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IMPACTS FROM DITCHING SALT MARSHES IN THE MID-ATLANTIC AND NORTHEASTERN UNITED STATES

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ABSTRACT

Tidal inundation extent and duration, and water drainage and retention by marsh peat – marsh hydrology – determine most physical and ecological characteristics of salt marsh systems. Ditching, installed across nearly all marshes on the US East Coast by 1940 to control mosquitoes, alters marsh hydrology. Two linchpin papers are used here as springboards to review the literature that describes the resulting effects, which clearly include reduced water table height for most marshes and changes in avian populations. Effects on invertebrate populations, including mosquitoes, are generally less, although to a smaller degree than is sometimes reported. Impacts on nekton are not clear, although probably negative. Tidal range and the degree of tide asymmetry appear to have greater effects on inter-marsh variations in effects from ditching than has generally been appreciated or studied. Overall, although changed patterns of nutrient releases and promotion of *Phragmites australis* invasions are important ecological effects extending beyond individual sites, and salt marsh aesthetics are marred, ditching impacts are less than certain other anthropogenic alterations of coastal processes that affect salt marshes and estuarine ecology to a much greater extent.

KEYWORDS

Ditching, salt marsh, impact, marsh functions, mosquito control, hydrology

INTRODUCTION

Salt marshes have great ecological importance (beginning with Teal 1962), with ecosystem services estimated at ~$10,000 U.S./ha (Costanza et al. 1997); thus, their proper functioning is important to overall coastal environmental conditions. Projects that undo tidal restrictions and mitigate mosquito control ditching are increasing (Crain et al. 2009); but, especially in the case of ditching, since 90% of salt marshes from Virginia to Maine were ditched before World War II (Bourn and Cottam 1950), reference sites are few (per Hanson & Shriver 2006), and it is unclear what baseline conditions should be used to determine restoration effectiveness.

Purpose of Ditching

Along the Atlantic coast of the United States, especially in the mid-Atlantic and northeastern regions, salt marshes had been altered through fire management by aboriginal peoples, and mown for cattle fodder in 1600s (Miller and Egler 1950); ditching began in the 1700s (Shisler 1990) to increase *Spartina patens* and other high marsh grass species acreages for salt haying (Daiber 1986, Sebold 1992), as had been customary in areas of Europe (Mitsch et al. 1994). This practice continued into the 20th Century (Philipp 2005), although the acreage so affected was limited (Bourn and Cottam 1950). Beginning in 1900, mosquito control ditching was begun, starting along the north shore of Long Island (New York), but rapidly spreading into New York City (Richards 1938) and coastal New Jersey (Smith 1904). The target was the predominant salt marsh mosquito, *Ochlerotatus* (also *Aedes*) *sollicitans*, which was so fierce a biting mosquito that it is said it retarded development along the Atlantic coast of the United States (Smith 1904). Most of the vast extent of mosquito control ditching occurred during the Great Depression, to combat high unemployment as much as to control mosquitoes (Glasgow

1938), but it has also continued where mosquito control programs reduced pesticide use in the late 20th Century, such as in Suffolk County (New York).

Salt marsh mosquitoes had and have little potential to spread disease. *Oc. sollicitans* is the coastal vector for the very dangerous disease Eastern equine encephalitis, which fortunately has low coastal incidence except under certain conditions that can occur in New Jersey (Crans 1977). Salt marsh mosquitoes do not transmit malaria or yellow fever. A less common salt marsh mosquito (*Culex salinarius*) was identified as the most important vector for human cases of West Nile disease in Connecticut (Andreadis et al. 2004), but areas such as Long Island that are infested by salt marsh mosquitoes have low infection rates, lower than expected given the geographic prevalence of infected birds and positive mosquito pools (Tonjes 2008). Salt marsh mosquito control was originally characterized as abatement of "nuisance" (Smith 1904), and modern mosquito control that focuses on *Oc. sollicitans* likely prevents few human illnesses (Turrell et al. 2005) but alleviates much human misery across most of the mid-Atlantic and New England coastlines.

Ditching Technologies

Mosquito control ditches had several construction idioms. Parallel ditches run in one direction, usually from the upland to open water, with relatively constant distances between each ditch, creating panels of vegetation. Grid ditching crosscuts the ditches, creating vegetation islands (sometimes called "checkerboarding"). Checkerboarding was used in larger marshes, but parallel ditching was found to be as effective and needed less maintenance (Richards 1938), and so predominated. Other general patterns, such as "herringbone" (acute angles to a main channel) (Lesser et al. 1976), were employed, but the generic term for the technology is often "grid ditching."

Typically, ditches were dug by hand into the marsh peat, with steep to vertical sides up to a meter deep and 50 to 250 cm wide. Distances between ditches ranged from 30 to 100 meters. Spacing decisions theoretically were guided by soil permeability; soils with greater hydraulic conductivity might have greater distances between ditches (Dale and Hulsman 1990). Mechanized ditching for mosquito control was introduced post-World War II, although salt marsh hayers in New Jersey used ditching machinery well before then (Sebold 1992). Marsh alterations and ditch maintenance are now almost always conducted with specialized low ground pressure treaded vehicles.

Scope and Approach of this Review

The massive reshaping of salt marsh environments should have tremendous impacts, and such is the general sentiment (see Daiber 1986). But there is not a robust literature documenting effects. Few studies were made when ditches were dug, and there are few appropriate, unditched reference sites to support contemporary work. General reference works either do not discuss ditches at all (e.g., Teal 1986, Mitsch and Gosselink 2000) or only briefly mention potential effects (Nixon 1982). Dale and Hulsman (1990) assessed some effects from ditching, but focused on more modern marsh management techniques. Bromberg Gedan et al. (2009) briefly discussed impacts of ditching, but found other alterations to be more important, especially in a global context. Crain et al. (2009) discussed some ditching impacts, but primarily were concerned with tide restrictions, which have a more robust contemporary literature.

