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New Salt Marshes for Old - Salt Marsh Creation and Management

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Abstract

Salt marshes are vulnerable to rising sea levels, coastal developments, pollution and disturbance, and at the same time they provide economic, social and environmental benefits. Recently salt marsh re-creation has been undertaken in the interest of both sea defence and nature conservation. The vegetation pattern on these newly created marshes is very different from that found on mature marshes. This suggests that the soil conditions may be limiting normal vegetation development and implies that special techniques will be needed to enhance the processes involved. For pioneer salt marsh to develop a proportion of the sediment load in the water covering the marsh at high tide has to be trapped by salt marsh plants and subsequently incorporated into the marsh substrate. This paper presents the results of recent experimental studies in this area of research and examines various aspects of the key processes involved and the critical implications for salt marsh management and coastal defence.

1. INTRODUCTION

Many regions of the European Union have fragile coastlines with habitats that are at risk from a variety of anthropogenic and natural forces. Principal among these are tidal (salt) marshes, inter-tidal areas of predominantly fine-grained sediments, stabilised by vegetation which forms distinct zones (pioneer, lower, middle and upper marsh) reflecting the extent and duration of tidal flooding (Dijkema 1987, Burd 1989). Salt marshes are very productive ecosystems and play an important role in many coastal environments (Boorman 1999, Doody 1992).

Salt marshes were once far more extensive around the coasts of Europe than they are now (e.g. Dixon *et al.* 1998) but large areas have been reclaimed to create farmland.

Reclamation, mostly carried out over the past 400 years (*e.g.* Pye 1992), has largely been achieved simply by building a sea wall, often just an earth embankment, to prevent tidal flooding, with sluices to allow continued drainage of the land. In addition, some tidal marshes have been lost through development, degradation or erosion.

These processes have left large areas of low-lying land protected from the sea by sea walls, often with little salt marsh remaining outside. The marshes that remain provide economic, social and environmental benefits but are particularly vulnerable to rising sea levels and climate change, coastal developments, pollution and disturbance (Boorman 1999)

For many years salt marsh re-creation has taken place within Europe as a result of abandonment of low-lying land following the failure of sea defences. Most of this land would have been inter-tidal marsh prior to reclamation and so it is simply reverting to its original state, although unmanaged breaches in the sea wall can cause scour and erosion as strong tidal currents pass through them (Boorman & Hazelden 1995a). Recently, however, there has been planned salt marsh re-creation both to improve sea defences and to create more of this fragile habitat (Boorman & Hazelden 1995b), sometimes to mitigate loss elsewhere. This shift in the perception of the value of inter-tidal marshes has been driven by changing farm economics and by over-production leading to less land being needed for food production, and by an increasing awareness of the need to protect fragile and threatened habitats (*e.g* The European Commission Habitat Directive 92/43/EEC).

Defending low-lying land from tidal inundation is expensive and no longer cost effective in many areas. Moving sea walls inland and re-creating a fringe of marsh in front of the sea wall (managed retreat or managed realignment) protects the wall from wave erosion. The salt marsh fringe limits the size and energy of waves reaching the sea walls, substantially reducing both the capital and maintenance costs (King & Lester 1995, Dixon *et al.* 1998). Moller *et al.* (1999, 2001) reported that wave energy on the north Norfolk coast in eastern England over tidal marsh was reduced by a factor of almost 3 compared to similar waves over sand flats, and that this wave attenuation was mostly due to increased surface friction over the marsh vegetation.

According to Nunn (2000) managed retreat is now a ‘serious engineering option’. Lee (2001) predicts a net gain of intertidal habitat from managed retreat around the coast of England and Wales over the next 50 years, with the creation of around 12,500 hectares, more than compensating for predicted losses.

