Estuaries and Coasts (2009) 32:855–870
DOI 10.1007/s12237-009-9203-7

Stratigraphic and Ecophysical Characterizations of Salt Pools: Dynamic Landforms of the Webhannet Salt Marsh, Wells, ME, USA

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Received: 28 January 2009 / Revised: 26 June 2009 / Accepted: 9 July 2009 / Published online: 4 August 2009

Abstract Salt pools are water-filled depressions common to north-temperate salt marshes. In Wells, ME, USA, cores reveal a unique salt pool signature consisting of water-saturated dark-gray mud often containing fragments of *Ruppia maritima*. Cores through pool sediment reenter salt marsh peat, not tidal flat sediment, demonstrating that most pools are of secondary origin. A principal component analysis of attribute data collected from 119 pools defines three distinct pool types: those with (1) surrounding high-marsh vegetation and thick heavily undercut banks (40% of the variance), (2) surrounding low-marsh vegetation and thicker slightly undercut banks (18% of the variance), and (3) surrounding low-marsh vegetation and less thick moderately undercut banks, containing *R. maritima* and a surficial drainage (15% of the variance). Cores and spatiotemporal analyses of aerial photographs between 1962 and 2003 reveal dramatic salt marsh surface dynamism suggesting that salt pools influence the geomorphological evolution of coastal marshes.

Keywords Ecogeomorphology · Sea level · Cores · Aerial photographs

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Introduction

Salt pools are shallow water-filled depressions common to many north-temperate salt marshes (Redfield 1972). Despite their widespread occurrence, pools are less understood than the vegetated marsh surface. The ultimate origin of pools, a classification of their properties, and the processes governing their development over time are all unresolved issues.

Earlier work focuses on salt pool genesis, specifically whether pools are primary features that begin on a tidal flat that later become surrounded by vegetation (Yapp et al. 1917) or secondary features that result from disturbance to a vegetated marsh, including: enduring algal mats (Harshberger 1916), tidal wrack (Ranwell 1964), and/or snow patches (Chapman 1960); scour, plucking, and/or sediment deposition from ice (Argow and Fitzgerald 2006); inadequate drainage resulting in waterlogged substrate (Redfield 1972); insufficient sedimentation and/or peat compaction (Redfield 1972); and intentional creation, e.g., from collapsed man-made ditches (Miller and Egler 1950). In coastal Louisiana, pool formation and enlargement are clearly contemporary processes that are directly linked to deltaic salt marsh fragmentation and breakup (Turner 1997; Day et al. 2000).

These competing hypotheses of pool formation (primary versus secondary origin) lend themselves to predictions of salt marsh stratigraphy tested through coring. If pools are primary features of salt marshes, then tidal flat sediment (muddy, sandy sediment likely containing shells of *Mya arenaria*) should underlie the salt pool sediment. If, however, pools are secondary features of salt marshes, then salt marsh peat, rather than tidal flat sediment, should underlie pools.

Understanding the role of salt pools within salt marsh environments is essential because (1) pools serve as important habitat for some estuarine plants and animals (MacKenzie and Dionne 2008) and it is likely that these organisms respond to within-pool habitat variations (Mandracchia and Ruber 1990; Master et al. 2005) and (2) pools contribute to salt marsh fragmentation and presage considerable wetland loss in some areas (Kearney et al. 1988; DeLaune et al. 1994; Hartig et al. 2002; Baily and Pearson 2007).

This last argument is critical as it touches upon the potentially dynamic nature of salt pools. Most studies that mention changes in salt pool morphology are descriptive (Chapman 1960; Redfield 1972), though a few are quantitative (Kearney et al. 1988; Adamowicz and Roman 2005). In addition, most studies express this dynamism as unidirectional, with salt pools generally enlarging over time, often hypothesized as the inability of the salt marsh to keep pace with rising sea level (Kearney et al. 1988; van Huissteden and van de Plassche 1998; Hartig et al. 2002). A few studies note that some salt pools may enlarge while others on the marsh surface contract (Redfield 1972; Boston 1983; Cavatorta et al. 2003) or that a single pool may enlarge at one end while contracting at the other (Yapp et al. 1917; Miller and Egler 1950). However, no previous studies provide evidence that pools may switch between processes of expansion and contraction over a given period of time.

The objectives of this study in the Webhannet Estuary, Wells, ME, USA are to:

(1) Describe the stratigraphic signature of salt pools
(2) Determine if salt pools are of primary or secondary origin
(3) Characterize salt pools based upon ecogeomorphological attributes
(4) Assess and describe the potential dynamic nature of salt pools through geologic coring and spatial analyses of a time series of aerial photographs between 1962 and 2003

Through these analyses, we will also address the larger question of whether salt pools presage the breakup of a New England salt marsh as these features do in other areas.

Materials and Methods

The study area is in the Wells National Estuarine Research Reserve and the Rachel Carson National Wildlife Refuge in the Webhannet Estuary, Wells, ME, USA (Fig. 1). This estuary is almost entirely tidal (Byrne and Ziegler 1977) and underlain by thick deposits of peat (3–5 m) up to 4,000 years old (Belknap et al. 1987, 1989; Kelley et al. 1995). The salt marsh surface is dominated by high-marsh meadow (~359 ha, mostly *Spartina patens*) intermixed with forb pannes (dominantly *Triglochin maritimum* and *Plantago maritima*), with the low-marsh plant *S. alterniflora* typically occurring along borders of tidal creeks and at lower elevations (~29 ha; Ewanchuk and Bertness 2004; Jacobson and Jacobson 1987). Salt pools are common (~51 ha; Kelley et al. 1995; Dionne unpublished data).

To determine whether a unique salt pool signature was definable and to test hypotheses regarding pool formation, we collected eight Eijkelkamp ("Dutch") hand auger cores from five pools in two locations of the Webhannet Marsh (Fig. 1). Roots, rhizomes, and stem fragments were visually identified and recorded in the field or in cores returned to the laboratory. We also reviewed the core logs and photographs of 36 Dutch and vibracores collected in 1984 to determine whether the unique salt pool signature described in 2005 could identify pool environments in previously logged cores and to verify patterns of pool development (Fig. 1; Belknap et al. 1989; Kelley and Belknap unpublished data).

We sampled 119 pools along six transects during the summers of 2004 and 2005 (Fig. 1). For each pool, we recorded presence/absence of a surficial outlet, the submerged aquatic plant *Ruppia maritima*, and *S. alterniflora* invasion into the pool. To calculate bank thickness (pool sediment–water interface to the salt marsh surface) and bank undercut values, we calculated the mean of five measurements per pool. To determine the adjacent vegetation type, we recorded the visual percentage cover in three 1-m^2 quadrats per pool. Quadrat locations were randomly determined except when neighboring pools precluded this, in which case, quadrats were located to prevent resampling.

To reduce the complex structure of these interrelated variables with the minimal loss of information, we employed a principal components analysis (PCA; SYSTAT 2004). For this analysis, percent cover vegetation values from each pool were combined and recalculated out of 300% then grouped into vegetation classes that reflect gross responses to marsh elevation: percent low marsh (*S. alterniflora* and mud), percent forb panne (*Agalinis maritima*, *Glaux maritima*, *Limonium nashii*, *Plantago maritima*, *Salicornia europaea*, *Suaeda linearis*, and *T. maritimum*), and percent high marsh (*Atriplex patula*,

