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SALTMARSH REVIEW

An overview of coastal saltmarshes, their dynamic and sensitivity characteristics for conservation and management

Laurie Boorman

LAB Coastal

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For further information please contact:

Diana Mortimer
Joint Nature Conservation Committee
Monkstone House
City Road
Peterborough
PE1 1JY

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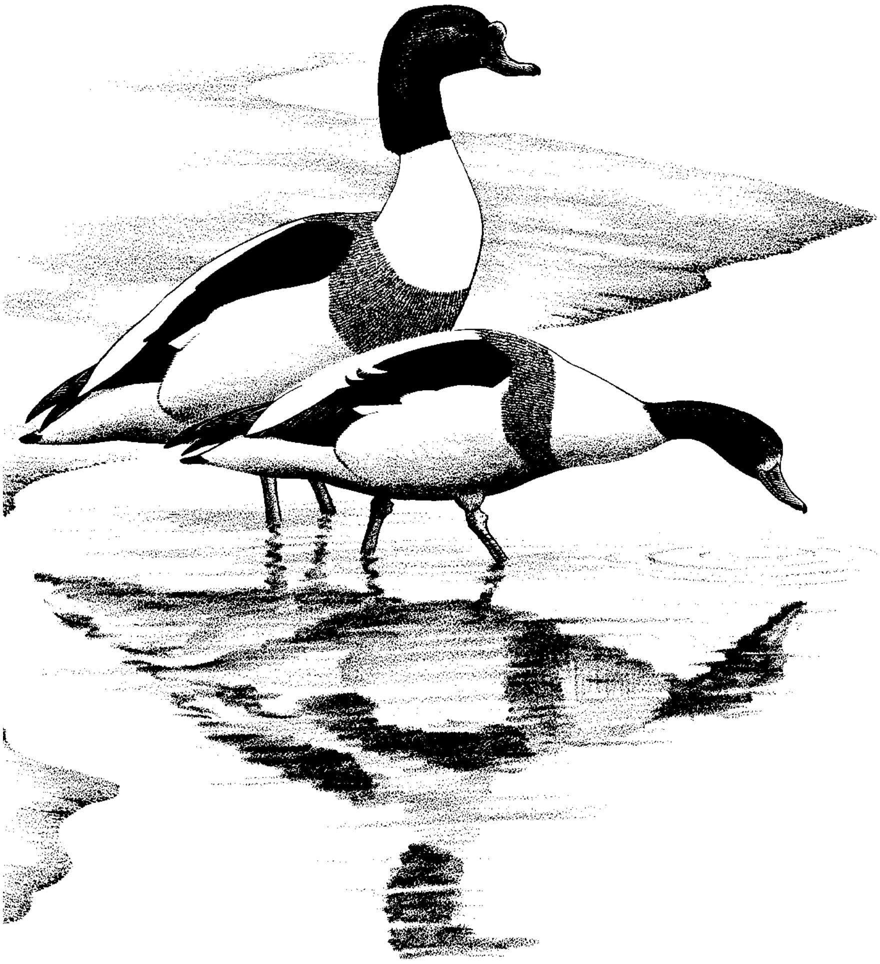

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Executive Summary

This report provides information on the structure and functions of saltmarsh, a habitat previously regarded as wasteland but which is now valued for its wide range of functions in relation to sea defence, nature conservation and supporting life in adjoining ecosystems.

The vertical development of the saltmarsh is dependent on the velocity of the water flow over the marsh. A cover of vegetation can have a major effect on marsh development by reducing the velocity and thus enhancing the deposition of sediment and reducing the possibility of sediment erosion.

Fluxes of organic matter, sediment and mineral nutrients can occur in most if not all saltmarshes. Generally young marshes will import nutrients but the nutrient reserves of older marshes are sufficient for there to be nutrient exports. Mature marshes can also export organic matter and if saltmarsh degeneration occurs they can release sediment.

A description is given of the history of the classification of British saltmarsh vegetation up to and including the development and application of the National Vegetation Classification. The 28 NVC communities making up the British saltmarsh vegetation are considered both in relation to the key plant species involved and in relation to factors affecting their distribution.

Sea level rise will increase the possibilities of both accretion and erosion with the whole coastal system becoming more dynamic. Climatic changes are likely to affect both the growth of saltmarsh plant species and their overall distribution. The ability of saltmarsh to adjust to climate change will be limited by the disjunct distribution of saltmarshes.

The coastline has seen widespread development with the spread of transport, industrial, residential and recreational facilities and all the associated infrastructure. In some cases the whole character of the estuary, including its geomorphology, has been changed as a result of large-scale reclamation and development.

The importance of monitoring rates of change and of developing suitable management techniques is emphasised. The first step in any programme for monitoring saltmarsh change is the establishment of detailed baselines against which future changes can be assessed. Baselines are needed both as the reference point for any monitoring programme and for making management decisions on the basis of that monitoring.

Suggestions are made regarding the possibilities for the development of advanced computer techniques for the formulation and application of saltmarsh management through the seamless integration of scientific data and saltmarsh process models within a Decision Support System (DSS).

The creation of new saltmarsh is likely to play an increasingly important role in the management of the coastal zone.

A number of specific research proposals are made relating to the effective management and creation of saltmarshes and saltmarsh ecosystems.

1. Introduction

1.1 Study Aims

The main aim of this study is to provide a scientific review of saltmarsh habitats based on existing literature and current scientific opinion, in order to inform coastal practitioners involved in the ecological conservation of saltmarshes. It is also designed to provide key information for a wide range of individuals involved in the management and conservation of saltmarshes and associated habitats.

Much of the recent research on saltmarshes may seem at first sight to be of specialist or academic interest, but understanding the underlying ecological principles is essential for the effective long-term management of saltmarshes.

This report concentrates on the structure and function of saltmarshes of England, Scotland, Wales and Ireland (with special reference to Northern Ireland). Research has been conducted on saltmarshes in many other areas of the world (e.g. North America, Australia and South Africa), much of which has considerable relevance for the conservation and management of UK saltmarshes.

1.2 Nature and importance of saltmarshes

Formation and development of saltmarsh

Saltmarshes can be defined as intertidal areas of fine sediment transported by water and stabilised by vegetation (Boorman, 1995). Once a cover of vegetation has become established the rate of sedimentation (accretion) frequently increases as more of the incoming sediment is intercepted and trapped by the increased surface roughness (Stumpf, 1983; Stevenson *et al.*, 1988). In addition, the vegetation also reduces the re-suspension of deposited material and, at the same time, organic matter is added to the marsh surface (Allen and Pye, 1992). This happens both by the accumulation of litter on the sediment surface and by root growth below the surface. There is some consolidation of the accumulated deposits but collectively these processes lead to a steady build-up in the surface level of the marsh and the stability of the deposited material.

There are four elements necessary for the development and growth of a saltmarsh: there has to be a relatively stable area of sediment that is covered by the tide for a shorter period than the time it is exposed; there has to be a supply of suitable sediment available within the period of tidal cover; the water velocities have to be sufficiently low for some of the sediment to settle out; and finally there has to be a supply of seeds or other propagules for the establishment of vegetation cover.

The primary colonisation of intertidal mudflat is crucially dependent on the arrival of sufficient quantities of the seeds of key colonising plant species; in north-west Europe these are usually annual species of *Salicornia* or *Suaeda*, or perennial grasses of the genus *Spartina*. These plants are tolerant of being covered by salt water for long periods. As the saltmarsh develops, the accumulation of new material raises the surface level of the new marsh in relation to the sea and this reduces the frequency and duration of tidal inundation. This enables species less tolerant of inundation to colonise, and more complex plant communities of mature saltmarsh gradually develop. Development of mature saltmarsh depends on sediment supply and the rate of sedimentation and typically takes between 40 and 80 years.

The development of the saltmarsh in terms of plant species and communities is also accompanied by developments in the soil structure and microflora. These developments involve the establishment of populations of bacteria and fungi which are involved in biogeochemical processes controlling the breakdown of organic matter and the cycling of plant nutrients. At the same time there are parallel developments of saltmarsh function; i.e. the processes whereby organic matter and mineral nutrients are exchanged with adjoining communities, both terrestrial and marine.

Major types of saltmarsh

Dijkema (1987) has described the major types of saltmarsh on the basis of their geomorphology for the Netherlands, but this classification is also applicable to UK saltmarshes. He recognised three major types of saltmarsh.

1. *Barrier-connected saltmarshes*. These marshes develop in the lee of spits or barrier islands, when the angle of the slope of the intertidal and immediate sub-tidal area is shallow on the exposed side. This type of saltmarsh is found in north Norfolk. The saltmarsh develops adjacent to sand dune or shingle and these transition zones can be rich in plant species.

2. *Foreland saltmarshes*. This type of saltmarsh develops in front of sheltered alluvial coastal plains (e.g. areas protected by a bay or offshore banks). There tend to be deeper sediment deposits in this type of marsh. Typical examples of this marsh are found around the Wash and at Dengie in Essex.

3. *Estuarine saltmarshes*. Estuarine marshes are found where rivers gradually merge into the open sea. There is usually, at least in the upper part of the system, an appreciable influence of fresh water and this influence can also be found in areas where the marsh joins higher ground and there are fresh-water seepages. Often estuarine marshes have been ‘reclaimed’ and converted to agricultural land. Natural upper estuarine marshes often have interesting transition communities to fresh-water wetlands which are still tidal, or sometimes to tidal woodland. This type of marsh is associated with the larger rivers of the east coast of Britain and also with many of the river valleys and rias of the upland coasts of the western seaboard.

There are four main saltmarsh zones and an upper transition zone in the UK but one or more of these zones may be absent in any area. These zones are based on the tidal regime but also tend to correspond with plant distributions. A distinction is sometimes made between sparsely vegetated mudflats and pioneer marshes. However, the considerable annual variation in the density of pioneer vegetation at the lower edge means that this separation is not very useful. UK saltmarsh zones are generally as follows:

1. Pioneer	Open communities with one or more of the following – *Spartina* spp., *Salicornia* spp., *Aster tripolium*. Zone covered by all tides except the lowest neap tides.
2. Low marsh	Generally closed communities with at least *Puccinellia maritima* and *Atriplex portulacoides* as well as the previous species. Zone covered by most tides.

3. Middle marsh	Generally closed communities with *Limonium* spp. and/or *Plantago*, as well as the previous species. Zone covered only by spring tides.
4. High marsh	Generally closed communities with one or more of the following – *Festuca rubra*, *Armeria maritima*, *Elytrigia* spp., as well as the previous species. Zone covered only by highest spring tides.
5. Transition zone	Vegetation intermediate between the high marsh and adjoining non-halophytic areas. Zone covered only occasionally by tidal surges during extreme storm events.

In areas exposed to high wave energy middle to high marsh can occur well above the level of normal spring tides. In areas restricted by the existence of a sea wall (e.g. East Anglia) the higher zone is virtually absent and the transition zone appears in a line along the sea wall.

Wildlife and nature conservation value of saltmarshes

The value of saltmarshes for wildlife conservation has been recognised for many years, particularly in terms of the wide variety of plants and animals associated with them. The diversity of fauna and flora reflects interactions between the two major elements of the habitat: the marine environment and the terrestrial element (Daiber, 1986). The creeks of tidal marshes also provide spawning sites and nursery areas for many fish species (Daiber, 1977, Costa *et al*., 1994, 1995).

Saltmarshes provide feeding, roosting and nesting areas for a wide range of bird species (Cadwalladr *et al*., 1972, Greenhalgh, 1975, Burger, 1977). The role of saltmarshes in providing bird habitats is particularly important in areas where unimproved meadowland has been almost totally replaced by intensive agriculture. A number of bird species associated with meadowland also make intensive use of saltmarsh habitats. Notable species are oystercatchers, lapwing (Allport *et al*., 1986) and redshank (Green *et al*., 1984).

Saltmarshes are particularly important for wintering wildfowl such as brent geese and widgeon (Boorman and Ranwell, 1977). Very large numbers graze on the saltmarsh vegetation during the winter months both as winter residents and during migration. Saltmarshes also provide habitat for certain passerine species, notably twite (Davies, 1987), which feed on the seeds of saltmarsh plants during the winter months.

In addition to the many plant and animal species that are directly associated with the saltmarsh itself there are other species that benefit indirectly from saltmarshes. Tidal saltmarshes have been identified as areas of high productivity providing a source of organic matter and nutrients for fish and a variety of invertebrates in adjacent marine habitats (Odum, 1961, Teal, 1962, Mitsch and Gosselink, 1986, Lefeuvre and Dame, 1994).

Human uses and impacts on saltmarsh

Humans have been exploiting saltmarshes for many millennia but initially this exploitation was at the level of subsistence fishing and shellfish gathering. Over the last few hundred years man has had a major impact on saltmarshes through the construction of tidal walls. These have enabled the conversion of saltmarsh to cattle grazing, and more recently for growing agricultural crops. This process is called ‘reclamation’ as most of the present saltmarsh areas were dry land shortly after the last ice age and were later submerged by rising sea levels. However, many people prefer to call it ‘land claim’.

Initially the pace of reclamation was slow, as the sea walls were built by hand at the seaward limit of high marsh and were only rebuilt further seaward when the marshes beyond had accreted sufficiently. Thus only the highest marsh was lost and was subsequently replaced by the development of new marsh further seawards. The advent of earthmoving machinery enabled much higher sea walls to be built almost at the seaward limit of saltmarshes. This meant that larger areas were reclaimed and losses could only be slowly replaced by the development of new marsh.

The ‘isostatic adjustment’ of the British Isles following the removal of ice from the Scottish Highlands after the last ice age means that this area is rising while southern Britain is gradually sinking (Figure 1.1). Because the level of southern England has fallen there has been a rise in the relative level of the sea. In the last few decades this process has been augmented by the rise in sea level as a result of climate change.

In completely natural situations saltmarsh can adapt to rising sea levels by a process of erosion at the seaward edge and the re-deposition of this material in the higher areas of the marsh. By this process the marsh can effectively move landwards and up the coastal slope to find a new equilibrium. This can still happen in remote areas of the north and west where there is no barrier at the landward edge of the marsh to limit the processes.

However, particularly in the south of England where the problem of rising sea levels is at its greatest, the presence of fixed sea walls means that marsh cannot re-form in a new position at a higher level further landwards. Effectively the marshes are progressively being lost by a process of ‘coastal squeeze’. The only ways that extensive new marshes can be created in this situation is by the very large-scale import of new sediment, or by the removal of the seawall itself to a more landward situation; this latter process of saltmarsh creation, or more correctly re-creation, is called ‘managed retreat’ or ‘managed realignment’. Given that any material deposited along the edge of the present marshes would be very vulnerable to being washed away by the sea, particularly in the situation of coastal squeeze, managed retreat is generally the only practical option to remedy the large-scale loss of marshes. Nevertheless in situations where marsh losses are less severe or where managed retreat is either very expensive or otherwise unacceptable, special measures to reduce the erosion of present marshes may well be an effective and appropriate alternative solution (Johnson, 2000). Work in Australia at the site of the 2000 Olympics has shown that it is possible to re-create saltmarshes even when an area has been infilled and developed industrially (Burchett, 1998a and b).

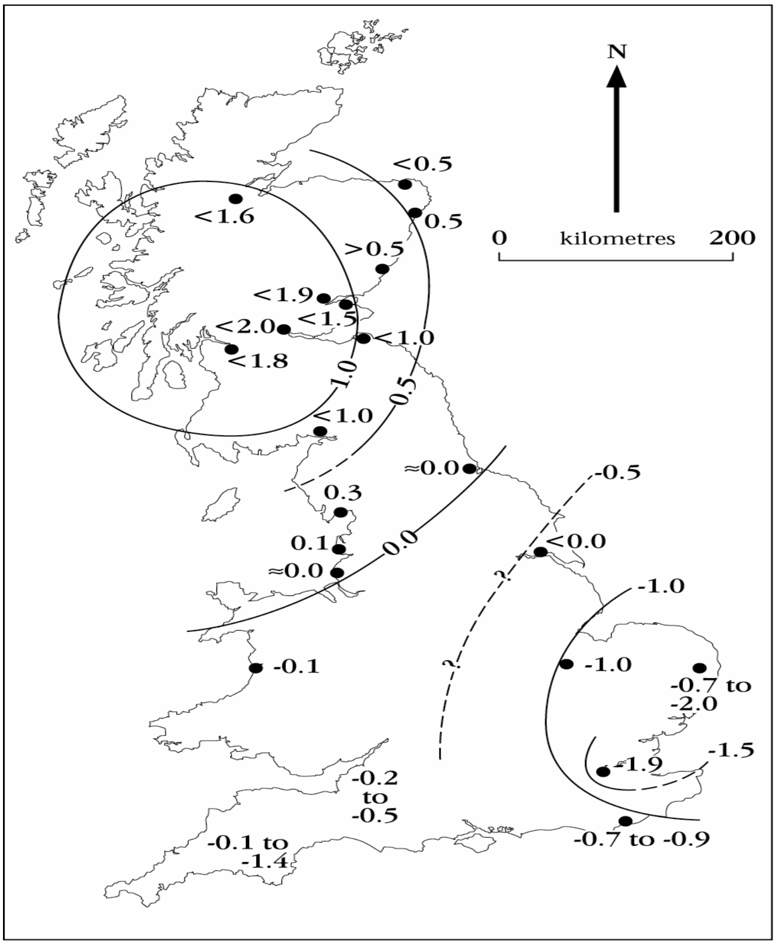


Figure 1.1. Isobases of uplift / subsidence following the late glacial and Holocene deglaciation of the British Isles, mm per year (after Shennan, 1989)

The creation or re-creation of saltmarshes is not only important for the conservation of species and habitats. Saltmarshes can play a major role in flood defence by providing a dynamic buffer between the land and the sea. The high wave energy created during storm events can be dissipated by the vertical erosion of the front of the saltmarsh, but the material eroded from the marsh remains on the fronting mudflats and is available for subsequent accretion during calmer interludes (Pethick, 1992). The effectiveness of this system of buffering will depend on the width of marsh that is present in front of the sea wall. For example, in Essex it has been shown that where the saltmarshes are 80 metres wide a 3-metre-high sea wall will give adequate protection. If there are 30 metres of marshes a 5-metre wall is needed. However, if there were no marshes in front of the wall a 12-metre wall would be required (NRA, 1992). Similar results have been obtained from north Norfolk where Möller *et al.* (2001) showed that saltmarshes formed effective buffers to wave action. This occurred through the reduction in water depth over the marsh and the increased friction of the vegetated surface reducing wave height.