2. PRINCIPLES OF SALT MARSH CREATION

In the natural course of events a salt marsh develops when an intertidal mud flat accumulates fine sediments to a level at which pioneer salt marsh plant species can colonise. The process of colonisation involves both the arrival of propagules of the key species, such as seed, rhizome portions etc., and the development of suitable conditions for their germination and establishment. For pioneer salt marsh to survive and develop a proportion of the sediment from the water which covers the marsh at high tide has to be trapped by the salt marsh plants and then incorporated into the marsh substrate. The techniques needed for the creation of new areas of salt marsh will depend on the starting point.

In one sense the earliest forms of salt marsh creation have been those where a helping hand was given to the natural processes of primary salt marsh development, particularly by the use of various types of structure to accelerate the rate of sedimentation and thus reduce the time needed before salt marsh plants could become established on mud flats. The best examples of this approach are the so-called Schleswig-Holstein method used in the Dutch and German Wadden Sea (Kamps 1962) and subsequently in England (Toft *et al.* 1995)and in the USA (Turner & Streever 2002).

However, the enhancement of the natural processes of marsh development will only apply when conditions are basically favorable and new areas of salt marsh are most often needed in areas where this does not apply, for example where marshes are threatened by large scale environmental pressures particularly rising sea levels (Boorman 1992, Dahl & Johnson 1991). New marsh may also be needed when nature conservation interests demand the restoration of former areas of salt marsh lost to development. In these areas the original land surface has often been raised.

Generally this situation would render marsh creation uneconomic but nevertheless there are circumstances in which conservation pressures outweigh other considerations.

The challenges are likely to be considerable but the results can be promising and give new insights into the processes of wetland vegetation colonisation and management (Burchett *et al.* 1998a & b).

The usual situation of salt marsh habitat creation is the removal or breaching of sea walls to allow tidal access to be restored to areas which were formerly salt marsh anyway. However, even this more direct approach is not without its problems and difficulties. The land within the sea wall, although formerly salt marsh, is commonly lower than the existing marsh outside the sea wall, partly through continued accretion outside the sea wall and through the consolidation of the land inside the wall due to the irreversible drying of the soil and the loss of organic matter by oxidation (Boorman & Hazelden 1995a, 1995b). There is evidence from Essex in eastern England that secondary marsh, marsh regenerating naturally after the failure of a sea wall during a storm surge, is generally at a higher level than typical primary salt marsh (Boorman 1995) and experience from experimental salt marsh creation in this area has indicated that the same is true for planned salt marsh creation (Boorman *et al.* 1997) with the most successful re-colonisation occurring at the level of natural high marsh even though mainly pioneer species were involved (Dagley 1995).

While the need for large scale salt marsh creation in England and Wales is clear (Lee 2001) it is equally clear that this is not going to be a simple or cheap process. Careful planning as part of an integrated programme of coastal zone management is needed for it to be fully cost-effective (Crooks & Turner 1999). Plans for the establishment of vegetation need to be carefully related to land levels and local tidal regimes in conjunction with the requirements of specific plant species.

The deposition of sediment and its integration into the marsh structure is only part of the whole process of marsh development. A striking feature of established salt marshes is the existence of a well developed and complex system of drainage creeks. The land involved in salt marsh creation often lacks any such surface drainage system, the original creeks having been largely obliterated by the agricultural use of the land, including cultivation. Re-establishment of the tidal flow does not automatically lead to the early re-establishment of a creek system on reclaimed soil, but nevertheless the speedy removal of the surface water as the tide ebbs is important for the dewatering of the soil which aids the establishment of marsh vegetation (French *et al.* 1995), and there is evidence that there are benefits in accelerating the natural development of an effective drainage system (Boorman 1999, Dixon *et al.* 1998). Salt marsh creeks also help to dissipate tidal energy (Pethick 1992) but they are nevertheless an often neglected component in the design of salt marsh creation schemes (Reed *et al.* 1999).

There are, however, many complex interactions between the deposition of sediment and the development of salt marsh creeks (Reed *et al.* 1999).