The aim here is to define the effects of ditches on “background” marsh conditions. Most studies which find effects relate them either to changes in marsh hydrology or report impacts to biota. Most of these studies are restricted in time (generally one year) and extent (typically, one marsh) and thus have restricted value. Two studies, each of which examine one of the key impacts, defy this general trend. One is Adamowicz and Roman (2005), which is a statistical analysis of hydrological features in paired ditched and unditched marshes across New England. Most salt marsh research has found marsh hydrology is a dominant factor in the overall ecology of a marsh. The second is an early report by Bourn and Cottam (1950), a multi-year study of initial ecological impacts from ditching, cited in some of the key general literature as source for the finding that ditches harm salt marsh ecosystems (one example is Daiber 1986, which was in turn cited more than 30 times according to the Web of Science). This review is founded on a close reading of both of these papers, and they are used a means for placing other, more limited studies into context.

PHYSICAL EFFECTS FROM DITCHING

Adamowicz and Roman (2005)

Crain et al. (2009) emphasize that hydrology is the primary factor in intertidal marsh processes, and note the manifold means that humans have altered it. Adamowicz and Roman (2005) primarily characterize the distribution and nature of ponds in paired ditched and unditched salt marshes in New England from Connecticut to southern Maine. Physical transects and "digital transects" on aerial photography were used to generate: 1) the percent of each transect composed of ponds; 2) the area of each pond touched by a transect; and 3) the distance to the nearest neighbor pond and waterway (ditch or natural creek). Field sampling included water depth and distance to each pond bottom, and generalized vegetation characterizations.

Adamowicz and Roman (2005) found significantly fewer ponds that covered a smaller total area in ditched marshes (Table 1), and a significant linear correlation between the intensity of ditching and loss of ponds. The correlation for loss of total pond surface area was stronger than the loss of pond density. Paired ditched and unditched data also showed that ditched areas had significantly fewer ponds covering a significantly smaller area. The amount of natural creeks correlated significantly and positively with pond surface area and pond density. Total pool area was significantly correlated with tidal range. Because tidal ranges in New England tend to increase with latitude, similar relationships held for geographical variation and pond density and area. Mean depth (about 30 cm) and average size (about 200 m^2) of ponds did not vary significantly between the two marsh types. Thus, ponds decrease in ditched marshes, and ditches cause ponds to drain while natural creeks do not. Ponds, which tend to be larger and more often found in high marsh than low marsh, are not morphologically different in ditched marshes – just fewer in number.

Other Studies of Marsh Hydrology in the Context of Adamowicz and Roman (2005)

Some less comprehensive studies comparing ditched and unditched marshes also found fewer ponds and less open water (Reinert et al. 1981, Merriam 1983, Lathrop et al. 2000). Reports generated immediately following ditching were mixed, however, as to whether marshes were drained following ditching (Bradbury 1938, Corkran 1938, Daigh et al. 1938, Taylor 1938). Redfield (1972) said ditches drain the water table, but found no difference in the number of ponds in ditched and unditched areas. Others limit water table impacts to sediments close to ditches and/or streams (Provost 1977, Hemond and Fifield 1982, Agosta 1985, Nuttle 1988, Montalto et al. 2006), although effects up to 15 m away from stream banks have been measured (Nuttle and Hemond 1988). Chapman (1974) pronounced it "optimistic" that ditches spaced 30 m ("100 ft") apart would drain a marsh. However, drainage of marshes by ditches is strongly endorsed by comprehensive mosquito management reviews (Daiber 1986, Dale and Hulsman 1990, Wolfe 1996).

Conceptually, the ability of a ditch to remove surface water or lower the water table depends on sediment type, and head pressure driving water through the sediments. The greater the hydraulic conductivity of the marsh sediments, and the greater the head difference between the water table and the mean water level in the ditch, the greater the flow from the water table. Where tidal ranges exceed 1 m (the typical ditch depth), ditches are likely to be dry at times. Where the tidal range is less than a meter, then the ditch is likely to hold water at all times, depending on the slope of the system. Where the ditches do not dry, the head pressure driving drainage will be smaller than where the ditches dry, but still should lead to lower marsh water tables. Thus, ditches should drain water from the water table under all conditions; the degree of impact will diminish with distance from the ditch, creating an “effective drainage” distance across a panel caused by overall peat hydraulic conductivity and the range of the tidal cycle. It is likely that when ditches dry completely the effective drainage distance affects all of a typical panel width, for typical marsh peat. Note that in some instances higher hydraulic conductivities have been found for creek bank sediments, limiting drainage elsewhere (Montalto et al. 2006).

Adamowicz and Roman (2005) worked in marshes where tide ranges all exceeded 1 m (S. Adamowicz personal communication 2009). In areas such as the south shore lagoonal system on Long Island, with lower tidal ranges (often less than 50 cm and sometimes less than 30 cm), ditches did not “drain” marshes, but rather “relocate[d] water from the marsh surface to the ditches” (Taylor 1938). With low tidal ranges, water persists in ditches throughout the tidal cycle, because the bottom of the ditches is lower than low tide levels. In these environments, the effect of ditches is primarily to enhance transport of standing waters from spring tides off the marsh surface rather than large effects of marsh water table heights, due to reduced head differences between the water table and the ditches compared to cases when the ditches dry each tidal cycle. More rapid drainage of lunar tides from the marsh surface is a subtle change in marsh hydrology, not discernable from aerial photography, maps of marsh waterways, or measurements of "average" marsh water tables.