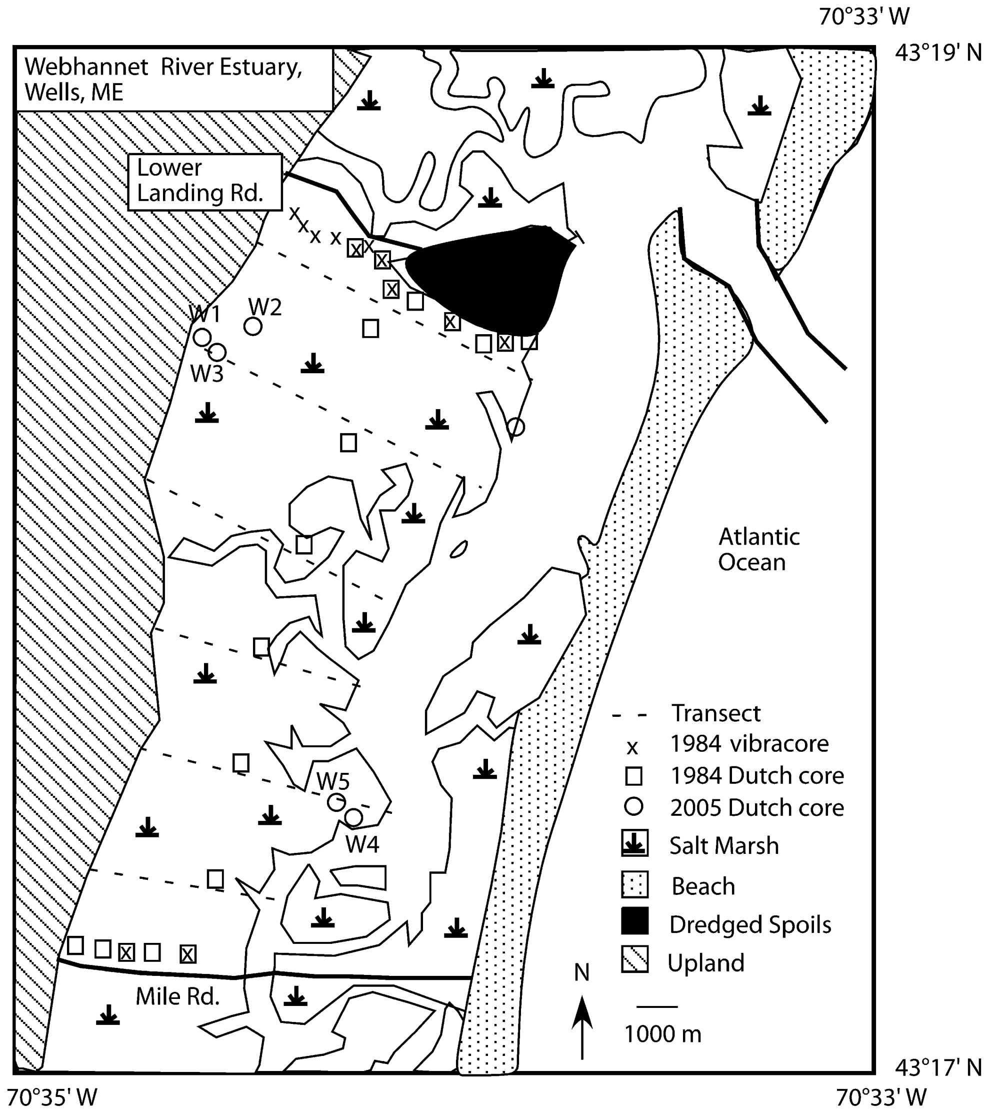


Fig. 1 Map of the study site in Wells, ME, USA, indicating transect and core locations

Distichlis spicata, *Juncus gerardii*, *Potentilla anserina*, *Puccinellia maritima*, and *S. patens*).

To assess potential salt pool dynamism and to quantify recent patterns of surficial change, we obtained scanned aerial photographs from 1962, 1977, 1991, and 2003 (Table 1). All images are from the same approximate tidal stage, though we do not know if a spring or neap tide or a large precipitation event immediately preceded the time of each image capture.

We georeferenced all photographs to the 2003 image using a set of well-distributed points and mosaicked photographs as needed (ERDAS 2006). Starting with the 2003 image, we screen-digitized 50 of the 119 field-sampled pools, then digitized each of those pools in each preceding image. Not all field-sampled pools were identifiable in the 2003 photograph; identification was biased toward larger and deeper (higher reflectance) pools that were uniquely shaped and/or spatially isolated.

Table 1 Date, type, scale, and source of the aerial photographs used in the spatial analyses of salt pools of the Webhannet Estuary, Wells, ME, USA

Date	Type	Scale	Source
1962	Black and white	1:20,000	Maine Geological Survey
1977	Black and white	1:12,000	Maine Geological Survey
1991	Color infrared	1:12,000	Maine Geological Survey
2003	Color positive	1:2,400	Maine Office of Geographic Information Systems

From the digitized data, we produced an event sequence for each pool over the time period from 1962 to 2003. In this method, each photograph represents a distinct marsh state and the resultant table records both the number and nature of salt pool events (birth, life, merge, split, and death) resulting in the marsh state observed (Table 2). This type of analysis quantifies the processes (but not area changes) that contribute to surficial salt marsh dynamics by tracking individual pools through time. By knowing the "start" (1962) and "end" (2003) shapes of an individual pool, one can describe the type(s) and number(s) of event(s) that occur between marsh states to that pool that result in the pool shape metamorphosis observed (if one occurs; Table 3). This method may underestimate true event activity because it is limited by the number and quality of the aerial images (marsh states) available for analysis.

Of the 50 digitized pools, 30 were then included in area and shape analyses (those recording "life" in all marsh states). These pools were selected because: (1) they exhibited the most common event sequence observed (60% of tracked pools) and (2) persistent "life" in all four states may wrongly imply stasis, an observation we wished to address. Area and perimeter values were automatically calculated (ERDAS 2006). We used the area values to calculate percent change in area, where a negative percentage indicates a loss of pool area:

$$\text{Percent change} = (\text{area in time}_2 - -\text{area in time}_1)/\text{area in time}_1 \times 100$$

To quantify pool shape, we calculated normalized circularity values, where quantities close to one indicate pools closest in form to a circle, while quantities close to zero indicate highly irregularly shaped pools (Pratt 2001):

$$\text{Normalized circularity} = 4\pi \times \ \text{area}/\text{perimeter}^2$$

When graphed versus time, these values show trends in individual pool shape. Pools with similar values for all time periods graph close to a straight line, indicating little shape change. Pools with dissimilar values for each time period graph as irregular lines, indicating more drastic shape changes over time.

Table 2 A verbal and pictorial description of each type of pool event used to create the individual pool event sequences observed to occur on the Webhannet Marsh surface over the time period 1962–2003

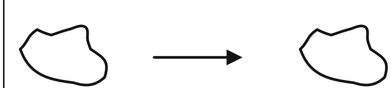
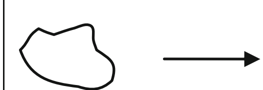
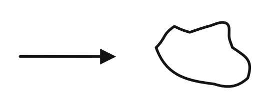
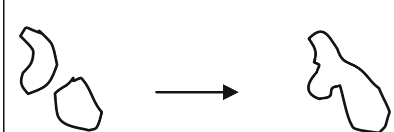
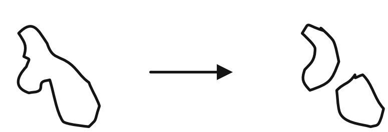
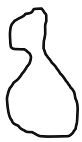
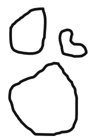
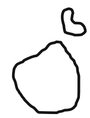
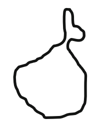
Pool Event	Code	Verbal Description	Pictorial Description Time 1 Time 2
Life	L	Existence of a pool on the marsh surface.	
Death	D	Disappearance of a pool on the marsh surface that cannot be explained by merging or splitting processes, such that standing water is not observed.	
Birth	B	Spontaneous appearance of a pool on the marsh surface that cannot be explained by merging or splitting processes, such that standing water is observed.	
Merge	M	The process of two or more pools coalescing to form one pool. The number of pools coalescing determines the number of merge events.	
Split	S	The process of a pool breaking apart into one or more other pools. The number of resultant pools determines the number of split events.	

Table 3 The event sequence and associated pictorial descriptions for a hypothetical pool depicting its shape metamorphosis, to demonstrate how pool events are recorded to produce Table 5. A hypothetical example is used so that all pool events are shown. The example illustrates how numbers greater than one can be recorded in Table 5. Pool events (a split and a birth, in this example) may result in multiple pools (3 L, in the 1977 state), while later events (a death recorded in 1991) reduce that number (2 L in 1991). Additional events in a later time period, like a merge, further reduce the number of pools (1 M and 1 L in 2003, in this example). Photographs are georeferenced so pool events are clearly distinguished between states. Letters refer to the event codes given in Table 2

	1962	1977					1991					2003				
	L	M	S	L	D	B	M	S	L	D	B	M	S	L	D	B
Pool X	1	0	1	3	0	1	0	0	2	1	0	1	0	1	0	0
Pictorial Description																

Results

Salt Pools in the Stratigraphic Record

Dutch cores collected in 2005 reveal a unique and consistently identifiable salt pool signature. Pool sediment is typically a water-saturated dark-gray mud often containing fragments of the submerged aquatic plant, *R. maritima* (Fig. 2). We identified this unit both at the pool sediment–water interface and at depth within some cores (Fig. 3). When occurring in the subsurface, the pool unit frequently had *S. alterniflora* roots penetrating the pool facies from above. We confidently identified this signature in six of the 36 1984 Dutch and vibracore logs (Fig. 3).

The 2005 cores reveal that all sampled pools are secondary features of the Webhannet Marsh because all pools formed over salt marsh peat, not tidal flat sediment (Fig. 3). Low or high/low mixed salt marsh environments typically underlie the pool units for the 2005 cores (but see the “neck” of pool W5; Fig. 3). The 1984 cores reveal similar patterns, though they exhibit greater variation. Only one of these six cores (WDC2) was taken through a 1984 extant salt pool; the remaining five cores were collected through 1984 vegetated salt marsh surfaces along the transect that parallels Lower Landing Road (Fig. 1). Almost all of these pools are secondary features underlain predominantly by low or high/low mixed salt marsh environments, though high marsh (WDC4, WDC8) and freshwater peat (WDC4) underlie some pool units (Fig. 3). The lower salt pool unit of core WDC8 is suggestive of a primary origin, although vegetated layers occurred in the core as well (Fig. 3).