1.3 Synopsis of saltmarsh distribution in the UK and Europe

European distribution of saltmarshes

Saltmarshes can be found in most of the countries of Europe with a coastline subject to a macro- or meso-tidal regime (Figure 1.2). Although these areas cover a wide latitudinal range they virtually all fall within the geographic limits of saltmarshes. There are somewhat rudimentary saltmarshes in suitable areas in arctic northern Europe while the south of Europe is still too far north for mangroves to provide an alternative (although in comparable areas in the southern hemisphere saltmarshes and mangroves can co-exist, e.g. Sydney, Australia). Nevertheless within this wide span there is a considerable range of marshes in terms of both species composition and plant community structure. The northern marshes have fewer species and a simple structure greatly influenced by a limited growing season. Southern marshes have a much wider range of species and communities and are characterised by continuous growth all year, although there is often a summer drought period during which growth is severely restricted.

Saltmarsh areas of the United Kingdom

The saltmarshes of Great Britain have been described in considerable detail by Burd (1995). Saltmarshes are found all around the coastline of Great Britain (Figure 1.3) but they vary considerably in character between essentially lowland areas and upland areas (Table 1.1). Lowland marshes are associated with the major estuaries and inlets in low-lying geographic areas – notably around the Wash, in Essex, north Kent, the Solent, the Severn estuary, the Welsh estuaries, Liverpool Bay and the Solway Firth. The upland areas have a scattered distribution of mainly small isolated marshes, either associated with minor estuaries or, commonly, at the head of sea lochs where there is shelter from wave action. Some of these marshes have a landward limit well above the high-water mark as a result of exposure to wave action and salt spray – in extreme cases saltmarsh vegetation can be found on exposed cliff tops many tens of metres above sea level. In addition, the higher rainfall in the north-west reduces salinity levels sufficiently to enable species normally found in the upper marsh to occur lower down in the marsh, occasionally in pioneer situations (Ranwell, 1972).

Table 1.1. Regional distribution of saltmarsh sites in the United Kingdom, showing distribution of sites by size (from Burd, 1995 and P.Corbett, pers. comm.)

Region	Area (ha)	Sites >100 ha	Sites <10 ha	All Sites	Av. Area (ha)
England	32,500	59	16	120	270.8
Scotland	6748	14	280	380	17.8
Wales	6089	8	15	57	106.8
N. Ireland	239	0	6	15	15.9
Total	**45,337**	**81**	**304**	**577**	**78.6**

Data from Northern Ireland refers to protected saltmarsh only; no data is available from the Republic of Ireland.

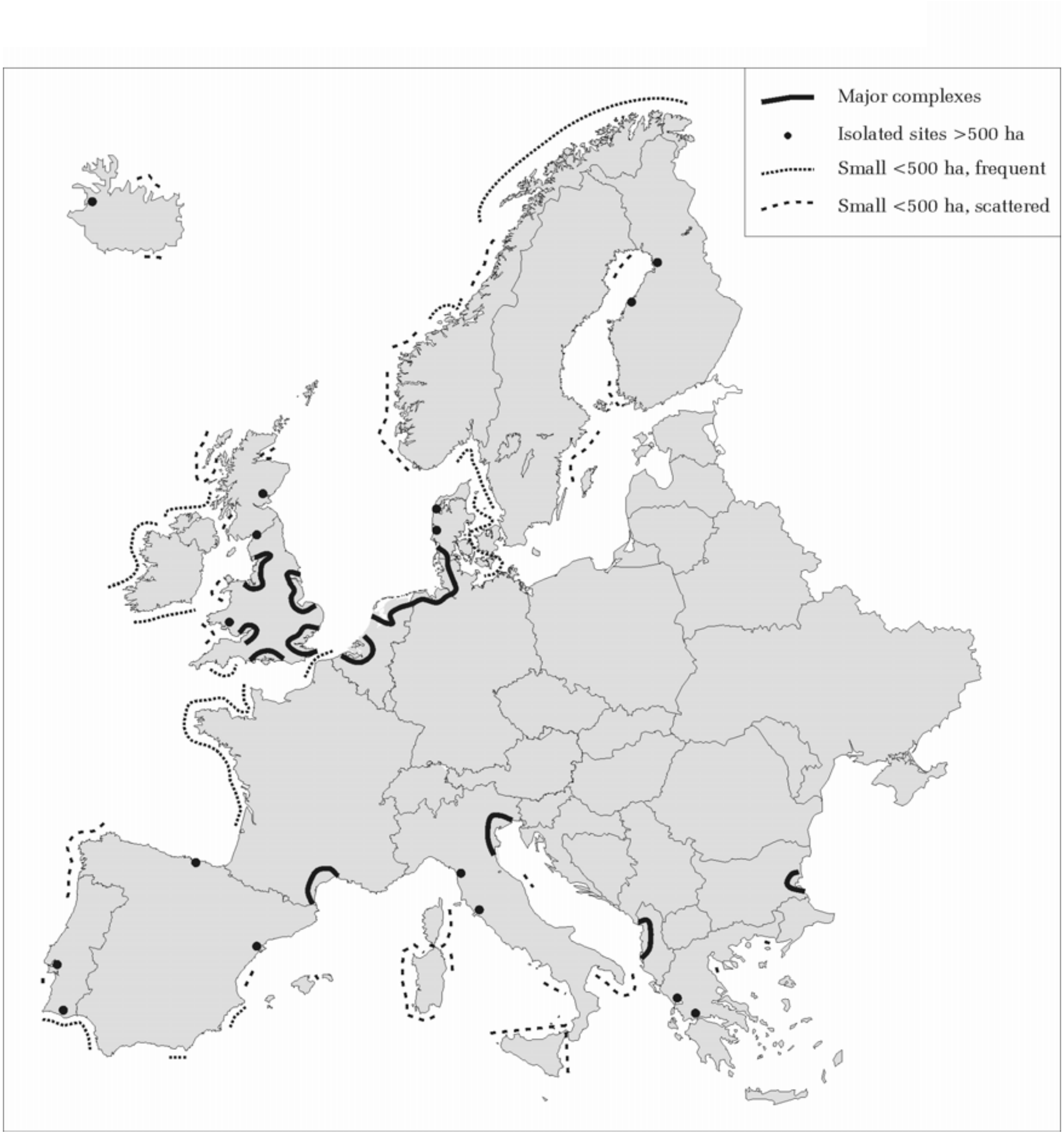


Figure 1.2. Outline distribution of saltmarshes in Western Europe (adapted from Dijkema et al., 1984)

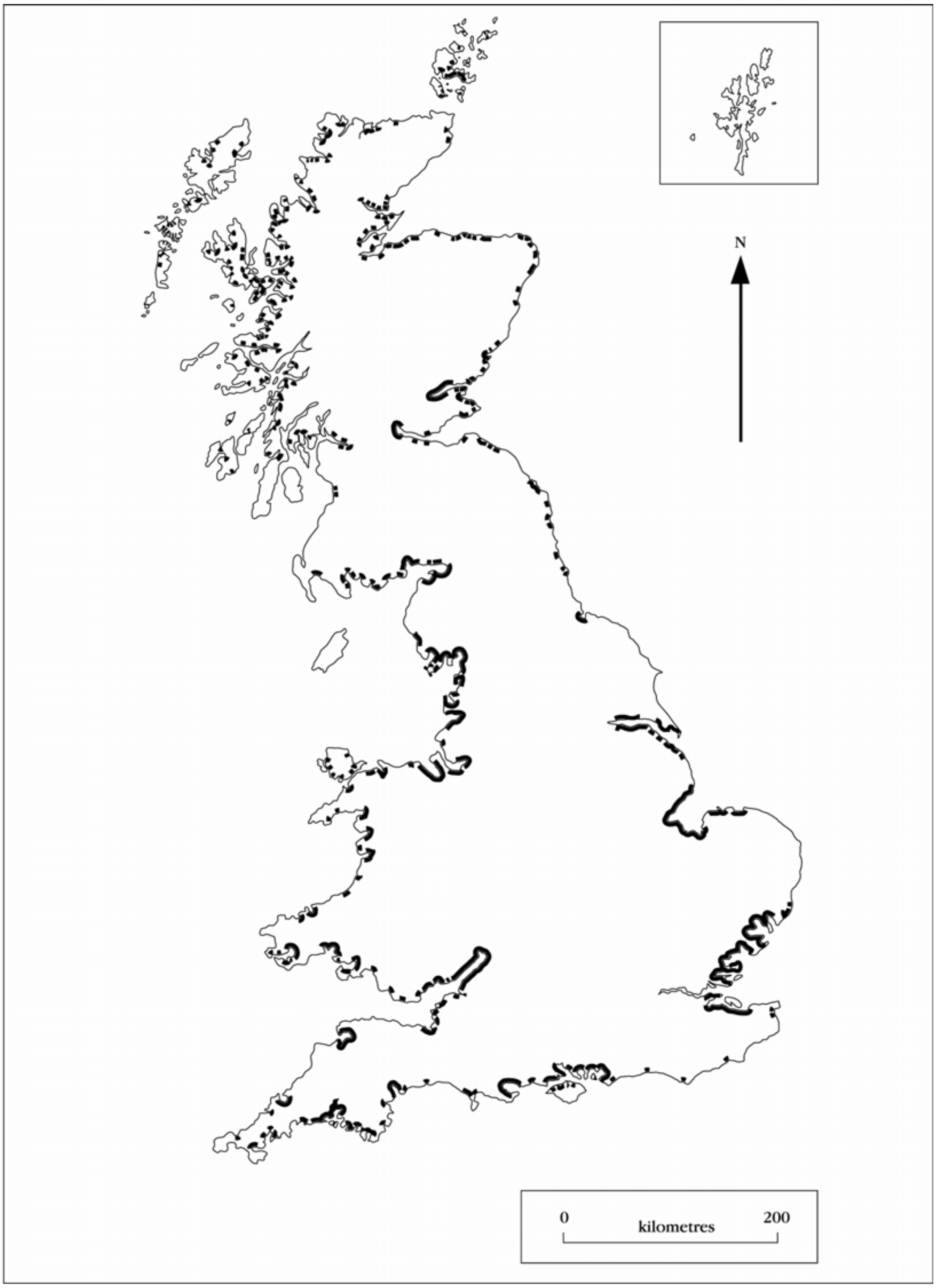
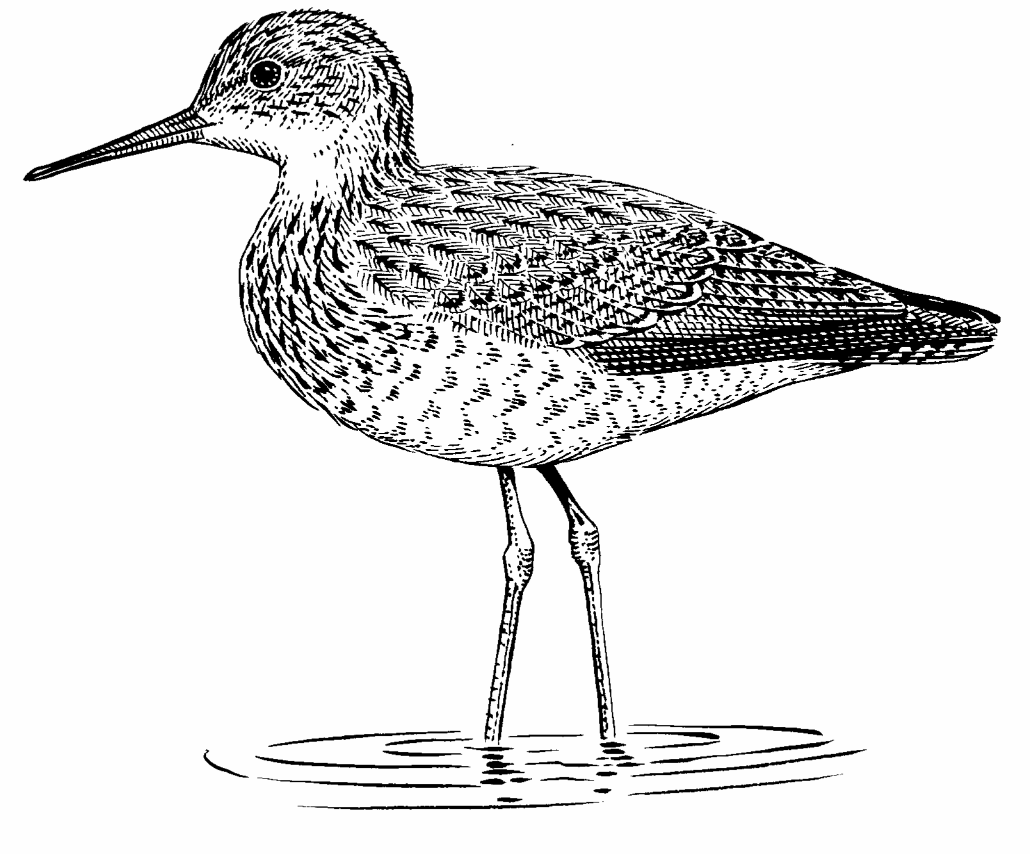


Figure 1.3. Distribution of saltmarshes in the United Kingdom (after Burd, 1989)

There are approximately 40 species of higher plants which are found in British saltmarshes (Boorman, 1966), but individual saltmarshes commonly have between ten and 20 species. Not all saltmarsh species are found across the UK and more species have a much wider distribution in southern areas. Two Mediterranean species reach northern limit in East Anglia or Lincolnshire – *Suaeda vera* and *Frankenia laevis* respectively. Both these species are associated with the transition zone at the upper edge of the marsh. The commonest communities of saltmarsh plants have a predominantly southern distribution and only limited occurrences in the north. These communities include pioneer species such as *Spartina anglica* (although often as a result of deliberate introduction) and *Salicornia spp*, middle marsh species such as *Atriplex portulacoides* and *Limonium vulgare*, and upper marsh species such as *Juncus maritimus*. In contrast, *Juncus gerardii* has a predominantly western and northern distribution while *Armeria maritima* and *Plantago maritima*, although found throughout the British Isles, are more common in northern areas.

A key distinction needs to be made between those saltmarshes which have a natural upper boundary with transition communities and those marshes where the landward limit is fixed by some form of artificial barrier, notably a sea wall. The presence of such a barrier usually limits the occurrence of transition communities and any rise in the level of the sea in relation to the land will lead to the loss of upper marsh plant communities and a reduction in the total area of saltmarsh. This occurs in the south and east of England where the process of coastal squeeze, isostatic adjustment, and sea level rise restricts vegetation communities. In much of the west and north of the British Isles any change in sea level generally results in a gradual adjustment of the plant species and communities to the new levels.



2. Environmental requirements and physical attributes

2.1 Physical Environment

Tidal regimes

Saltmarshes have been defined as areas of intertidal mud stabilised by a cover of vegetation (Boorman, 1995). Put another way, the environmental feature which distinguishes coastal saltmarshes from terrestrial habitats is tidal submergence (Adam, 1990). Whichever definition is preferred, it is clear that the regular ebb and flow of the tide bringing salinity, but also mineral nutrients, organic matter and sediment, is central to the growth, development and indeed survival of saltmarshes. While saltmarshes will grow perfectly well if subjected (artificially) to flooding twice daily to a fixed depth, natural tidal cycles are far more complex and these complexities have important consequences for the saltmarsh.

The range of the tide, the difference between low water and high water, is dependent on the geography of the coastline. In funnel-shaped bays or estuaries the tidal range is much greater than along open coasts. As the tide moves into such places the wave of the incoming tide is compressed by the coastline and the tidal range increases. At the head of an estuary frictional effects result in the tidal range decreasing. The same effect is also seen where the mouth of the estuary is constricted, limiting the influence of the tide. Any one particular saltmarsh site thus has its own characteristic tidal range. The maximum (spring) tidal range around the coasts of Britain and Ireland varies between less than two metres and more than twelve metres (Table 2.1). In general, estuaries have a tidal range of four to five metres, while on more open coasts the range is around three metres.