Ditches Propagate Tides into Marshes

In any tidal basin, there will be an asymmetry between the time periods that the tide floods and the tide ebbs, meaning either the ebb or flood tide will have more residence time in a marsh (Boon 1975). Modeling by Zheng et al. (2003) found that changes in tidal channel morphologies affect water movement in channel networks, and can change the tidal asymmetry. Thus, potentially, ditching can affect the residence time of tides in the marsh. The potential for effects depends on specific site morphologies. Thus, while it is impossible to specify that ditching increases or decreases tidal residence within marshes generally, it is possible that a change can occur in either direction in any particular setting.

Collins et al. (1986) speculated that the removal of some volume of marsh peat could reduce the amount of water available to flood over the top, assuming that each basin has only a set volume of tidal input. However, coastal models (such as Zheng et al. 2003) depict tides at the coastline as a constant height of water rather than a fixed volume, suggesting that the presence of ditches will not appreciably change the amount of water delivered over a marsh. Fixed volumes of tidal inputs are considered when the flows are restricted to channels (e.g., Roman et al. 1995).

Ditch networks extend up into the high marsh. This means they transmit water at high tides (other than astronomical maximums) to high marsh areas that otherwise would not be affected by tidal flows except at astronomical high tides; in low tidal ranges, these ditches may retain water at all times in such higher marsh elevations.

Ditches can also connect to upland drainage networks, such as fresh marshes or stormwater systems. This means they may serve as conveyances of upland water into the marsh. In some such systems, total channel lengths in marshes correlate closer to watershed area than to the size of the tidal prism. This implies that the size and morphology of marsh waterways are more the result of drainage running through them to the estuary (Marani et al. 2003) than tidal forcing, suggesting upland drainage can be very important for the hydrology of such marshes.

Impact of Ditches on Marsh Hydrology

The general finding of Adamowicz and Roman (2005) that ditching reduces ponds, and that thus ditching decreases the marsh water table, holds under most conditions. Drainage may not be very effective where tidal ranges are extremely low. Ditches allow tides to penetrate higher into a marsh than might otherwise occur, and may facilitate transport of fresh water from uplands in some systems.

BIOLOGICAL IMPACTS FROM DITCHING

Bourn and Cottam (1950)

This study was not a peer reviewed journal article, but it has the imprimatur of the US Fish and Wildlife Service. The research was conducted in Bombay Hook National Wildlife Refuge, Delaware, from 1935 to 1946. One site (240 ha) was on the Mispillion River, and the other straddled Herring Creek, with one ditched and one unditched tract. Vegetation was surveyed, in 1936, 1938, 1939, 1941, and 1946 at Mispillion River, with elevations taken in 1936 and 1941. The Herring Creek areas were mapped in 1936. At Herring Creek quadrats ~ 1.75 m per side were used to sample invertebrates to a depth of 2.5 cm from 1936 to 1938 in each of four major plant zones (*Spartina alterniflora*, *Distichlis spicata*, *Spartina patens*, and *Scirpus robustus* [*Scirpus*]). Analyses were also made of stomach contents of 14 species of birds (identified as "common to the tidewater marshes, including rails, sandpipers, yellowlegs, and willets").

Bourn and Cottam (1950) mapped but did not quantify vegetation changes (Lesser et al. 1976 measured the area changes from the maps, see Table 2). Installation of ditches at 50 m intervals in 1936 at Mispillion Creek resulted in much of the lower elevation substrate becoming soft mud, leading to considerable loss of *S. alterniflora*. *Pluchea camphorata* (*Pluchea*, saltmarsh fleabane) invaded much of the die-off areas. *Iva spp.* and *Baccharis spp.* established themselves along spoil banks alongside ditches. *Baccharis spp.* growth continued in 1938. The ditches clogged, resulting in loss of *Pluchea* and re-establishment of *S. alterniflora*, a pattern that continued through 1941. By 1946, *Baccharis spp.* had become the dominant marsh plant. *S. alterniflora* was restricted to the center areas of the marsh, in the centers of panels (*Iva spp.* and *Baccharis spp.* grew at ditch banks). The ditches had widened at their mouths, accelerating the spread of *Baccharis spp.*, and clogged at their upper ends, where standing water supported *S. alterniflora*. An interpretative table of vegetation types and associated elevations for 1936 and 1941 showed many species in 1941 were found at lower elevations than in 1936, and some did not grow at the higher elevations where they had grown immediately after ditching.

The map of vegetation at Herring Creek was said to allow the distribution to be "grasped readily by the reader;" in any case, it showed *S. alterniflora* covered approximately 50 percent of the ditched marsh, and 75 percent of the unditched marsh. *S. patens* was a relatively minor part of the unditched marsh, but a major constituent in the ditched areas. *Scirpus* was prominent in the unditched marsh, but entirely absent in the ditched area. Some scattered *Spartina cynosuroides* was mapped in the unditched marsh (in *S. alterniflora* areas), but was the dominant plant in one large tract in the ditched area. High marsh plants occurred at lower elevations in the ditched area.

Invertebrate sampling found extensive differences between ditched and unditched areas, although no statistical analyses were made. Reductions were greatest for the *Scirpus* zones. The relatively open substrate for *Scirpus* was noted as prime avian foraging habitat, so the loss of invertebrates represented a potential effect on birds.

Stomach contents showed that marsh birds consumed 80 percent invertebrates (by volume). Mollusks and crustaceans were said to be the most important prey, but data showed beetles (with weevils) were most common (crustaceans were second).

Bourn and Cottam (1950) concluded that with ditching:

- there was a change in major marsh plant species, with *S. alterniflora* habitat changed to bare mud or plant species usually found in drier marsh areas
- woody plants became dominant
- invertebrate populations became depauperate; this effect was attributed to a drier substrate
- ponds in the marsh became subject to tidal cycles, and lost resident *Ruppia maritima* (widgeon grass) through air exposure at low tides
- muskrat (*Ondatra zibethicus*) populations fell, which eliminated muskrat trapping and caused economic loss.