Salt Pool Characterization

The first three principal components of the PCA explain 73% of the total variance of the data (Table 4) and reveal three distinct pool types (Fig. 4). The first pool type has relatively thick heavily undercut banks, is surrounded by high-marsh vegetation, and does not have *S. alterniflora* invasion into the pool (40% of the total variance; Table 4; Fig. 4a). The second pool type has very thick but only slightly undercut banks, is surrounded by low-marsh vegetation with few forbs, and lacks both a surficial drainage and *R. maritima* (18% of the total variance; Table 4; Fig. 4b). The final pool type has less thick moderately undercut banks, contains *R. maritima*, and is surrounded by low-marsh vegetation (15% of the total variance; Table 4; Fig. 4c). We observed no strongly associated trends between pool types and either shape or location on the salt marsh, though pools described by Fig. 4a tended to be circular.

Salt Pool Dynamism

Both geologic cores and spatial analyses reveal that salt pools are dynamic features of the Webhannet Marsh. Half of all cores demonstrate this dynamism, with the salt pool unit occurring multiple times within a single core, interspersed among vegetated marsh states (Fig. 3). Multiple spatial analyses also confirm this pattern. All event processes (life, death, birth, merge, and split) occur on the marsh surface, though not all pools experienced all five processes (Table 5). The most common event sequence was for a pool to experience life in all four states (60% of pools; Table 5). Pools not exhibiting this event sequence tended to experience a combination of events since 1962 and were likely to undergo both splits and merges (Table 5). The periods from 1962 to 1977 and 1977 to 1991 were most active in terms of the number of merge and split events recorded (Table 5).

Further analyses of pools exhibiting the most common event sequence (L in all four states; $n=30$) demonstrate that these pools were highly dynamic over the 1962 to 2003

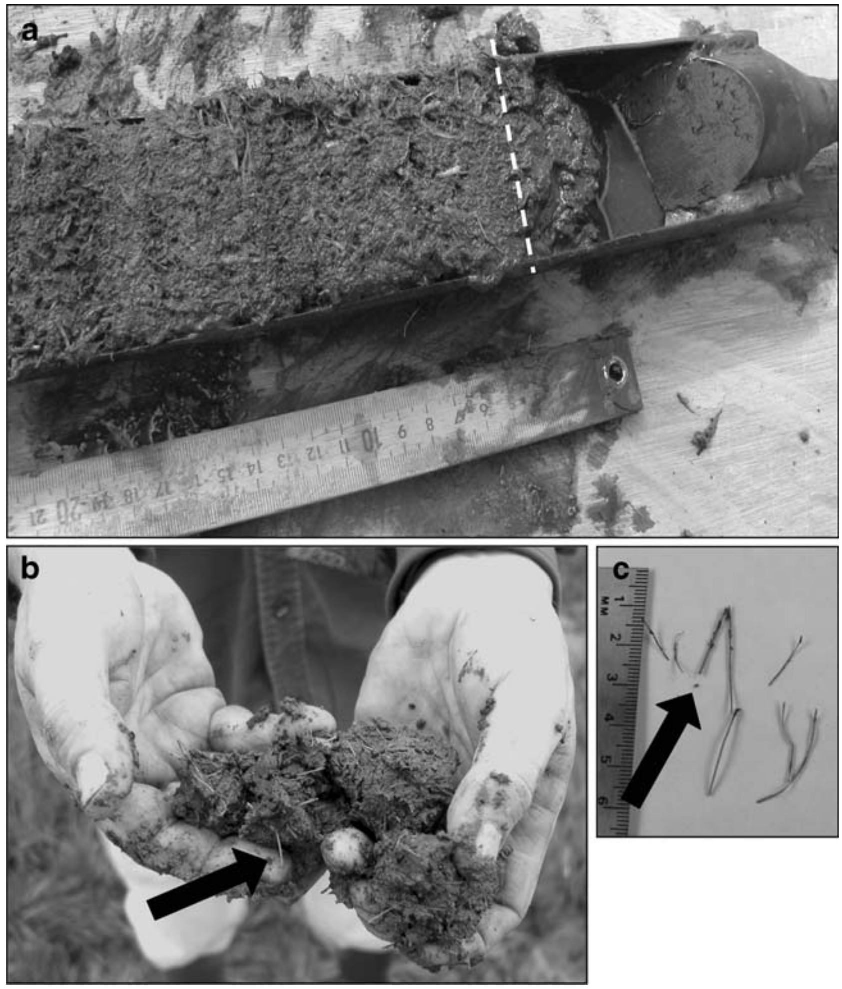


Fig. 2 The salt pool unit as revealed by a Dutch core from the surface of a pool (*right* of the *dotted line*, **a**). The signature is characterized by water-saturated dark-gray mud, often containing distinct unrooted fragments (1–3 cm in length) of the submerged aquatic plant, *Ruppia maritima* (see *arrows* in **b** and close-up in **c**). This signature was identifiable not only at the sediment–water interface but also at depth within some cores (see Fig. 3)

time period. All pools experienced shape and area changes, with individual pools exhibiting different patterns of change over that time (Fig. 5). Most pools were irregularly shaped and changes in shape and area were not unidirectional over time. Instead, individual pools both expanded and contracted with the sequence of area change varying by pool. The most common pattern was for a pool to contract, then expand, then contract (15 of 30; Table 6). Most pools decreased in area between 1962 and 2003 (24 of 30, 80%). In all time periods, simultaneous expansion and contraction of pools occurred (Fig. 5). This suggests that pool area (and percent change) was not uniformly influenced by local precipitation or drought events nor by extreme high or low tidal excursions.

Discussion

Salt Pool Identification in the Stratigraphic Record

Cores collected in 2005 and core logs from 1984 reveal a unique and consistently identifiable salt pool signature. The water-saturated dark-gray mud of pools is consistent with characterizations by Gehrels (1994) and van Huissteden and van de Plassche (1998), although they did not note the presence of *R. maritima* (Fig. 2). Though *R. maritima* is observed in association with salt pool environments (Yapp et al. 1917; Miller and Egler 1950), it has not been formally described within the stratigraphic record as a unique salt pool identifier until this study. Of further distinction is the low-marsh peat deposit that typically succeeds the pool deposit at depth. This observation is consistent with those of Ward et al. (2008). Earlier work often interpreted this sequence as a succession from a tidal flat or creek to a low-marsh environment but is now recognized as the infilling of a shallow pool or the colonization of a drained pool by *S. alterniflora*.

Two potential problems arise in the identification of pool deposits: (1) pools may not contain *R. maritima* and (2), at depth, sediment compaction may obscure the salt pool unit. Although the stratigraphic position of a pool deposit aids identification, additional physical, geochemical, isotopic, and/or macrofossil and microfossil markers would be advantageous to further constrain the salt pool signature.