The results of the first large-scale salt marsh creation at Tollesbury, Essex, England (Boorman 1999) indicated that the rapid rate of accretion in the early stages of salt marsh creation following managed re-alignment is favourable in helping to provide a suitable substrate at an appropriate level for effective marsh development. This occurred without there being any evidence of unfavourable erosion elsewhere. However, before the trials were started there was careful hydrodynamic modelling of the area to ensure that there would not be excessive erosion or accretion in adjoining areas. With the scale of future salt marsh creation by managed re-alignment of the sea wall as anticipated by Lee (2001) the question of the existence of sustainable sources of sediment for marsh building could become more of a problem. The logical answer to this problem would be the use of dredge spoil and this has been done extensively in the United States (Streever 2000 & Zedler 2001). There are, however, a number of uncertainties notably, the supply of sufficient quantities of uncontaminated sediment, the stability of the placed material and the course of development of such marshes. In England there are a number of trials underway to test the use of dredge spoil (Atkinson *et al.* 2001).

While managed re-alignment can undoubtedly be successful is returning land which was formerly salt marsh back to its original condition this may not always be a viable option (Johnson 2000). In a detailed study of the marshes in the Lymington/Keyhaven area of southern England Johnson identifies four circumstances in which he suggests that such an approach would not be feasible. These are (a) where there are areas of nature conservation importance immediately inside the sea wall, (b) where landfill covers the former marsh surface, (c) where there is high ground behind the sea wall and (d) where recent improvements have been made to the current sea wall. In most of these circumstances, except (c), it should be possible to overcome the problems. Under European Law loss of marsh by development must be compensated for by the creation of equivalent areas of marsh (Atkinson *et al.* 2001). Where the creation of salt marsh involved the loss of areas of conservation interest inside the old sea wall, these fresh-water habitats could also be re-created elsewhere. The work of Burchett *et al.* (1998a, 1998b) in Australia shows the possibility of re-creating salt marsh following the removal of the infill material covering the former marsh surface. The question of the re-alignment of recently reconstructed sea walls is basically an economic one but international obligations may hold sway over financial considerations.

Nevertheless Johnson (2000) makes the important point that salt marsh creation may not always be the best option. He demonstrates the importance of an assessment of the root causes of salt marsh degeneration and loss, and of the design and application of techniques for the rehabilitation of existing salt marshes as a possible alternative or supplement to salt marsh creation. At the same time it has to be recognised that to achieve the current high targets for the maintenance of, and even increase in, the current areas of salt marsh in the UK salt marsh creation is going to have to play a major role in the future. However as Thom (2000) points out 'there is a clear need to apply a better and more effective management scheme to coastal restoration projects'. He goes on to emphasise the importance of having 'a clear goal statement' setting performance criteria against which success can be judged, 'a conceptual model' providing the knowledge base and 'a decision framework' to manage the project through all its stages.

3. SEDIMENT TRAPPING AND MARSH DEVELOPMENT

Salt marshes have been defined as intertidal areas of fine sediments stabilised by vegetation (Boorman 1995) and the transport agent responsible for the import of these sediments is the water column associated with the diurnal tidal cover. The accretion rate of sediment on an area of salt marsh is generally considered on an annual basis. These rates are usually determined by one of two methods, either by the inclusion at a known time of some form of marker layer, such as a kaolin layer (Brown *et al.* 1998) or by tracing buried radionuclides (Cundy & Croudace 1996), or by precision surveying the marsh surface (Stoddart *et al.* 1989, Boorman *et al.* 1998).

The rates of salt marsh accretion in the UK over a period of decades are generally of the order of 4 - 5 mm y^{-1} (Cundy & Croudace 1996), but over shorter terms they can be up to 33 mm yr^{-1} in pioneer marsh in the Wash and probably of the order of 5 - 6 mm yr^{-1} in Essex (Pethick 1992). In north Norfolk however, sedimentation has been estimated at 6 mm yr^{-1} on the low marsh and as low as 2 mm yr^{-1} on the high marsh (Pye 1992). All these figures are based on a period of a year or more and represent the long term average (*i.e.* the net effect of up to 706 individual tides per year). It should be noted that only the lowest marsh will be covered by every tide and the high marsh will only be covered by the highest of the spring tides a few times a year.