Because the ditches were not maintained in this marsh, *S. alterniflora* recovered somewhat over the study period. The most serious impact was deemed to be the loss of invertebrates, and, given the scope of East Coast ditching, this was projected as a major ecological effect, especially to birds.

Other Findings of Biological Impacts in Light of Bourn and Cottam (1950)

Vegetation

Many studies find shifts in vegetation associated with ditching, but not the general destruction of low marsh. Woody, upland-type vegetation has been found out on the open marsh after ditching (Daigh et al. 1938, Daigh and Stearns 1939, Miller and Egler 1950, Kuenzler and Marshall 1973, Shisler 1973, Chapman 1974, Cooper 1974, Burger and Shisler 1978, Clarke et al., 1984), often because hand-digging resulting in spoil piles alongside the ditches, effectively raising marsh elevation. The effect was apparently acute in New Jersey (see Shisler 1973), and where the aesthetic effects from blocking open marsh vistas are often mentioned in conversations with marsh managers. Shisler (1973) and Kuenzler and Marshall (1973) also note that remnant ditch spoils can lead to ponding, either from decreased percolation from marsh compression or trapped water – although this would impede woody plant establishment.

For hundreds of years, ditches have been dug to support salt haying (Daiber 1986, Mitsch et al. 1994, Dreyer and Niering 1995, Bart 1997, Phillipp, 2005), but there are few explicit literature references to salt hay (*S. patens*) areal expansion across marshes following mosquito ditching (except Taylor 1938), or findings of *S. patens* being greater in ditched areas compared to unditched areas (except Merriam 1974). The cause of zonation between low marsh (an *S. alterniflora* monoculture) and high marsh (usually dominated by *S. patens*) is usually identified as the frequency of tidal inundations (see Mitsch and Gosselink 2000), as the ability of *S. alterniflora* to cope with root zone anoxia from constant flooding allows it to grow where *S. patens* cannot (per Pennings and Bertness 1999). So, in a broad conceptual sense, unless ditching changes the areas of the marsh overwashed by daily tides, it should not cause *S. patens* to replace *S. alterniflora*. Less short-form *S. alterniflora* has been found at some ditched marshes, attributed to pond shores being prime habitat for this *S. alterniflora* variant and ditching reducing ponds (Reinert et al. 1981). Short-form *S. alterniflora* is often classified as a high marsh species (per Adamowicz and Roman 2005); still, persistent flooded sediments in high marsh exist because of water table conditions, not from daily tidal flooding, and so reduced water table heights from ditching, resulting in less root zone anoxia, would allow *S. patens* to replace short-form *S. alterniflora*. At the upper reaches of the *S. alterniflora* zone in the low marsh, reductions in the water table could be great enough to support sufficient drainage of daily tides in some areas to create enough unsaturated sediments to support some *S. patens* growth. This could conceivably result in substantial shifts in plant composition where the marsh slope is very shallow, as in some of the large remnant marshes in New Jersey. Where mashes fringe the shoreline or depth from the shore is not great, large changes in plant zonation are not likely.

Montalto et al. (2006) found consistently "high" water tables (~10 cm from ground surface to water) across the high marsh where *S. patens* was found. Nonetheless, the sediments were only completely saturated during spring tides, whereas sediments experiencing daily tidal flooding are saturated twice a day. It is possible that additional drainage in the vicinity of ditches might expand the areas where sediments are less frequently saturated, and so allow for *S. patens* areal expansion.

Phragmites australis (*Phragmites*) is a native fresh or brackish water plant (Orson 1999), but an invasive European variant (Salstonstall 2002) now grows in vast monotypic stands across fresh and salt marshes in the northeast US. *Phragmites* thrives under drier conditions in a marsh (Minchinton et al. 2006), and one pattern of its spread is along ditches, and then into panels (Bart et al. 2006). Ditches are thought to have drier banks due to drainage of the water table, and salinities are often lower. The sediments are more aerated, and sulfide concentrations, as a result, are lower (Chambers et al. 2003). In *Phragmites* stands, soil salinities and the water table are lower, the micro-topography is smoother, and soils are more oxygenated (Windham and Lathrop 1999), characteristics sometimes also found at ditch edges. *Phragmites* was planted across the Meadowlands in New Jersey with the express purpose of stabilizing ditch banks (Headlee 1945), and this practice may have occurred elsewhere. Bart et al. (2006), while noting not all *Phragmites* results from human intervention, found ditching and ditch maintenance to be important mechanisms for invasions, through the spread and burial of rhizomes by ditching machinery use, as drier, more aerated sediments promote rhizome sprouting.