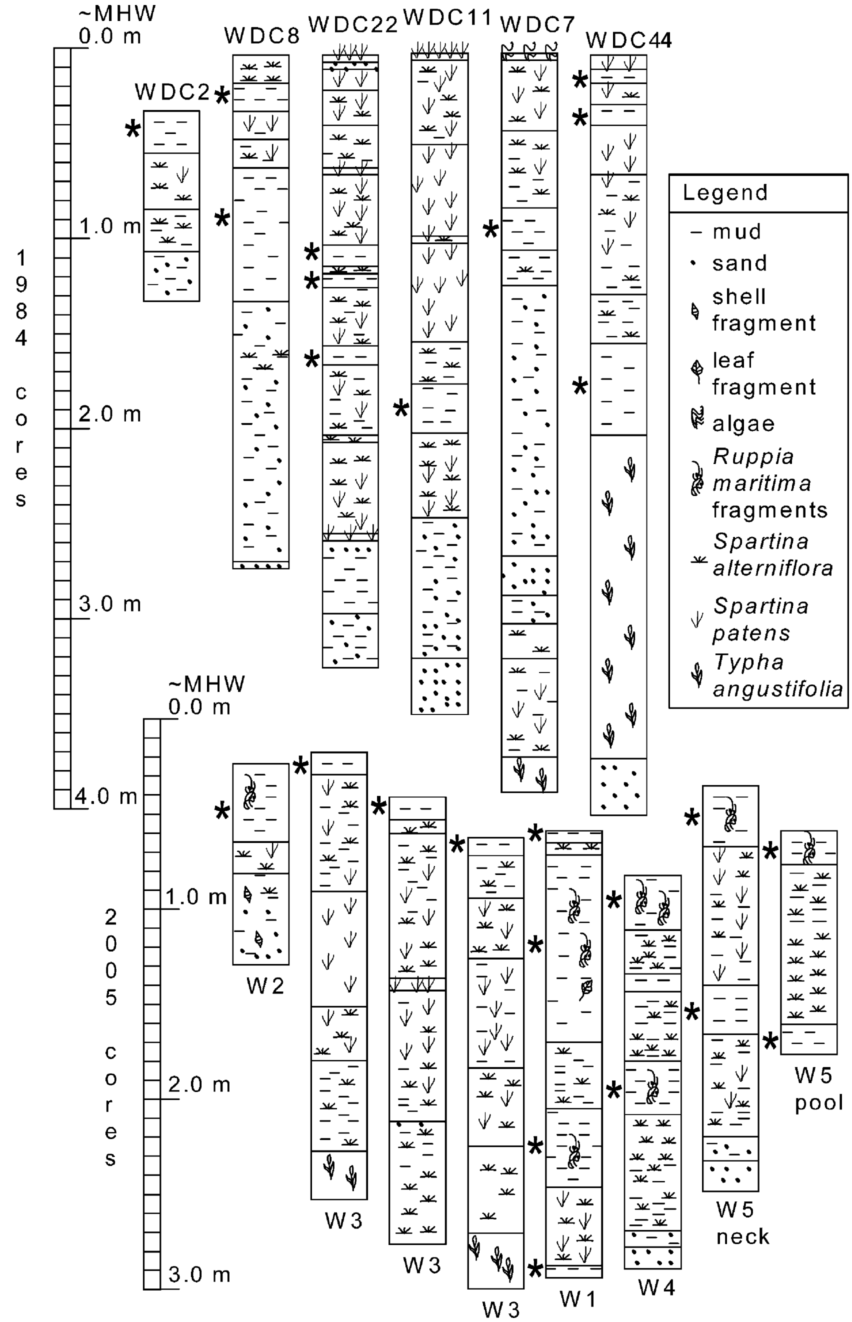


Fig. 3 Stratigraphic sequences of the eight Dutch cores collected from salt pools in 2005 (*bottom*) and the records of those 1984 cores that showed evidence of salt pool environments (six of 36 Dutch and vibracore logs; *top*). Only one 1984 core (WDC2) was taken through a 1984 pool; the remaining 1984 cores were taken through the vegetated salt marsh surface. *Asterisks* indicate salt pool environments. The records show that almost all salt pools are secondary and often dynamic features of this environment (pool sediment occurs above salt marsh peat in most cases and interspersed among vegetated marsh states within the same core, respectively)

Salt Pools: Primary or Secondary Features of Salt Marsh Environments?

The results of this study support the hypothesis that many pools of the Webhannet Marsh are secondary features. All cores, with one possible exception, reveal that pools formed secondarily because salt marsh peat, not tidal flat sediment, underlies pool deposits (Fig. 3). If the stratigraphic records of these cores are conformable, the stratigraphic units directly underlying pool deposits indicate that pools form in low or high/low mixed salt marsh environments. These contacts may be erosional, however, as the result of sulfate reduction (van Huissteden and van de Plassche 1998) and/or destructive disturbances like ice plucking (Argow and Fitzgerald 2006) that remove material from the stratigraphic record. If this is the case, the records simply indicate that pool origin was secondary and do not inform us about the microenvironment in which they formed. The event tree analysis also supports the hypothesis that many pools are secondary features as evidenced by the three pool “births” recorded in Table 5. These results are consistent with studies that note the appearance (Cavatorta et al. 2003) and increased density (Pethick 1974) of salt pools over time, in turn

Table 4 Results of the PCA showing the component loadings for each variable and the percent of the total variance of the original data explained by each principal component

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
Presence/absence of *Ruppia maritima*	0.145	−0.512	0.578	−0.565	0.229	0.038	−0.101	0.000
Presence/absence of a surficial outlet	−0.138	−0.720	−0.095	0.500	0.445	0.071	0.002	0.000
Presence/absence of *Spartina alterniflora* invasion	−0.761	−0.308	−0.217	−0.241	0.006	−0.345	0.319	0.000
Average bank undercut	0.775	0.005	0.244	0.231	0.012	−0.529	−0.118	0.000
Average bank thickness	0.739	0.189	0.474	−0.137	0.083	0.122	0.391	0.000
Percent high-marsh vegetation	0.799	0.003	−0.519	−0.224	0.203	0.012	0.028	0.000
Percent forb panne vegetation	0.352	−0.695	0.029	0.093	−0.614	0.073	0.028	0.000
Percent low-marsh vegetation	−0.839	0.191	0.473	0.182	−0.018	−0.031	−0.033	0.000
Percent of total variance explained	40.4	17.9	14.6	9.8	8.5	5.3	3.5	0.0

largely rejecting the hypothesis first proposed by Yapp et al. (1917) that pools are of primary origin.

The sequence of deposits (clean sand to muddy sand) beneath the lower pool unit of core WDC8 does suggest that this pool is of primary origin, however. Assuming that the stratigraphic sequence is conformable, the sequence may be interpreted as a pool formed via damming from tidal creek bank collapse, meeting the

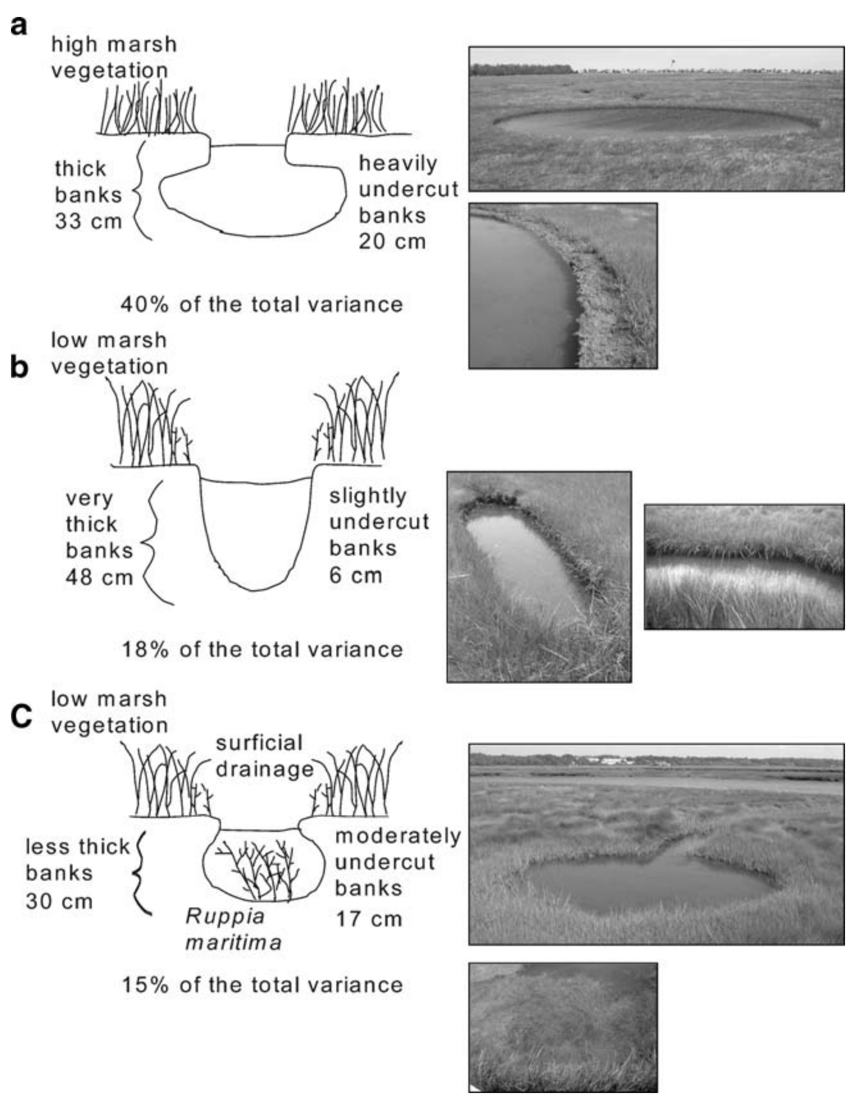


Fig. 4 **a**–**c** The three pool types as revealed by the principal component analysis (n=119). The cartoons are in cross section and describe the characteristic features of each pool type. Mean bank thickness and mean bank undercut values are given for each pool type. Pictures taken in the field reflect real-life examples of each pool type

Table 5 Event sequence analysis quantifying the number of events (life (L), death (D), birth (B), merge (M), split (S)) resulting in each marsh state (1962, 1977, 1991, 2003; $n=50$). The year 1962 is the reference state, so only the life event is recorded. This type of analysis follows individual pools through time, quantifying events that affect the salt marsh surface

Pool ID	1962	1977					1991					2003				
	L	M	S	L	D	B	M	S	L	D	B	M	S	L	D	B
1	1	0	0	1	0	0	0	0	1	0	0	0	1	2	0	0
2	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
3	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
4	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
5	18	17	2	3	0	0	6	60	57	0	0	5	5	43	14	0
6	1	0	10	11	0	0	0	0	10	1	0	2	0	8	1	0
7	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
8	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
9	1	0	1	2	0	0	0	1	3	0	0	1	0	2	0	0
10	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
11	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
12	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
13	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
14	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
15	1	0	1	2	0	0	1	0	1	0	0	0	1	2	0	0
16	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
17	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0
18	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
19	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0
20	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
21	1	0	0	1	0	0	0	1	2	0	0	0	0	1	1	0
22	1	0	2	3	0	0	0	1	4	0	0	0	0	3	1	0
23	2	1	0	1	0	0	0	0	1	0	0	0	1	2	0	0
24	1	0	0	1	0	0	0	1	2	0	0	0	0	1	1	0
25	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
26	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
27	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
28	2	0	1	3	0	0	1	0	2	0	0	0	1	3	0	0
29	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0
30	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
31	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
32	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
33	1	0	0	1	0	0	0	0	1	0	0	0	1	2	0	0
34	1	0	0	1	0	0	0	1	2	0	0	0	0	2	0	0
35	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
36	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
37	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
38	1	0	2	3	0	0	0	0	3	0	0	0	0	3	0	0
39	1	0	2	3	0	0	2	0	1	0	0	0	0	1	0	0
40	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
41	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
42	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
43	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
44	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
45	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0

Table 5 (continued)

Pool ID	1962	1977					1991					2003				
	L	M	S	L	D	B	M	S	L	D	B	M	S	L	D	B
46	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
47	1	0	3	4	0	0	0	0	4	0	0	1	1	3	0	0
48	23	15	0	8	0	0	6	0	2	0	0	1	0	1	0	0
49	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
50	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
Totals	87	33	24	78	0	2	16	65	129	1	1	10	11	113	18	0

criteria for a primary pool as outlined by Yapp et al. (1917). The low incidence of pools of primary origin in this study substantiates Miller and Egler (1950) who predict a low occurrence of primary pools on a "mature" marsh surface (or one that is thousands of years old, like the Webhannet Marsh).