The distribution of annual accretion rates across an individual marsh has been studied recently by the use of transects between fixed points with surface heights being recorded at 100 mm horizontal intervals.

These have been shown to be an effective way of determining accretion rates (Boorman *et al.* 1998). There were marked differences in the patterns of annual accretion at the three sites studied with mean rates of between 2 and 12 mm yr^{-1} (Boorman 2001). Within a site there was also considerable variation in the patterns of accretion. The differences partly reflected the species composition of the vegetation but it was not clear whether high rates of accretion were brought about by the occurrence of particular plant species or whether those species occurred where rates of accretion were high.

Daily accretion rates were determined by the use of the filter paper sediment traps attached to the marsh surface measuring directly the addition of sediment to the marsh surface (Pitman 1993, Boorman *et al.* 1996, Boorman 2000). These have shown that there is great variation in short term accretion rates both in time and in space across the surface of the marsh. The actual pattern of sediment deposition across a marsh depends not only on the level of the marsh in relation to the tide (i.e. the frequency and duration of inundation) but also on the nature of the sediment itself. Comparative studies in Essex and Norfolk have shown that while in Essex the sediment is deposited more or less evenly across the surface of the marsh in Norfolk the deposition of sediment is inversely proportional to the distance from the nearest creek. The difference is explained by the sediment in Essex being predominantly fine-grained material which is only deposited near the time of high water when there is little water movement while in Norfolk there is a considerable proportion of silt and fine sand which will only remain in suspension when the water velocity is high (Boorman *et al.* 1996).

The amount of sediment which is available for deposition will be determined by the depth of the tidal cover together with the suspended sediment load while the actual deposition will depend on the duration of appropriate near-surface water velocities in relation to particle-size and settling rates.

The velocity experienced within the water column is influenced not only by the state of the tidal cycle but also by the vegetation cover itself (Stevenson *et al.* 1988, Boorman *et al.* 1998). The principle of the vegetation cover retarding the water flow to a velocity at which sediment can settle out is straightforward but the details are more complex. It has been shown that retardation is related to the height of the vegetation but only over a limited range with the tallest vegetation being less effective (USSCS 1954, Howard-Williams 1992). Studies in salt marshes have shown that this principle depends on the species composition of the vegetation as well as the height (Boorman *et al.* 1996).

Short vegetation was shown to be quite effective when it had sufficient stiffness to withstand the higher water velocities without being flattened by the flow. There were also significant differences in both the pattern of accretion and the overall accretion rates for areas dominated by the five main species of salt marsh plants. The effect of vegetation was most marked when there were significant proportions of coarser sediments; the settlement of fine sediment takes place only when the velocities approached zero.

Experimental studies have shown that the quantity of sediment deposited during two consecutive tides can often be many times the equivalent net annual accretion rate indicating that there is considerable reworking of sediment before its long term incorporation into the marsh.