Table 2.1. Maximum tidal range of selected British and Irish coastal sites (metres)

Location	Coast	Description	Tidal range (m)
Plymouth	south	estuary	4.7
London Bridge	east	upper estuary	6.6
Lowestoft	east	open coast	1.9
Immingham	east	estuary	6.4
Lerwick	north	open coast	1.7
Ullapool	west	bay	4.5
Barrow	west	estuary	8.2
Shannon	west	estuary	4.5
Avonmouth	west	estuary	12.2

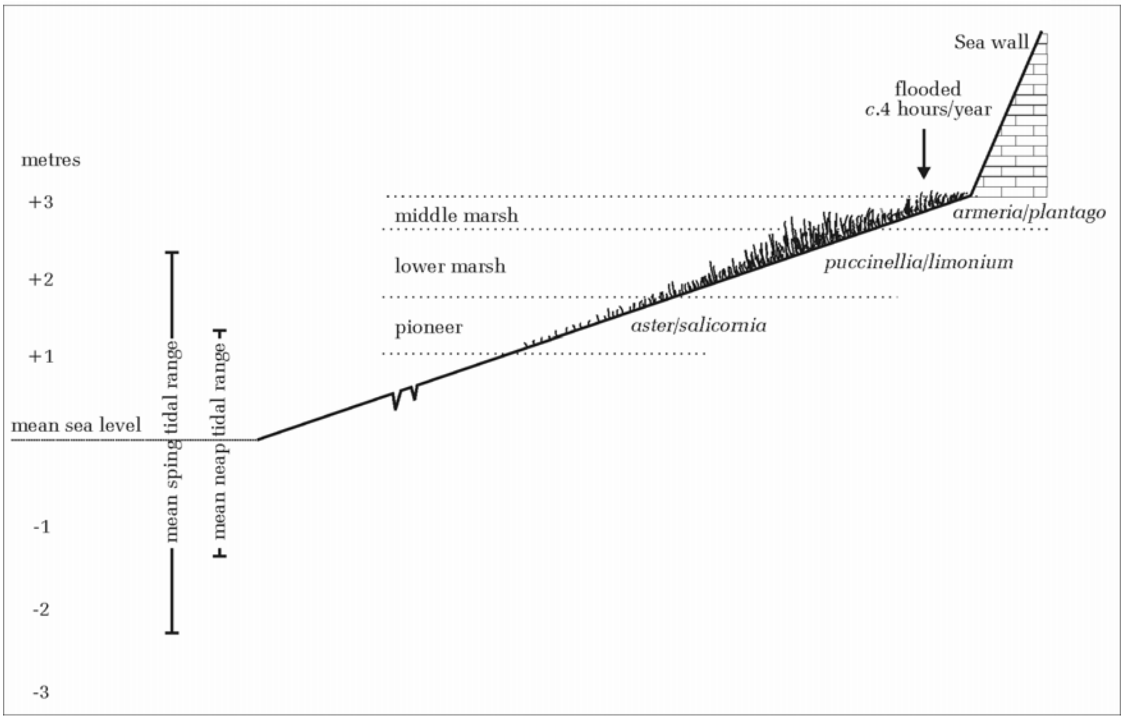
There are regular patterns to the magnitude of the tides experienced at a particular place. The observed tidal range is subject to a number of cyclical changes. The first of these is the fortnightly cycle between ‘spring tides’, when the range is at a maximum, and ‘neap tides’, when it is at a minimum. This cycle is associated with the phases of the moon, the spring tides occurring a day or so after the full or new moon and neaps just after half moon. Typically a neap tide will be two-thirds to a half of the range of the corresponding spring tide. The size of the spring tides also varies seasonally with the highest springs (and lowest neaps) occurring at the spring and autumn equinoxes. There are also some very long-term cycles in the magnitude of the tides, such as the 18.6-year cycle related to changes in the orbits of the sun and moon. The expected tidal level at any time for any place can be calculated by reference to standard tide tables (e.g. the Admiralty Tide Tables, published annually by the Hydrographer of the Navy) or by one of the software packages now available for tidal prediction.

As well as these regular changes in tidal levels there can be variations from day to day as a result of climatological changes, particularly wind and atmospheric pressure. Low atmospheric pressure will result in sea levels being raised, while high pressure will result in them being depressed. These differences are quite small and are only of real importance to deep-draft vessels navigating in shallow water. The effect of the wind can be very much greater with persistent on-shore winds raising tidal levels and off-shore winds lowering them. In certain areas the shape of the coastline can amplify the effect of strong winds. Persistent gales from the north or north-west can cause a build up in the sea level of the southern North Sea to a marked extent. These storm surges occur to some extent every year but they are generally moderate in amplitude (e.g. one metre or less) and often pass relatively unnoticed.

Much bigger storm surges occur at a low frequency but these can, nevertheless, be extremely damaging with water levels reaching two metres or more above their normal levels. Effectively there is no ebbing of a particular tide and the next flood tide comes on top of the previous one with devastating effects for both human and natural systems. Such an event may only occur once in many decades but its effects can often be long-lasting. The details of these effects will be considered later, but broadly they can include an enhancement of many of the normal tidal-driven processes in the marsh, together with major erosion of parts of the marsh or of the sea wall at the landward edge of the marsh.

The range of the changes in water level to which a typical saltmarsh site is subjected is shown in Figure 2.1. The distribution of the saltmarsh vegetation is determined by these water levels. Vegetation will only become established and survive in places where the ground surface is more often exposed than flooded, i.e. it is significantly above the mean sea level for a particular site. The bottom of the pioneer zone is usually at the level where the surface is covered by the sea by all but the smallest of the neap tides but is only submerged for around 40% of the time. In contrast the high and middle marsh are only submerged for about 10% of the time, being reached by only the higher spring tides. In between these two extremes the marsh can be divided into pioneer marsh, which is covered by virtually all the neap tides, and low marsh covered by only the spring tides.

Figure 2.1. Diagrammatic representation of the tidal changes in the water level at a typical saltmarsh site, indicating the major vegetation zones



Water movements

The effects of tidal inundation and water flow have direct impacts on saltmarsh vegetation. Generally, high water velocities are experienced in the marsh creeks which carry the water to and from the open sea. The velocities experienced will depend on the tidal range and the geomorphology of the marsh but typically are within the range of 0.5–2 metres per second (much higher values can be reached locally and for short periods). These rates of flow are sufficiently high to impede the colonisation of the vegetation down the sides of the creek although mature clumps of vegetation which become detached and fall into the creeks may survive for quite long periods.

Water velocities over the marsh surface are generally rather lower than in the creeks, partly because the water flow is no longer constricted by the creek banks but also because it is slowed by the roughness of the saltmarsh vegetation. This reduction in the velocity of the water flow is crucial to sediment accretion (Boorman, 1998). Two processes are involved. First, the vegetation impedes the water flow, particularly near the surface of the marsh, enabling suspended sediment to settle. Second, the vegetation cover reduces the re-suspension of material and potential loss of the sediment which has been deposited (Leonard and Luther, 1995, Boorman, 1998).

In some saltmarshes there are significant movements of water through the marsh soil. These are particularly significant in marshes where there are layers of coarse sediment between the finer layers. These movements can be significant for the transport of dissolved organic matter and plant nutrients to and from the main creek water flows, and they also affect the aeration of the saltmarsh soils. Even when the marsh sediments are composed predominantly of fine material there can often be visible seepages between the more consolidated layers of soil; these can affect the growth of marsh vegetation and might be a source of weakness during periods of erosion.

The water velocities experienced across the saltmarsh surface are not simply the result of the twice-daily tidal flow over the marsh. Studies in north Norfolk have shown that wave action can critically affect saltmarsh vegetation and conversely a stable vegetated marsh surface can significantly reduce wave height and impact (Möller *et al.*, 1996). It should be noted that the main effect of waves over the surface is through marked local increase of the water velocities experienced at the marsh surface. Overall the dynamic of the movements of water and sediments on the saltmarsh is complex. The analysis and modelling of the processes is further complicated by the many interactions between physical and biological processes, including the impacts of soil fauna and the microalgae and bacteria which contribute to bio-films on the surface of the mineral soil. Patterson and Black (1999) have recently made a comprehensive review of the subject.

Although not strictly a water movement, waterlogging can have major effects on saltmarsh vegetation. Waterlogging can result when the particle size of the soil sediment is small or even when there is a layer of very fine sediment on the surface of the soil. Waterlogging results in anaerobic soil conditions with the build-up of compounds toxic to normal plant growth. A few species of plants can cope with these conditions owing to the presence of air-conducting tissues in their roots, but many other species are either completely excluded from such areas or cannot extend their root systems beyond the upper slightly aerated layers of the soil. These effects are shown by the lack of species such as *Atriplex portulacoides* which are intolerant of waterlogging, and which are consequently restricted to the sides of the creeks where conditions are not so severe.

Climatic effects

Wind speed and direction and atmospheric pressure can affect tidal processes and so affect saltmarsh (see above). Other factors such as high winds may affect the marsh directly through increased wave action that can cause erosion. Conversely, strong onshore winds as the tide rises over the mudflats beyond the marsh cause surface erosion of the outer flats, enhancing the sediment load of the incoming tide and increasing accretion on the marsh. Studies in Essex and Norfolk have shown that short periods of increased accretion may be of major significance in determining long-term growth of the marsh surface (Boorman, 2000).

In common with all plant communities, temperature and rainfall affect saltmarsh vegetation. The close proximity of the sea influences the temperature regime experienced on the marsh. The sea reduces the extremes of temperature experienced along the coast, and water covering the marsh can significantly alter soil temperatures. The relative warmth of the incoming tide can enhance the growth of the saltmarsh vegetation in the autumn. Conversely, in the spring it appears that soil temperatures are kept lower by being covered by cold water. It is likely that the net effect is largely one of a slight postponement of seasonal changes.

In virtually the whole of the UK there is a period during the winter when the growth of saltmarsh vegetation is halted through low soil and air temperatures. The length of this period varies regionally as well as seasonally. By October most saltmarsh plants have produced their seed and the annual species have begun to show signs of senescence. The timing of the death of annual species and the loss of leaves from most of the perennial species varies considerable from season to season with the timing of the first frost. There is a gradual loss of dead material from the marsh surface during the winter but the skeletal remains of annuals such as *Salicornia* spp. often survive into the early spring. In southern Britain the resumption of plant growth in the saltmarsh occurs between February and April with the germination of annual species and the production of new shoots and leaves on perennials.

There have been some years in East Anglia recently when growth has been maintained at low levels through the winter, but in other years the marshes have been covered by snow for several days, although at the low marsh the warmer sea water has removed this cover. Occasionally it has been reported that significant damage has been done to saltmarsh vegetation by the action of ice. Sea ice has frozen to the marsh surface and subsequently the vegetation has been carried away with the ice by the tide.

In the south east of Britain summer drought can inhibit saltmarsh plant growth. This is partly due to a direct shortage of water but the effect is significantly enhanced by raised soil salinity when evapo-transpiration is high. The effect is greatest in the high marsh when hot dry weather coincides with neap tides that do not cover the marsh. This effect is localised in the lower parts of the marsh when salt water concentrates and subsequently evaporates. A period of rainfall, however, soon disperses these areas of hyper-salinity.

In the higher marsh heavy rainfall can reduce the surface salinity and enhance the germination of saltmarsh species. It has been shown that the germination of all species other than those associated with pioneer marsh is enhanced by a lowering of the soil salinity (Boorman, 1966).

2.2 Chemical environment

Salinity

Saltmarshes have been defined as occurring in areas regularly inundated by sea water and hence with a high salinity. Salinity influences the germination of seeds and seed root elongation (Katembe *et al.*, 1998). These findings are consonant with the general observation that established saltmarsh perennials are far more tolerant of salinity and flooding than the seedling stages of those species. The majority of saltmarsh plant species are non-obligate halophytes (i.e. plants tolerating enhanced salinities but not needing them) and generally show improved growth performance in non-saline habitats (Boorman, 1966). The crucial factor is that the non-obligate halophytes found in saltmarshes grow less vigorously than many of the exclusively non-halophytic species. Halophytes growing under normal non-halophytic conditions are unable to compete with these non-halophytic species and are thus confined to the saltmarsh habitat where their competitors are excluded by the raised salinity. The exception to this is found in the lower marsh where an ability to withstand prolonged immersion is needed as well as an ability to withstand the salinity. These lower marsh species generally only thrive in the presence of at least a degree of salinity (i.e. are obligate halophytes).

Plant nutrients

Saltmarsh plants have similar nutrient requirements to non-saline-tolerant species and like these species they need a well-developed root-system for the effective uptake of nutrients. Root growth can be restricted both by raised salinity and low oxygen concentrations in the soil and this can restrict the ability of the plant to acquire sufficient quantities of phosphorus and nitrogen. It has been shown that flooding can restrict the ability of saltmarsh plants to take up nutrients (Bouma *et al.*, 2001).

Dutch and American studies have shown that raising nitrogen levels can result in an enhancement of plant growth (Valiela and Teal, 1979, Kiehl *et al.*, 1997); nitrogen level is also a controlling factor in the development of algal blooms. Studies on the primary productivity of a range of saltmarsh plants have shown good correlation between productivity and phosphorus levels but no correlation with nitrogen levels (Hazelden and Boorman, 1999). It seems clear that both elements are critical for good plant growth and even a slight shortage of either of them will lead to the concentrations of the other one becoming the limiting factor (Boorman, 1999). The whole subject is still very much under investigation (e.g. Verhoeven *et al.*, 2001).

Other chemicals

The are many pollutants in the estuarine environment, including heavy metals and complex organic pollutants, for instance herbicides, insecticides and industrial organics such as poly-chlorinated biphenyls. These substances occur widely in the environment but detailed surveys along the Essex estuaries have show there can be locally high concentrations (Scrimshaw *et al.*, 1994). The re-mobilisation of buried deposits of pollutants can occur during storms.

It is unclear what effects the relatively low concentrations of these pollutants have on saltmarsh biota or to what extent the re-working of saltmarsh sediments will lead to the release of significant levels of buried pollutants. Nevertheless it has been shown that the heavy metal cadmium found in the sediments of the Sado estuary in Portugal is readily taken up by leaves of *Atriplex portulacoides* and the levels of cadmium in the leaves represent a potential health hazard to grazing animals (Reboredo, 1992). Selenium and heavy metals including copper, nickel, zinc, lead, cadmium and iron have been shown to accumulate in the litter of common saltmarsh plant species (Zawislanski *et al.*, 2001). Concentrations in the decaying litter increase as much as 150 times compared with the levels in plant tissue. Other species such as *Spartina alterniflora* and *Phragmites australis* have been shown to accumulate metals from the marsh sediment and then release them from their leaves into the environment (Burke *et al.*, 2000).

2.3 Biotic environment

Higher plants

The range of higher plants that are able to tolerate the effects of salinity and inundation in UK saltmarshes is limited. The level of the marsh in relation to the local tidal regime primarily determines the distribution of these species but this is not the sole factor in determining plant distributions. Species found on the lower marsh are restricted to those tolerant of inundation and salinity. At higher marsh levels species are generally determined by inter-specific competition and often to the detriment of the less competitive but more environmentally tolerant lower marsh species.

The pioneer communities are in general structurally simple with just a few species and limited ground cover. The surface of the ground beneath the plants is generally bare. In places where the vegetation is denser there may be an increase in accretion leading to the development of raised mounds with the space between these mounds being colonised gradually.

With the development of more mature plant communities the ground cover becomes almost complete. Any bare ground that may occur from time to time is usually colonised by individuals of one or more of the pioneer annual species. There is a degree of differentiation in both the vertical and horizontal planes. Saltmarsh perennials have different structural forms, leading to the development of a degree of layering between the prostrate species (including both rosette species such as *Armeria maritima* and *Plantago maritima* and creeping grasses such as *Puccinellia maritima*) and taller growing species such as *Aster triploium* or the woody *Atriplex portulacoides*. When at high densities, either of the latter two species can form single-species stands with bare or almost bare ground below them, but more often the larger plants are sufficiently spaced for the development of an under-storey layer of vegetation. As the saltmarsh plant communities become more mature there is an accompanying development of a distinct litter layer as fallen plant material accumulates and is subsequently incorporated into the soil surface.

The vegetation structure of a mature saltmarsh depends very much on whether grazing takes place. In the UK the vegetation of ungrazed marshes is generally 0.5–1 metre tall but with considerable spatial variation in height. Grazed saltmarsh vegetation has a very characteristic appearance forming a dense mat of vegetation often less than 0.1 metre in height. Trampling can produce similar effects to that of grazing but generally there are fewer species in a grazed sward than in a trampled sward.

Algae

In the pioneer communities the sediment surface is frequently covered by a film of microalgae (diatoms) or a mat of filamentous algae. The role that these two types of algae play in the stabilisation of sediment will be discussed later.

Algal mats and films can also be found in the vegetation gaps in more mature saltmarsh communities but are less common. There are, however, a number of macro-algae that can be found mixed in with the vegetation of the mature saltmarsh. These are usually free-living forms of species more readily recognised when growing attached to stones, rocks or large shells. They can amount to up to 10% of the total standing crop of the plant community but their occurrence and distribution tends to be irregular in space and time. It would appear that they could provide shelter for associated small invertebrates as well as seed germination sites.

Algae can play an additional and rather different role in mature saltmarsh. From time to time floating mats of mixed species of algae and seaweed are deposited by spring tides on the surface of the marsh and these can sometimes be sufficiently dense to lead to the death of the vegetation beneath. Re-colonisation of these bare areas can be recognised by the occurrence of irregular patches of different species to those in adjacent vegetation.

Microflora

The soils of the pioneer saltmarsh are relatively simple with little differentiation but there is a gradual development of fungal and bacterial communities. These fungal and bacterial species play a major role in the breakdown of plant material together with the release of plant micro- and macro-nutrients. It has been shown that the decay of plant material is mediated by the activities of fungal and bacterial species (Newell and Palm, 1998) and importantly certain saltmarsh plant species have mycorrhizal associations (Rozema *et al.*, 1986, Carvahlo *et al.*, 2001). It is highly probable that these associations play a major role in the processes of saltmarsh development, but there is little information on their rates of development or spread.

Microfauna

Microfaunal species have many complex roles and actions. Small invertebrates can limit the role of microalgae in stabilising the mud surface and they can also affect seed germination and plant establishment. This can be through the effects of small invertebrate species grazing on the algal film that stabilises the mud surface or through these small animals eating the seeds of the saltmarsh plants. Conversely, although the occurrence of algal mats stabilises the soil surface, the over-development of these mats can inhibit plant germination and thus the microfauna can make a direct contribution to the establishment of higher plant species.

Macrofauna

The actions of the macrofaunal element of the saltmarsh are complex and varied. The smaller molluscs feed directly on the leaves of many of the saltmarsh plant species. The larger species of crabs have both an indirect impact through the effects on small prey species of invertebrates. They also have a more direct impact on the vegetation by their burrowing action helping to aerate the saltmarsh soil and to incorporate surface organic matter into the soil.

3. Biology and ecological functioning

3.1 Successional development

Primary colonisation of mudflats

The colonisation of mudflats by pioneer saltmarsh species is the critical first step in the development of saltmarsh. While this initial development of the marsh is often in major steps with long intervals in between, most marshes still have a limited pioneer zone. Like many other pioneer communities, the general appearance is one of scattered individual plants with considerable bare ground between them. The other notable feature is the variability in the seaward limit of this zone. The boundaries of the other saltmarsh zones are relatively stable, changing only slowly as the marsh gradually grows vertically through surface accretion. The lower limit of the pioneer zone can vary greatly from season to season, and while this variation is often quite small in vertical terms because of the usually gentle slope of the upper flats, it can vary by tens of metres from year to year.

The principal reason for these changes is the tidal regime during the period of seed germination. It is crucial for the germination and establishment of the plants to have a period of a few days with little or no disturbance from the action of the tide. If the weather conditions are suitable for germination while water levels remain high the extension of the pioneer zone seawards will be limited. Similarly a period of stormy weather while the seedlings are still small may result in substantial losses through erosion. A seedling's success depends on its ability to extend its root to a sufficient depth in the soil so as to anchor it securely against the action of the tide. The deposition of fresh sediment will benefit this process. Recent experiments have shown that some pioneer saltmarsh species also show enhanced root and shoot growth rates when rates of sedimentation are increased (Boorman, 2001). It can be seen that small variations in time and space in the patterns of tidal flow and sedimentation can have major effects on plant colonisation in the pioneer zone.