Our results also suggest an alternate mechanism for pool formation. Core WDC4 reveals freshwater peat beneath the

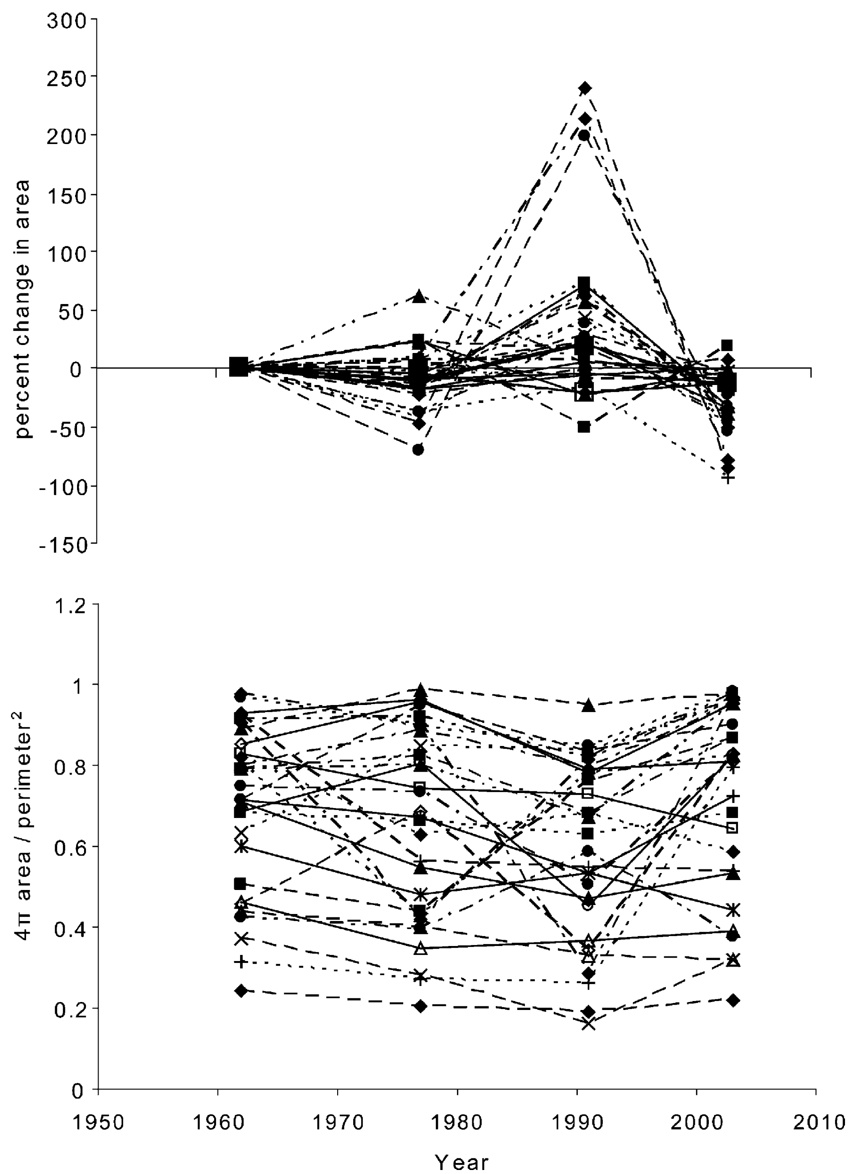


Fig. 5 *Lines* trace the changes in area and shape for individual pools. Analyses reveal that individual pools are dynamic over the 41-year time period from 1962 to 2003 (n=30). Area indicates a percent change in area while changes in shape are captured by calculating normalized circularity values for each pool for each time. Individual pools are marked by differences in *symbols* and *lines*

Table 6 The number of pools experiencing each potential change in area sequence for each marsh state (1962–1977, 1977–1991, 1991–2003; n=30)

Pattern of area change			Number of pools
1977	1991	2003	
Loss	Gain	Loss	15
Gain	Gain	Loss	4
Loss	Loss	Gain	3
Gain	Loss	Loss	3
Gain	Loss	Gain	3
Loss	Gain	Gain	2
Loss	Loss	Loss	0
Gain	Gain	Gain	0

salt pool unit (Fig. 3). If the record is conformable, it suggests that pools may form during the transition from freshwater to salt marsh environments as the freshwater wetland surface becomes increasingly inundated by salt water, as suggested by Miller and Egler (1950). The contact may be erosional; nevertheless, the pool is a secondary feature.

An Ecogeomorphologic Characterization of Salt Pool Environments

Results of the PCA (Table 4; Fig. 4) reveal three pool types distinct to the Webhannet Marsh and indicate variation in salt pool ecogeomorphic characteristics. These results confirm observations from other studies that recognize similar variation in pool attributes at the salt marsh landscape scale (Yapp et al. 1917; Miller and Egler 1950;

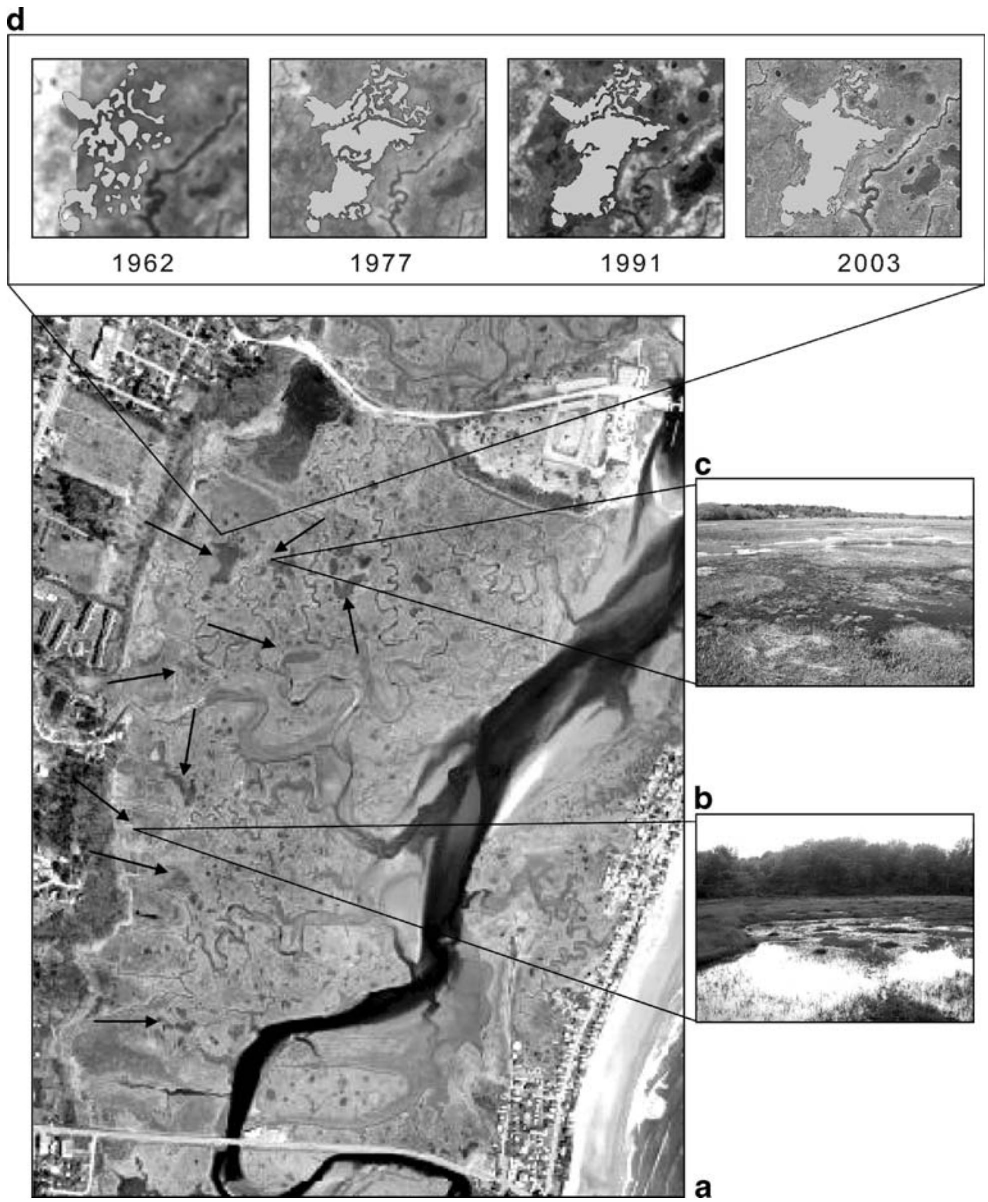


Fig. 6 Aerial photograph from 2003 with *arrows* indicating large pools in interior marsh sections, located far from tidal creeks (*a*). These areas may experience reduced sedimentation rates and expand via surficial flooding and coalescence with neighboring pools, as the close-up pictures from 2005 (*b*, *c*) and the time series of aerial photographs show (*d*)

