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1 **IMPACTS FROM DITCHING SALT MARSHES IN THE MID-ATLANTIC AND**
2 **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.

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KEYWORDS

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

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INTRODUCTION

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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

55 1938), but it has also continued where mosquito control programs reduced pesticide use in the
56 late 20th Century, such as in Suffolk County (New York).

57 Salt marsh mosquitoes had and have little potential to spread disease. *Oc. sollicitans* is
58 the coastal vector for the very dangerous disease Eastern equine encephalitis, which fortunately
59 has low coastal incidence except under certain conditions that can occur in New Jersey (Crans
60 1977). Salt marsh mosquitoes do not transmit malaria or yellow fever. A less common salt marsh
61 mosquito (*Culex salinarius*) was identified as the most important vector for human cases of West
62 Nile disease in Connecticut (Andreadis et al. 2004), but areas such as Long Island that are
63 infested by salt marsh mosquitoes have low infection rates, lower than expected given the
64 geographic prevalence of infected birds and positive mosquito pools (Tonjes 2008). Salt marsh
65 mosquito control was originally characterized as abatement of “nuisance” (Smith 1904), and
66 modern mosquito control that focuses on *Oc. sollicitans* likely prevents few human illnesses
67 (Turrell et al. 2005) but alleviates much human misery across most of the mid-Atlantic and New
68 England coastlines.

69 **Ditching Technologies**

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

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

86 **Scope and Approach of this Review**

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

97 The aim here is to define the effects of ditches on “background” marsh conditions. Most
98 studies which find effects relate them either to changes in marsh hydrology or report impacts to
99 biota. Most of these studies are restricted in time (generally one year) and extent (typically, one
100 marsh) and thus have restricted value. Two studies, each of which examine one of the key

101 impacts, defy this general trend. One is Adamowicz and Roman (2005), which is a statistical
102 analysis of hydrological features in paired ditched and unditched marshes across New England.
103 Most salt marsh research has found marsh hydrology is a dominant factor in the overall ecology
104 of a marsh. The second is an early report by Bourn and Cottam (1950), a multi-year study of
105 initial ecological impacts from ditching, cited in some of the key general literature as source for
106 the finding that ditches harm salt marsh ecosystems (one example is Daiber 1986, which was in
107 turn cited more than 30 times according to the Web of Science). This review is founded on a
108 close reading of both of these papers, and they are used a means for placing other, more limited
109 studies into context.

110 **PHYSICAL EFFECTS FROM DITCHING**

111 **Adamowicz and Roman (2005)**

112 Crain et al. (2009) emphasize that hydrology is the primary factor in intertidal marsh
113 processes, and note the manifold means that humans have altered it. Adamowicz and Roman
114 (2005) primarily characterize the distribution and nature of ponds in paired ditched and
115 unditched salt marshes in New England from Connecticut to southern Maine. Physical transects
116 and “digital transects” on aerial photography were used to generate: 1) the percent of each
117 transect composed of ponds; 2) the area of each pond touched by a transect; and 3) the distance
118 to the nearest neighbor pond and waterway (ditch or natural creek). Field sampling included
119 water depth and distance to each pond bottom, and generalized vegetation characterizations.

120 Adamowicz and Roman (2005) found significantly fewer ponds that covered a smaller
121 total area in ditched marshes (Table 1), and a significant linear correlation between the intensity
122 of ditching and loss of ponds. The correlation for loss of total pond surface area was stronger
123 than the loss of pond density. Paired ditched and unditched data also showed that ditched areas

124 had significantly fewer ponds covering a significantly smaller area. The amount of natural creeks
125 correlated significantly and positively with pond surface area and pond density. Total pool area
126 was significantly correlated with tidal range. Because tidal ranges in New England tend to
127 increase with latitude, similar relationships held for geographical variation and pond density and
128 area. Mean depth (about 30 cm) and average size (about 200 m²) of ponds did not vary
129 significantly between the two marsh types. Thus, ponds decrease in ditched marshes, and ditches
130 cause ponds to drain while natural creeks do not. Ponds, which tend to be larger and more often
131 found in high marsh than low marsh, are not morphologically different in ditched marshes – just
132 fewer in number.

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

134 Some less comprehensive studies comparing ditched and unditched marshes also found
135 fewer ponds and less open water (Reinert et al. 1981, Merriam 1983, Lathrop et al. 2000).
136 Reports generated immediately following ditching were mixed, however, as to whether marshes
137 were drained following ditching (Bradbury 1938, Corkran 1938, Daigh et al. 1938, Taylor 1938).
138 Redfield (1972) said ditches drain the water table, but found no difference in the number of
139 ponds in ditched and unditched areas. Others limit water table impacts to sediments close to
140 ditches and/or streams (Provost 1977, Hemond and Fifield 1982, Agosta 1985, Nuttle 1988,
141 Montalto et al. 2006), although effects up to 15 m away from stream banks have been measured
142 (Nuttle and Hemond 1988). Chapman (1974) pronounced it “optimistic” that ditches spaced 30
143 m (“100 ft”) apart would drain a marsh. However, drainage of marshes by ditches is strongly
144 endorsed by comprehensive mosquito management reviews (Daiber 1986, Dale and Hulsman
145 1990, Wolfe 1996).

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

160 Adamowicz and Roman (2005) worked in marshes where tide ranges all exceeded 1 m
161 (S. Adamowicz personal communication 2009). In areas such as the south shore lagoonal system
162 on Long Island, with lower tidal ranges (often less than 50 cm and sometimes less than 30 cm),
163 ditches did not “drain” marshes, but rather “relocate[d] water from the marsh surface to the
164 ditches” (Taylor 1938). With low tidal ranges, water persists in ditches throughout the tidal
165 cycle, because the bottom of the ditches is lower than low tide levels. In these environments, the
166 effect of ditches is primarily to enhance transport of standing waters from spring tides off the
167 marsh surface rather than large effects of marsh water table heights, due to reduced head
168 differences between the water table and the ditches compared to cases when the ditches dry each

169 tidal cycle. More rapid drainage of lunar tides from the marsh surface is a subtle change in marsh
170 hydrology, not discernable from aerial photography, maps of marsh waterways, or measurements
171 of “average” marsh water tables.

172 **Ditches Propagate Tides into Marshes**

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

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

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

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

197 **Impact of Ditches on Marsh Hydrology**

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

203 **BIOLOGICAL IMPACTS FROM DITCHING**

204 **Bourn and Cottam (1950)**

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

214 (identified as “common to the tidewater marshes, including rails, sandpipers, yellowlegs, and
215 willets”).

216 Bourn and Cottam (1950) mapped but did not quantify vegetation changes (Lesser et al.
217 1976 measured the area changes from the maps, see Table 2). Installation of ditches at 50 m
218 intervals in 1936 at Mispillion Creek resulted in much of the lower elevation substrate becoming
219 soft mud, leading to considerable loss of *S. alterniflora*. *Pluchea camphorata* (*Pluchea*,
220 saltmarsh fleabane) invaded much of the die-off areas. *Iva spp.* and *Baccharis spp.* established
221 themselves along spoil banks alongside ditches. *Baccharis spp.* growth continued in 1938. The
222 ditches clogged, resulting in loss of *Pluchea* and re-establishment of *S. alterniflora*, a pattern that
223 continued through 1941. By 1946, *Baccharis spp.* had become the dominant marsh plant. *S.*
224 *alterniflora* was restricted to the center areas of the marsh, in the centers of panels (*Iva spp.* and
225 *Baccharis spp.* grew at ditch banks). The ditches had widened at their mouths, accelerating the
226 spread of *Baccharis spp.*, and clogged at their upper ends, where standing water supported *S.*
227 *alterniflora*. An interpretative table of vegetation types and associated elevations for 1936 and
228 1941 showed many species in 1941 were found at lower elevations than in 1936, and some did
229 not grow at the higher elevations where they had grown immediately after ditching.