It has already been noted that the dead remains of annual plant species can persist through the winter, and the shelter these remains can provide will benefit the rate of colonisation the following spring. Additionally these plant remains will help to ensure that the seeds of these species are retained on site and not washed away. These comments apply only to the annual species and are different for pioneer perennial species.

Development of closed plant communities

Once vegetation is more or less permanently established within an area, the next stage is the increase in the density of shoots or individuals to a stage when the cover of vegetation over the ground is more or less complete (Figure 3.1). This process can occur either with pioneer annuals such as *Salicornia* and *Suaeda* spp. and their allies, or with colonising perennials such as *Spartina* spp. The presence of a closed or nearly-closed canopy marks the onset of maturity of the pioneer community. This is seen in the increased rates of sedimentation resulting from the protection provided by the increasingly dense vegetation cover. The next stage in saltmarsh development is the arrival of saltmarsh plant species less tolerant of flooding and inundation than the pioneer species.

Figure 3.1. Development of the vegetation canopy during saltmarsh succession. This picture shows a mixed community between NVC SM10 and SM11, with *Aster tripolium* becoming dominant over an understory of *Suaeda maritima* and *Puccinellia maritima* while the ground surface is covered by an algal mat consisting mainly of species of green algae *Enteromorpha*. Photograph © L A Boorman.

Maturation of vegetation

The development of the lower marsh communities is marked by the increasing diversity which follows the arrival of a range of new species. The lower marsh is a more stable community than the pioneer marsh and this can be seen by the arrival of some perennial species among the annual colonisers. Typically, *Aster tripolium* spreads rapidly in the lower areas of marsh. It has a high seed production and although it is often a long-lived perennial it can also behave in lower areas as a biennial or short-lived perennial species, sometimes even being found among the colonising species.

Another species associated with the lower marsh is the grass *Puccinellia maritima*. It is not as tolerant of inundation as *Aster* and in contrast to the often tall *Aster* is a low-growing species, but it can spread rapidly in the lower marsh. Areas of bare mud at a higher level than the usual pioneer marsh communities can be colonised directly by the stoloniferous *Puccinellia* forming a compact dense green sward. There are various other perennial saltmarsh species which usually follow on quite quickly, particularly the woody sub-shrub *Atriplex portulacoides*, although where the sediment is fine and the soil drainage is poor it tends to be limited to the banks of the creeks. These three species can be taken to represent the peak development of the lower marsh.

The next stage is the development of the middle marsh with the establishment of such species as *Limonium vulgare*, *Plantago maritima* and *Triglochin maritima*. These are all rosette perennials, long-lived species but with relative low seed production and thus slow rates of spread. The resulting complex patterns of individuals and species may be taken to represent the climax of the saltmarsh succession even though there is still the potential for the even less inundation-tolerant but more competitive high marsh species to invade. Most of the species characteristic of the pioneer and lower marsh can also survive, usually as scattered small individuals, in the middle marsh.

The transition to high marsh communities is not found everywhere. In much of south and east Britain the presence of a sea wall impedes the development of high marsh communities. High marsh communities are generally found only where there is a natural and gradual slope from middle marsh through to non-saline areas. The species composition of high marsh is rather variable depending on the nature of the soil. In wet areas the development of high marsh is characterised by the arrival of species such as *Juncus gerardii* and *J. maritimus* and the subsequent assemblage of damp-loving species contrasts with the drier upper marsh species of *Elytrigia atherica*, *Festuca rubra* and *Seriphidium maritimum*. With the intense competition in the dense stands found in the high marsh the survival of the species characteristic of the pioneer and lower marsh is very restricted. In the upper parts of the high marsh non- or marginally-saline species, such *Lotus corniculatus* and *Leontodon autumnalis*, can also be found, but this indicates the development of transition communities.

Transition communities

The nature of any transition community will depend on the vegetation adjoining the upper edge of the saltmarsh. Commonly this will be a damp grassland community where the land gradually slopes up into higher ground. Brackish wetland communities are also common along the line of fresh water seepages from higher ground down into the marsh. However, there is a range of other transition communities from the transition into sand dune or dune slack to the uncommon saltmarsh woodland transitions found in the southwest of England.

Marsh decay and regeneration

The process of development can sometimes be reversed, with the processes of decay and loss of species diversity replacing natural developments. This can occur at any stage within the saltmarsh succession but in the more advanced stages of marsh development any process of degeneration is likely to be more marked. This is because mature saltmarsh species are badly adapted for colonising areas which have been degraded. In some cases recolonisation will begin with the introduction of pioneer species.

3.2 Vegetation structure

Structure of pioneer communities

The pioneer plant communities are generally simple in structure with mono-specific stands. There is little differentiation into vegetation layers and there is only a transient layer of litter on the soil surface. Even when several species are found together in the pioneer zone it is often in the form of relatively large clumps of single species rather than mixed stands with a more complex structure. The dominant bio-physical processes in the pioneer communities are those concerned with the trapping of sediment and the building up of the soil surface. Below the surface the simple, largely inorganic soils of the non-vegetated flats are gradually replaced by an increasingly complex soil structure and more diverse microflora and microfauna.

Early changes in community structure

The increase in species diversity that accompanies the transition from pioneer to lower marsh communities facilitates the development of structure to the community. In the early stages this is through the development of a mosaic comprising individuals and groups of individuals of the various component species. Following this two-dimensional differentiation very closely is the development of a third dimension to the community structure as the various species develop an element of layering, with prostrate species along the soil surface, tall species developing in the vertical plane and intermediate species in between. There can even be an under layer of algal species growing directly on the surface of the soil itself. It should be pointed out that although most individual areas of lower and middle marsh will show the various elements of this differentiation, at any particular point in the marsh there may only be one or two of the elements mentioned.

Structure of mature marsh vegetation

The mature marsh will have a vegetation structure similar to that described above for the lower marsh, but there will be greater species diversity and all the structural elements will be better developed. The structural diversity will be more uniformly distributed over the surface of the marsh. It should be noted, however, that the full degree of structural differentiation will only be found where the marsh is ungrazed by larger grazing animals. Even light grazing will reduce the vertical and horizontal elements in the structure of the community. However, there can be local grazing, for example by the marine gastropod *Hydrobia*, on leaves of plants without any major effect on community structure. The details of the architecture of the saltmarsh vegetation canopy have recently been reviewed by Keer and Zedler (2002).

Relation to other vegetation types

The structure of mature saltmarsh vegetation is basically similar to that of damp inland grassland but without the elements contributed by regular tidal flow, notably the incidental occurrence of elements of algal communities. Without the tidal flow as a transport agent the litter layer in grassland communities is generally better developed. There is usually also a greater variety of meso-faunal grazing species associated with inland grassland communities than with saltmarshes.

3.3 Effects of nutrients on vegetation

Nutrient requirements of pioneer communities

The general effects of plant nutrients on the vegetation have been considered in the previous section but some further comments are appropriate in relation to the development of saltmarsh vegetation. The upper mudflats on which the pioneer saltmarsh develops are relatively low in nutrients, and it is crucial for the plants colonising these areas to be able to absorb nutrients from the soil and from the water whenever they are available. The increase in the organic content of the soil, partly by the incorporation of plant litter and other organic matter into the soil through the activities of various invertebrates and partly by the root growth of the pioneer plant species, is a key element of the establishment and development of saltmarsh communities.

Effects of nutrient levels on marsh development

Perennial species are better able to withstand the environmental stresses associated with intertidal areas. The development of the mature saltmarsh communities is paralleled by the building up of reserves both within the plants themselves and within the soil. The proportion of the plant biomass within the root decreases as the plant community matures (Cartaxana and Catarino, 1997). In the pioneer zone there is a great need for a well-developed root system to anchor the plant securely against the action of the tide. This requirement decreases as the marsh matures and the augmentation of above-ground growth facilitates the structural development of the vegetation. The mature marshes have higher levels of nutrients in both the plants and soil. It has been shown that the competitive ability of the saltmarsh plant species and thus the dynamics of the vegetation can be significantly affected by the nutrient supplies available within the marsh (Emery *et al*., 2001).

Nutrient influences on transition vegetation

The nutrient balances of the transition vegetation will largely be determined by the nutrient status of the adjoining communities. Generally these non-saline communities will have a higher nutrient status than that of the saltmarsh. Often an enhancement of the growth of high marsh vegetation can be seen along the line of seepages and while this may in part be due to the lowering of salinity there is generally also a nutrient enhancement which favours plant growth. Other factors affecting the nutrient status of transition communities are the run-off of fertilizer residues from adjoining agricultural land, the seepages from the dung of cattle on adjoining land and local enhancement of the nutrient status around dung deposits on the marsh itself.

3.4 Primary productivity

Methods of determining saltmarsh productivity

First of all a clear distinction has to be made regarding the relationship between standing crop, or biomass, and productivity. The standing crop is the weight of plant material per unit area at a particular time. This may or may not be considered the same as the biomass of that species or community, as the latter term usually includes the below-ground component. The standing crop is generally determined by clipping the vegetation from a number of sample areas and determining the dry weight of the samples and thus the mean dry weight per unit area (usually expressed as grams per square metre). The dry weight of the standing crop will vary through the year from very low values at the end of the winter to a peak towards the end of the growing season. This increase in the standing crop can be seen as paralleling productivity but it is almost always considerably less than the true productivity. This is because there is a continual loss of material from the standing crop and thus the peak standing crop is always less than the true productivity. This point is best illustrated by reference to the situation in a mown or grazed community where the standing crop is kept at very low levels, in both senses, by the continual removal of plant material. The productivity of this community is represented by the total weight at the end of the growing season of all the material which has been removed together with the material which has been lost by decay during the season.

Productivity thus has to be determined by a method which allows for the removal of material: this involves estimating the rate of loss of organic matter by decay and preventing grazing where necessary. The method consists of taking successive cuts at monthly intervals during the growing season and separating the material into living, standing dead and litter according to the method of Smalley (Linthurst and Reimold, 1978). Precautions are taken to ensure that subsequent sample areas do not overlap areas sampled previously. These methods were used in a recent four-nation study on saltmarsh productivity (Boorman, 2000) and the results are comparable with other methods employed elsewhere.

The results of these studies showed that the saltmarshes of Essex and Norfolk had a net annual primary productivity of 450–500 g/m^2 per year (Boorman and Ashton, 1997) and these figures were similar to those from France and the Netherlands. The results from the study site in Westerschelde in the Netherlands was markedly higher, but this was explained by the degree of eutrophication of the estuary (Lefeuvre, 1996).

A note of caution must be applied to all the determinations made of above-ground productivity which are based on the weight of mixed vegetation rather than on the sum of the productivity of individual species. Because of the seasonal differences in the production and losses shown by individual species the sum of the production of each species is generally much higher than the overall production determined from the vegetation as a whole. Caution needs to be taken in comparisons between different figures, especially when very mixed communities are involved.

The method described above and other similar methods are all concerned with the above-ground productivity. In theory similar methods could be employed to determine productivity below ground, but the disturbance to the habitat would generally be unacceptable and in practice great difficulties occur in separating fine roots from the often very cohesive saltmarsh soils. It is also very difficult to make the distinction between living and dead material that is needed to estimate rates of turnover. The best that can be achieved is to make simultaneous and approximate estimates from time to time of standing crop and below-ground biomass and to obtain from these figures an approximate estimate of the productivity.

Some of the early results on below-ground productivity gave very high figures but more recent results have been rather lower. Recently the use of isotopes to trace carbon allocation and biomass production seems to confirm the inaccuracy of the earlier studies;

nevertheless it is clear that below-ground productivity is still very much higher than above-ground productivity. A survey of a range of recent results indicated that below-ground productivity was on average four times greater than above ground productivity (Boorman, 2000).

Change in productivity during marsh development

There are changes in the above-ground productivity of saltmarshes during their development, but the pattern is obscured by the large contribution made by certain species at different stages in saltmarsh succession. In particular, the high productivity of *Spartina* in some pioneer communities and of *Elytrigia* in some high marsh communities tends to dominate the rather lower productivities of the more frequent saltmarsh species (Hazelden and Boorman, 1999). The general picture that emerges is that there is moderately high productivity in the pioneer marsh, then a fall in productivity with the development of lower marsh but after this a steady increase in productivity as the saltmarsh develops into mature middle marsh, until finally there is a reduction in productivity in the high marsh (see Table 3.1)

Table 3.1. Net annual primary productivity (NAPP) of the four major saltmarsh zones studied in England, France, and the Netherlands (from Hazelden and Boorman, 1999)

Marsh zone	Main species	Range NAPP Average g/m^2 per year	
Pioneer marsh	*Salicornia*	233–849	465
Pioneer marsh	*Suaeda*	1032	1032
Lower marsh	*Puccinellia*	317–701	485
Middle marsh	*Puccinellia*	417–824	586
Middle marsh	*Atriplex*	631–1708	1137
High marsh	*Elymus*	362–1260	593

Geographical variations in plant productivity

There are clear variations in the above-ground productivity of saltmarsh plants between the UK and the Netherlands on the one hand and Portugal and France on the other. It is quite difficult to make meaningful comparisons because there are different species with notably high and notably low productivities in each area. Generally it appeared that, apart from some of the *Spartina* stands, the highest productivities were found in the Portuguese marshes and rather lower productivities in the UK marshes; France and the Netherlands tended to be intermediate.

From these results and other field observations it emerged that while saltmarshes in England and the Netherlands had broadly similar above-ground productivities the warmer conditions in the west of France (the production studies were in Brittany) resulted in significantly higher productivities. The levels of productivity of the Portuguese marshes were higher than the French but not as much as might have been expected from the temperature differences. The winters in Portugal were considerably warmer than in west France but against this the hot dry Portuguese summers inhibited growth, and this could explain the relatively small differences between these two areas.

3.5 Ecological functions of saltmarshes

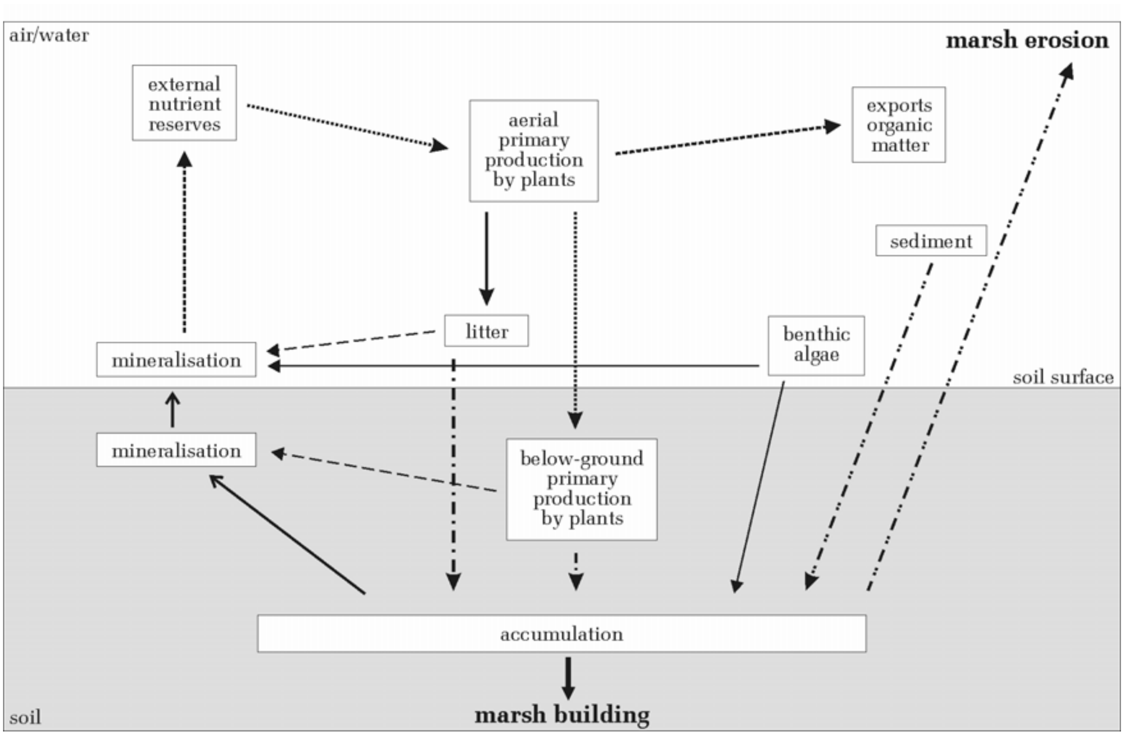
Fluxes and exchanges of organic matter

The fluxes of organic matter between the saltmarsh and the sea are driven by the tidal flow of water in and out of the marsh (Figure 3.2); however, the end result is greatly affected by the form of the organic matter (Boorman *et al.*, 1996, Boorman *et al.*, 2000, Boorman, 2000). The organic matter in saltmarshes can occur in three forms, dissolved organic matter (DOC), particulate organic matter (POC) and coarse floating organic matter (COM). The behaviour of DOC and POC is essentially the same as that of the suspended sediment and is based on the flux of the tidal flow (Boorman, 2000). The amounts and routes of COM are very variable and while under calm conditions they are similar to those of POC and DOC they can be wind-driven rather than following the usual tidal routes. Studies in Essex suggested that the export of COM accounted for only 7–8% of the total productivity. These marshes were regularly covered by the tide. On high-level marshes with infrequent tidal cover there is normally very little export of material. The occasional storm tide can result in the export of large quantities of COM, but even when this occurs it is not clear what its final fate will be. Very often the material is deposited along the drift-line well above the normal high water mark and effectively taken out of circulation.