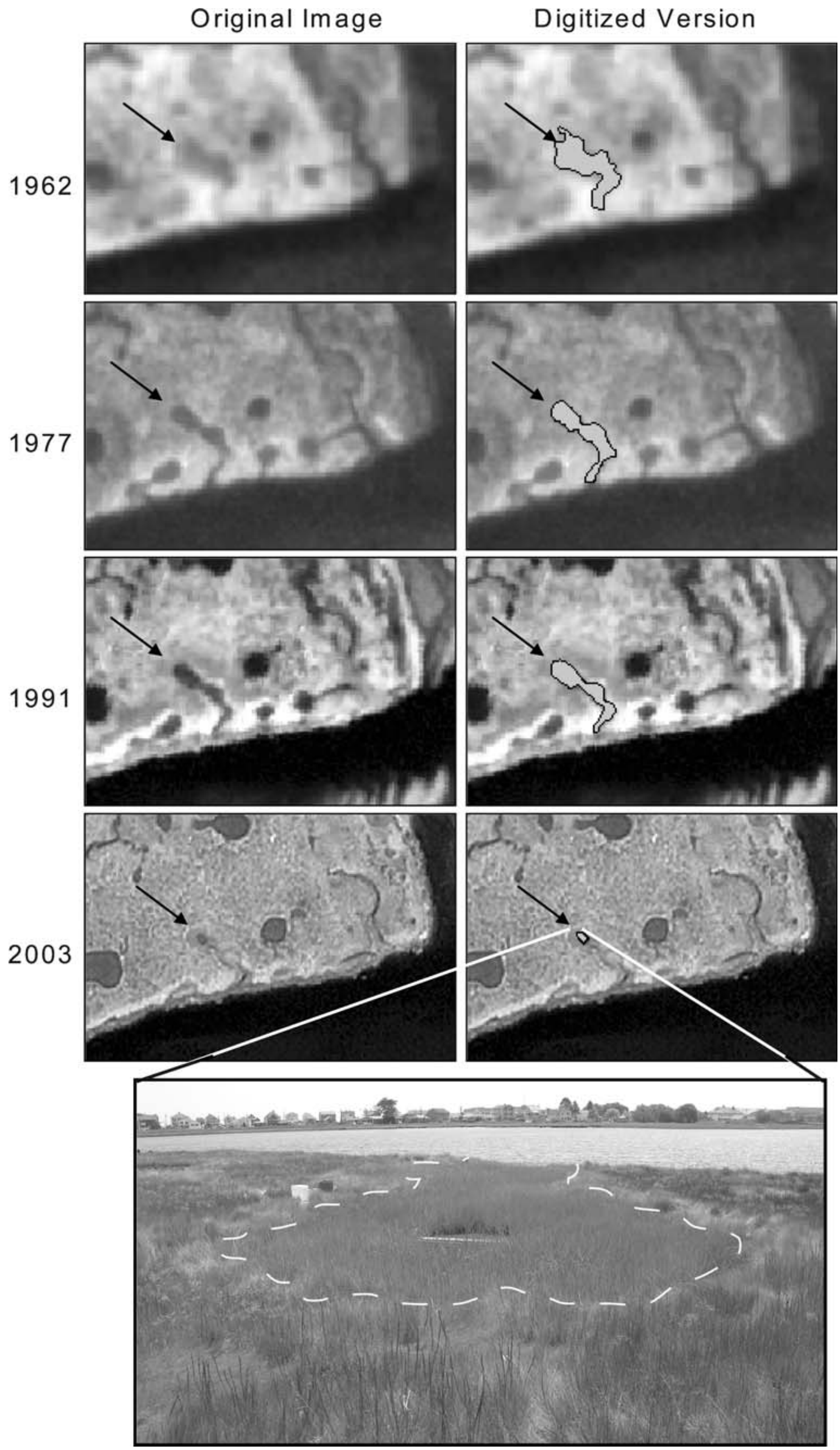


Fig. 7 Pool W4 experienced dramatic shape and area changes over the time period from 1962 to 2003 by being "tapped" and drained by the nearby tidal creek (the *dark area* surrounding the point of land in each image). *Arrows* highlight the pool in each image (original image left, digitized image right). The photograph on the *bottom* is pool W4 in the field in 2005. Its previous extent remains visible (*dotted line*) as it has in-filled with *Spartina alterniflora*, distinct from the surrounding high-marsh platform. A small vestigial pool remains in the center and may continue to drain or act to nucleate subsequent pool expansion. The location of pool W4 is given in Fig. 1

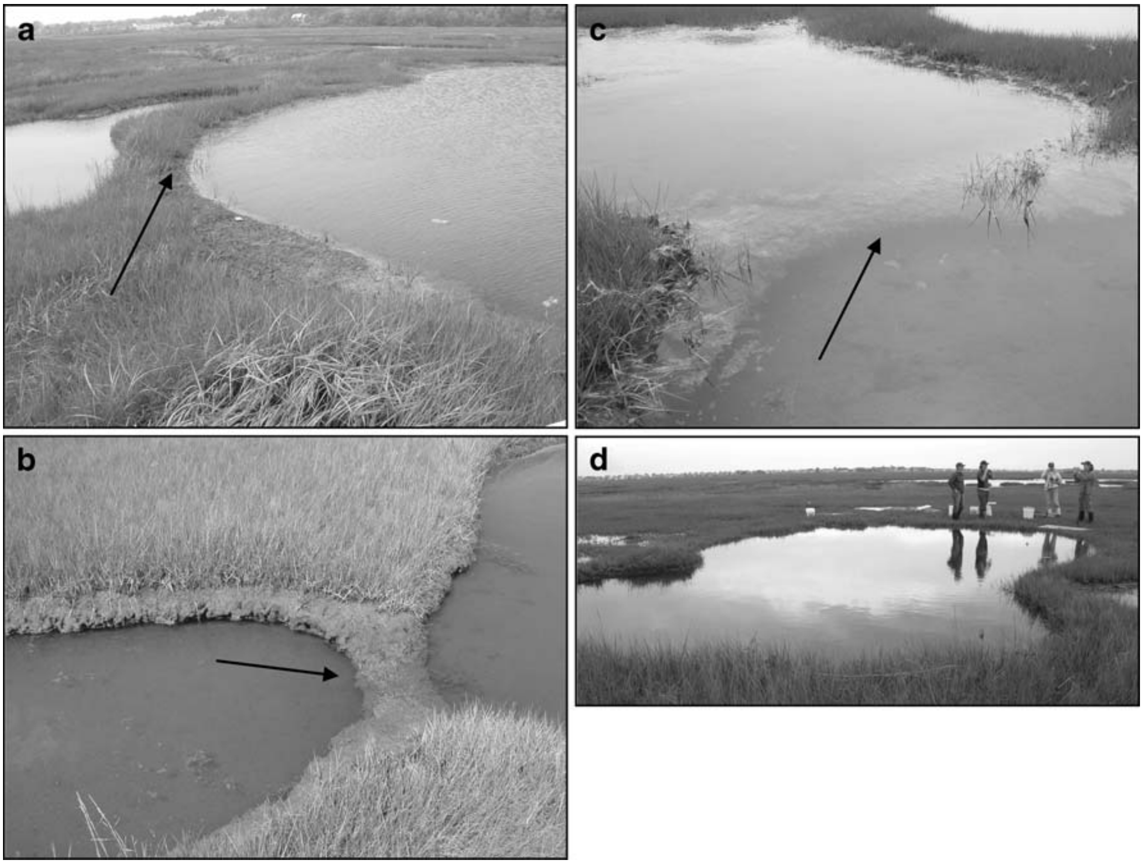


Fig. 8 An example of how neighboring pools may merge over time by connections in the subsurface, as suggested by van Huissteden and van de Plassche (1998). Photographs are from 2004 to 2005 and represent a mosaic of pools (from the overall group studied) experiencing different stages of this process. *Arrows* highlight the "land bridge" or "ridge" (sensu Redfield (1972)) feature of interest. Seemingly distinct pools separated by an intact "land bridge" may actually connect in the subsurface (**a**). Over time, this subsurface connection may destabilize the "land bridge" causing it to collapse and submerge (**b** and **c**). Eventually, the submerged "land bridge" may degrade and altogether disappear, resulting in the merge of the two pools (**d**)

Chapman 1960; Adamowicz and Roman 2005). It is likely that these among-pool differences influence the distribution and abundance of facultative pool species, though this study does not address what drives those differences or what ecological patterns they may in turn generate. This study provides a foundation for future work that seeks to explain or predict ecological patterns in pool flora and fauna diversity based on ecogeomorphic attributes. For example, pools described by Fig. 4a with severely undercut banks or "overhangs" (sensu van Huissteden and van de Plassche 1998) or pools described by Fig. 4c with *R. maritima* and a surficial outlet may host greater or more diverse nekton populations by providing refuge, forage, and/or access to the microhabitat.