230 The map of vegetation at Herring Creek was said to allow the distribution to be “grasped
231 readily by the reader;” in any case, it showed *S. alterniflora* covered approximately 50 percent of
232 the ditched marsh, and 75 percent of the unditched marsh. *S. patens* was a relatively minor part
233 of the unditched marsh, but a major constituent in the ditched areas. *Scirpus* was prominent in
234 the unditched marsh, but entirely absent in the ditched area. Some scattered *Spartina*
235 *cynosuroides* was mapped in the unditched marsh (in *S. alterniflora* areas), but was the dominant

236 plant in one large tract in the ditched area. High marsh plants occurred at lower elevations in the
237 ditched area.

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

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

245 Bourn and Cottam (1950) concluded that with ditching:

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

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

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

260 *Vegetation*

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

271 For hundreds of years, ditches have been dug to support salt haying (Daiber 1986, Mitsch
272 et al. 1994, Dreyer and Niering 1995, Bart 1997, Phillipp, 2005), but there are few explicit
273 literature references to salt hay (*S. patens*) areal expansion across marshes following mosquito
274 ditching (except Taylor 1938), or findings of *S. patens* being greater in ditched areas compared
275 to unditched areas (except Merriam 1974). The cause of zonation between low marsh (an *S.*
276 *alterniflora* monoculture) and high marsh (usually dominated by *S. patens*) is usually identified
277 as the frequency of tidal inundations (see Mitsch and Gosselink 2000), as the ability of *S.*
278 *alterniflora* to cope with root zone anoxia from constant flooding allows it to grow where *S.*
279 *patens* cannot (per Pennings and Bertness 1999). So, in a broad conceptual sense, unless ditching
280 changes the areas of the marsh overwashed by daily tides, it should not cause *S. patens* to replace
281 *S. alterniflora*. Less short-form *S. alterniflora* has been found at some ditched marshes,

282 attributed to pond shores being prime habitat for this *S. alterniflora* variant and ditching reducing
283 ponds (Reinert et al. 1981). Short-form *S. alterniflora* is often classified as a high marsh species
284 (per Adamowicz and Roman 2005); still, persistent flooded sediments in high marsh exist
285 because of water table conditions, not from daily tidal flooding, and so reduced water table
286 heights from ditching, resulting in less root zone anoxia, would allow *S. patens* to replace short-
287 form *S. alterniflora*. At the upper reaches of the *S. alterniflora* zone in the low marsh, reductions
288 in the water table could be great enough to support sufficient drainage of daily tides in some
289 areas to create enough unsaturated sediments to support some *S. patens* growth. This could
290 conceivably result in substantial shifts in plant composition where the marsh slope is very
291 shallow, as in some of the large remnant marshes in New Jersey. Where marshes fringe the
292 shoreline or depth from the shore is not great, large changes in plant zonation are not likely.

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

299 *Phragmites australis* (*Phragmites*) is a native fresh or brackish water plant (Orson 1999),
300 but an invasive European variant (Saltonstall 2002) now grows in vast monotypic stands across
301 fresh and salt marshes in the northeast US. *Phragmites* thrives under drier conditions in a marsh
302 (Minchinton et al. 2006), and one pattern of its spread is along ditches, and then into panels (Bart
303 et al. 2006). Ditches are thought to have drier banks due to drainage of the water table, and
304 salinities are often lower. The sediments are more aerated, and sulfide concentrations, as a result,

305 are lower (Chambers et al. 2003). In *Phragmites* stands, soil salinities and the water table are
306 lower, the micro-topography is smoother, and soils are more oxygenated (Windham and Lathrop
307 1999), characteristics sometimes also found at ditch edges. *Phragmites* was planted across the
308 Meadowlands in New Jersey with the express purpose of stabilizing ditch banks (Headlee 1945),
309 and this practice may have occurred elsewhere. Bart et al. (2006), while noting not all
310 *Phragmites* results from human intervention, found ditching and ditch maintenance to be
311 important mechanisms for invasions, through the spread and burial of rhizomes by ditching
312 machinery use, as drier, more aerated sediments promote rhizome sprouting.

313 There is clear evidence of vegetation shifts in ditched marshes from water table declines,
314 loss of ponds, and general marsh drying. However, expansion of *S. alterniflora* along the ditches
315 (reported by Taylor 1938, Miller and Egler 1950, Heuser et al. 1975, Provost 1977, Niering and
316 Warren 1980, Kennish, 2001), usually attributed to higher salinity levels, is likely the result of
317 expansion of waterlogged soils, as *S. alterniflora* dominates marsh vegetation when saturated
318 soils prevent *S. patens* from growing at all (Pennings and Bertness 1999). Waterlogged soils
319 along ditch banks may occur due to ditches propagating tides into the marsh, but a more common
320 understanding is that ditch banks are better drained than interior panel peats (per Bart and
321 Hartman 2002 and Montalto et al. 2006, with reference to tidal channel banks). Bank side
322 sediments respond to changes in tidal levels, both saturating and draining in concord with tide
323 heights (Nuttall 1988). So, if tidal residence time is increased by ditching, bank waterlogging
324 could increase, and *S. alterniflora* could be favored. If tidal residence time is decreased, banks
325 drain more quickly, and this could favor *Phragmites*. Because ditching can change tidal
326 asymmetry, differences in tidal residence time due to ditching could account for reports of
327 expansion of *S. patens* in some marshes post-ditching, and expansion of *S. alterniflora* in other

328 marshes. An alternate explanation is tied to shifts in nutrient conditions. Tidal inflows are the
329 greatest source of nitrogen to the marsh (Valiela and Teal 1979), and enhanced nitrogen
330 concentrations have been measured in ditches (Koch and Gobler 2009); where tides are greater
331 than 1 m, marsh sediments are net exporters of nitrogen (Childers 1994). Nutrient additions can
332 allow *S. alterniflora* to grow in the high marsh, replacing *S. patens* (Bertness et al. 2002).
333 However, nutrient additions also have been found to reduce overall *Spartina spp.* fitness,
334 signaled by decreased subsurface biomass (Turner et al. 2009). Ditches may not be important
335 players in this process: Nuttle and Hemond (1988), based on mass transport considerations,
336 thought it unlikely much nitrogen was transported into bankside sediments, and Bart and
337 Hartman (2002), based on sulfide-ammonia interactions, thought it unlikely that nutrients were
338 key in observed changes in speciation patterns where banksides were well aerated. Chambers et
339 al. (2003) speculated that overall marsh nutrient enrichment may have been important in
340 promoting *Phragmites* expansion, as it has been noted (see Bertness et al. 2002) nutrient
341 additions may favor *Phragmites* over *Spartina spp.* It is possible, then, but not universally agreed
342 to, that penetration of the tide into the marsh could lead to *S. alterniflora* expansion, but
343 increased nutrients are not likely to play a role.