Fluxes and exchanges of mineral nutrients

The fluxes of mineral nutrients associated with saltmarshes are unclear and there are considerable seasonal variations, particularly when the exchanges between the various forms of inorganic nitrogen are taken into account. Recent European studies suggest that there is a net export of dissolved nitrogen from the saltmarshes and probably of phosphorus as well. It appeared that the magnitude and direction of these exchanges was affected by the concentrations and gradients of these elements in offshore waters. The build-up of production-enhancing phosphorus levels in Westerschelde was attributed to high levels of phosphorus in the estuary. It is clear too that while saltmarshes can have large nutrient reserves, particularly of nitrogen, these are essentially leaky in their storage of mineral nutrients, with intermittent nutrient releases occurring both from the decomposition of organic matter and also directly from living plant tissues. The export of nutrients occurs mostly from metabolically active younger marshes rather than more mature marshes, but it can also occur when the processes of degeneration affect older marshes.

Figure 3.2. The exchanges and fluxes of organic matter, sediment and mineral nutrients associated with saltmarshes



Are saltmarshes sources or sinks?

The comments in the previous section raise the interesting question whether saltmarshes should be regarded as sources or sinks. Current evidence suggests that given the appropriate circumstances they can function in either way and this will depend to some extent on their functional age. The term ‘functional maturity’ is used because the chronological age of a saltmarsh is a poor indicator of the functioning of that marsh (Boorman, 1999). Parts of an old marsh system can become rejuvenated and regain the activities normally associated with a chronologically young system. Functionally young marshes appear to be sinks of organic matter and sediment, whereas old marshes can at times be sources of both. Saltmarshes can act as sinks for a wide range of pollutants including heavy metals, insecticides, herbicides and industrial chemicals. However, they can also act as sources of these environmentally damaging substances through reworking of sediments.

3.6 Geographical variation in marsh functions

Environmental factors affecting marsh functions

The relationship between marsh functions and environmental factors is complex and at present it is only possible to make certain generalisations. Periods of stormy weather tend to exaggerate many saltmarsh activities. If there is a tendency for the marsh to erode this is likely to be exacerbated by severe weather; conversely, a stable marsh system will often show the highest rates of accretion under the same circumstances. Similar observations could probably also be applied to a range of other marsh functions. Low temperatures will reduce the rates of most of the chemical and biological functions of the marsh. Low soil moisture levels will also reduce the rates of most biological functions, but as these generally occur during the summer in conjunction with long hot periods the rates of chemical functions will remain high.

Geographical distribution of functional marsh types

There is probably no overall large-scale geographical pattern to the various functional types of saltmarsh. Patterns tend to be locally or regionally based. In areas where a rise in sea level and the gradual sinking of land is affecting the marshes there will be a tendency towards relatively low-level and often degenerating marsh forms. In other areas where there is an abundant sediment supply the dominant marsh form will be pioneer and actively growing marshes. In upland areas there is usually a rather distinct form of marsh which is biologically active but relatively inert in the geomorphological sense. This is typical of the marshes which are often found at the heads of the sea lochs on northern and western coasts.

4. Biodiversity

4.1 Variation in UK saltmarshes

Distribution of saltmarsh types

The geographical distribution of saltmarsh types is broadly a reflection of the interactions between the local geomorphology and the local climate. Both of these elements have a strong regional bias and thus the regional distribution of saltmarsh types has a similar, parallel, regional bias. Nevertheless the major marsh types can be found in a range of distinctive regional settings while at the same time retaining the characteristic features of estuarine marsh types.

Classifications of saltmarsh vegetation

There have been many and very varied approaches to the classification of saltmarsh vegetation. One approach has treated the complexities of vegetation growing in a range of extreme environments as almost inconsequential. Other work has forced saltmarsh communities to conform to normal mainstream vegetation classification with no allowance made for the special circumstances of saltmarsh growth and development.

In the UK the early studies of saltmarsh vegetation were dominated by the classical study of Tansley (1939) and this has been reviewed by Adam (1990). Contrasting research was provided by the phytosociological approach based on the work of Braun-Blanquet and further developed by Westhoff and van der Maarel (1973). Although their work specifically covered the Netherlands their classification of saltmarsh vegetation is also applicable to most of the saltmarshes of lowland Britain (Westhoff and den Held, 1975).

The continental approach, treating plant communities as having their own distinctive unity and thus being similar to organisms, has received little favour in the UK; however, there has been no clear consensus on the best way forward. Reviews of existing methods and some new ideas were put forward by Shimwell (1971) and by Whittaker (1973) using some of the elements of the phytosociological and Tansleyan approaches. A key problem was the concept favoured by some workers that the assemblages of species found in a particular area of saltmarsh provided no more than a reflection of the environmental conditions found in that area as a result of its geomorphological history. This statement effectively denied the possibility of there being species-to-species interactions. On the other hand the concepts behind the phytosociological approach were somewhat strained by the unique conditions occurring during the development of saltmarshes. At the present time the theoretical background problems in the description and classification of saltmarsh vegetation have been put to one side in order to provide a working tool. The *National Vegetation Classification* (NVC: Rodwell, 1991–2000) covers the whole of mainland Britain together with the Isle of Man, the Isles of Scilly and the Scottish islands, but not the Channel Islands or any part of Ireland. The fifth and final volume, which includes coastal vegetation (Rodwell, 2000), represents the culmination of a remarkable project. It should be noted that full consideration has been given to the various other approaches already referred to. The background to the project and the details of data collection and analysis are fully covered in the preamble to each volume and therefore are not repeated here, save to say that the whole study is based on a total of 35,000 quadrat samples of vegetation.

NVC saltmarsh classification

The NVC describes 28 communities of saltmarsh vegetation (Rodwell, 2000), but three of these relate to *Zostera* and *Ruppia* in tidal flats and ditches and are therefore not treated here. The remaining 25 communities (see Appendix 1) are subdivided into lower saltmarsh (13 communities), middle saltmarsh (9 communities), and upper saltmarsh (3 communities).[1]

Lower saltmarsh communities (SM4–15, SM26)

The category of lower saltmarsh here includes both pioneer or colonising marsh and lower marsh. Three of the communities are dominated by *Spartina* spp. (SM4–6); one each is dominated respectively by *Sarcocornia perennis* (SM7), annual *Salicornia* spp. (SM8) and *Suaeda maritima* (SM9). Four are dominated by various mixtures of *Aster tripolium* and/or *Puccinellia maritima* (SM10–13); one by *Atriplex portulacoides* (SM14); one by a mixture of *Juncus maritimus* and *Triglochin maritimum* (SM15); and finally there is a local community dominated by a species which is normally associated with cliff communities, *Inula crithmoides* (SM26). Of these communities six may be regarded as pioneer communities (SM4, SM5, SM6, SM8, SM9 and SM10) and thus may be described as forming pioneer marsh in the sense described earlier.

Middle saltmarsh communities (SM16–20, SM22, SM23 and SM27)

The nature of the communities classified under the NVC's 'middle marsh' category suggests that it includes a high proportion of the elements of the high marsh category as described in relation to the tidal regimes. This anomaly can partly be explained on the basis that while in the east the *Festuca rubra*-dominated type (SM16) is strictly an upper marsh community, in large areas of the west the higher rainfall and consequent reduction in salinity enables it to extend down into what would generally be regarded as middle marsh. This appears to apply also to the community dominated by *Serphidium maritimum* (SM17) and the community dominated by *Juncus maritimus* and *J. gerardii* (SM18).

There are also six specialised communities with a very local distribution. In the north-west there is the saltmarsh dominated by *Blysmus rufus* (SM19) and the marsh dominated by *Eleocharis uniglumis* (SM20). In north Norfolk and Sussex there are two communities dominated by *Suaeda vera* and *Limonium binervosum* (SM21) and by *Atriplex portulacoides* and *Frankenia laevis* (SM22).

Scattered across Britain are areas dominated by *Spergularia marina* and *Puccinellia distans* (SM23). In addition the NVC middle marsh category also includes a rather mixed assemblage of communities in which the ephemerals *Sagina nodosa* and *S. maritima* are found in bare areas among stands of *Puccinellia maritima* and *Juncus gerardii* (SM27).

[1] In the *Phytosociological Conspectus of British Plant Communities* (Rodwell, 2000, p. 498) SM10, SM11, SM12 and SM13 are placed within the alliance *Puccinellion maritimae* (communities of the lower parts of saltmarshes, generally inundated by spring tides), SM14, SM16–22, SM25and SM26 within *Armerion maritimae* (perennial communities of the upper parts of saltmarshes, rarely inundated by spring tides), and SM15 within *Halo-Scirpion* (vegetation of flushed depressions in upper saltmarsh).

Upper saltmarsh communities (SM24, SM25 and SM28)

These all come in the high marsh tidal category occurring on or near the drift line at the top of the marsh. Two of the communities are grass-dominated. In the south and east the grass *Elytrigia atherica* commonly terminates the saltmarsh zone (SM24). In the north and west it is replaced by *Elytrigia repens* which extends down into the saltmarsh itself (SM28). In scattered localities in the south-east of England there is a third type of community at the upper end of the saltmarsh dominated by the Mediterranean shrub species *Suaeda vera* (SM25).

Other saltmarsh communities (S4, S12, S20, S21, S28, MG11–13 and M28)

This completes the list of saltmarsh plant communities described under the NVC, although there is also a group of plant communities described from the transition zone at the top of the saltmarsh. These include three mesotrophic grassland communities (MG11–13) together with five swamp communities (S4, S12, S20, S21 and S28). In addition stands of tall fen community with *Filipendula ulmaria* and *Iris pseudacorus* (M28) can locally be prominent at the top edge of the saltmarsh.

It is important to note that while the NVC has provided a very useful framework for the classification of British saltmarsh vegetation it does have some limitations. These relate to the generalities of the classification, which precluded going into the finer details of some of the important communities. Whilst some of the saltmarsh communities are classified into sub-communities and, in one instance, into variants, other types are inadequately described. This has considerable implications both for detailed local studies in which a single community is clearly divisible into a number of sub-categories and for regional studies where subdivisions of the NVC categories are of particular significance. It is unfortunate that some communities with a very local distribution are recognised and that some of the common communities are so wide in their scope that their value and use is limited. Section 10 contains recommendations for further work to address this.

English saltmarshes

The saltmarshes of England were described by Burd (1989) as part of a national survey of British saltmarshes for the Nature Conservancy Council. With limited time and resources this survey used 15 vegetation categories related to the provisional NVC saltmarsh classification available at the time. More recent and more detailed surveys of specific areas have been made including Morecambe Bay (Hawker, 1998), the Severn Estuary (Dargie, 1998), the Wash (Hemphill and Whittle, 2002) and north Norfolk (Stark *et al.*, 2002). There are a number of other reports relating to smaller local areas available from English Nature.

England has by far the largest area of saltmarsh of the four countries which make up the UK, with an estimated total area of 32,500 hectares – five times that of Wales or Scotland. Of the seven counties with over 2,500 ha of saltmarsh, six are in England, of which three are in the east (Lincolnshire, Norfolk and Essex), two in the north-west (Cumbria and Lancashire) and one in the south (Hampshire). Collectively these six account for 70% of the English saltmarshes, and the east of England from Lincolnshire to Kent has no less than 45% of the English total. In the east and south marshes are large: by contrast in the south-west and the north-east there are many scattered smaller marshes. In the north-west they tend to be associated with the major estuaries.

All of the 13 NVC lower saltmarsh communities are found in England (Figure 4.1). Seven of these are spread widely around the English coast (SM6, SM8, SM10, SM12–15) while five are restricted to the south or south east (SM4, SM7, SM9,SM11 and SM26). The remaining category (SM5) is restricted to Hampshire and Dorset.

Of the NVC middle saltmarsh categories five (SM16–18, SM23 and SM27) are found all round the coast (Figure 4.1) while two are restricted to the north-west (SM19 and SM20), one to Norfolk (SM21) and one to the south-east (SM22).

The three, rather specialised, upper saltmarsh categories are all localised with SM26 restricted to Norfolk, SM24 to the south and SM28 to the west (Figure 4.1).

The distributions of the various saltmarsh communities partly reflect the distributions of saltmarsh habitat, but generally they reflect the climatic requirements of one or more of the key species concerned. There is a distinct southern element reflected in the distribution of species such as *Inula crithmoides* and *Sarcocornia perennis* which could be explained by the milder climate. There is an East Anglian element with species such as *Frankenia laevis* and *Suaeda vera* reflecting the warm but distinctly drier, more continental climate. There is also a western element where a wetter climate favours species such as *Juncus maritimus* and *Eleocharis uniglumis*.

Welsh saltmarshes

The saltmarshes of Wales were described by Burd (1989) as part of the NCC survey of British saltmarshes. A detailed survey of the Welsh saltmarsh resource is currently being conducted by the Countryside Council for Wales (P Rhind pers. comm.). There are an estimated 6,000 ha of saltmarsh in Wales (the Burd 1989 survey suggests that the figure is 6,700 ha) and of this nearly half (2,876 ha) is found in Llanelli and West Glamorgan. Saltmarshes are, however, found in all the major estuaries and inlets around the Welsh coast and in other sheltered locations, such as in the lee of spits at Abermenai Point, Anglesey or in the shelter of islands such as Holy Island.

Of the 13 NVC lower saltmarsh communities nine (SM6, SM8–10, SM12–14 and SM26) are found in Wales (Figure 4.1). These are distributed all around the Welsh coast with the exception of SM9 which is restricted to a single location on Anglesey. Elsewhere in the UK it is mainly found in East Anglia but with a few scattered locations in the west of Scotland

Five of the nine NVC middle saltmarsh communities are found in Wales (Figure 4.1) and of these two (SM16 and SM18) are found all round the coast, two (SM19 and SM20) are restricted to the north-west of the principality and one (SM17) is limited to the south-west.

Scottish saltmarshes

The saltmarshes of Scotland were described by Burd (1989) as part of the NCC survey of British saltmarshes but this information is currently being updated by Scottish Natural Heritage (S. Angus, pers. comm.). The total area of saltmarsh in Scotland appears to be similar to that in Wales being quoted at 6,089 ha (Burd, 1989) and 6,567 ha (Posford Duvivier, 1998). Generally the saltmarsh occurs over a large number of relatively small sites; the average site appears to have an area of less than 18 ha and 75% of the sites have an area of less than 10 ha. The county with the largest area of saltmarsh in Scotland is Nithsdale with 1,079 ha followed by Ross and Cromarty with 718 ha and Wigtownshire with 590 ha. The area with the next largest area of saltmarsh is the Western Isles but here it is the high number of sites rather than the size of sites which accounts for its position.

While the saltmarshes in Scotland are common and scattered all around the coast the number of saltmarsh communities is less than those found in England or in the much smaller area of Wales. Only eight of the 13 NVC lower saltmarsh communities are found in Scotland (Figure 4.1) and of these six are effectively limited to the Solway estuary in the south-west (SM6, SM7, SM8, SM10, SM14 and SM15). Effectively the *Puccinellia*-dominated SM13 is the only widespread NVC lower saltmarsh community in Scotland.

However, six of the nine NVC middle saltmarsh communities are found in Scotland (Figure 4.1). Of these two (SM23 and SM27) are found all round the coast, three are found extensively on the west coast (SM18, SM19 and SM20) and one is restricted to the Solway (SM17). Climatic conditions are probably the controlling factor here and if it were not for the warmth brought to the west coast by the Gulf Stream the saltmarshes in Scotland would be more severely restricted in terms of both plant species and plant communities.

The marshes of the south-facing coasts of Dumfries and Galloway leading in to the Solway estuary are particularly interesting. These marshes appear to represent a natural geographical limit which has been referred to by a number of authors as the 'Solway Line' (Adam, 1990). The marshes of the Solway range from the wide extent of the Caerlaverock marshes totalling over 560 ha and the Wigtown marshes (553 ha) to the smaller but interesting bay head marshes at Auchencairn (78 ha) and Fleet (28) and extensive small marshes in the inner Solway.

Limonium vulgare, *L. humile* and *Atriplex portulacoides* are typical of the saltmarsh species which reach their northern limit along the north coast of the Solway (although there are scattered occurrences of *L. vulgare* further north on the east coast). *L. vulgare* also nears its western limits along the Solway with its role being taken over by *L. humile* in the westernmost localities such as Auchencairn Bay. It is particularly striking that where *L. humile* grows on its own it appears to have a wider ecological range than when growing with *L. vulgare* (Boorman, 1966).