The presence of circular pools, like those described by PC1 of this study (Table 4; Fig. 4a), is noted in the literature (Yapp et al. 1917; Chapman 1960); however, it is unclear why these pools maintain that form. Perhaps they expand uniformly in a homogenous subsurface and/or maintain their shape via eddies formed during tidal flooding, as suggested by Yapp et al. (1917) and Chapman (1960). More likely, a connection may exist between their shape and the surrounding marsh vegetation type. The thick fibrous *S. patens* peat allows bank overhangs of greater than 1 m to persist in some places (personal observation). Expansion occurs in the subsurface via oxidation that undercuts pool banks (van Huissteden and van de Plassche 1998), leaving the surficial peat layer intact while masking an irregularly shaped pool in the subsurface. Redfield (1972) too notes round pools (his "potholes") occur preferentially in high marsh.

Other pools that are shallower, more irregularly shaped, and surrounded by low-marsh vegetation (like those described by PC3 and Fig. 4c) may experience a different mode of pool expansion via surficial flooding of the adjacent salt marsh surface. Prolonged flooding may kill vegetation through water logging and salinity stress and may result from decreased sedimentation rates, peat compaction, or an elevated water table due to a large tidal or precipitation event. This mode of expansion may be

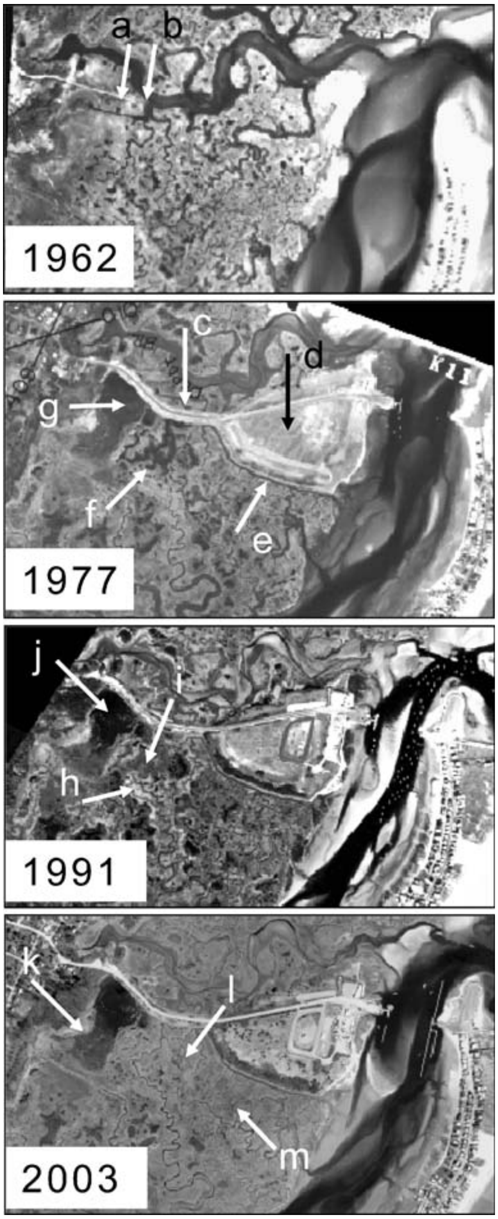


Fig. 9 Time series of aerial photographs indicating the area of the Webhannet Marsh closest to Lower Landing Road. *Arrows* and *letters* highlight changes in surficial marsh hydrology as a result of the construction of Lower Landing Road and the creation of the dredge spoils and drainage ditch. The 1962 photograph shows the extent of Lower Landing Road (*a*) and an arm of the main tidal channel (*b*) before major road construction in the mid-1960s. By 1977, the channel arm is cut off by construction of the road (*c*) and the hydrology of the marsh altered by the weight of the dredge spoils (*d*) and the existence of a dredged drainage ditch (*e*). Large pools have formed via flooding in areas where small tidal creeks (*f*) and small pools (*g*) once were located. By 1991, tidal creeks (*h*) have worked their way into portions of the flooded area draining some of the 1977 pool area (*i*). The large pool south of Lower Landing Road remains intact (*j*), however, and by 2003 has expanded considerably (*k*). Other large pools (*l*, *m*) have drained via tidal creek capture during that time period, likely due to the weight of the dredge spoils on the salt marsh surface and the surrounding dredged drainage ditch

common in areas of interior marsh, in locations far from tidal creeks that experience reduced sedimentation rates (Temmerman et al. 2005). Continued submergence of the marsh surface may inhibit vegetative growth and propagate continued pool expansion through merges with neighboring pools (Redfield 1972; Kirwan et al. 2008). This process is observed in our aerial photograph analyses and may result in the swath of large shallow pools observed in interior sections of the Webhannet Marsh (Fig. 6).

Salt Pools: Dynamic Features of North-Temperate Salt Marshes

Our results confirm that salt pools of the Webhannet Marsh are highly dynamic (Figs. 3 and 5, Table 5). Identification of a unique salt pool signature reveals that some pools are ephemeral, draining, revegetating, becoming pools again, and either staying as such or once more revegetating (Fig. 3, cores W1, W4, W5 neck, W5 pool, WDC4, WDC8, and WDC22). Spatiotemporal analyses confirm these patterns (Tables 4 and 5; Fig. 5). Event trees show pools experiencing a multitude of events, including birth, death, merges, and splits, all of which are dynamic processes (Table 5). Despite 60% of pools recording the seemingly static “life” for all four marsh states, the majority of these pools experienced dramatic changes in both shape and area over the 41-year time period (Fig. 5; Table 6).

The idea of salt pool dynamism is not new, yet it has been slow to gain traction, and few studies have documented the phenomena in as comprehensive a manner as this one. Pethick (1974) and Cavatorta et al. (2003) both identify an increase in pool density over time. Other studies describe how small pools coalesce to form large pools (Redfield 1972; Kearney et al. 1988; van Huissteden and van de Plassche 1998; Day et al. 2000; Hartig et al. 2002) or that large pools may subdivide to form small pools (Yapp et al. 1917; Chapman 1960). Individual pools may simultaneously experience processes of expansion and contraction (Miller and Egler 1950) or become captured by nearby tidal creeks in the surface or subsurface, drain, and partially revegetate, leaving remnant pools behind to continue to drain or nucleate pool expansion once again (Yapp et al. 1917; Redfield 1972; van Huissteden and van de Plassche 1998). This study documents all of these observations. Pools of the Webhannet Marsh changed their shape and gained or lost area (Fig. 5) through merges with nearby pools or creeks (Figs. 6, 7, and 8). These merges often occurred via elongate open-water features termed “necks” that extend outward from the pool body.

Anthropogenic modifications may contribute to marsh surface dynamism by enhancing the exchange between tidal creeks and pools and altering flooding and drainage patterns, as seen in the Webhannet Marsh with the construction of Lower Landing Road in the mid-1960s (Fig. 9). Pools may enlarge rapidly, accommodating abrupt alterations in salt marsh hydrology (Fig. 9 g, f). Alternatively, creeks can incise or "tap" (sensu van Huissteden and van de Plassche (1998)) pools to drain them and then progress across pools, in a stepping stone model, to drain large areas of marsh over short periods (Fig. 9 h, i, l). Of the 1984 cores that contained pools, most were located just south of Lower Landing Road (Fig. 1) in the dynamic area just described (Fig. 9). In addition, the active flooding and draining periods in 1977 and 1991 are reflected in the event trees, with most of the split and merge events recorded during those times attributed to pools located along the transect closest to Lower Landing Road (Table 5, pools 1–8; Fig. 1). Though pools may respond dynamically to anthropogenic alterations of the marsh surface, cores reveal that many pools existed prior to European settlement of this area (>1 m below surface; Fig. 3).