There is clear evidence of vegetation shifts in ditched marshes from water table declines, loss of ponds, and general marsh drying. However, expansion of *S. alterniflora* along the ditches (reported by Taylor 1938, Miller and Egler 1950, Heuser et al. 1975, Provost 1977, Niering and Warren 1980, Kennish, 2001), usually attributed to higher salinity levels, is likely the result of expansion of waterlogged soils, as *S. alterniflora* dominates marsh vegetation when saturated soils prevent *S. patens* from growing at all (Pennings and Bertness 1999). Waterlogged soils along ditch banks may occur due to ditches propagating tides into the marsh, but a more common understanding is that ditch banks are better drained than interior panel peats (per Bart and Hartman 2002 and Montalto et al. 2006, with reference to tidal channel banks). Bank side sediments respond to changes in tidal levels, both saturating and draining in concord with tide heights (Nuttle 1988). So, if tidal residence time is increased by ditching, bank waterlogging could increase, and *S. alterniflora* could be favored. If tidal residence time is decreased, banks drain more quickly, and this could favor *Phragmites*. Because ditching can change tidal asymmetry, differences in tidal residence time due to ditching could account for reports of expansion of *S. patens* in some marshes post-ditching, and expansion of *S. alterniflora* in other marshes. An alternate explanation is tied to shifts in nutrient conditions. Tidal inflows are the greatest source of nitrogen to the marsh (Valiela and Teal 1979), and enhanced nitrogen concentrations have been measured in ditches (Koch and Gobler 2009); where tides are greater than 1 m, marsh sediments are net exporters of nitrogen (Childers 1994). Nutrient additions can allow *S. alterniflora* to grow in the high marsh, replacing *S. patens* (Bertness et al. 2002). However, nutrient additions also have been found to reduce overall *Spartina spp*. fitness, signaled by decreased subsurface biomass (Turner et al. 2009). Ditches may not be important players in this process: Nuttle and Hemond (1988), based on mass transport considerations, thought it unlikely much nitrogen was transported into bankside sediments, and Bart and Hartman (2002), based on sulfide-ammonia interactions, thought it unlikely that nutrients were key in observed changes in speciation patterns where banksides were well aerated. Chambers et al. (2003) speculated that overall marsh nutrient enrichment may have been important in promoting *Phragmites* expansion, as it has been noted (see Bertness et al. 2002) nutrient additions may favor *Phragmites* over *Spartina spp*. It is possible, then, but not universally agreed to, that penetration of the tide into the marsh could lead to *S. alterniflora* expansion, but increased nutrients are not likely to play a role.

It is important to note that Lesser et al. (1976) resampled the Mispillion River site, and produced maps that simplified Bourn and Cottam's (1950) groupings somewhat (Table 2). These researchers noted the ditches had been "maintained" (redug) in 1966; they asserted that their data that showed resurgence of *S. alterniflora* back to original densities demonstrated that *S. alterniflora* could thrive without extensive shoaling in ditches. Lesser et al. (1976) also noted that the Mispillion River was dredged at its channel mouth in 1933 and 1935, and in the river bed in 1935 and 1938, and thought this might have reduced tide heights. They believed increases in sea level from 1946 to 1974 were sufficient to re-establish *S. alterniflora* and cause woody plants to retreat. This is a plausible explanation of Bourn and Cottam's (1950) data, but one that lessens the 1950 conclusion that ditching was the sole cause of the large impacts measured on vegetation patterns.

Since aspects of vegetation distribution in salt marshes are determined by marsh hydrology, changes in that hydrology can be expected to alter the vegetation. Predicting the form of vegetation change is uncertain, as particularities of ditching and underlying marsh hydrology influence the expression of hydrological changes. Nonetheless, although it is possible that Bourn and Cottam (1950) overstated the effect ditching had on marsh vegetation patterns at their study site, evidence from other sites show it is likely that ditches affect salt marsh vegetation distributions. The changes are not easily predictable, however.

Invertebrates

Although Bourn and Cottam (1950) found great impacts to invertebrate populations, few other studies have tested for similar effects. One reason for this may be controls on marsh invertebrate populations are not well-defined. Plant speciation and variation in plant distributions change invertebrate habitats (Rader 1984, Capehart and Hackney 1989), and fish predation is thought to be an important control (Knieb 1984, Vince et al. 1976), although avian predation has not been found to affect invertebrate populations significantly (Clarke et al. 1984, Ashley et al. 2000, Sherfy and Kirkpatrick 2003). This suggests that if ditching changes vegetation distributions (see above) or fish populations (see below), invertebrate populations should also be affected.

Two restricted studies of ditching impacts on invertebrates are contradictory: Lesser et al. (1976) sampled fiddler crabs (*Uca* spp.) and salt marsh snails (*Melampus bidentatus*) in the same marshes where Bourn and Cottam (1950) worked, and found greater concentrations of snails and crab burrows in the ditched areas. Clarke et al. (1984) found marsh surface invertebrate diversity to be greatest in maintained ditch areas (differences in overall diversity, including below-marsh surface, water column, and benthic communities, were not statistically significant across different habitats). Additionally, Resh (2001) found that shallow ditches (called "runnels" by Dale and Hulsman 1990) affect invertebrate diversity (but not biomass). Crain et al. (2009) assumed that effective mosquito control implied impacts to other marsh invertebrate populations, which is a reasonable inference.

Accounts differ as to whether ditching effectively reduces mosquito populations. Some have found reductions (Smith 1904, Bradbury 1938, Taylor 1938, Daigh et al. 1938, Dreyer and Niering 1995), and theoretical discussions, based on larvae habitat loss and greater opportunities for fish predation, also support ditching effectiveness (Glasgow 1938, Cooper 1974, Provost 1977, Dale and Hulsman 1990 Crain et al. 2009). Fish gut analyses, however, find few to no mosquito larvae as prey (Harrington and Harrington 1961; Smith et al. 2000, Currin et al. 2003, McMahon et al. 2006).

Bourn and Cottam (1950) thought ditches, if not maintained, were ineffective mosquito control. Pools behind ditch spoils support mosquito breeding (Shisler 1973, Kuenzler and Marshall 1973), and tidal restrictions in ditched marshes can lead to mosquitoes (Cowan et al. 1986). Daiber (1986) cited Delaware reports that found mosquito breeding was unaffected by ditching, but also noted other reports found ditching reduced mosquito numbers. Richards (1938) found continued breeding at the upland edge of marshes. Nixon (1982) judged that ditching was of "questionable value" for mosquito control. Recent studies of ditch modifications compared the treatments to control ditched marshes; the ditched marshes produced measurable numbers of mosquitoes (Rochlin et al. 2009, James-Pirri et al. 2009, Leisnham and Sandoval-Mohapatra 2011, Rochlin et al. 2012), which of course suggests the ditches are not that effective at mosquito control.