344 It is important to note that Lesser et al. (1976) resampled the Mispillion River site, and
345 produced maps that simplified Bourn and Cottam's (1950) groupings somewhat (Table 2). These
346 researchers noted the ditches had been "maintained" (redug) in 1966; they asserted that their data
347 that showed resurgence of *S. alterniflora* back to original densities demonstrated that *S.*
348 *alterniflora* could thrive without extensive shoaling in ditches. Lesser et al. (1976) also noted
349 that the Mispillion River was dredged at its channel mouth in 1933 and 1935, and in the river bed
350 in 1935 and 1938, and thought this might have reduced tide heights. They believed increases in

351 sea level from 1946 to 1974 were sufficient to re-establish *S. alterniflora* and cause woody plants
352 to retreat. This is a plausible explanation of Bourn and Cottam's (1950) data, but one that lessens
353 the 1950 conclusion that ditching was the sole cause of the large impacts measured on vegetation
354 patterns.

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

362 *Invertebrates*

363 Although Bourn and Cottam (1950) found great impacts to invertebrate populations, few
364 other studies have tested for similar effects. One reason for this may be controls on marsh
365 invertebrate populations are not well-defined. Plant speciation and variation in plant distributions
366 change invertebrate habitats (Rader 1984, Capehart and Hackney 1989), and fish predation is
367 thought to be an important control (Knieb 1984, Vince et al. 1976), although avian predation has
368 not been found to affect invertebrate populations significantly (Clarke et al. 1984, Ashley et al.
369 2000, Sherfy and Kirkpatrick 2003). This suggests that if ditching changes vegetation
370 distributions (see above) or fish populations (see below), invertebrate populations should also be
371 affected.

372 Two restricted studies of ditching impacts on invertebrates are contradictory: Lesser et al.
373 (1976) sampled fiddler crabs (*Uca* spp.) and salt marsh snails (*Melampus bidentatus*) in the same

374 marshes where Bourn and Cottam (1950) worked, and found greater concentrations of snails and
375 crab burrows in the ditched areas. Clarke et al. (1984) found marsh surface invertebrate diversity
376 to be greatest in maintained ditch areas (differences in overall diversity, including below-marsh
377 surface, water column, and benthic communities, were not statistically significant across
378 different habitats). Additionally, Resh (2001) found that shallow ditches (called “runnels” by
379 Dale and Hulsman 1990) affect invertebrate diversity (but not biomass). Crain et al. (2009)
380 assumed that effective mosquito control implied impacts to other marsh invertebrate populations,
381 which is a reasonable inference.

382 Accounts differ as to whether ditching effectively reduces mosquito populations. Some
383 have found reductions (Smith 1904, Bradbury 1938, Taylor 1938, Daigh et al. 1938, Dreyer and
384 Niering 1995), and theoretical discussions, based on larvae habitat loss and greater opportunities
385 for fish predation, also support ditching effectiveness (Glasgow 1938, Cooper 1974, Provost
386 1977, Dale and Hulsman 1990 Crain et al. 2009). Fish gut analyses, however, find few to no
387 mosquito larvae as prey (Harrington and Harrington 1961; Smith et al. 2000, Currin et al. 2003,
388 McMahon et al. 2006).

389 Bourn and Cottam (1950) thought ditches, if not maintained, were ineffective mosquito
390 control. Pools behind ditch spoils support mosquito breeding (Shisler 1973, Kuenzler and
391 Marshall 1973), and tidal restrictions in ditched marshes can lead to mosquitoes (Cowan et al.
392 1986). Daiber (1986) cited Delaware reports that found mosquito breeding was unaffected by
393 ditching, but also noted other reports found ditching reduced mosquito numbers. Richards (1938)
394 found continued breeding at the upland edge of marshes. Nixon (1982) judged that ditching was
395 of “questionable value” for mosquito control. Recent studies of ditch modifications compared the
396 treatments to control ditched marshes; the ditched marshes produced measurable numbers of

397 mosquitoes (Rochlin et al. 2009, James-Pirri et al. 2009, Leisnham and Sandoval-Mohapatra
398 2011, Rochlin et al. 2012), which of course suggests the ditches are not that effective at mosquito
399 control.

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

406 *Birds*

407 The greatest worry expressed by Bourn and Cottam (1950) was for large impacts from
408 ditching to bird populations, although somewhat surprisingly they did not make any direct
409 measurements of effects. Conducting good bird sampling in salt marshes is difficult (Conway
410 and Droege 2006) and few studies have compared populations in ditched and unditched marshes
411 (e.g., Hanson and Shriver, 2006). Still, it is commonly asserted that ditched marshes support
412 fewer water fowl (Urner 1935, Bradbury 1938, Cottam 1938, Ferrigno 1970, Ferrigno et al.
413 1975, Reinert et al. 1981, Nixon 1982, Daiber 1986, Dreyer and Niering 1995, Wolfe 1996),
414 mostly from losses of open water (Reinert et al. 1981, Clarke et al. 1984) or reduced amounts of
415 submerged aquatic vegetation (Bourn and Cottam 1950, Nixon 1982). Despite one study finding
416 a ditched marsh was good seaside sparrow (*Amodramus maritimus*) habitat (Marshall and
417 Reinert 1990), more studies have found the opposite for that species of concern (Post and
418 Greenlaw 1975, Merrimam 1983, Dreyer and Niering 1995). However, one specific study found
419 no differences in overall avian populations (Buckley and Buckley 1982); mixed results, such as

420 less foraging for some species in ditched areas, although others were unaffected (Clarke et al.
421 1984), or no change in gross numbers but species shifts (Brawley et al. 1998), are also reported.

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

426 *Muskrats*

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

436 *Fish/Other Nekton*

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

442 One Long Island study found shallow ditches in a micro-tidal marsh (which had poor
443 water quality) did not support as many fishes and species as creeks did (Corman and Roman
444 2011). When ditches were converted to ponds and more natural appearing channels in another
445 Long Island marsh, there were significant increases in overall nekton populations (Rochlin et al.
446 2012). Unpublished data from that study link the more numerous fish populations to better water
447 quality. However, other direct research has tended to find that ditches may be good habitat.
448 Adding ditches to a marsh increased overall fish use by a factor of five, mostly by increasing
449 juvenile numbers (Kuenzler and Marshall 1973). Ditches had greater fish abundances compared
450 to pools in an unditched area, possibly due to reduced bird predation (Clarke et al. 1984). Ditches
451 were found to support typical salt marsh resident species, but also juveniles of species that may
452 have been using the marsh as a nursery (James-Pirri et al. 2010).

453 Adding ditches, because a correlation has been found between channel and edge areas
454 and fish use of marshes (Minello and Rozas 2002), theoretically can increase fish use of the
455 marsh (endorsed by Daiber 1986). Ditching has been demonstrated to double channel edges in a
456 marsh (Lathrop et al. 2000), and crabs were found in increased numbers in ditched areas,
457 possibly due to more burrowing opportunities (Rockel 1969). However, the generation of berms
458 as a result of construction can be an impediment to marsh surface access (Reed et al. 2006), and
459 ditches generally have poorer water quality (Kuenzler and Marshall 1973, Corman and Roman
460 2011), although this is not generally documented. Still, some resident marsh fish (especially
461 mummichogs, *Fundulus heteroclitus*) are tolerant of very poor water conditions (Knieb 1997),
462 and ditches can give access to otherwise unexploited marsh surface productivity (Whalley and
463 Minello 2002), including mosquito larvae (see above).