Our results reveal that salt pool dynamics may contribute to marsh fragmentation, though it is unclear whether pools may contribute to permanent vegetated marsh loss in the Webhannet Estuary. Our results indicate contradictory processes of pool area gain and loss. Pools experiencing multiple event processes were more likely to experience merge events with other pools during the latter two marsh periods (1977–1991, 1991–2003), suggesting that overall pool area may be increasing, as has been noted in other salt marshes (e.g., Kearney et al. 1988; Hartig et al. 2002; Cavatorta et al. 2003). The results of our area analysis, however, reveal the majority of pools lost area over the 41-year time period, though pools experiencing multiple events may experience different area trends than the analyzed subset. An analysis that followed randomized blocks of salt marsh over time, comparing the ratio of vegetated marsh to pool area, in addition to tracking event process sequences, would best address the question of how pools contribute to salt marsh fragmentation and potential loss.

Finally, understanding the dynamic role of salt pools within north-temperate salt marsh environments has broad implications for how we interpret the stratigraphic record as revealed by geologic coring. The dynamic exchange between salt pools and tidal creeks suggests one mechanism by which salt marshes transition between low- and high-marsh states that is potentially independent of changes in local sea level and agrees with the earlier observations of Kelley et al. (2001). Such understanding may be an important contribution to how we think about the geomorphological evolution of coastal marshes and their response to changes in local sea level. Through our description of salt pool origin and dynamics, this study expands the context within which salt marsh ecosystems should be protected and managed. Future studies should link this new understanding to improved management of these critical tidal wetland environments.

Acknowledgements The authors thank the editors of *Estuaries and Coasts* as well as two anonymous reviewers for comments that improved this manuscript. The authors thank the Kendall Foundation, the National Science GK-12 Teaching Fellowship Program, the Maine Sea Grant Program, and the University of Maine Graduate Student Government for funding this work. We also thank the Wells National Estuarine Research Reserve, the Rachel Carson National Wildlife Refuge, and the Maine Geological Survey for access to the study site and aerial photographs. Thank you to J. Albright, J. Bowdoin, L. Brothers, K. Jones, and K. Lee for help in the field.

References

Adamowicz, S.C. and C.T. Roman. 2005. New England salt marsh pools: A quantitative analysis of geomorphic and geographic features. *Wetlands* 25: 279–288.

Argow, B.A. and D.M. FitzGerald. 2006. Winter processes on northern salt marshes: Evaluating the impact of in-situ peat compaction due to ice loading, Wells, ME. *Estuarine, Coastal and Shelf Science* 69: 360–369.

Baily, B. and A.W. Pearson. 2007. Change detection mapping and analysis of salt marsh areas of central southern England from Hurst Castle spit to Pagham Harbour. *Journal of Coastal Research* 23: 1549–1564.

Belknap, D.F., B.G. Andersen, R.S. Anderson, W.A. Anderson, H.W. Borns Jr., G.L. Jacobson Jr., J.T. Kelley, R.C. Shipp, D.C. Smith, R. Stuckenrath, W.B. Thompson, and D.A. Tyler. 1987. Late quaternary sea-level changes in Maine. In *Sea-level fluctuation and coastal evolution. Special publication 41*, ed. D. Nummedal, O. Pilkey, and J.D. Howard, 71–85. Tulsa: Society of Economic Paleontologists and Mineralogists.

Belknap, D. F., R. C. Shipp, R. Stuckenrath, J. T. Kelley, and H. W. Borns, Jr. 1989. Holocene sea-level change in coastal Maine, p. 85-106. In W. A. Anderson and H. W. Borns, Jr. (eds.), Neotectonics of Maine. Maine Geological Survey Bulletin, No. 40.

Boston, K.G. 1983. The development of salt pans on tidal marshes with particular reference to south-eastern Australia. *Journal of Biogeography* 10: 1–10.

Byrne, R.J. and J.M. Ziegler. 1977. *Coastal engineering study: Wells Harbor, Maine*. Waltham: Department of the Army, New England Division, Corps of Engineers. 89 pp.

Cavatorta, J.R., M.E. Johnston, C.S. Hopkinson, and V. Valentine. 2003. Patterns of sedimentation in a slat-marsh dominated estuary. *Biological Bulletin* 205: 239–241.

Chapman, V.J. 1960. *Salt marshes and salt deserts of the world*. New York: Interscience.

Day Jr., J.W., L.D. Britsch, S.R. Hawes, G.P. Shaffer, D.J. Reed, and D. Cahoon. 2000. Pattern and process of land loss in the Mississippi Delta: A spatial and temporal analysis of wetland habitat change. *Estuaries* 23: 425–438.

DeLaune, R.D., J.A. Nyman, and W.H. Patrick Jr. 1994. Peat collapse, ponding and wetland loss in a rapidly submerging coastal marsh. *Journal of Coastal Research* 10: 1021–1030.

ERDAS IMAGINE. 2006. Version 8.7, Leica Geosystems GIS and Mapping, LLC., Atlanta, Georgia, USA.

Ewanchuk, P.J. and M.D. Bertness. 2004. Structure and organization of a northern New England salt marsh plant community. *Journal of Ecology* 92: 72–85.

Gehrels, W.R. 1994. Holocene sea-level changes in the northern Gulf of Maine: regional trends and local fluctuations determined from foraminiferal analyses and paleotidal modeling. Orono, Maine: University of Maine, Ph.D. thesis, 337 pp.

Harshberger, J.W. 1916. The origin and vegetation of salt marsh pools. *Proceedings American Philosophical Society* 55: 481–485.

Hartig, E.K., V. Gornitz, A. Kolker, F. Mushacke, and D. Fallon. 2002. Anthropogenic and climate-change impacts on salt marshes of Jamaica Bay, New York City. *Wetlands* 22: 71–89.

Jacobson, H.A. and G.L. Jacobson Jr. 1987. Variability of vegetation in tidal marshes of Maine, U.S.A. *Canadian Journal of Botany* 67: 230–238.

Kearney, M.S., R.E. Grace, and J.C. Stevenson. 1988. Marsh loss in Nanticoke Estuary, Chesapeake Bay. *Geographical Review* 78: 205–220.

Kelley, J.T., W.R. Gehrels, and D.F. Balknap. 1995. Late Holocene relative sea-level rise and the geological development of tidal marshes at Wells, Maine, USA. *Journal of Coastal Research* 11: 136–153.

Kelley, J.T., D.F. Belknap, and J.F. Daly. 2001. Comment on "North Atlantic climate-ocean variations and sea level in Long Island Sound, Connecticut, since 500 cal yr A.D". *Quaternary Research* 55: 105–107.

Kirwan, M.L., A.B. Murray, and W.S. Boyd. 2008. Temporary vegetation disturbance as an explanation for permanent loss of tidal wetlands. *Geophysical Research Letters*. doi:10.1029/2007GL032681.

MacKenzie, R.A. and M. Dionne. 2008. Habitat heterogeneity: Importance of salt marsh pools and high marsh surfaces to fish production in two Gulf of Maine salt marshes. *Marine Ecology Progress Series* 368: 217–230.

Mandracchia, M.A. and E. Ruber. 1990. Production and life cycle of the gastropod *Hydrobia truncata*, with notes on *Spurwinkia salsa* in Massachusetts salt marsh pools. *Estuaries* 13: 479–485.

Master, T.L., J.K. Leiser, K.A. Bennett, J.K. Bretsch, and H.J. Wolfe. 2005. Patch selection by snowy egrets. *Waterbirds* 28: 220–224.

Miller, W.R. and F.E. Egler. 1950. Vegetation of the Wequetequock-Pawcatuck tidal-marshes, Connecticut. *Ecological Monographs* 20: 143–172.

Pethick, J.S. 1974. The distribution of salt pans on tidal salt marshes. *Journal of Biogeography* 1: 57–62.

Pratt, W.K. 2001. *Digital image processing: PIKS inside*, 3rd ed. New York: Wiley.

Ranwell, D.S. 1964. *Spartina* salt marshes in S. England. II. Rates and seasonal pattern of sediment accretion. *Journal of Ecology* 52: 79–94.

Redfield, A.C. 1972. Development of a New England salt marsh. *Ecological Monographs* 42: 201–237.

SYSTAT. 2004. Version 11.0, SYSTAT Software, Richmond, California, USA.

Temmerman, S., T.J. Bouma, G. Govers, and D. Lauwaet. 2005. Flow paths of water and sediment in a tidal marsh: relations with marsh developmental stage and tidal inundation height. *Estuaries* 28: 338–352.

Turner, R.E. 1997. Wetland loss in the northern Gulf of Mexico: Multiple working hypotheses. *Estuaries* 20: 1–13.

van Huissteden, J. and O. van de Plassche. 1998. Sulphate reduction as a geomorphological agent in tidal marshes ("Great Marshes" at Barnstable, Cape Cod, USA). *Earth Surface Processes and Landforms* 23: 223–236.

Ward, L.G., B.J. Zaprowski, K.D. Trainer, and P.T. Davis. 2008. Stratigraphy, pollen history and geochronology of tidal marshes in a Gulf of Maine estuarine system: Climatic and relative sea level impacts. *Marine Geology* 256: 1–17.

Yapp, R.H., D. John, and O.T. Jones. 1917. The salt marshes of the Dovey Estuary. *Journal of Ecology* 5: 65–103.