Given that, particularly in the short term, accretion rates could be high with several millimetres of sediment being deposited on the plants during a single tide it was considered that this sediment could have a significant effect on the plants themselves particularly at the seedling stage. Experiments have recently investigated the effect of rates of sedimentation and tidal submersion regimes on the growth of seedling and small plants of key salt marsh species (Boorman *et al.* 2001). These experiments were conducted in a tidal mesocosm where there were variable inundation regimes with the addition of various quantities of sediment on a two weekly basis. The pioneer species *Aster tripolium* and *Salicornia europaea* both responded positively to the addition of sediment even at a rate of 2.5 mm $fortnight^{-1}$, equivalent to accretion of 60 mm y^{-1}, although growth was reduced by increasing inundation. In contrast the middle marsh species *Limonium vulgare* was intolerant of all but the lowest rates of accretion with even the equivalent of 30 mm y^{-1} resulting in a 70% seedling mortality during the two months of the experiment (Boorman 2001). Interestingly another middle marsh species, *Triglochin maritima*, was tolerant of both high rates of sediment addition and high frequencies of inundation. Work in France on *Puccinellia maritima*, a species of the middle marsh, also sometimes found in pioneer situations, has shown that moderate rates of accretion (4 mm $month^{-1}$, equivalent to 48 mm y^{-1}) stimulate growth but higher rates (8 mm $month^{-1}$, equivalent to 96 mm yr^{-1}) result in increasing mortality (Langlois *et al.* 2001). It appears that those species with a strong vertical component to their growth pattern such as the pioneer species *Aster* and *Salicornia* benefit significantly from moderate rates of accretion but that those species with a primarily horizontal (soil surface) growth pattern such as the middle marsh species *Limonium* and *Puccinellia* are sensitive to all but the lowest rates of accretion.

These studies indicate the complex relationship between sediment deposition and vegetation growth.

Even within a single marsh the sediment loading in the water column was by no means constant across the marsh. When there was erosion along the cliff edge of the marsh, the sediment of the adjacent water column was markedly higher and this was reflected by locally higher rates of accretion (Boorman 2001) and there were also indications that the same process was occurring, on a smaller scale, elsewhere within the marsh. Even when the short term accretion rates were corrected for the probable frequency of these events (i.e. the predicted frequency of tidal cover to that depth of water) the equivalent annual accretion rates were higher than those actually recorded. This was explained by the subsequent recirculation, and possible loss, of a significant proportion of the sediment that was initially deposited on the marsh surface. It is difficult to estimate the magnitude of this effect. The retention of sediment on the marsh surface will also be positively affected by the vegetation cover (Boorman *et al.* 1998) particularly the growth form of the dominant species in a particular marsh zone.

Sedimentation at the Tollesbury site, where fine sediment is deposited evenly across the whole marsh surface, tends to be at a maximum when there is enhanced wave action on the outer mudflats when surface erosion releases sediment which markedly increases the sediment load. In the more exposed Norfolk marshes it appears that the coarser sediments are more locally derived, being carried from the creek beds when critical water velocities are exceeded during particularly high tides (Boorman *et al.* 1996, Boorman 2000). The material in the creek beds was progressively replaced by material from further seawards over longer periods. Periods of high rates of accretion occur intermittently as episodic events with relatively low rates of accretion during the intervening periods. Similar results have been obtained on New England marshes; although long term accretion rates were of the order of 2-6 mm y^{-1}, a period of storms resulted in annual rates of up to 24 mm (Cahoon & Reed 1996).

The upward growth of the salt marsh is enhanced by the addition and incorporation of organic matter resulting from the primary productivity of the salt marsh plants. There is the addition of plant litter to the surface of the marsh and also, probably more significantly, there is the below-ground production of organic matter by the salt marsh plants (Allen & Pye 1992, Boorman 2000). Recent work in Essex has shown that with present, rather low, rates of accretion, below-ground production could account for around 10% of the vertical growth of the marsh (Boorman 2000).

However, upward growth of the marsh surface is offset by the process of soil consolidation and compaction, which are considered in the next sections.

4. SOIL CHANGES AFTER INUNDATION

Since reclamation and conversion to farmland (grassland or arable), the soils on what was once tidal marsh or mudflats will have altered, physically, chemically and biologically. Soluble salts, particularly NaCl, will have been leached from the soil and agro-chemicals added. The soils will have dried out irreversibly (ripened), their density will have increased and porosity decreased (Crooks 1999, Crooks & Pye 2000, Dent *et al.* 1976, Hazelden & Boorman 2001). Additionally, in non-calcareous clayey soils, deflocculation of the clay may have resulted in the breakdown of soil structure and impeded soil drainage (Hazelden *et al.* 1986).