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

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

480 **Impact of Ditches on Biota**

481 Overall, Bourn and Cottam's (1950) report, which is the basis for many an indictment of
482 ditching for effects on marsh ecology, is not a fair evaluation of impacts to biota from ditching.
483 The section of the report which was most quantitative (but not statistically analyzed), the
484 invertebrate data from Herring Creek, are complicated, and the findings from there have not been
485 duplicated. The effects on vegetation that were mapped may have resulted, at least partially,

486 from causes other than ditching. No data were collected to support a claim that ditches would
487 appreciably and significantly alter marsh bird populations across the East Coast of the U.S.

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

496 **SOME OTHER IMPACTS IDENTIFIED BY BOURN AND COTTAM (1950)**

497 **Ditches Fill and Widen**

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

509 dead vegetative matter under plants that bridge ditches when they fall (Chapman 1974, Collins et
510 al. 1986).

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

519 **Marsh Acidification**

520 Although Bourn and Cottam (1950) did not specifically address the problem in their
521 research, they stated that an impetus for the USFWS to study ditches was observations of gasses
522 from ditches, and generation of hydrogen sulfide at oyster beds (indirectly from ditching effects).
523 Marsh peats sequester large amounts of sulfur (Hussein and Rabenhorst 1999), usually as iron
524 sulfides, especially pyrite (Dharmasri et al. 2004). Exposure of anoxic sediments to aerobic
525 conditions can oxidize and hydrolize pyrites, producing sulfuric acid (Hussein and Rabenhorst,
526 1999), so that digging ditches has the potential to acidify the surrounding area (Frey and Basan
527 1985, Daiber 1986, Saffigna and Dale 1999). However, the only documented case of a supposed
528 link between ditches and marsh acidification was in a diked marsh, with the effects limited to the
529 fresh water portion (Soukup and Portnoy 1986). Others find that, due to drainage near bank
530 edges promoting sediment aeration, that edge sediments (including ditches) have little to no
531 sulfide present (Nuttle and Hemond 1988, Bart and Hartman 2002, Chambers et al. 2003)

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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

555 the most important mechanism for the transport of nutrients from the marsh. However, a model
556 of nitrogen cycling in marshes found that the balance towards nitrogen exports or imports
557 through the creekbank depended on the sources and speciation of the nitrogen inputs (Thomas
558 and Christian 2001). As most denitrification in marshes has been found to occur in the muddy
559 bottoms of creeks (Kaplan et al. 1979), ditching, which increases creek-like bottom sediments,
560 should result in augmented denitrification and so potentially less export of biologically available
561 nitrogen.

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

566 **Ditches and Phragmites**

567 Ditching appears to foster conditions that support invasions by *Phragmites* (Bart et al.
568 2006), and, once established, *Phragmites* tends to enhance conditions for its own benefit,
569 excluding native grasses (Minchinton et al. 2006). Monospecific *Phragmites* leads to changes in
570 bird use of the marsh (Benoit and Askins 1999, Fell et al. 2000, Parsons 2003, Trocki and Paton
571 2006), but not all such changes are judged to be negative (Parsons 2003). Generally, fish,
572 invertebrate, and plankton diversity is less in ditches and creeks within *Phragmites* stands than in
573 other marsh areas (Warren et al. 2001), and decreases in the quality of marsh habitat for fish
574 (Able and Hagan 2000, Able and Hagan 2003, Hagan et al. 2007) are more apparent as
575 *Phragmites* becomes more dominant (Hunter et al. 2006). Weis and Weis (2003) found
576 ecological disadvantages associated with *Phragmites* to be overstated; and *Phragmites* may raise
577 the elevation of marshes (Minchinton et al. 2006), a profound effect in light of accelerating sea

578 level rise. Nonetheless, more find that *Phragmites* causes numerous, generally negative effects
579 on native marsh biota, and it appears ditching has been an important agent in *Phragmites*
580 expansion.

581 CONCLUSIONS

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

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

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

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

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

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

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

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REFERENCES

- 652
- 653 Able, K.W. 1999. Measures of juvenile fish habitat quality: examples from a National Estuarine
654 Research Reserve. *In: Fish habitat: Essential fish habitat and rehabilitation*. Edited by:
655 L.R. Benaka. Am. Fish. Soc. Symp. No. 22, Bethesda, MD. pp. 134-147.
- 656 Able, K.W., and Hagan, S.M. 2000. Effects of common reed (*Phragmites australis*) invasion on
657 marsh surface macrofauna: response of fishes and decapod crustaceans. *Estuaries*
658 **23**(6):633-646.
- 659 Able, K.W., and Hagan, S.M. 2003. Impact of common reed, *Phragmites australis*, on essential
660 fish habitat: influence on reproduction, embryological development, and larval
661 abundance of mummichog (*Fundulus heteroclitus*). *Estuaries* **26**(1):40-50.
- 662 Adamowicz, S.C., and Roman, C.T. 2005. New England salt marsh pools: a quantitative analysis
663 of geomorphic and geographic features. *Wetlands* **25**(2):279-288.
- 664 Agosta, K. 1985. The effect of tidally induced changes in creekbank water table on pore water
665 chemistry. *Estuar. Coast. Shelf S.* **21**:389-400.
- 666 Andreadis, T.G., Anderson, J.F., Vossbrinck, C.R., and Main, A.J. 2004. Epidemiology of West
667 Nile Virus in Connecticut: a five-year analysis of mosquito data 1999-2003. *Vector-borne*
668 *Zoonot. Dis.* **4**(4):360-378.
- 669 Ashley, M.C., Robinson, J.A. Oring, L.W., and Vinyard, G.A. 2000. Dipteran standing stock
670 biomass and effects of bird predation at constructed wetlands. *Wetlands* **20**(1):84-90.
- 671 Bart, D. 1997. The use of local knowledge in understanding ecological change: a study of salt
672 hay farmers' knowledge of *Phragmites australis* invasion. MA Thesis, Rutgers
673 University.

- 674 Bart, D.J., and Hartman, J.M. 2002. Constraints on the establishment of *Phragmites australis* in a
675 New Jersey salt marsh and possible links to human disturbance. *Wetlands* **22**:201-213.
- 676 Bart, D., Burdick, D., Chambers, R., and Hartman, J.M. 2006. Human facilitation of *Phragmites*
677 *australis* invasions into tidal marshes: a review and synthesis. *Wetlands Ecol. Manage.*
678 **14**:53-65.
- 679 Benoit, L.K., and Askins, P.A. 2002. Relationship between habitat area and the distribution of
680 tidal marsh birds. *Wilson Bull.* **114**(3):314-323.
- 681 Bertness, M.D., Ewanchuk, P.J., and Silliman, B.R.. 2002. Anthropogenic modification of New
682 England salt marsh landscapes. *Proc. Nat. Acad. Sci. USA* **99**(3):1395-1398.
- 683 Boon, J.D. III. 1975. Tidal discharge asymmetry in a salt marsh drainage system. *Limnol.*
684 *Oceanogr.* **20**(1):71-80.
- 685 Bourn, W.S., and Cottam, C. 1950. Some biological effects of ditching tide water marshes. U.S.
686 Fish Wildl. Res. Rep. 19.
- 687 Bowen, J.L., and Valiela, I. 2004. Nitrogen loads to estuaries: using loading models to assess the
688 effectiveness of management options to restore estuarine water quality. *Estuaries*
689 **27**(3):482-500.
- 690 Bradbury, H.M. 1938. Mosquito control operations on tide marshes in Massachusetts and their
691 effect on shore birds and water fowl. *J. Wildl. Manage.* **2**:49-52.
- 692 Brawley, A.H., Warren, R.S. and Askins, R.A. 1998. Bird use of restoration and reference
693 marshes within the Barn Island Wildlife Management Area, Stonington, Connecticut,
694 USA. *Environ. Manage.* **22**(4):625-633.
- 695 Bromberg Gedan, K., Silliman, B.R., and Bertness, M.D. 2009. Centuries of human-driven
696 change in salt marsh ecosystems. *Annu. Rev. Mar. Sci.* **1**:117-141.