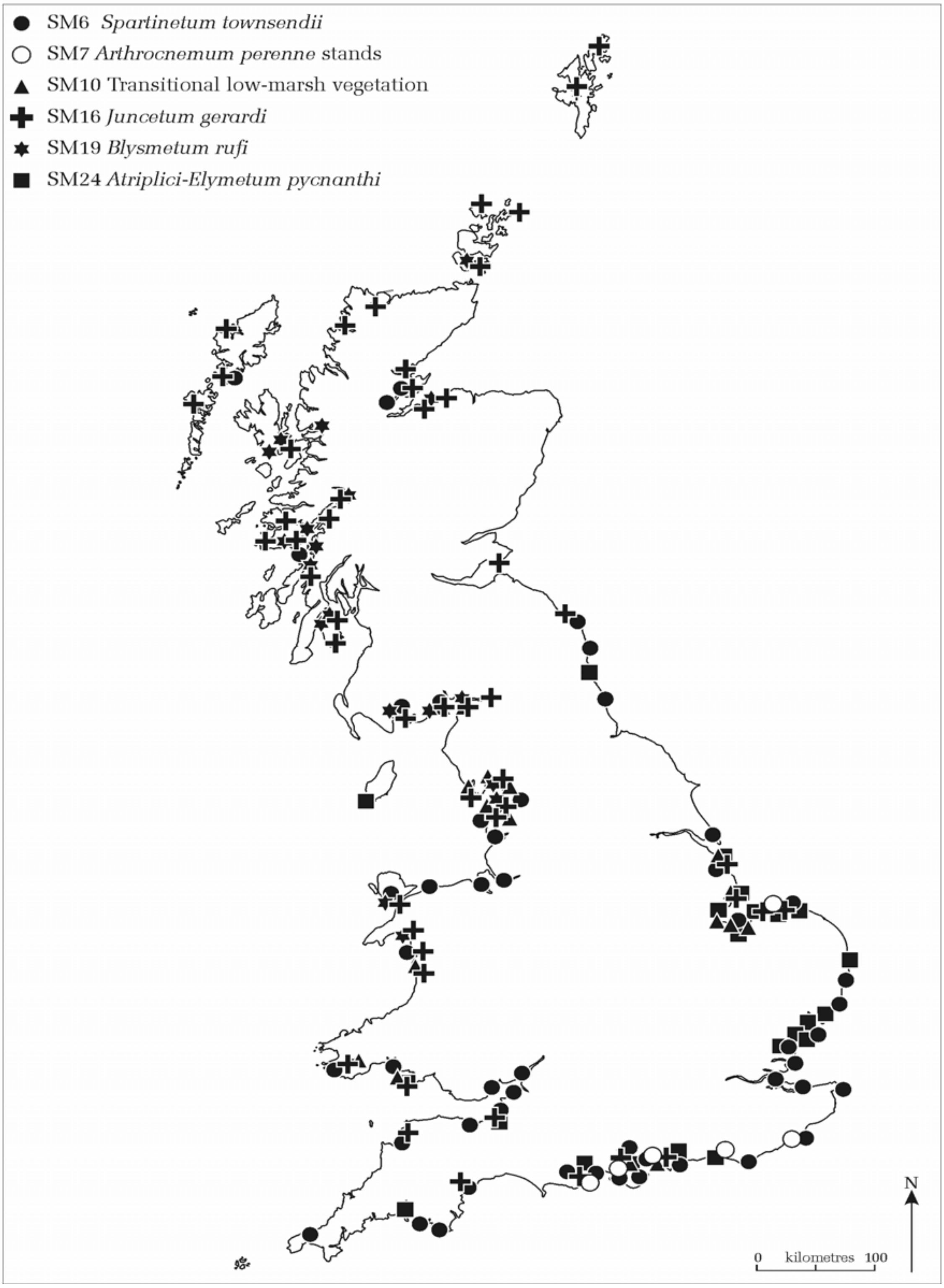


Figure 4.1. Distribution of the NVC saltmarsh vegetation categories in the UK (adapted from Rodwell, 2000)

Irish saltmarshes

Ireland too has extensive saltmarshes. The NVC, which is a classification for British vegetation only, has not been extended to the saltmarshes of Ireland but it is currently being applied to the marshes of Northern Ireland (P. Corbett, pers. comm.). Around the coast of Ireland there are large estuarine marshes as well as smaller bay head or loch head marshes similar to those found in the west of Scotland. The major difference in the saltmarshes of Ireland is the replacement of *Limonium vulgare*, the species common in most English, Scottish and Welsh marshes, with *L. humile*, continuing the trend set in the west of the Solway and in west Pembrokeshire (Boorman, 1966). *Limonium humile* is widespread around most of Ireland but it is absent from county Londonderry, reaching its northern limit on the east coast at Larne Lough in county Antrim. It does, however, occur right up the west coast of Ireland from west Cork to Donegal. In Ireland *Atriplex portulacoides* is absent from the north coasts from west Mayo through to Antrim. *Atriplex portulacoides* reaches its northern limit at Ballymacormich Point in north Down. There are small differences in the distribution of some of the other saltmarsh species around the Irish coast but these largely reflect the rather limited occurrence of saltmarshes in certain areas, particularly Armagh, Leitrim, Meath, Londonderry, Kilkenny and north-east Galway.

The nature of the Irish saltmarshes is related to geographical variations, with the most extensive marshes being associated with major estuaries such as the Blackwater and the Shannon as well as in major inlets such as Clew Bay, Sligo Bay, and Galway Bay. The marshes are often heavily grazed and this generally leads to a reduction in the floristic diversity. The effects of grazing are often dramatically shown when there are ungrazed islands of marsh with tall luxuriant vegetation isolated by channels or soft mudflats from the closely grazed marshes on the main body of the marsh. In the west of Ireland extreme exposure often leads to saltmarsh plant communities being found at levels well above the high tide mark and in association with some of species of upland grassland.

In Northern Ireland saltmarshes are found all around the coast, mostly in units of one hectare or less, but they are particularly well developed at Strangford Lough, Mill Bay (Carlingford Lough), the Roe estuary (Lough Foyle), Lough Larne and the Bann Estuary. These five sites account for 90% of the saltmarsh area of Northern Ireland. Strangford Lough is the most diverse saltmarsh site with 14 of the 17 NVC saltmarsh communities and sub-communities (Appendix 3). Ten of the 25 NVC saltmarsh categories have been found in Northern Ireland including the rare SM19 (*Blysmus rufus* saltmarsh community) and SM20 (*Eleocharis uniglumis* saltmarsh community). Both of these are found at Killard in the east but SM20 is also found at Grangemore in the north of the province. As well as the published NVC categories one unassigned community and one unassigned sub-community were identified in the area. There was a community, found across Northern Ireland, where there had been extensive secondary colonisation of SM16 by *Spergularia media*. Near the Giant's Causeway in Antrim, there was a variant of SM16 (the sub-community dominated by *Juncus gerardii*) but with *Schoenus nigricans*. The preliminary report of the application of the NVC (which was not intended to encompass Irish vegetation) to Northern Ireland marshes underlines the need for further sampling to cover the range of plant communities which exist there.

Other European saltmarshes

The saltmarshes of the UK are paralleled by various European marshes (Dijkema *et al.*, 1984, Dijkema, 1987). There are very extensive estuarine saltmarshes in the south of the Netherlands not dissimilar from those in Kent and Essex. The Wadden Sea coasts of the Netherlands, Germany and Denmark have vast areas of the barrier marshes. These are similar but on a much larger scale to the marshes of north Norfolk and are floristically more diverse. Like the Norfolk marshes the marsh sediments have a distinct sandy component and are relatively well drained.

The saltmarshes of the north of Denmark and of Norway and Sweden have distinct parallels with the marshes of Scotland and although some species are absent having reached their northern limits other continental species make up the deficit. *Puccinellia* plays a major part in these marshes but less familiar species are also significant.

The saltmarshes in the Bay of Mont St. Michel are quite similar to the marshes of Norfolk, with a distinct sandy influence but a considerably more benign climate. In some ways the saltmarshes of Portugal are surprising similar to those of more northern areas but there are species not found further north and the familiar northern European species take on rather unusual appearances owing to the lack of any real winter break in their growing season.

4.2 Key species confined to saltmarshes

Plant species

The existence of around 40 species of higher plants that are found exclusively in saltmarshes or occasionally on inland areas of saline soil has already been referred to. While all but about ten of these species can be grown in non-saline conditions their competitive ability is limited and consequently they are not able to survive in the long term. Some are occasionally found growing temporarily under non-saline conditions in open habitats but they rarely persist from season to season except as transient small populations in scattered isolated patches.

In exposed coastal areas, particularly of the west and north, saltmarsh species may be found well above the highest tidal level and even some considerable horizontal distance from the sea. This can be explained by the occurrence of wind-blown salt spray and this has been confirmed by reference to raised soil chloride levels. This effect is sometimes emphasised when salt spray affects areas of open habitat when stands of salt-tolerant species can survive the extreme conditions.

There are several Red Data Book vascular plant species of saltmarsh: *Atriplex pedunculata*, *Chenopodium chenopodioides*, *Euphrasia heslop-harrisonii*, *Hierochloe odorata*, *Limonium bellidifolium*, *L. binervosum* ssp. *anglicum* and ssp. *binervosum*, *L. britannicum* ssp. *britannicum*, *celticum* and *transcanalis*, *Limosella australis*, *Polygonum maritimum*.

There are quite a number of algal species found in saltmarshes belonging to most of the major algal groups. While most of these algae have similar forms occurring in other habitats, in many cases they are subtly different. These are often free-living forms of algae species, which are normally attached to their substrate or species in the saltmarsh which are distinct from those in other marine habitats. The survival of these special forms is certainly dependent on the saltmarsh habitat although they may be linked to nearby marine habitats. The total number of algal species found in saltmarshes is much larger than the number of higher plants. Occasionally algal growth can be sufficient to inhibit the growth of higher plants. Dense growth or mats of algae are often associated with increased nutrient loading in the estuarine water.

In addition to higher plants and algae there are a number of bryophytes which can be found in British saltmarshes. Adam (1990) records over 50 species of mosses but of these only one is restricted to saltmarshes. Mosses are however restricted to the higher levels in the marsh which might only be flooded by the tide 100 times per year. A single species of liverwort has been recorded but this is not restricted to saltmarshes (Adam, 1990).

The occurrence of mycorrhizal fungi has already been referred to as well as a number of micro-fungal species involved in the breakdown of plant litter. It has been shown that certain saltmarsh species such as *Aster* require the occurrences of associated mycorrhizal fungi if they are to reach their full growth potential (Carvahlo *et al.*, 2001). There are also a number of parasitic fungi which affect various species of saltmarsh plants. The rust species *Uromyces limonii* which affects *Limonium* species is the commonest example.

Invertebrates

All levels of a saltmarsh support invertebrate communities (Kirby 1992). In Britain the terrestrial saltmarsh invertebrate fauna has been estimated to comprise 293 resident species of which 148 are found exclusively in saltmarshes (Doody, 1992). There is more interest in the upper reaches of the saltmarsh where it grades into freshwater and fully terrestrial habitat. Natural features such as open sandy areas and small pools can greatly increase the interest.

A number of fly species live in bare mud as larvae, and the adults tend to accumulate in these locations in the spring and summer. These include various species of craneflies and dolichopodids. Hoverflies can also be found visiting sea aster (*Aster tripolium*).

There is a range of ground-dwelling predators that live on saltmarshes. Many of these feed on insects which have been accidentally blown onto the marsh or are wounded or moribund in some way. These predators include a number of species of shorebugs (*Saldidae*) each of which live in a distinct part of the saltmarsh.

Beetles also utilise saltmarsh. Ground predators and scavengers include the ground beetles (*Carabida*e) but there are also a number of specialist rove beetles which construct tunnels in the sand and graze on algae.

In and under the marsh surface there is a wide range of marine invertebrates from the smallest soil-dwelling worms to quite large burrowing crabs. The macro-benthic fauna, of species perhaps more characteristic of the mudflat environment, is varied and abundant particularly in the pioneer zone. In the higher and drier marsh area the marine invertebrate fauna is largely limited to detritivores such as the amphipod *Corophium* and grazers such as the gastropod *Hydrobia*.

Vertebrate species

The two major groups of vertebrates associated with saltmarshes are birds and fish. Occasionally mammalian species are also found but their occurrence is largely incidental as they move in from adjacent habitats to exploit opportunities for grazing. In Britain rabbits and hares can be found grazing along the upper edges of a saltmarsh, but although less commonly seen the hare can also be found grazing at considerable distances from the edge of the saltmarsh and appears to be, at least locally, a part of the saltmarsh fauna.

Saltmarshes are an exceptionally important habitat for a wide variety of birds which use it for roosting, feeding, moulting and breeding. There is a high degree of seasonal variation in bird numbers and species composition on saltmarshes. In general, densities are far higher throughout the winter period.

The composition of breeding species varies significantly regionally. With the exception of redshank, the lower saltmarsh rarely forms primary breeding habitat in terms of bird densities (Fuller, 1982). This is dues to a combination of frequent flooding, lack of vertical structure for nesting, localised food supplies and related density dependent factors (e.g. territoriality). The elevation of the saltmarsh affects the frequency of flooding and this governs which species will breed. Few species are capable of successful breeding on areas of lower saltmarsh. Redshank, however, provide an exception to this since their young float and thus may survive flooding (Cadbury, 1973). The mid to upper marsh is characterised by nesting species such as reed bunting, skylark, meadow pipit and linnet, often in high concentrations. Colonial species such as black-headed gull nest in discrete colonies and tend to concentrate their foraging away from the saltmarsh. Other species, including starling, house sparrow and shelduck, tend to use saltmarshes for feeding but nest in other habitats. In instances where brackish marsh and reedbeds occur at the interface between saltmarsh and terrestrial habitats typical species include moorhen and sedge warbler. The strandline at the upper extreme of the saltmarsh can provide important habitat for a range of seed and invertebrate eating passerines, most commonly blackbird, dunnock and greenfinch.

In the winter and during passage saltmarshes are particularly important for waterbird populations which use it for feeding, roosting and moulting. The UK's saltmarsh resource is of exceptional importance due to its geographic location – a north temperate island adjacent to a major continental landmass. A moderate climate, influenced by the water mass of the Atlantic and proximity to the Gulf Stream, ensures that most UK saltmarshes remain unfrozen throughout the winter, whilst a relatively large tidal amplitude ensures that adequate areas of intertidal habitat are exposed at low tide for feeding birds (Evans, 1984).

Many species of bird found on saltmarshes have very specific food requirements and this influences their distribution. Brent geese follow a sequential pattern of habitat use. It is thought that the use of agricultural land in winter reflects the inability of intertidal food sources to support the population (Summers and Critchley, 1990). It is likely that this is, in part, due to the early depletion of *Zostera* and *Enteromorpha* (Charman and Macey, 1978). However, it has also been shown that feeding on improved grassland mainly occurs during a critical period in winter when food in these areas is superabundant, easily digestible and of better quality than that found in saltmarshes (Nugteren, 1994).

Other important factors include levels of disturbance, presence of stock grazing, and proximity of saltmarsh to other (feeding) habitats.

While many birds utilise the exposed surface of the saltmarsh the creeks and channels of the marsh provide habitats for a range of species of fish. The marshes provide spawning sites and nursery areas as well as feeding opportunities (Boorman, 1999). The fish feed on the invertebrate fauna which become active when the tide covers the area, and some feed directly on the algal mats covering the mud surface. It should also be noted that an even wider range of fish benefit indirectly from the saltmarsh by feeding on the invertebrates of the mudflats and shallow waters in the sub-tidal zone, which themselves feed on organic matter exported from the saltmarsh.

4.3 Key associated species

Plant species

Reference was made in the preceding section to the range of plant species which while not exclusively saltmarsh species contribute to the floristic diversity of the high marsh. The upper edge of the marsh and the saltmarsh transition zones provide an important habitat for a range of plant species now restricted in other areas away from the marsh and for whom the marsh edge provides an important refuge. This applies to a number of grassland species as well as some species associated with fen and other wetland habitats. This view is supported by the occurrence of various grassland communities (NVC categories MG11–13) and swamp or fen communities (SS4, S20, S21 and S28 and M28).

Invertebrates

Again it is difficult to draw a hard and fast line between species found as casuals on the saltmarsh and those with a significance reliance on the marsh. These species may use the marsh as an alternative feeding ground as a result of habitat loss elsewhere. Typical species might include, for example, ground beetles (*Amara strenua* and *Anisodactylis poeciloides*), and plant bugs (*Orthotylus rubidus*).

Vertebrate species

The situation is similar when it comes to distinguishing between bird species found as casuals on the saltmarsh and those with a significance reliance on the marsh. For example, when skylark were widely found on inland grassland their occurrence on saltmarshes would have scarcely merited attention, but with the decrease in this species through habitat loss saltmarshes now constitute an important area for the species. This would also apply to a number of other species.

Areas of closely cropped turf, typical of grazed upper saltmarsh, can provide an ideal terrestrial habitat for natterjack toads, providing these areas are only inundated occasionally. Most upper saltmarsh habitats occupied by natterjacks also have other features important to the toads, such as embankments, small areas of dune, or dry stone walls in which the toads can find cover (Beebee and Denton, 1996).

5. Sensitivity to natural events

5.1 Sedimentary processes

Sediment sources and import

The survival of nearly all saltmarshes is related to the supply of sediment for the accretion of the marsh surface. The only exception to this may be seen in some Highland loch head marshes where the saltmarsh survives despite there being virtually no new sediment coming into the system. But these are self-contained systems which are surviving under very sheltered conditions. The supply of sediment is needed to make up for any circumstances when the balance switches from accretion to erosion.

The occurrence of sediment-loaded water seawards of the saltmarsh is thus the pre-requisite for the continued growth and survival of the marsh. While growth and survival may seem to be rather different terms they are in many ways linked, as without periods of growth to offset inevitable periods of erosion the marsh will not be able to survive. The ultimate source of this suspended sediment is not of immediate importance as far as the survival of the marsh is concerned, although it is important with regard to the continuing long-term sediment supply.

The agent for the import of the sediment is the tidal flow and any restriction or limitation to this can reduce the import of the material to the marsh. While there will be natural changes in the tidal regime either as the result of astronomical or meteorological conditions, the effect is generally small and thus only of limited consequences for the marsh.

The main influences on the overall tidal imports of sediment are through those factors which may affect the sediment loading of the inflowing water. These can include both changes in the river flow of the upper estuaries and the extent to which the mudflats are remobilised as the tide floods over them. Wind- and wave-induced turbulence at this stage of the flood tide can greatly increase the sediment which is available for accretion on the surface of the marsh. British estuaries are distinct from many other locations in that most of the sediment comes from a marine source (e.g. boulder clays or London clay), with only around 5–10% from a fluvial source.

Sediment deposition

We have seen that there are various processes which can affect the supply of sediment available for deposition on the marsh surface. The deposition of sediment is dependent on a reduction of the rate of water flow over the marsh surface or on naturally low flow velocities. The reduction in water flow is brought about by the roughness created by the saltmarsh vegetation (Boorman *et al.*, 1998). Environmental processes which affect the growth of the vegetation can thus also affect the rate of sediment accretion. The rate of sediment deposition is thus dependent not only on the sediment supply, but also on the duration of the tidal cover and the extent to which the tidal flow is impeded sufficiently to facilitate sediment deposition. The rate of deposition of sediment can significantly affect the growth and establishment of many saltmarsh plants (Boorman *et al.*, 2001). While some plants respond positively to small increases in the rate of sediment addition, high rates of sedimentation will inhibit the growth of many species and can cause significant plant mortality. When saltmarshes are beginning to form on bare mudflats, there is evidence that diatoms and algae play a role in the initial accretion processes.

Sediment recirculation

Sediment deposited on the marsh may be transient. Recent studies in the marshes of the Western Scheldt have shown that the sum amount of sediment deposited by a single tide can over the year greatly exceed that needed to achieve the measured annual rates of accretion (Boorman, 2001). Despite high short-term rates of deposition the very much lower annual rates clearly show that there is considerable recirculation of sediment after its initial deposition (Boorman, 1999). Some of this sediment is reworked through erosion of the marsh surface, but generally the major cause of the loss of material is the erosion of the marsh edge (Reed, 1988).

