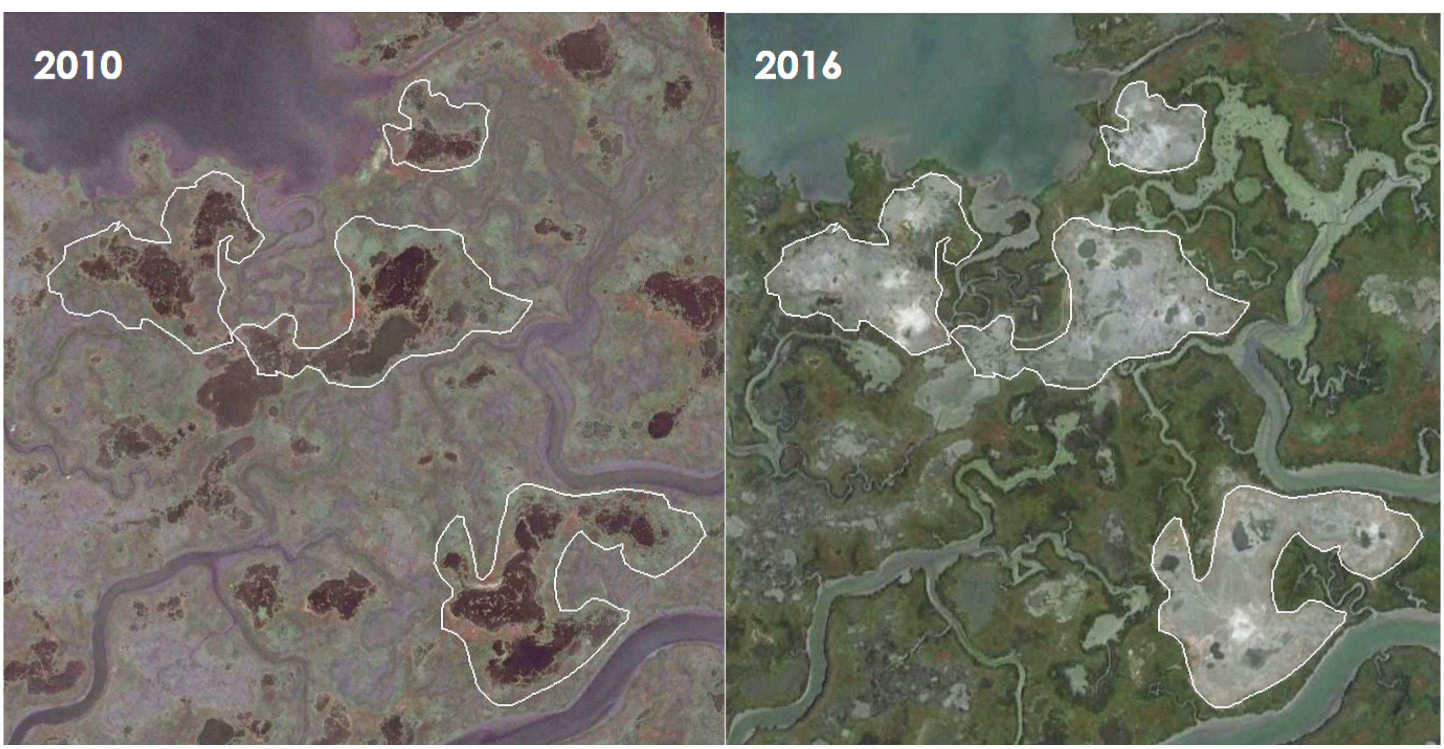
Finally, pond recovery, when the vegetated marsh platform keeps pace with RSLR and the pool platform accretes faster than RSLR, occurs in marshes with high tidal range and moderate RSLR. These marshes experience cyclical pool dynamics where vegetation recovery proceeds after pool breaching. Examples of this regime are Atlantic Coast marshes near Cape May, New Jersey and Plum Island, Massachusetts (Mariotti 2016). This framework can be used to guide conservation practitioners in evaluating whether pools represent permanent marsh loss and the results of this evaluation then can inform conservation and management decisions.

Without an evaluation of this kind, conservation practitioners risk taking action where it may not be warranted. One recent project near Cape May, New Jersey interpreted marsh pools as permanent marsh loss (U.S. Army Corps of Engineers 2014; Greenvest LLC 2015) where pools form, breach, and experience eventual vegetation recovery (Mariotti 2016).

The New Jersey Department of Environmental Protection-led project, in collaboration with several partner agencies, consulting groups and NGOs, used sediment from Army Corps intra-coastal waterway maintenance dredging to fill a series of pools along with adjacent areas of vegetated marsh with dredged sediment at a site in southern New Jersey comprising approximately 50 acres (Figure 5). The project is considered a demonstration project in anticipation of more widespread implementation of the technique throughout New Jersey if deemed successful.