Operational managers find that when ditches are maintained the overall frequency of mosquito brood production decreases, although some breeding continues. Large broods causing the most nuisance still emerge sometimes. Overlapping larvicide programs and a paucity of appropriate records make it difficult to determine the effectiveness of ditch maintenance, although the great effort expended over many decades implies program managers believe benefits are achieved.

Birds

The greatest worry expressed by Bourn and Cottam (1950) was for large impacts from ditching to bird populations, although somewhat surprisingly they did not make any direct measurements of effects. Conducting good bird sampling in salt marshes is difficult (Conway and Droege 2006) and few studies have compared populations in ditched and unditched marshes (e.g., Hanson and Shriver, 2006). Still, it is commonly asserted that ditched marshes support fewer water fowl (Urner 1935, Bradbury 1938, Cottam 1938, Ferrigno 1970, Ferrigno et al. 1975, Reinert et al. 1981, Nixon 1982, Daiber 1986, Dreyer and Niering 1995, Wolfe 1996), mostly from losses of open water (Reinert et al. 1981, Clarke et al. 1984) or reduced amounts of submerged aquatic vegetation (Bourn and Cottam 1950, Nixon 1982). Despite one study finding a ditched marsh was good seaside sparrow (*Amodramus maritimus*) habitat (Marshall and Reinert 1990), more studies have found the opposite for that species of concern (Post and Greenlaw 1975, Merrimam 1983, Dreyer and Niering 1995). However, one specific study found no differences in overall avian populations (Buckley and Buckley 1982); mixed results, such as less foraging for some species in ditched areas, although others were unaffected (Clarke et al. 1984), or no change in gross numbers but species shifts (Brawley et al. 1998), are also reported.

In general, ditching appears to affect overall bird distributions in marshes, as it reduces open water areas, and open water is generally the most significant factor affecting many marsh bird populations (but note that Bourn and Cottam [1950] thought invertebrate prey was the primary issue). Narrow ditches are not adequate compensation for the loss of pools and ponds.

Muskrats

Bourn and Cottam (1950) cite decreases in muskrats, once a major economic resource, as one of the primary motivations for their study. Others also note, without attribution, losses of muskrats after ditching (Daiber 1986, Wolfe 1996); Corkran (1938) found no change in muskrats, however. Ditch modification project manuals often warn of damage from muskrats (e.g., Hruby and Montgomery 1985), and Nixon (1982) identified muskrats as a notable marsh inhabitants (he used ditched marshes as the archetype for New England). Marshes ditched for salt hay production were noted to have good muskrat populations (Bart 1997). Widespread ditching in the 1930s may have coincided with market changes that made muskrat harvesting no longer viable. Ditching seems not to have removed all muskrats from salt marshes.

Fish/Other Nekton

Bourn and Cottam (1950) only mention salt marsh fish in passing, noting killifish are potential mosquito larvae predators. As is the case, seemingly, with the other important marsh biota, it is difficult to sample creeks and similar waterways well (Knieb 1997; although see James-Pirri et al. 2010); this may be why few studies of ditching impacts on fish have been conducted (Talbot et al. 1986).

One Long Island study found shallow ditches in a micro-tidal marsh (which had poor water quality) did not support as many fishes and species as creeks did (Corman and Roman 2011). When ditches were converted to ponds and more natural appearing channels in another Long Island marsh, there were significant increases in overall nekton populations (Rochlin et al. 2012). Unpublished data from that study link the more numerous fish populations to better water quality. However, other direct research has tended to find that ditches may be good habitat. Adding ditches to a marsh increased overall fish use by a factor of five, mostly by increasing juvenile numbers (Kuenzler and Marshall 1973). Ditches had greater fish abundances compared to pools in an unditched area, possibly due to reduced bird predation (Clarke et al. 1984). Ditches were found to support typical salt marsh resident species, but also juveniles of species that may have been using the marsh as a nursery (James-Pirri et al. 2010).

Adding ditches, because a correlation has been found between channel and edge areas and fish use of marshes (Minello and Rozas 2002), theoretically can increase fish use of the marsh (endorsed by Daiber 1986). Ditching has been demonstrated to double channel edges in a marsh (Lathrop et al. 2000), and crabs were found in increased numbers in ditched areas, possibly due to more burrowing opportunities (Rockel 1969). However, the generation of berms as a result of construction can be an impediment to marsh surface access (Reed et al. 2006), and ditches generally have poorer water quality (Kuenzler and Marshall 1973, Corman and Roman 2011), although this is not generally documented. Still, some resident marsh fish (especially mummichogs, *Fundulus heteroclitus*) are tolerant of very poor water conditions (Knieb 1997), and ditches can give access to otherwise unexploited marsh surface productivity (Whalley and Minello 2002), including mosquito larvae (see above).

Ditching decreases open water generally, especially ponds, and there is some evidence that ponds are more isolated in ditched marshes (Adamowicz and Roman 2005). Ponds are often found to be very important habitat for characteristic marsh fish (Smith and Able 1994, Mackenzie and Dionne 2008). Greater isolation of ponds may mean their fish populations cannot be restocked if the ponds dry out or some other ecological catastrophe strikes.

Knieb (1997) suggested all artificial aquatic habitats in marshes have natural functional analogs, and ditches act like tidal channels; Corman and Roman (2011) disagree, as their data showed distinct water quality differences. A comprehensive report on fish in marshes did not find any special role for ditches as habitat (Rountree and Able 2007). Since ditches result in less overall surface water area by draining ponds, there is a trade-off between a smaller area of ditches with greater edge habitat compared to a larger area of ponds and pools, with greater predation pressure in the ponds and pools. On balance, losses of high quality habitat in ponds are probably not mitigated by extra edge habitat associated with ditching, because water quality in the ditches is generally too poor to serve as adequate replacement habitat for the habitat lost by lowering the water table, although even poor water quality results in ditches being acceptable habitat for mummichogs (Corman and Roman 2011).