Sediment erosion

The erosion of sediment from the marsh surface depends on the environmental conditions which prevail before the newly deposited sediment becomes stabilised, either through the spread of the vegetation cover or through the physical consolidation of the sediment particles. Clearly any inhibition of plant growth will limit its ability to hold recently deposited sediment secure and thus environmental conditions can play an important role.

The chemical and biological process which result in the consolidation of recently deposited sediment are complex (Boorman *et al*., 2002), but the loss of water from the fresh sediment through evaporation plays a part and therefore conditions favouring evaporation are significant.

A further factor which has not received much attention is the effect of rain on recently deposited marsh sediment. If a marsh is visited during a period of heavy rain and low tide the water running from the surface of the marsh into the small upper creeks can be seen to be carrying a significant load of sediment. While only small amounts of sediment erosion would be needed to produce this effect there is a potential for the process to have an impact on overall net rates of sediment accretion.

5.2 Climate change and sea level rise

Effect of sea level rise on sedimentary processes

The effect of sea level rise on saltmarshes is acceleration of erosion at the seawards edge of the marsh accompanied by the potential for increased accretion and marsh development at the upper levels of the marsh. In natural undisturbed systems this may simply result in the whole marsh system moving landwards but frequently the presence of a sea wall prevents the formation of new marshes and the net effect is therefore one of marsh loss (Boorman *et al*., 1989).

A rise in sea level has the potential to increase the quantities of sediment available in a coastal system beyond the confines of the saltmarsh. The increase in the depth of water and thus the accessibility to increasingly large waves means that the whole system will become more active. While this can certainly benefit accreting systems there are wider consequences. The whole pattern of banks and creeks can change drastically with major consequences for saltmarsh systems, particularly where potentially beneficial natural process are in any way restricted.

Effect of sea level rise on coastal systems

The potential impacts of sea level rise can thus best be appreciated by considering the effects on coastal systems as a whole. While in many ways the saltmarshes can be seen as terrestrial habitat spreading out at the edges of the sea because of their geomorphology and biology, they form an integral part of the whole coastal system and have to be treated as such (Pethick, 1992).

Sea level rise can have particularly complex effects with regard to estuarine systems, where a change in sea level provides the driving force for the readjustment of saltmarshes and mudflats across the estuary as a whole. The natural tendencies are the loss of material in the lower estuary with a steepening of the slope of the shoreline and an increase in deposition in the upper estuary. In major estuarine systems changes resulting from rising sea levels are already having, and will continue to have, important implications for saltmarsh conservation and management.

Effect of climate change on saltmarsh vegetation

Apart from the direct effects of sea level rise on the saltmarshes, the changing climate will itself have a range of effects on the saltmarsh vegetation (Boorman, 1992). The relatively small size of the British Isles as compared with the scale of models used in the predictions of climate change make it difficult to forecast with any certainty the scale of the climatic changes likely to be experienced.

McCarthy *et al.* (2001) anticipate that natural ecosystems will change as a result of increasing temperatures and atmospheric concentrations of CO_2 and that many plants will spread further northwards. They also predict that there will be an increase in the net primary production of ecosystems which may be enhanced by increased nitrogen deposition. They anticipate the rate of change will encourage more rapid floral and faunal shifts leading to a loss of biodiversity. The question naturally arises, what the consequences of these predictions will be for the saltmarsh habitats and their associated species.

The distribution of many saltmarsh plants is likely to change with southern species spreading northwards, but as the majority of saltmarsh plants have a predominantly southern distribution this is unlikely in itself to have serious consequences for biodiversity and conservation. It is quite possible that the ‘Solway Line’ representing the northern limit of a range of saltmarsh species may over the coming decades move significantly northwards, extending the ranges of these species up the coastline of Argyll. *Atriplex portulacoides* is typical of these species and it is likely to extend its range northwards up the east and west coasts of Scotland and all around the coast of Ireland. The relatively species-poor marshes of the Highlands of Scotland are likely to increase their biodiversity with the arrival and spread of more southern species. One northern saltmarsh species which could be adversely affected is *Blysmus rufus* which could eventually be lost from England, Wales and Ireland and become restricted to the north of Scotland (Cook and Harrison, 2001). These authors also suggest that *Puccinellia maritima* could disappear from south and east England, but given its present European distribution this would seem to be relatively unlikely. However, even if this was eventually the case, there are other saltmarsh species which are likely to respond positively to the changing conditions and fill any niches left. The marshes of Spain and Portugal have well-developed plant communities with a wide species diversity and good vegetation cover despite the much warmer climate. These comments on possible change in the distribution of plants of the saltmarshes are likely to apply also to at least some of the animal species associated with the marsh.

For both plants and animals the discontinuous nature of the saltmarsh habitat would limit the rates of spread possible under favourable climatic conditions. The possibility of warmer and drier summers in the south-east could favour the distribution of Mediterranean species such as *Frankenia laevis* and *Suaeda vera* and it is possible that continental *Atriplex pedunculata* could return to East Anglia. Again the speed of any change would be slowed by habitat discontinuities. If however there is sufficient creation of new saltmarsh to maintain the present total area and network, changes in species distribution could be balanced by concurrent losses.

The predicted increase in primary productivity is unlikely to have a major effect on the saltmarsh communities themselves, but if this leads to an increase in the export of organic matter there could be benefits to the food chain in the saltmarsh and in other adjacent ecosystems. The balance of plant species could change, particularly if species respond differently to more favourable growing conditions; but as yet there is insufficient information to be able to project this. It is clear that the combined effects of sea level rise and climate change are likely to markedly affect the functioning of the marsh metabolism (Miller *et al.*, 2001).

5.3 Extreme events

Effect of extreme events on sedimentary processes

If there are uncertainties over the details of the overall climatic changes projected over the next decades, there is an even greater uncertainty over the magnitude and frequency of extreme events. Research suggests there might be more and greater extremes in climatic events.

The key processes involved in the building or loss of saltmarshes are often driven by episodic extreme events. These may be extremes of tides, winds, fresh water flows, and even temperature, or more often various combinations of these. The potential increasing frequency of extremes is likely to make saltmarsh processes more dynamic. Any changes are likely to have a greater magnitude and to occur with a greater frequency. This has considerable implications for the survival of saltmarshes over the long term.

In a study of changes along the open coast marshes of the Dengie peninsular in Essex, Pethick (1992) showed that storms resulted in 1.5 metre waves at the marsh edge and they caused a lowering of some 50 mm in the mean surface level of the marsh. These losses were recovered within two years, but given that the marsh would have continued accreting in this period the full recovery was only achieved five years after the storm. The implication here is that if there is an increase in the frequency of extreme events shorter and shorter periods will be available for recovery.

Effect of extreme events on saltmarsh systems

The uncertainties in prediction make it difficult to assess the detail of any changes that may occur to saltmarsh systems. Temperatures and rainfall, or more specifically the lack of rainfall or extremes of temperature, are more likely to affect the saltmarsh ecosystem than are winds, tides and waves which drive the sedimentary processes. The fact that the distribution of the majority of saltmarsh plants is based in the south means that there is unlikely to be a species loss in the way that northern species might be excluded by warmer climates, but climatic irregularities may well limit the spread of the southern species northwards. However, the more frequent occurrence of climatic extremes is likely to make saltmarsh plant species more vulnerable and sensitive to other pressures and this increases the need for careful management. The greatest effect of climatic extremes on saltmarsh systems is, nevertheless, likely to be through the indirect impact on sedimentary processes.

6. Sensitivity to human activities

6.1 The role of saltmarshes in flood defence

Natural responses of saltmarshes

Saltmarshes provide a natural form of flood defence and coast protection in that they are able to absorb wave action; under severe conditions this may lead to erosion of the outer edge. Under favourable conditions these losses are made good by the normal process of accretion and, where necessary, by plant recolonisation. Coastal processes can eventually restore even massive losses of marshes after severe storms. These responses provide coastal habitats and ecosystems with a vital buffer against attack from the sea. Additionally, saltmarsh buffers are naturally self-repairing and maintenance-free. However, they do not necessarily prevent the sea flooding across areas landwards of the saltmarsh.

Saltmarshes and sea walls

Sea walls were built not so much to prevent the flooding of coastal grasslands and other habitats as to enable the utilisation of the productive land that could be developed from the marsh once the sea was permanently excluded. The sea walls were initially of simple, relatively low, earth banks keeping the sea out of the high marsh inside the wall. With extensive areas of marsh beyond the wall acting as a natural wave break there were generally few problems in wall maintenance that could not be solved by a man with a shovel. Generally the marshes beyond the wall were still accreting and when they reached a sufficiently high level new walls were built enclosing more land; but there were always extensive marshes to the middle marsh level between the wall and the open sea.

With the advent of machinery larger and higher walls were built almost to the edge of the marsh to satisfy the demand for more agricultural land. This had a number of serious consequences that were not appreciated at the time. These new walls at the outer edge of the marsh gave little opportunities for fresh marsh growth outside the sea wall and, even when fresh marsh growth was possible, marsh development was a slow process starting from something only a little higher than pioneer marsh. Because there was now very little marsh beyond the wall to absorb the energy of severe storms, the ferocity of the storms was absorbed by the wall itself, sometimes with disastrous consequences. But the lack of saltmarshes which could protect the sea walls was not the only consequence of these changes. At the time the saltmarsh was seen purely as an opportunity for the creation of new agricultural land. However, the conversion of considerable areas of saltmarsh to agricultural land has meant that large areas of saltmarshes were lost completely, together with their biodiversity.

The importance of flood defence to the North Sea coastline of the UK was underlined by the devastating floods of 1953 and a series of smaller events subsequently (Möller *et al.*, 2001); this led to the extensive construction of new ‘hard’ engineering flood defences. In recent years these problems have been accentuated by the onset of climate change; higher sea levels combining with an increased frequency of storms have caused ever more severe wave attack on the marshes, leading to coastal squeeze. Building higher sea walls only served to emphasise the problems of coastal squeeze which were caused by the lack of high-level marsh outside the sea walls.

The initial response to the increasing problem of sea wall erosion was to reinforce with concrete blocks or even to construct concrete walls. The problem here was that block work was generally ineffective as it could easily be undermined by wave action. If even a small area of blocks was washed away whole sections soon became unstable and were removed by wave action. Concrete walls seemed to provide the answer but were massively expensive and attracted much criticism on aesthetic grounds. Any marsh outside the line of the wall before construction was rapidly eroded, leaving a bare concrete face dropping down to low-level mudflats. The high biodiversity associated with saltmarshes was lost completely. Furthermore, while it was relatively cheap to repair a grass-covered bank, if there was any damage to a concrete wall even small repairs were very expensive.

Integrating natural processes with flood defence requirements

The realisation that natural processes could contribute to flood defence occurred gradually, helped by ever higher costs of sea wall maintenance and repair and by the onset of sea level rise accentuating the existing problems along low-lying coasts. The first step was the realisation of the value of the marshes and particularly the way that they could function as natural and potentially self-repairing wave breaks. Secondly, coastal managers began to consider alternative and potentially more cost-effective and sustainable options for coast protection (Möller *et al.*, 2001). These included the beach nourishment on the Lincolnshire coast and foreshore recharge of the intertidal on the Orwell Estuary and the managed realignment of the flood defence lines in Essex. The latter option involved the removal of the sea wall to a position further landward, leaving former agricultural land outside the new sea wall. The land then reverted to what it had been several hundreds of years before, *i.e.* saltmarsh, thus reducing the wave energy at the sea wall. This enabled the new wall to be constructed to a lower standard at a considerable saving in cost. At the same time there was at least a partial restoration of the biodiversity that had been lost through the building of the original wall and the erosion of the marshes beyond it.

6.2 Coastal developments

Range of coastal developments

The coastline has attracted people for a wide variety of reasons. These include port facilities and associated industries, residential and holiday homes, water sports and other forms of coastal recreation. In addition there are traditional activities of fishing and agriculture.

Most uses of the coastline demand a stable boundary between land and sea.. All uses of the coastline have their own characteristic impact . These impacts include an ever-increasing demand for space resulting in the use and biological loss of intertidal areas, the destruction of sub-tidal habitats to provide deep-water access to facilities, and pollution caused by the disposal of waste materials and by-products. There can often be a high degree of disturbance to habitats not otherwise immediately affected, for example by various forms of water sports. In addition, the competing demands on space by these activities require larger areas to be utilised.

Impacts on saltmarshes

The primary effect of coastal development on saltmarshes is the direct loss of often very large areas of saltmarsh as a result of building activities or other forms of industrial development. There have been direct losses of saltmarsh to development recently in virtually all the major estuaries around the British coastline.

While the large-scale developments such as Felixstowe docks attract major headlines, the cumulative effect of many small-scale activities can also be considerable. For example, marina developments are often quite limited in scale but the numbers of such developments involved point to a significant impact overall.

The impact of the various activities is by no means restricted to the boundaries of the site itself. Damage by the construction of roads and tracks for access and damage by trampling all increase the area and extent of impact. There is also the impact on the geomorphology of the whole saltmarsh–mudflat ecosystem system through, for example, the dredging of local navigation channels which can affect the adjacent marshes.

On a much larger scale major estuarine developments, particularly those near the mouth of an estuary and the deepening of the major navigational channels, can change the tidal regimes of the whole of the estuary with major impacts on the saltmarshes.

Conflict resolution

Little can be done to compensate for the loss of major areas of marshes and mudflats to industrial developments, with the exception of extensive marsh creation schemes. However, at the planning stage measures can be taken to reduce secondary effects and avoid some of the direct conflicts between the different activities in the coastal zone. The key is to identify potential conflicts as early as possible and thus provide opportunities to localise their impact and to reconcile conflicting pressures as far as possible. Too often in the past problems have increased because of an unwillingness to accept the wider consequences of activities that particular groups regard as valid and to work together to provide satisfactory solutions. These problems are being addressed where integrated forms of coastal zone management have been adopted.

6.3 Recreation and disturbance

Range of uses of saltmarshes

The uses of saltmarshes include both direct ones such as wildfowling, bird-watching and walking, and indirect ones such as the use of the area for board- and dinghy-sailing during high water. Activities adjacent to saltmarshes such as yacht moorings and the wash resulting from the passage of large or fast boats have impacts on the adjoining marshes.

Direct impacts of recreation

The direct effects of recreation lie in the physical destruction of marshes for the construction of marinas, including the dredging of access channels, the building of boat sheds and the storage of boats. Moorings laid in the saltmarsh creeks can also result in physical damage to the adjacent marsh from boats swinging into the marsh at high tide. Saltmarshes are also very sensitive to any form of trampling. This can result from access to recreational craft moored or stored in the area and from walking and sightseeing. While bait-digging is not usually carried out in saltmarshes themselves it may involve access across saltmarshes with resulting damage from trampling. Although not strictly a recreational activity, the continued use of particular areas for scientific research can also lead to damage if inadequate steps are taken to localise and reduce it. The forms of damage to the saltmarsh referred to above directly affect the saltmarsh vegetation and any damage to the vegetation cover of the saltmarsh carries with it the risks of erosion damage over a much wider scale. It will also have an impact on the soil fauna with possible consequences for the functioning of the marsh ecosystem as a whole.

Indirect impacts of human activities

The direct impacts described above are generally localised and are thus relatively easy to quantify. The indirect effects of recreation are much more generalised and widespread and are thus much more difficult to evaluate and control. The main one of these is the disturbance caused by the direct presence of humans or by the passage of boats, sailboards, water skiers, etc. Wildfowlers can cause indirect disturbance as well as the killing of target species, but the effect of wildfowling is relatively limited, partly because any form of disturbance created would affect the target species as well and is therefore avoided. Where shooting is controlled by a recognised club, the effect on bird numbers is strictly monitored and controlled. However, in some areas uncontrolled shooting does cause problems. It is difficult to assess the effects of the various forms of disturbance on bird populations but the increasing recreational use of saltmarshes clearly affects the utilisation of the area by birds. Recent increases in the recreational use of saltmarshes during winter, when birds are most dependent on this habitat, are likely to increase disturbance.

Conflict resolution

The main steps involved in the resolution of conflicts between the various uses of saltmarshes consist in the identification of the full range of impacts, both direct and indirect, together with their location in terms of space and time. It is also important to identify both the threshold beyond which the damage occurs at unacceptable levels and the areas of the marsh which are particularly sensitive. The full consideration of the interests of all the users of the saltmarshes and adjacent areas can also contribute to the likelihood of finding some common ground on which to formulate integrated management and additionally to facilitate the implementation of any management decisions.

There are a number of ways in which the impacts can be reduced and hopefully kept at acceptable levels. The first is to identify which parts of the marsh are the most vulnerable and whether there are particularly sensitive seasons of the year. For example, the areas favoured by nesting birds in summer and by wildfowl for feeding and roosting in winter can usually be identified and disturbance limited through marking areas and/or careful wardening. Damage to saltmarshes can be reduced by limiting the level of trampling pressure as far as possible; where the use of paths across the marsh cannot be avoided the damage caused can be minimised either by the use of different routes in rotation or by the judicious use of geotextiles to reinforce the marsh surface. Where creeks have to be crossed on a regular basis the construction of simple wooden footbridges can sometimes limit the overall damage to the marsh system.

6.4 Introduced species

Animal species

Alien animal species have not had any significant impacts in saltmarshes although there are threats to the fauna of the intertidal areas, *e.g.* the Pacific oyster. The main impact on saltmarshes from introduced species is through the use of the saltmarshes for the grazing of domestic stock. Some areas of saltmarsh have been used for grazing for centuries and this has changed the nature of the vegetation. Grazing may have reduced or even excluded certain species but other species have exploited the opportunities provided by the shorter vegetation. Generally the resulting communities have their own specific biodiversity and conservation interest and probably their use for grazing has tended to minimise other possibly more damaging forms of land use. The areas of saltmarsh that are regularly grazed are generally those on more sandy substrates, such as the Solway marshes, which limits the damage that could be caused by trampling. The marshes which are the most liable to damage from trampling, with poorly drained soils made up of fine sediments, are themselves generally left ungrazed because of the inherent risk to the stock of sinking in the mud and being drowned when the tide comes in.