697 Buchsbaum, R.N., Catena, J., Hutchins, E., and James-Pirri, M.J. 2006. Changes in salt marsh
698 vegetation, *Phragmites australis*, and nekton in response to increased tidal flushing in a
699 New England salt marsh. *Wetlands* **26**(2):544-557.

700 Buckley, F.G., and Buckley, P.A. 1982. Microenvironmental determinants of survival in
701 saltmarsh-nesting common terns. *Colon. Waterbirds* **5**:39-48.

702 Burger, J., and Shisler, J. 1978. The effects of ditching a salt marsh on colony and nest site
703 selection by herring gulls (*Larus argentatus*). *Am. Midl. Nat.* **100**(1):54-63.

704 Capehart, A.A., and Hackney, C.T. 1989. The potential role of roots and rhizomes in structuring
705 salt-marsh benthic communities. *Estuaries* **12**(2):119-122.

706 Chambers, R.M., Osgood, D.T., Bart, D.J., and Montalto, F. 2003. *Phragmites australis* invasion
707 and expansion in tidal wetlands: interactions among salinity, sulfide, and hydrology.
708 *Estuaries* **26**(2B):398-406.

709 Chapman, V.J. 1974. Salt marshes and salt deserts of the world. 2nd ed. Strauss & Cramer
710 GMBH, Leutershausen, Germany.

711 Childers, D.L. 1994. Fifteen years of marsh flumes: a review of marsh-water column interactions
712 in southeastern USA estuaries. *In: Global wetlands: Old World and New. Edited by W.J.*
713 *Mitsch. Elsevier Science, BV, New York, N.Y. pp. 277-293.*

714 Childers, D.L., Day, J.W., Jr., and McKellar, H.N., Jr. 2000. Twenty more years of marsh and
715 estuarine flux studies: revisiting Nixon (1980). *In: Concepts and controversies in tidal*
716 *marsh ecology. Edited by M.P. Weinstein and D.A. Kreeger. Kluwer Academic*
717 *Publishers, Boston, MA. pp. 391-423.*

- 718 Clarke, J.A., Harrington, B.A., Hruby, T., and Wasserman, F.E. 1984. The effect of ditching for
719 mosquito control on salt marsh use by birds in Rowley, Massachusetts. *J. Field Ornithol.*
720 **55**(2):160-180.
- 721 Collins, J.N., Collins, L.M., Leopold, L.B., and Resh, V.H. 1986. The influence of mosquito
722 control ditches on the geomorphology of tidal marshes in the San Francisco Bay area: the
723 evolution of salt marsh mosquito habitats. *Proc. Calif. Mosq. Vect. Control Assoc.* **54**:91-
724 95.
- 725 Conway, C.J., and Droege, S. 2006. A unified strategy for monitoring changes in birds
726 associated with North American tidal marshes. *In: Terrestrial vertebrates of tidal*
727 *marshes: Evolution, ecology, and conservation. Edited by R. Greenberg, J.E. Maldonado,*
728 *S. Droege, and A.V. McDonald. Studies in Avian Biology, V. 32. Cooper Ornithological*
729 *Society, Camarillo, CA. pp. 282-297.*
- 730 Cooper, A.W. 1974. Salt marshes. *In: Coastal ecological systems of the United States, Volume*
731 *II. Edited by H.T. Odum, B.J. Copeland, and E.A. McMahan. The Conservation*
732 *Foundation, Washington, D.C. pp. 55-98.*
- 733 Corkran, W.S. 1938. New developments in mosquito control in Delaware. *Proc. N.J. Mosq.*
734 *Exterm. Assoc.* **25**:130-137.
- 735 Corman, S.S., and Roman, C.T. 2011. Comparison of salt marsh creeks and ditches as habitat for
736 nekton. *Mar. Ecol. Prog. Ser.* **434**:57-66.
- 737 Costanza, R., d'Ange, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem,
738 S., O'Neill, R.V., Pareulo, J., Raskin, R.G., Sutton, P., and van den Bolt, M. 2007. The
739 value of the world's ecosystem services and natural capital. *Nature* **387**:253-260.

740 Cottam, C. 1938. The coordination of mosquito control with wildlife conservation. Proc. N.J.
741 Mosq. Exterm. Assoc. **25**:217-227.

742 Cowan, D.P., Hruby, T., Litwin, L.S., and Lent, R.A. 1986. Open marsh management on Great
743 South Bay, Islip, New York: Baseline study: 1984-1985. Cornell University Laboratory
744 of Ornithology, Islip, N.Y.

745 Crain, C.M., Gedan, K.B. and Dionne, M. 2009. Tidal restrictions and mosquito ditching in New
746 England marshes. *In*: Human impacts on salt marshes: A global perspective. *Edited by*:
747 B.R. Silliman, E.D. Grosholz, and M.D. Bertness. University of California Press
748 Berkeley, CA. pp. 149-169.

749 Crans, W.J. 1977. The status of *Aedes sollicitans* as an epidemic vector of eastern equine
750 encephalitis in New Jersey. Mosq. News **37**(1):85-89.

751 Currin, C.A., Wainwright, S.C., Able, K.W., Weinstein, M.P., and Fuller, C.M. 2003.
752 Determination of food web support and trophic position of the mummichog, *Fundulus*
753 *heteroclitus*, in New Jersey smooth cordgrass (*Spartina alterniflora*), common reed
754 (*Phragmites australis*), and restored salt marshes. Estuaries **26**(2B):495-510.

755 Daiber, F.C. 1986. Conservation of tidal marshes. Van Nostrand Reinhold, New York, NY.

756 Daigh, F.C., and Stearns, L.A. 1939. Effect of ditching for mosquito control on the pH of marsh
757 soils. Proc. N.J. Mosq. Exterm. Assoc. **26**:39-43.

758 Daigh, F.C., MacCreary, D., and Stearns, L.A. 1938. Factors affecting the vegetative cover of
759 Delaware marshes. Proc. N.J. Mosq. Exterm. Assoc. **25**:209-216.

760 Dale, P.E.R., and Hulsman, K. 1990. Critical review of salt marsh management methods for
761 mosquito control. Rev. Aquat. Sci. **3**(2,3):281-311.

762 Deegan, L.A., Hughes, J.E., and Rountree, R.A. 2000. Salt marsh ecosystem support of marine
763 transient species. *In: Concepts and controversies in tidal marsh ecology. Edited by M.P.*
764 *Weinstein and D.A. Kreeger. Kluwer Academic Publishers, Boston, MA. pp. 333-365.*

765 Dharmasri, L.C., Hudnall, W.H., and Ferrell, R.E., Jr. 2004. Pyrite formation in Louisiana
766 coastal marshes: scanning electron microscopy and X-ray diffraction evidence. *Soil Sci.*
767 **169**(9):624-631.