The flora and fauna within the soil will also have changed. Thus, when this land is once again opened up to tidal flooding in an attempt to re-create tidal marsh, it is in these altered soils, and in the new sediment deposited on them, that the salt marsh plants must germinate and become established.

Generally terrestrial soils, even when regularly covered by sea water, are not well suited to the establishment and growth of salt marsh plants. The development of salt marsh in areas re-opened to tidal flooding, whether by accident or design, is accompanied by changes in the structure and chemistry of the soil as the interstitial fresh water is replaced by salt water.

Importantly, it is also usually accompanied by the deposition of fresh sediment on the low-lying land surface. The primary establishment of salt marsh vegetation normally follows the deposition of a certain depth of new estuarine sediment (Boorman *et al.* 1997).

MacLeod *et al.* (1999) demonstrated how slowly sea water penetrated the reclaimed marsh sediments at Orplands Farm in Essex in eastern England where after two years the estuarine water had reached only 20 cm depth in the soil. Hazelden & Boorman (2001) recorded changes in salinity at the Tollesbury managed retreat site in Essex where, over a year after the sea wall was breached, and despite an influx of sediment, the salinity (measured as electrical conductivity) had not reached the levels of 35-40 dS m^{-1} recorded in adjacent natural marshes.

Time is needed for changes in hydrological and edaphic factors and it may take many tens of years before a regenerated marsh returns to its natural state, particularly in terms of its soil physical, hydrological and nutrient characteristics (Craft *et al.* 1999, Onaindia *et al.* 2001).

Boorman *et al.* (1997) reported that species zonation with regard to length and frequency of inundation on the newly-created marsh at Tollesbury in Essex was different from that on nearby natural salt marsh. Such differences have implications for marsh creation techniques.

There are specific interactions between the soil micro-organisms and the plant species within the marsh (e.g. Burke *et al.* 2002, Carvalho *et al.* 2001). In some cases it may not be possible for the plants to thrive without the complementary microbial or fungal assemblage present. There may also be interactions with the invertebrate fauna which hinder the establishment or management of salt marsh following restoration (e.g. Emmerson 2000, Gerdol & Hughes 1993, Hughes 2000, Reading *et al.* 2001).

There is concern that, following tidal inundation, changes in the soil chemistry might result in heavy metals being leached from the soils into the sea. Emmerson *et al.* (2001) found this indeed to be the case, but concluded that there was unlikely to be significant loss into the environment. MacLeod *et al.* (1999) also showed that the main effect of tidal inundation was the enrichment by marine associated metals (Ca, K, Mg and Na).

Thus, following restoration of land to the inter-tidal zone, soil conditions limit normal vegetation development. Although these conditions revert only very slowly to those in a natural marsh, the accumulation of fresh sediment helps overcome the limitations.

5. SEDIMENT ADDITION AND SOIL TRANSFORMATIONS

Re-creation of tidal marsh usually involves the deposition of new marine or estuarine sediment on top of an old reclaimed soil surface. The old soil will have ripened, a process that is irreversible, and, although its moisture content will increase with regular flooding, it will not return to the same physical state as before reclamation. In sites where reclaimed land has naturally reverted to tidal marsh following unrepaired storm breaches of the sea walls, such as at North Fambridge and Northey Island in Essex, the old soil forms a relatively dense and hard layer buried by the sediment that has accumulated since the land reverted to inter-tidal habitat in 1897 (Crooks 1999, Crooks & Pye 2000, Hazelden & Boorman 2001).

Transformation of fresh sediment into a consolidated salt marsh soil involves various processes. De-watering is brought about both by the cyclical drying and re-wetting and by the extraction of water by plant roots. It is also influenced by the collective activities of the intertidal invertebrate fauna and of the interstitial algae.

However, this process can be hindered by the underlying old reclaimed soil which is dense and relatively impermeable and so acts as an ‘aquaclude’, preventing water draining readily from the new sediment (Crooks & Pye 2000).