Impact of Ditches on Biota

Overall, Bourn and Cottam's (1950) report, which is the basis for many an indictment of ditching for effects on marsh ecology, is not a fair evaluation of impacts to biota from ditching. The section of the report which was most quantitative (but not statistically analyzed), the invertebrate data from Herring Creek, are complicated, and the findings from there have not been duplicated. The effects on vegetation that were mapped may have resulted, at least partially, from causes other than ditching. No data were collected to support a claim that ditches would appreciably and significantly alter marsh bird populations across the East Coast of the U.S.

Still, Bourn and Cottam's (1950) conclusions have been justified by others. Some vegetation shifts occur for most ditching projects, ranging from woody species incursions out onto the marsh, small expansions of *S. patens* (where lower water tables decreased the saturated zone), invasion of *Phragmites* along ditch banks, or expansion of *S. alterniflora* up ditches. Water fowl habitat quality is generally reduced, and marsh fragmentation may harm other birds. Where ponds drain, overall numbers of fish probably decrease. Ditching can provide some mosquito control, but the ditch systems require maintenance, with supplemental larviciding to ensure nuisance elimination.

SOME OTHER IMPACTS IDENTIFIED BY BOURN AND COTTAM (1950)

Ditches Fill and Widen

Like many marsh channel systems (Redfield 1972), some ditch systems can be structurally unchanged even after 75 years (Dale and Hulsman 1990). However, Bourn and Cottam (1950) found Mispillion River ditches filling (plugging) at one end and widening at their mouth. Similar ditch changes are widely noted. Ditch "aggradation" is when they fill from the upland end and became covered by *S. alterniflora* (Miller and Egler, 1950). This may occur because ditches "overdrain" marshes and so collect sediments (Redfield 1972). However, ditches also can become wider, starting at the mouth, losing depth (becoming "bowl-like" in profile), leading to a *S. alterniflora* fringe in high marsh areas (Miller and Egler 1950). Some ditches dug "a spade deep and wide" were 20 m wide after 65 years, and lateral erosion at ditch mouths is common (but not universal) (Dale and Hulsman 1990). Erosion in the interior portion of a ditch can result in bank slumping and blockages (Lathrop et al. 2000), potentially fostered by trapped dead vegetative matter under plants that bridge ditches when they fall (Chapman 1974, Collins et al. 1986).

Inflow-outflow asymmetries may bear on whether ditches infill or not. Where the flood tide period exceeds the ebb tide flow period, the overall velocities of ebb tides must exceed flood tides, and net erosion of loose material is likely to occur. Conversely, in an ebb tide dominated areas, net deposition is likely to occur. However, flow velocities must be large enough for sediment transport to occur. Where velocities are very weak, sediments will clog the ditches. If flow slows near the head of a ditch system, then materials may to settle there, while higher flow velocities at the ditch mouth could widen the ditch mouths. This appears to be the case for Mispillion River (Bourn and Cottam 1950).

Marsh Acidification

Although Bourn and Cottam (1950) did not specifically address the problem in their research, they stated that an impetus for the USFWS to study ditches was observations of gasses from ditches, and generation of hydrogen sulfide at oyster beds (indirectly from ditching effects). Marsh peats sequester large amounts of sulfur (Hussein and Rabenhorst 1999), usually as iron sulfides, especially pyrite (Dharmasri et al. 2004). Exposure of anoxic sediments to aerobic conditions can oxidize and hydrolize pyrites, producing sulfuric acid (Hussein and Rabenhorst, 1999), so that digging ditches has the potential to acidify the surrounding area (Frey and Basan 1985, Daiber 1986, Saffigna and Dale 1999). However, the only documented case of a supposed link between ditches and marsh acidification was in a diked marsh, with the effects limited to the fresh water portion (Soukup and Portnoy 1986). Others find that, due to drainage near bank edges promoting sediment aeration, that edge sediments (including ditches) have little to no sulfide present (Nuttle and Hemond 1988, Bart and Hartman 2002, Chambers et al. 2003)

DITCHING AND SEVERAL LARGER ECOLOGICAL ISSUES

Ditches and the Marsh Export Hypothesis

Marshes have been recognized as important sources of resources to associated estuaries since seminal work was published in the 1960s by Odum (1961) and Teal (1962), although Nixon (1980) found the original exposition to not be without flaws. Isotopic analyses have confirmed that carbon is transmitted from salt marshes to estuaries (Sullivan and Currin 2000), although mechanisms by which this occurs are not confirmed. Food web transfer associated with fish predation seems to be most likely (Deegan et al. 2000, Odum 2000, Smith et al. 2000, Fry et al., 2008). Thus, since ditching appears to reduce the quality of fish habitat within the marsh, and so should decrease this export, it may negatively affect estuarine fisheries.

Ditches and Eutrophication

Because ditches allow for water to circulate faster between the estuary and the marsh, or perhaps because there is a greater surface area of reactive sediments in ditches than would otherwise be present, ditch water may be a source of notable amounts of nitrogen (primarily as ammonium and dissolved organic nitrogen) to the estuary. Where ditches are numerous, they could contribute significantly to overall nitrogen loadings – 20 percent for one embayment (Koch and Gobler 2009). Since marsh ground water is anoxic, reduced species of nitrogen are released. Reduced forms of nitrogen in estuaries appear to promote nuisance algal blooms (Taylor et al. 2006).

The balance of nutrient loading from salt marshes has been studied for decades without a clear determination to date. One view is that salt marshes mitigate overall nutrient loading to estuaries (Valiela and Cole 2002, Tobias et al. 2003) by storing nitrogen in sediments (White and Howes 1994). Gardner (1975) and Childers et al. (2000) found pore water seepage to channels as the most important mechanism for the transport of nutrients from the marsh. However, a model of nitrogen cycling in marshes found that the balance towards nitrogen exports or imports through the creekbank depended on the sources and speciation of the nitrogen inputs (Thomas and Christian 2001). As most denitrification in marshes has been found to occur in the muddy bottoms of creeks (Kaplan et al. 1979), ditching, which increases creek-like bottom sediments, should result in augmented denitrification and so potentially less export of biologically available nitrogen.