768 Dreyer, G.D., and Niering, W.A. 1995. Tidal marshes of Long Island Sound: Ecology, history,
769 and restoration. *The Connecticut College Arboretum, No. 34.*

770 Ferrigno, F. 1970. Preliminary effects of open marsh water management on the vegetation and
771 organisms of the salt marsh. *Proc. N.J. Mosq. Exterm. Assoc. 57*:79-94.

772 Ferrigno, F., Slavin, P., and Jobbins, D.M. 1975. Open marsh water management. *Proc. N.J.*
773 *Mosq. Exterm. Assoc. 62*:30-38.

774 Frey, R.W., and Basan, P.B. 1985. Coastal salt marshes. *In: Coastal sedimentary environments.*
775 *2nd ed. Edited by R.A. Davis. Springer-Verlag, New York, N.Y. pp. 225-301.*

776 Fry, B., Cieri, M., Hughes, J., Tobias, C., Deegan, L.A., and B. Peterson, B. 2008. Stable isotope
777 monitoring of benthic-planktonic coupling using salt marsh fish. *Mar. Ecol. Prog. Ser.*
778 **369**:193-204.

779 Gardner, L.R. 1975. Runoff from an intertidal marsh during tidal exposure – recession curves
780 and chemical characteristics. *Limnol. Oceanogr. 20*(1):81-89.

781 Glasgow, R.D. 1938. Mosquitoes and wild life as interrelated problems in human ecology. N.Y.
782 *State Mus. Bull. 316*:7-20.

783 Hagan, S.M., Brown, S.A., and Able, K.W. 2007. Production of mummichog (*Fundulus*
784 *heteroclitus*): response in marshes treated for common reed (*Phragmites australis*)
785 removal. *Wetlands* **27**(1):54-67.

786 Hanson, A.R., and Shriver, W.G. 2006. Breeding birds of northeastern saltmarshes: habitat use
787 and conservation. *In: Terrestrial vertebrates of tidal marshes: Evolution, ecology, and*
788 *conservation. Edited by R. Greenberg, J.E. Maldonado, S. Droege, and A.V. McDonald.*
789 *Studies in Avian Biology, V. 32. Cooper Ornithological Society, Camarillo, CA. pp. 141-*
790 *154.*

791 Harrington, R.W., and Harrington, E.S. 1961. Food selection among fishes invading a high
792 subtropical salt marsh: from onset of flooding through the progress of a mosquito brood.
793 *Ecology* **42**(4):646-666.

794 Headlee, T. 1945. Mosquitoes of New Jersey and their control. Rutgers University Press, New
795 Brunswick, N.J.

796 Hemond, H.F., and Fifield, J.L. 1982. Subsurface flow in salt marsh peat: a model and field
797 study. *Limnol. Oceanogr.* **27**(1):126-136.

798 Hrubby, T., and Montgomery, W.G. 1985. Open marsh water management for open tidal marshes
799 in the Northeast: a manual of methods. Massachusetts Audubon Society, Lincoln, MA.

800 Hunter, K.L., Fox, D.A., Brown, L.M., and Able, K.W.. 2006. Response of resident fishes to
801 stages of *Phragmites australis* invasions in three mid Atlantic estuaries. *Estuaries Coasts*
802 **29**(3):487-798.

803 Hussein, A.H., and Rabenhorst, M.C. 1999. Modeling of sulfur sequestration in coastal marsh
804 soils. *Soil Sci. Soc. Am. J.* **3**:1954-1963.

805 James-Pirri, M.-J., Ginsberg, H.S., Erwin, R.M., and Taylor, J. 2009. Effects of open marsh
806 water management on numbers of larval salt marsh mosquitoes. *J. Med. Entomol.*
807 **46(6):1392-1399.**

808 James-Pirri, M.-J., Roman, C.T., and Swanson, J.L. 2010. A method to quantitatively sample
809 nekton in salt-marsh ditches and small tidal creeks. *Trans. Am. Fish. Soc.* **139(2):413-**
810 **419.**

811 Kaplan, W., Valiela, I., and Teal, J.M. 1979. Denitrification in a salt marsh ecosystem. *Limnol.*
812 *Oceanogr.* **24(4):726-734.**

813 Kennish, M.J. 2001. Coastal salt marsh systems in the U.S.: a review of anthropogenic impacts.
814 *J. Coast. Res.* **17(3):731-748.**

815 Knieb, R.T. 1984. Patterns of invertebrate distribution and abundance in the intertidal salt marsh:
816 Causes and questions. *Estuaries* **7(4A):392-412.**

817 Knieb, R.T. 1997. The role of tidal marshes in the ecology of estuarine nekton. *Oceanogr. Mar.*
818 *Rev.* **35:163-220.**

819 Koch, F., and Gobler, C.J. 2009. The effects of tidal export from salt marsh ditches on estuarine
820 water quality and plankton communities. *Estuaries Coasts* **32(2):261-275.**

821 Kuenzler, E.J., and Marshall, H.L. 1973. Effects of mosquito control ditching on estuarine
822 ecosystems. Water Resource Research Institute Report No. 81, University of North
823 Carolina.

824 Lathrop, R.G., Cole, M.P., and Showalter, R.D. 2000. Quantifying the habitat structure and
825 spatial pattern of New Jersey (U.S.A.) salt marshes under different habitat regimes.
826 *Wetlands Ecol. Manage.* **8:163-172.**

827 Leisnham, P.T., and Sandoval-Mohapatra, S. 2011. Mosquitoes associated with ditch-plugged
828 and control tidal salt marshes on the Delmarva peninsula. *Int. J. Environ. Res. Public*
829 *Health* **8**:3099-3013.

830 Lesser, C.R., Murphey, F.J., and Lake, R.W. 1976. Some effects of grid system mosquito control
831 ditching on salt marsh biota in Delaware. *Mosq. News* **36**:69-77.

832 MacKenzie, R.A., and Dionne, M. 2008. Habitat heterogeneity: importance of salt marsh pools
833 and high marsh surfaces to fish production in two Gulf of Maine marshes. *Mar. Ecol.*
834 *Prog. Ser.* **368**:217-230.

835 Marani, M., Belluco, E., D'Alpaos, A., Defina, A., Lanzoni, S., and Rinaldo, A. 2003. On the
836 drainage density of tidal networks. *Water Resour. Res.* **39**(2):1040.
837 doi:10.1029/2002WR001051.

838 Marshall, R.M., and Reinert, S.E. 1990. Breeding ecology of seaside sparrows in a
839 Massachusetts salt marsh. *Wilson Bull.* **102**(3):501-513.

840 McKinney, R.A., Charpentier, M.A., and Wigand, C. 2009. Assessing the wildlife habitat value
841 of New England salt marshes: I. Model and application. *Environ. Monit. Assess.* **154**:29-
842 40.

843 McMahan, K.W., Johnson, B.J., and Ambrose, W.G., Jr. 2005. Diet and movement of the
844 killifish, *Fundulus heteroclitus*, in a Maine salt marsh assessed using gut contents and
845 stable isotope analyses. *Estuaries* **28**(6):966-973.

846 Merriam, T.L. 1983. Food habits of nestling seaside sparrows in unaltered and ditched salt
847 marshes on Long Island, New York. *In: The seaside sparrow: Its biology and*
848 *management.* Edited by T.L. Quay, J.B. Funderburg, Jr., D.S. Lee, E.F. Potter, and C.S.