In clayey sediments (most salt marshes are on fine-grained material) the mineralogy of the clay and its cohesive/dispersive behaviour play an important role in the geotechnical behaviour of the accumulating material (Dexter & Chan 1991, Anson & Hawkins 1998). Some clay minerals, smectite for example, retain water between the clay particles and swell to accommodate this water. These then shrink and crack as they dry out.

Cohesion and dispersion of clay minerals are controlled by the cations adsorbed onto the clay minerals and the concentration of dissolved salts in the soil solution (e.g. Crooks & Pye 2000, Hazelden *et al.* 1986). Sodium-saturated clays, common in marine and estuarine environments, are easily deflocculated and dispersed because the charge on the monovalent sodium ion is relatively weak. These clays remain flocculated if the concentration of salts in the soil solution remains high, but if rainfall leaches the salts then these clays readily deflocculate. Once deflocculated the individual clay particles are easily taken into suspension and the sediment readily eroded. In contrast calcium-saturated clays are more tightly flocculated because the charge on this divalent ion is stronger. These clays remain flocculated even when in almost pure water. Thus the stability of the accumulating sediment against erosion is controlled, to some extent, by the nature and chemistry of the clay minerals. Calcareous tidal marsh soils, often calcareous from the inclusion of shell debris within the sediment, are generally more resistant to erosion than those which are non-calcareous.

The upper layers of new sediment are reinforced by the roots of the colonising salt marsh plants and by algae. Initially newly deposited sediment has a very low bulk density; values as low as 0.35 g ml^{-1} have been recorded by Boorman *et al.* (2000). Hazelden & Boorman (2001) recorded low values of 0.5 g ml^{-1} for the upper 15 cm of established natural marsh. As sediment becomes buried by the deposition of fresh sediment above it, then physical pressure of the over-burden helps consolidate the sediment. This increases the soil bulk density and shear strength. Boorman *et al.* (2000) reported that consolidation and compaction of the upper 600 mm of marsh sediment is about 1 mm per year for active salt marshes at Tollesbury. Consolidation of new marsh sediments and the consequent increase in its strength contributes to the long term survival of the salt marsh.

6. THE DEVELOPMENT OF SALT MARSH VEGETATION

The arrival of the first pioneer plant species on an area newly opened, or re-opened, to tidal inundation is only the first step in a long sequence of events before mature salt marsh plant communities and salt marsh function are fully developed. The fact that this is possible can be seen where the failure of the sea wall, usually as the result of a tidal surge during a storm, has been followed by the development of apparently normal salt marsh vegetation. A typical example of this can been seen at North Fambridge in Essex where salt marsh has developed following breaches in the sea wall in 1897 (Boorman & Hazelden 1995a & b). While the vegetation is similar to natural marshes in the area the pattern of the creeks still follows that of the drainage of the area while it was farmland. The development of these marshes over the past hundred years indicates that there has been an average rate of accretion of approximately 10 mm y^{-1} which is significantly above the natural rate of some 3-5 mm y^{-1}. There are unfortunately no records of the vegetation development following the breaching of the walls at Fambridge.

In a survey of all the areas in Essex where land had been abandoned following failure of the sea wall it became clear that natural marsh regeneration had only occurred where the land involved was at a relatively high level, equivalent to the upper marsh zone outside the sea wall (Boorman *et al.* 1997). It has to be noted that most of the land immediately behind the present sea wall is at a level corresponding to that of pioneer marsh or even lower. This would seem to impose a limit on the opportunities for salt marsh creation.

The first example of deliberate salt marsh creation in England by means of managed retreat was in Northey Island, in the estuary of the river Blackwater in Essex where, in 1991, the sea wall was breached to allow the flooding of an area of 0.8 ha (Dagley 1995). Colonisation of the site was rapid with the arrival of twenty five species after only two years. However, the area was untypical of most of the sites being considered for salt marsh creation as it was only covered by the higher spring tides. In addition the small size of the site meant that plant colonisation only had to take place over short distances. Although the Northey Island site is at a relatively high level and only infrequently covered by the tide, plant colonisation was mainly by pioneer species of salt marsh plants, species which would normally colonise at the lowest levels of the marsh.