Given what we know about pool dynamics and its role in providing diverse wildlife habitat, there is no clear ecological justification for placing dredged material on marshes and marsh pools experiencing a pond recovery regime, particularly those with a marsh platform that is predominately above mean high water. On the other hand, if a marsh is in a drowning or pond collapse regime, the use of dredged sediment to reverse permanent marsh loss may be warranted. Given their rarity, marshes that have not been directly altered by humans are crucial resources that need guarded against direct human alteration, at least until there is well-documented evidence for sea level rise-driven degradation. These marshes need to be conserved both for their high wildlife habitat value as well as for their scientific importance. Unaltered marshes are essential to our understanding of fundamental tidal marsh processes and for learning how such processes are affected by sea level rise and global climate change. The natural cyclical dynamics of pools has only become widely recognized in the last decade (e.g., Mariotti 2016; Wilson et al. 2014). These recent insights into the role of pools in tidal marsh geomorphology would not have been possible if it were not for the existence of naturally functioning tidal marshes with unaltered hydrology. For restoration, knowledge of unaltered marsh character and function is essential for guid-

FIGURE 5. Cape May Coastal Wetlands Wildlife Management Area near Avalon, New Jersey before and after sediment deposition on marshes and in pools. Tidal range 1.23 m. (Source Imagery © Google Earth.)



ing restoration designs and as a reference for evaluating restoration outcomes.

With the critical conservation importance of unaltered marshes in mind, dredged material application on previously unaltered marsh raises concern. Waterways and marinas that require frequent maintenance dredging are often directly adjacent to many of these unaltered marshes, as in the example of pool-filling in southern New Jersey. In this region of New Jersey, there are thousands of acres of relatively unaltered marshes within the wetland complexes stretching from Cape May to Great Bay. The unaltered component is comprised primarily of lagoonal marshes between mainland and back barrier marshes that are ditched (Figure 6). They are likely among the largest tracts of unaltered tidal wetlands in the northeastern United States. To the north, Little Egg Harbor, Barnegat Bay and other northern New Jersey marshes are profoundly and perhaps irreversibly altered by ditching and open marsh water management.

SETTING RESTORATION PRIORITIES

Worldwide, there are vast areas of tidal marshes that have suffered direct human impacts from impoundment, tidal restriction, dredging, ditching and mosquito control alterations. Such marshes would benefit greatly from management, including the use of dredged material, to restore function, habitat quality and increase sea level rise resilience.

Restoration is a response to ecological degradation that is the result of human impacts. In the case of tidal marshes these impacts are direct alterations as well as impacts from climate change. Restoration cannot typically respond to degradation that has not yet occurred (e.g. future sea level rise). Existing degradation as a result of sea level rise can be addressed with restoration, but such actions at the site level can only treat the symptoms of degradation (not its cause). With this in mind, reversing past direct alterations that have caused marsh degradation is a particularly fruitful restoration approach because management can potentially treat the root cause of degradation and ultimately improve resilience to current and future sea level rise. For example, in Delaware Bay where the loss of elevation from marsh impoundment and farming has greatly reduced the long-term resilience of marshes to sea level rise, the addition of dredged sediment (to raise marsh elevations) could increase the capacity of these marshes to persist in the future. Likewise, restoring natural hydrology to marshes affected by ditching (Figure 6) in conjunction with sediment addition would, by correcting hydrological impairments and reducing elevation deficits, restore natural dynamic processes and improve wildlife habitat value.

Even among unaltered marshes, there may be ways to productively use dredged material for marsh conservation. Although the greater vegetated portion of these unaltered marshes may be keeping vertical pace with sea level, marsh loss is occurring in some locations due to horizontal erosion. For example, erosion of the marsh edge, caused by wind-driven waves along the shores of broad bodies of

FIGURE 6. Sloughs Gut Project (Delaware) restored natural tidal marsh hydrology without sediment addition including breached and unbreached pools to a grid-ditched marsh. Tidal range 0.75m. (Source Imagery © Google Earth.)

water and exacerbated by boat wakes, is driving horizontal loss of marshes (Mariotti and Fagherazzi 2013). Since mudflats adjacent to marsh edges play an important role in dampening wave action, the use of dredged material to augment intertidal flats is one potential way to help stem marsh edge erosion (Foster et al. 2013).

CONCLUSION

The signs and causes of marsh degradation must be correctly identified in order to plan restoration actions that (1) do no harm to functioning ecosystems, (2) produce lasting results, and (3) use scarce restoration dollars effectively. There are many ways to productively use dredged material to conserve, manage and restore tidal wetlands. The broad acceptance of dredged sediment use for tidal marsh conservation is an important step forward in the management of marshes. However, sediment must be used in a way that does not adversely impact systems that are currently functioning well, such as unaltered marshes with dynamic pool systems. ■

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FIGURE 7. Marshes between barrier islands and the mainland in southern New Jersey. Notice the ditched sections along the mainland and the barrier island, while large sections of relatively unaltered marshes are surrounded by open water. (Source Imagery © Google Earth.)

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