849 Robbins. Occasional Papers of the North Carolina Biological Survey, 1983-5. pp. 115-
850 122.

851 Miller, W.R., and Egler, F.E. 1950. Vegetation of the Wequetequock-Pawcatuck tidal marshes,
852 Connecticut. Ecol. Monogr. **20**:143-172.

853 Minchinton, T.E., Simpson, J.C., and Bertness, M.D. 2006. Mechanisms of exclusion of native
854 coastal marsh plants by an invasive grass. J. Ecol. **94**:342-354.

855 Minnello, T.J., and Rozas, L.P. 2002. Nekton in Gulf Coast wetlands: fine-scale distributions,
856 landscape patterns, and restoration implications. Ecol. Appl. **12**(2):441-455.

857 Mitsch, W.J., and Gosselink, J.G. 2000. Wetlands. 3rd ed. John Wiley and Sons, New York, N.Y.

858 Mitsch, W.J., Mitsch, R.H., and Turner, R.E. 1994. Wetlands of the Old and New Worlds:
859 ecology and management. *In: Global wetlands: Old World and New. Edited by W.J.*
860 *Mitsch.* Elsevier Science, BV New York, N.Y. pp. 3-56.

861 Montalto, F.A., Steenhuis, T.S., and Parlange, J-Y. 2006. The hydrology of Piermont marsh, a
862 reference for tidal marsh restoration in the Hudson river estuary, New York. J. Hydrol.
863 **316**:108-128.

864 Niering, W.A., and Warren, R.S. 1980. Vegetation patterns and processes in New England salt
865 marshes. BioScience **30**:301-307.

866 Nixon, S.W. 1980. Between coastal marshes and coastal waters – a review of twenty years of
867 speculation and research on the role of salt marshes in estuarine production and water
868 chemistry. *In: Estuarine and wetland processes with emphasis on modeling. Edited by P.*
869 *Hamilton and K.B. MacDonald.* Plenum Press, New York, N.Y. pp. 437-525.

870 Nixon, S.W. 1982. The ecology of New England high salt marshes: a community profile.
871 FWS/OBS-81/55. U.S. Fish Wildl. Serv., Washington, D.C.

872 Nuttle, W.K. 1988. The extent of lateral water movement in the sediments of a New England salt
873 marsh. *Water Resour. Res.* **24**:2077-2085.

874 Nuttle, W.K., and Hemond, H.F. 1988. Salt marsh hydrology: implications for biogeochemical
875 fluxes to the atmosphere and estuaries. *Global Biogeochem. Cycles* **2**(2):91-114.

876 Odum, E.P. 1961. The role of salt marshes. *NY Conservationist*, June-July, p. 12.

877 Odum, E.P. 2000. Tidal marshes as outwelling/pulsing systems. *In: Concepts and controversies*
878 *in tidal marsh ecology. Edited by M.P. Weinstein and D.A. Kreeger. Kluwer Academic*
879 *Publishers, Boston, MA. pp. 3-7.*

880 Orson, R.A. 1999. A paleoecological assessment of *Phragmites australis* in New England tidal
881 marshes: Changes in plant community structure during the last few millennia. *Biol.*
882 *Invasions* **1**:149-158.

883 Parsons, K.C. 2003. Reproductive success of wading birds using *Phragmites* marsh and upland
884 nesting habitats. *Estuaries* **26**(2B):596-601.

885 Pennings, S.C., and Bertness, M.D. 1999. Using latitudinal variation to examine effects of
886 climate on coastal salt marsh patterns and process. *Wetlands Biogeochem.* **3**:100-111

887 Phillipp, K.R. 2005. History of Delaware and New Jersey salt marsh restoration sites. *Ecol. Eng.*
888 **25**:214-230.

889 Post, W., and Greenlaw, J.S. 1975. Seaside sparrow displays: their function in social
890 organization and habitat. *Auk* **92**:461-492.

891 Provost, M.W. 1977. Source-reduction in mosquito control: past and future. *Mosq. News*
892 **37**(4):689-698.

893 Rader, D.N. 1984. Salt-marsh benthic invertebrates: small-scale patterns of distribution and
894 abundance. *Estuaries* **7**(4A):413-420.

- 895 Redfield, A.C. 1972. Development of a New England salt marsh. *Ecol. Monogr.* **42**(2):1-237
- 896 Reed, D.J., Peterson, M.S., and Lezina, B.J. 2006. Reducing the effect of dredged material levees
897 on coastal marsh function: sediment deposition and nekton utilization. *Environ. Manage.*
898 **37**(5):671-685.
- 899 Reinert S.E., Golet, F.C., and DeRagon, W.R. 1981. Avian use of ditched and unditched salt
900 marshes in southeastern New England: a preliminary report. *Proc. Northeast Mosq.*
901 *Control Assoc.*
- 902 Resh, V.H. 2001. Mosquito control and habitat modification: case history studies from San
903 Francisco Bay wetlands. *In: Bioassessment and management of North American*
904 *freshwater wetlands. Edited by R.P. Rader, D.P. Batzer, and S.A. Wissinger. Wiley &*
905 *Sons, New York, N.Y. pp. 413-428.*
- 906 Richards, A.G., Jr. 1938. Mosquitoes and mosquito control on Long Island, New York, with
907 particular reference to the salt marsh problem. *N.Y. State Mus. Bull.* **316**:85-172.
- 908 Rochlin, I., Iwanejko, T., Dempsey, M.E., and Ninivaggi, D.V. 2009. Geostatistical evaluation of
909 integrated marsh management on mosquito vectors using before-after-control-impact
910 design. *Int. J. Health Geographics* **8**:35. doi:10.1186/1476-072X-8-35.
- 911 Rochlin, I., James-Pirri, M.-J., Adamowicz, S.C., Dempsey, M.E., Iwanejko, T., and Ninivaggi,
912 D.V. 2012. The effects of integrated marsh management (IMM) on salt marsh vegetation,
913 nekton, and birds. *Estuaries Coasts* **35**(3):727-742.
- 914 Rockel, E.G. 1969. Marsh physiography: influence on the distribution of organisms. *Proc. N.J.*
915 *Mosq. Exterm. Assoc.* **56**:102-116.
- 916 Roman, C.T., Garvine, R.W., and Portnoy, J.W. 1995. Hydrologic modeling as a predictive basis
917 for ecological restoration of salt marshes. *Environ. Manage.* **19**(4):559-566.

918 Roman C.T., Jaworski, N., Short, F.T., Findlay, S., and Warren, R.S. 2000. Estuaries of the
919 northeastern United States: Habitat and land use signatures. *Estuaries* **23**:743-764.

920 Rountree, R.A., and Able, K.W. 2007. Spatial and temporal habitat use patterns for salt marsh
921 nekton: implications for ecological functions. *Aquat. Ecol.* **41**:25-45.

922 Saffigna, P.G., and Dale, P.E.R. 1999. Acid sulfate soils in intertidal mosquito breeding habitats
923 and implications for habitat modification. *J. Am. Mosq. Control Assoc.* **15**(4):520-525.

924 Salstonstall, K. 2002. Cryptic invasion by a non-native genotype of the common reed,
925 *Phragmites australis*, into North America. *Proc. Nat. Acad. Sci. USA* **99**:2445-2449.

926 Sebold, K.R. 1992. From marsh to farm: the landscape transformation of coastal New Jersey.
927 Historic American Buildings Survey/Historic American Engineering Record, National
928 Park Service, U.S. Department of the Interior, Washington, D.C.