The first large-scale salt marsh creation in England was on a 21 ha site further down the Blackwater at Tollesbury (Boorman *et al.* 1997). In 1995 the old sea wall was breached and the sea flooded across the area for the first time in over 200 years.

Much of the site was at the level of the lower or pioneer marsh outside the sea wall and, as anticipated, early colonisation has been limited to the higher areas and was by the pioneer species *Salicornia europaea* and *Suaeda maritima*. Both seed and plants of species characteristic of the middle and higher marsh were introduced but the success rates were generally low. Even five years after the breaching of the sea wall only twelve species of salt marsh plants were found. Only four of these occurred with a frequency of 5% or more and only the two original colonisers (*Salicornia* and *Suaeda*) reached over 10 % frequency (Reading *et al.* 2001). The reasons for this are complex and varied. It is clear that colonisation will only occur in areas when the flooding frequency is considerably lower than that at which the species concerned would normally grow. At both Northey Island and Tollesbury new salt marsh developed through colonisation by pioneer salt marsh species at levels at which middle and high marsh species might be expected to grow.

The low success of the various planting techniques employed at Tollesbury seemed to confirm that this was not simply a failure of the non-pioneer and therefore relatively slow spreading species to reach the area. One factor which was considered to be important was the state of the substrate. Initially the newly flooded agricultural land was dense and compact but this was soon changed by the high rates of accretion in the early stages which resulted in large areas being covered by relatively soft mud. Neither of these substrates seemed to be ideal for plant growth. Given the compact nature of the newly flooded ground, the slow development of a new system of drainage creeks was perhaps not surprising. An effective creek drainage system can benefit salt marsh colonisation and development. Mature salt marsh soils are well developed with a wide range of bacterial and fungal species including mycorrhizal associations which support certain salt marsh plants (Boorman 1999) and it would be reasonable to anticipate that a lack of these organisms could impede salt marsh development.

The mud that was deposited following the flooding of the salt marsh creation sites not only provided for the possibility of the colonisation of the area by salt marsh species, it has also provided a habitat for the many marine invertebrates and there is increasing evidence that these organisms can significantly affect the establishment of the salt marsh plant species.

7. CONCLUSIONS

The problems associated with the relatively early years of these salt marsh creation experiments should perhaps be viewed against the background of the apparent successful regeneration of salt marsh following wall failure, albeit over a much longer time scale.

Despite the early problems these attempts are being viewed as being encouraging as are the salt marsh creation efforts in other areas in the USA (Turner and Streever 2002), in Australia (Burchett *et al.* 1998a & b), and Italy (Scarton *et al.* 2000). The development of the vegetation cover and, subsequently, of the full range of salt marsh plant communities is however only part of the picture since there are many other parts to salt marsh ecosystem. Studies are already being conducted into the ecological conditions in natural and created marshes (Havens *et al.* 2002, Scatolini & Zedler, 1996) and on the effect of time on the natural regeneration of salt marsh (Onaindia *et al.* 2001). It is important that the full range of ecological functions are restored in order to provide a habitat that is the full ecological equivalent of the that lost. An important advance in this respect is the development of a new environmental assessment technique, 'habitat equivalency analysis' or 'HEA' for determining the extent to which success has been achieved in salt marsh creation (Strange *et al.* 2002). The application of this technique has shown that there is often a significant lag in the development of ecological processes such as nutrient cycling that are necessary for a fully functioning salt marsh. However this approach also underlines that there is a need for a greater understanding of what are the full range of salt marsh functions. Nevertheless, while many questions remain to be answered, it will be increasingly possible to make up for recent losses in the total area of salt marsh by creation and effective management.

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