On balance, since ditching increases relative drainage compared to unditched marshes, nutrient loadings to open waters should be increased in ditched areas. Other pollutants also tend to be stored for some time in marsh sediments (Teal 1986), and they may be released more quickly from ditched marshes.

Ditches and Phragmites

Ditching appears to foster conditions that support invasions by *Phragmites* (Bart et al. 2006), and, once established, *Phragmites* tends to enhance conditions for its own benefit, excluding native grasses (Minchinton et al. 2006). Monospecific *Phragmites* leads to changes in bird use of the marsh (Benoit and Askins 1999, Fell et al. 2000, Parsons 2003, Trocki and Paton 2006), but not all such changes are judged to be negative (Parsons 2003). Generally, fish, invertebrate, and plankton diversity is less in ditches and creeks within *Phragmites* stands than in other marsh areas (Warren et al. 2001), and decreases in the quality of marsh habitat for fish (Able and Hagan 2000, Able and Hagan 2003, Hagan et al. 2007) are more apparent as *Phragmites* becomes more dominant (Hunter et al. 2006). Weis and Weis (2003) found ecological disadvantages associated with *Phragmites* to be overstated; and *Phragmites* may raise the elevation of marshes (Minchinton et al. 2006), a profound effect in light of accelerating sea level rise. Nonetheless, more find that *Phragmites* causes numerous, generally negative effects on native marsh biota, and it appears ditching has been an important agent in *Phragmites* expansion.

CONCLUSIONS

It has been asserted by general surveys of salt marshes that ditches substantially changed this environment (Daiber 1986, Roman et al. 2000) although other comprehensive appraisals of salt marshes (Teal 1986, Weinstein and Kreeger 2000, Mitsch and Gosselink 2000) do not even recognize that ditching has occurred. One model of marsh habitat values weighted the degree of ditching more heavily than any other of 21 assessment attributes (based on "professional judgment") (McKinney et al. 2009). Yet, another assessment of human impacts to salt marshes on a global scale, although evaluating ditching as damaging, found it to be less so than many other human alterations of marsh environments (Bromberg Gedan et al. 2009).

Quantitative studies clearly demonstrating impacts from ditching are few. It may be that changes that occurred in the 1930s (and earlier) were so obvious that documenting them was not necessary. Now that there are only a few East Coast unditched marshes, differences to salt marshes caused by ditching are not so evident. Bourn and Cottam (1950) is considered to be a conclusive report documenting important ecological changes due to ditching, but a close reading suggests the universality of that report is overstated. Nixon (1980) judged that most studies on the ecological impacts of ditching contain only "casual impressions and anecdotal information … reflect[ing] the biases of 'mosquito controllers' or conservationists." This seems overly harsh; still, many studies extend site-specific data to general cases, and the results may spring from site selection biased by already having observed the effects that the study was intended to validate.

Adamowicz and Roman (2005) clearly showed an underlying, important trait of marshes varied due to ditching. There are fewer ponds in marshes after ditching, almost certainly from lowering the marsh water table. Other impacts flow from this: a shift to more *Spartina patens* and other high marsh plants, and declines in overall habitats for birds and fishes. It may be that, at the lowest tidal ranges, the drainage effect is either extremely muted or not applicable, and this may be a cause for particular studies contradicting more generally reported findings. Tidal asymmetry, where particular systems are either ebb- or flood-tide dominated, and the degree of the asymmetry, may be an under-appreciated, unstudied factor that determines whether *Spartina alterniflora* or *Phragmites australis* spread, the persistence of the ditch systems, and whether these systems export or sequester nutrients. Changes to channel networks can cause changes to tidal flows, so ditching could have had profound impacts on what is an important but unmeasured system element.

The weight of evidence is that ditching negatively affected certain marsh attributes (Table 3). These are only qualitative generalizations, however, so the absolute importance of the effects is difficult to determine. Accelerating the spread of *Phragmites* may be the most consequential impact from the immense expanse of grid-ditching. Nonetheless, cutting miles of ditches into marsh surfaces across the Atlantic coast did not have the broad ecological effects on salt marshes and their associated estuaries that filling marshes or creating tidal restrictions did. For instance, fish habitat in the Mullica River-Great Bay estuary (New Jersey) has been described as "relatively unaltered" (Able 1999), and yet nearly all marshes surrounding that estuary have been ditched.

The aesthetics of ditching are clearly inferior. Salt marshes are generally perceived as being part of the natural, wilder world. The regular geometrical structures that criss-cross eastern

US marshes make it clear that these are not truly wild settings, but rather are managed environments. The common call for “marsh restoration” in many shoreline management programs, although many of the sites do not have identified, particular restoration goals, may be at least partly in reaction to this intrusion of the human into the wilder world of the marsh. Since the cause of the alteration was mosquito control purposes – and the need for salt marsh mosquito control is not clear for many – it only makes the effect on many sensibilities greater.

A focus on this obvious marsh blight may be harmful, if it becomes a distraction from greater problems. Salt marshes are imperiled systems. Eutrophication, changes in herbivory patterns, sudden and not so sudden marsh die-backs, and rapid increases in sea level threaten marshes from within, and other effects such as dredging, increasing development of upland areas, and the general physical, biological, and chemical degradation of estuaries threaten the systems from without. These forces threaten the perseverance of marshes in ways that ditching did not, if a century of history has been correctly interpreted here. Therefore, a focus on impacts associated with ditching may be misdirection from greater problems that our salt marshes face today.

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