929 Sherfy, M.H., and Kirkpatrick, R.L. 2003. Invertebrate response to snow goose herbivory on
930 moist-soil vegetation. *Wetlands* **23**(2):236-249.

931 Shisler, J.K. 1973. Pioneer plants on spoil piles associated with mosquito ditching. *Proc. N.J.*
932 *Mosq. Exterm. Assoc.* **60**:135-141.

933 Shisler, J.K. 1990. Creation and restoration of coastal wetlands of the Northeastern United
934 States. *In: Wetland creation and restoration: the status of the science. Edited by J.A.*
935 *Kusler and M.E. Kentula. Island Press, Washington, D.C. pp. 143-170.*

936 Smith, J.B. 1904. Report of the NJ State Agricultural Experiment Station upon the mosquitoes
937 occurring within the state, their habits, life history, etc. MacCrellish & Quigley, Trenton,
938 N.J.

939 Smith, K.J., and Able, K.W. 1994. Salt marsh tide pools as winter refuges for the mummichog,
940 *Fundulus heteroclitus*, in New Jersey. *Estuaries* **17**:226-234.

- 941 Smith, K.J., Taghon, G.L., and Able, K.W. 2000. Trophic linkages in marshes: ontogenetic
942 changes in diet for young-of-the-year mummichog, *Fundulus heteroclitus*. *In: Concepts*
943 *and controversies in tidal marsh ecology. Edited by M.P. Weinstein and D.A. Kreeger.*
944 *Kluwer Academic Publishers, Boston, MA. pp. 221-237.*
- 945 Soukup, M.A., and Portnoy, J.W. 1986. Impacts from mosquito control-induced sulfur
946 mobilisation in a Cape Cod Estuary. *Environ. Conserv.* **13**:47-50.
- 947 Sullivan, M.J., and Currin, C.A. (2000) Community structure and functional dynamics of benthic
948 macroalgae in salt marshes. *In: Concepts and controversies in tidal marsh ecology. Edited*
949 *by M.P. Weinstein and D.A. Kreeger. Kluwer Academic Publishers, Boston, MA. pp. 81-*
950 *106.*
- 951 Talbot, C.W., Able, K.W., and Shisler, J.K. 1986. Fish species composition in New Jersey salt
952 marshes: effects of marsh alterations for mosquito control. *Trans. Am. Fish. Soc.*
953 **115**:269-278.
- 954 Taylor, N. 1938. A preliminary report on the salt marsh vegetation of Long Island, New York.
955 *N.Y. State Mus. Bull.* **316**:21-84.
- 956 Taylor G.T., Gobler, C.J., and Sanudo-Wilhelmy, S.A. 2006. Speciation and concentrations of
957 dissolved nitrogen as determinants of brown tide *Aureococcus anophagefferens* bloom
958 initiation. *Mar. Ecol. Prog. Ser.* **312**:67-83.
- 959 Teal, J.M. 1962. Energy flow in the salt marsh ecosystem of Georgia. *Ecology* **43**(4):614-624.
- 960 Teal, J.M. 1986. The ecology of regularly flooded salt marshes of New England: A community
961 profile. Biological Report 85(7.4), U.S. Fish Wildl. Serv., Washington, D.C.
- 962 Thomas, C.R., and Christian, R.R. 2001. Comparison of nitrogen cycling in salt marsh zones
963 related to sea level rise. *Mar. Ecol. Prog. Ser.* **221**:1-16.

964 Tobias, C.R., Cieri, M., Peterson, B.J., Deegan, L.A., Vallino, J., and Hughes, J. 2003.
965 Processing watershed-derived nitrogen in a well-flushed New England estuary. *Limnol.*
966 *Oceanogr.* **48**(5):1766-1778.

967 Tonjes, D.J. 2008. Estimates of worst case baseline West Nile virus disease effects in a suburban
968 New York county. *J. Vect. Ecol.* **33**(2):293-304.

969 Trocki, C.L., and Paton, P.W.C. 2006. Assessing habitat selection by foraging egrets in salt
970 marshes at multiple spatial scales. *Wetlands* **26**(2):307-312.

971 Turner, R.E., Howes, B.L., Teal, J.M., Milan, C.S., Swenson, E.M., and Goehring-Toner, D.D.
972 2009. Salt marshes and eutrophication: an unsustainable outcome. *Limnol. Oceanogr.*
973 **54**(5):1634-1642.

974 Turrell, M.J., Dohm, D.J., Sardelis, M.R., O'Guinn, M.L., Andreadis, T.G., and Blow, J.A. 2005.
975 An update on the potential of North American mosquitoes (Diptera:Culicidae) to transmit
976 West Nile Virus. *J. Med. Entomol.* **42**(1):57-62.

977 Urner, C.A. 1935. Relation of mosquito control to bird life of the salt marshes. *Proc. N.J. Mosq.*
978 *Exterm. Assoc.* **22**:130-136.

979 Valiela, I., and Cole, M.L. 2002. Comparative evidence that salt marshes and mangroves may
980 protect sea grass meadows from land-derived nitrogen loads. *Ecosystems* **5**(1):92-102.

981 Valiela, I., and Teal, J.M. 1979. The nitrogen budget of a salt marsh ecosystem. *Nature* **280**:652-
982 656.

983 Vince, S., Valiela, I., Backus, N., and Teal, J.M. 1976. Predation by the salt marsh killifish
984 *Fundulus heteroclitus* (L.) in relation to prey size and habitat structure: consequences for
985 prey distribution and abundance. *J. Exp. Mar. Biol. Ecol.* **23**:255-266.

- 986 Warren, R.S., Fell, P.E., Grimsby, J.L., Buck, E.L., Rilling, G.C., and Fertik, R.A. 2001. Rates,
987 patterns, and impacts of *Phragmites australis* expansion and effects of experimental
988 *Phragmites* control on vegetation, macroinvertebrates, and fish within tidelands of the
989 lower Connecticut River. *Estuaries* **24**(1):90-107
- 990 Weinstein, M.P., and Kreeger, D.A. (editors). 2000. Concepts and controversies in tidal marsh
991 ecology. Kluwer Academic Publishers, Boston, MA.
- 992 Weis, J.S., and Weis, P. 2003. Is the invasion of the common reed, *Phragmites australis*, into the
993 tidal marshes of the eastern US an ecological disaster? *Mar. Pollut. Bull.* **46**:816-820.
- 994 Whalley, S.D., and Minello, T.J. 2002. The distribution of benthic infauna of a Texas salt marsh
995 in relation to the marsh edge. *Wetlands* **22**(4):753-766.
- 996 White, D.S., and Howes, B.L. 1994. Long-term ¹⁵N-nitrogen retention in the vegetated
997 sediments of a New England salt marsh. *Limnol. Oceanogr.* **39**(8):1878-1892.
- 998 Windham, L., and Lathrop, R.G., Jr. 1999. Effects of *Phragmites australis* (common reed) on
999 aboveground biomass and soil properties in brackish tidal marsh on the Mullica River,
1000 New Jersey. *Estuaries* **22**(4):927-935.
- 1001 Wolfe, R.J. 1996. Effects of Open Marsh Water Management on selected tidal marsh resources:
1002 a review. *J. Am. Mosq. Control Assoc.* **12**(4):701-712.
- 1003 Zheng, L., Chen, C., and Liu, H. 2003. A modeling study of the Satilla River estuary, Georgia. I.
1004 Flooding-drying process and water exchange over the salt marsh-estuary-shelf complex.
1005 *Estuaries* **26**(3):651-669.