Plant species

The plant species which has had the greatest impact on saltmarshes has undoubtedly been the introduced *Spartina alterniflora* and the subsequent planting and spread of the tetroploid hybrid *Spartina anglica*. The history of the introduction and spread of *Spartina* and its hybrids and their impact on British saltmarshes has been well studied and documented by Ranwell (1972) and updated by Gray *et al.* (1991) and Raybould (2000) and therefore will not be considered further here. However, many of the concerns expressed in the 1960s on the possible loss of large areas of mixed species-rich marsh to stands dominated by *Spartina* have proved to be unfounded.

Future threats

The main threats to saltmarshes in the future must lie in the great increase in leisure activities in the coastal zone and the consequent direct and indirect human impacts on all coastal habitats. Against this, while there are potential threats from the introduction of alien species this can not be seen as a major threat, given the current awareness of the dangers inherent in the introduction of non-native species of plants or animals.

6.5 Pollution

Saltmarshes can, and frequently do, act as filters and can accumulate a wide variety of pollutants. These pollutants can be divided into three groups: agricultural chemicals, industrial chemicals and those substances which contribute to the nutrient enrichment of estuarine and coastal waters.

Agricultural chemicals

Various agricultural chemicals, including herbicides such as atrazine and organochlorine insecticides, occur widely in the environment, particularly in or near agricultural land; generally they are found at low levels, but recently significant levels have been detected in saltmarsh sediments (Scrimshaw *et al*., 1994). Furthermore, detailed surveys have shown that these substances are widely distributed in the sediments along the Essex coast with higher levels in certain sites (Scrimshaw *et al*., 1996). Additionally, the occurrence of these pollutants in some of the deeper layers of sediments suggests that their distribution can be affected by the reworking of sediments. The impact of these chemicals on the biota is difficult to assess as they only occur at very low levels and most of the available data on their specific effects on plant and animal species relate to much higher levels.

Industrial chemicals

Various industrial chemicals such as polychlorinated biphenyls (PCB) also occur widely in the environment and have been detected in saltmarsh sediments. Again, detailed surveys have shown that these substances are widely distributed in the sediments along the Essex coast (Scrimshaw *et al*., 1996), with the possibility of redistribution of these pollutants following the reworking of sediments. PCBs have also been reported in marshes along the Atlantic coast of North America but with only limited effects on the saltmarsh fungal flora (Newell and Wall, 1998).

Another pollutant commonly found in saltmarsh sediments is tributyltin (TBT) and its breakdown derivatives. TBT was formerly used extensively in anti-fouling paint and this appears to be the major source of these compounds in the coastal environment (Clarke *et al*., 1988). Although TBT is rapidly degraded while in the water column with a half-life of days to weeks (Stewart and Mora, 1989), it is very persistent in anaerobic sediment with a probable half-life of the order of tens of years (Dowson *et al*., 1996). The increased concentrations of heavy metals in saltmarshes pose the question whether these substances can affect the ecosystems involved. Although TBT is best known for the very serious effects that it has on marine invertebrates, particularly molluscs (Fletcher *et al*., 1994), it also appears to affect the growth of some saltmarsh species (Boorman, unpublished data).

The anti-fouling compounds which have replaced TBT are not without their potential impact on the biota of saltmarshes. For example, Irgarol is used extensively to inhibit the growth of algae on ships' hulls and there are at least possibilities that this and related chemicals could have some effect on the growth of saltmarsh vegetation.

As well as tin in its organic forms, various other heavy metals have also been shown to occur in saltmarsh sediments, including cadmium (Reboredo, 1992), lead, chromium and mercury (Windham *et al*., 2001). While there is no evidence that at the levels recorded these metals have any effect on the saltmarsh plants, which can absorb and accumulate quite high concentrations, it is considered that plant feeders, including grazing stock, could well be deleteriously affected.

The heavy metal pollution in the Sado, Portugal, is attributed to direct industrial pollution, although pollution of the Long Island saltmarshes in the USA by a range of metals has been attributed to atmospheric deposition (Cochran *et al*., 1998). The presence of organic pollutants and heavy metals in saltmarshes could be a threat to their long-term survival (Leggett *et al.*, 1995). This is emphasised by the way that various processes of accumulation and release of metal have been shown to occur (Zawislanski *et al.*, 2001, Burke *et al.*, 2000).

The control of the various forms of pollution of saltmarshes is partly a question of the control of their release into the environment generally and partly a matter of ensuring that all waste material from industrial and agricultural activities in the coastal zone is disposed of in a safe, non-polluting manner. This comment also applies to the domestic and recreational use of potentially damaging substances. The matter of the reworking of buried deposits of pollutants is one that demands serious attention, particularly with regard to natural or human activities involving the disturbance of the deeper layers of sediment.

Oil pollution

The pollutants described so far have all been largely invisible; this is not generally true of oil pollution. In most navigable estuaries small oil spills occur on a regular basis, as well as discharges from refineries and other industrial sites, and from agricultural and domestic sources. Some marshes have been affected by major oil spills from grounded oil tankers but overall it is the more frequent and sometimes chronic small spills which have the greatest effect. The effects of oil on saltmarsh vegetation were extensively reviewed by Baker (1979 and 1983) and later by Adam (1990). Saltmarsh plant species vary greatly in their sensitivity to the effects of oil but generally perennial species appear to be more resistant than annual species. Oil deposits on saltmarshes are unsightly and pose a hazard to birds and other animals, but while there is often pressure for cleaning operations these may cause considerable further damage. The options available include burning, cutting and sediment stripping or the use of chemical dispersants, but all these may cause more long-term damage than allowing the oil to weather naturally. In severe cases of pollution the only solution may be the wholesale stripping of sediment and subsequent replanting.

The marshes near New York were denuded of vegetation over a large area following the spillage of 2.5 million litres of fuel oil in 1990 (Bergen *et al.*, 2000). Restoration was undertaken to halt surface erosion and the further loss of vegetation cover. The planting of *Spartina alterniflora* was generally successful with above-ground biomass similar to that found in uncontaminated areas. In the control (untreated) areas large portions still remained bare seven years after the event, indicating a high level of persistent contamination. This was confirmed by the analysis of soil samples. However, the success of the revegetation appeared to be dependent on the planting techniques used and on the wave energy experienced at the planting sites; the impact of goose grazing also had an effect when the plant densities were low.

Eutrophication of coastal waters

So far we have considered organic pollutants and heavy metals, but the eutrophication of coastal waters by various plant nutrients, particularly nitrogen and phosphorus, can also have damaging effects at high concentrations. Eutrophication of coastal waters can result in the rapid growth of certain fast-growing algal species (Pederson and Borum, 1996) and algal mats have been observed to smother the germination and growth of pioneer saltmarsh species such as *Salicornia* species (Boorman, unpublished data). The high production recorded in saltmarshes of the Western Scheldt (Lefeuvre, 1996) was attributed to high phosphorus levels in the estuary.

7. Changing features and structures

7.1 Vegetation succession

Natural vegetational changes

Like other plant communities in many different habitats the pioneer vegetation of a young saltmarsh develops and matures through natural processes of succession into a range of mature saltmarsh vegetation communities. There are differences between saltmarsh succession and the succession of other communities. For example, chalk grassland over a period of many tens of years develops into a climax community, one or other forms of woodland (in southern Britain typically beech woodland). Saltmarsh communities ultimately become the starting point for a range of terrestrial communities. However, this process is extremely slow and saltmarsh may persist for many years. This is because as the saltmarsh surface rises due to accretion it is less frequently covered by the tide, but these infrequent inundations are still sufficient to maintain salinity and so exclude halophobic species.

If the marshes are developing seawards those farthest from the sea will eventually become non-saline damp grassland and this process will be accelerated if the land is rising relative to the sea. If grazed the grassland will remain as a plagioclimax or deflected climax, but in the absence of grazing it will eventually become some form of woodland. The upper saltmarsh in estuarine situations with a significant freshwater inflow may eventually become some form of swamp or fen which will then be subject to the natural successional process typical of that vegetation type.

In situations where the marshes are not significantly developing seawards or where the land is sinking in relation to the sea the high marsh communities will be continually and rather subtly rejuvenated, giving the effect of their having the long-term stability normally associated with climax plant communities. This is the situation seen in many of the typical loch head marshes found around the west coast of Scotland.

Rates of development of saltmarsh vegetation

The rate of development of saltmarsh vegetation is thus largely determined by the rate of accretion in relation to the tidal range, which determines the vertical range that is open to colonisation and survival of saltmarsh plants. At Tollesbury, Essex, for example, the difference between the bottom edge of the pioneer zone and the lower edge of the sea wall, which represents the truncated top of the saltmarsh, is approximately 1.8 metres. The lower marsh communities start at about 0.6–0.8 metre above the bottom of the pioneer zone, while the middle marsh (the highest community in this area) is limited to the top 0.30 metre or so. This means that the height of the lower marsh (the main area of marsh in this area) extends over approximately the same vertical distance of 0.6–0.8 metre. The middle marsh starts about 1.5 metres above the start of the pioneer zone (Table 7.1).

The long-term rate of sedimentation at Tollesbury is probably of the order of around 5–6 mm per year overall. Recent studies on saltmarsh creation in this area (Boorman *et al.*, 1997) have indicated that in the early stages of vegetation development the rate of accretion may be considerably higher, perhaps reaching 15 mm per year.

On that basis it is estimated that the pioneer zone would take at least 40 years to develop into low marsh, but the low marsh would probably take a further 150 years or more to reach the middle marsh stage and perhaps another 50–100 years for the existing, but limited, middle marsh to develop (*i.e.* a total of at least 250 years). Given the lack of long-term data on accretion rates and on changes in sea level relative to the land it would, however, be unwise to make specific interpretations from these figures on the age of the marshes at Tollesbury, although on the earliest 6-inch OS maps their outline appears broadly similar to that of the present time.

Some 15 km to the south there are saltmarshes at North Fambridge. This area of reclaimed land, formerly protected by the sea wall, was flooded in 1897 when the wall failed during a severe storm. The area is now covered by saltmarsh plant communities which have accreted some 1.2 metres during the past century. The pioneer marsh extends vertically for approximately 0.8 metre with 0.4 metre or rather less of lower marsh above it. On the Tollesbury figures the pioneer marsh would have taken around 50 years to develop and the lower marsh a further 60–70 years. However, we know that these marshes are 105 years old so the Tollesbury estimates would appear to be marginally on the low side (Table 7.1).

It will be seen from the background of these calculations that the determining factor in the rate of development of saltmarsh communities is considered to be the rate of accretion. If accretion rates are higher than those cited above will this mean a more rapid development of the various saltmarsh communities? In theory it would, but there are limits to the rate of accretion that some plant species can withstand. This is particularly true of middle and high marsh species (Boorman, 2001) but even the growth of the middle to low marsh species *Puccinellia maritima* can be inhibited by burial under as little as 8 mm of sediment (Langlois *et al.*, 2001). Although the rates at which inhibition of growth was observed were higher than the annual rates commonly recorded in the field the experimental rates were short-term rates (the experiment lasted eight weeks). Even quite moderate annual rates of accretion are likely to include periods of high rates with the potential for inhibiting the growth of plant species sensitive to the effects of burial. The maximum annual rate of accretion a saltmarsh community can withstand will depend on the nature of the community and the evenness of the distribution of that accretion through the year. The pioneer communities appear to be the least sensitive and show a positive response even to quite high rates of accretion. Pioneer communities in the Wash show rates of accretion as high as 14–33 mm per year (Pye, 1995) without apparent adverse effects on the growth of vegetation. The low and middle saltmarsh plant communities of Dengie, Essex, have recorded accretion rates of up to 10 mm per year. Again the crucial factor would appear to be the evenness of distribution of the higher rates of accretion through the year. If 10 mm of accretion occurs during a single storm then it is likely to have a deleterious effect on middle and upper saltmarsh communities. In the longer term a single period or a very few periods such as this are likely to have the effect of a degree of rejuvenation of the saltmarsh while regular recurrence of such events could lead to a major loss of vegetation cover resulting in erosion and reversion to pioneer plant communities.

Table 7.1 Saltmarsh zones and rate of vegetation/saltmarsh development at (a) Tollesbury and (b) North Fambridge, Essex; note that there is limited vertical development of the lower marsh zone at North Fambridge

Location	Vegetation zone	Vertical height range of zone (m)	Estimated rate of accretion (mm/yr)	Estimated time of development (years)	Estimated total time of development	Known age (years)
Tollesbury	Pioneer	0.7	15	46	246	?
	Lower	0.7	5	140		
	Middle	0.3	5	60		
Fambridge	Pioneer	0.8	15	53	133	105
	Lower	0.4	5	80		

The matter of the regeneration of saltmarsh communities is an interesting one. Experience at Northey Island, Essex, showed that even when the area colonised was at the level of high marsh communities the initial vegetation colonisation was still by pioneer species, and that the plant species characteristic of high marsh only came in at a later stage (Dagley, 1995). Nevertheless it seems that the subsequent rate of development is faster than for primary succession. In a Spanish saltmarsh natural regeneration resulted in the development of species diversity at nearly twice the rate achieved during the primary colonisation (Onaindia *et al.*, 2001). The authors suggest that the rate of recolonisation is determined both by the time required for species arrival and by the time needed for the restoration of normal hydrological and edaphic factors.

Conservation and management of saltmarsh vegetation

With the rates of succession of saltmarsh plant communities largely being controlled by pace of sediment accretion there are not the management problems associated with, for example, grassland communities which, when unmanaged, can develop rapidly into scrub communities with a loss of species diversity. Generally the management of saltmarsh communities is mainly concerned with the prevention of damaging external influences such as trampling or pollution. If the communities to be conserved have been developed under a grazing regime, whether by wild animals, wild birds or farm stock, management will require the maintenance of this or a similar grazing regime; similarly if there has been a regime of cutting the vegetation for hay. If the tidal or salinity regimes are changed by external factors such as a alterations to freshwater flows or the tidal regime as a result of physical barriers or channel changes nearby, management strategies will have to take this into account.

When the saltmarshes have developed to the high marsh level with very little middle, low marsh and pioneer plant communities, there are difficult management problems to be faced. While the high marsh communities are relatively stable there is at least a partial reduction in species diversity and taking the area as a whole there will not be the previous wide range of plant communities. In many cases, however, the missing communities may be found in adjacent areas and this may be considered to be acceptable in terms of saltmarsh management and conservation. In other cases the problem may be resolved by saltmarsh creation in areas nearby.

However, if there is only high marsh in a particular area and this is not acceptable, it is possible to rejuvenate the marsh in various ways. The more drastic of these would involve action to encourage the formation of new marsh at the seawards edge by increasing the degree of wave protection, by augmenting the supply of sediment or by encouraging sediment accretion. If none of these are possible then some success can be achieved by turf cutting, a technique practised in the Netherlands. Here turves of soil and vegetation are removed from the marsh surface, thus lowering the level of the marsh and providing bare ground to be recolonised by saltmarsh plants. This secondary succession will, at least in the short to medium term, provide areas of pioneer and lower marsh communities, but there are considerable cost implications when practised on anything other than a small scale; if practised on a large scale the risks of initiating serious erosion would have to be carefully assessed.

7.2 Effects of Climate Change

Effects of climate change on natural processes

The effect of sea level rise on saltmarshes has already been considered. Unless there is the opportunity for the marshes to reform at a higher level, losses of particularly higher marsh communities will occur. What though of the implications of climatic changes themselves on saltmarshes? Given that the rates of saltmarsh succession are largely determined by accretion rates, climatic changes are unlikely to have a major effect. Climatic changes are, however, likely to affect the balance of the species composition of many of the plant communities and, as has already been described, on the distribution range of many of the saltmarsh plant and animal species. Fortunately most of the species likely to be affected by climatic changes are southern species which may be able to spread northwards as the climate warms.

Probably the most significant aspect of climate change for saltmarsh development is the likelihood of increased frequency and magnitude of storms. This is likely to result in more dynamic saltmarsh ecosystems, and if a particular saltmarsh system is finely balanced between accretion and erosion major changes may be triggered which could go either way.

Management implications of climate change

At present there is probably not enough precise information to enable specific management options to be formulated. Clearly there are going to be vegetational changes regarding the northern distribution limits of several species (see Section 5 – ‘Effects of climate change on saltmarsh vegetation’). There is unlikely, though, to be a significant reduction in the distribution of these species in the southern areas. The process of spread northwards may be slowed by the isolated situation of many saltmarsh areas but that is unlikely to be a matter of concern for saltmarsh conservation. Some of the species-poor communities in the more northern and western areas will probably become rather more diverse as southern species spread, but there is little that can be done about these changes. Climatically induced land use changes, particularly in respect to agricultural practices, may have management implications for saltmarshes, for example, in the maintenance of existing grazing regimes. Work under the MONARCH Project (Cook and Harrison, 2001) has suggested that some bird species would be negatively affected by climate change. *e.g.* redshank (*Tringa totanus*) and dunlin (*Calidris alpina*), while others such as oystercatcher (*Haematopus ostralegus*) are predicted to expand.

Mitigation options

It is highly probable that climate change will have implications for saltmarsh conservation but it is also likely that the possibilities for mitigating these changes will be limited. Probably the only thing that can be done at this stage overall is the application of appropriate monitoring regimes to determine rates of change and to detect any possible unexpected changes. There are likely to be quite difficult questions regarding the definition of what precisely it is desirable to conserve, particularly as the nature of communities themselves is likely to alter as the climate changes. The formulation of mitigation options itself demands that decisions be made on what precisely is to be conserved. Only then can appropriate mitigation options be formulated.

It has been suggested that 'landbanking', where land is managed to produce new areas of saltmarsh, for example through coastal realignment, could be used to offset losses caused by climate change.

7.3 The rate of change

Rates of adaptation to change

The rate of adaptation to changes in environmental circumstances is likely to become increasingly important with the climatic changes that are predicted. However, the current lack of knowledge about the details of these changes, their timing and magnitude, still means that there is much uncertainty about the overall rates of change which we can expect in saltmarsh communities over the coming years. It is reasonably certain that the rates of change will increase significantly but this may well have positive as well as negative consequences.

Saltmarsh management options

The major implication of climate change for saltmarsh management options must be an increasing need to institute and maintain a comprehensive scheme of monitoring. Moreover monitoring will need to be done at a range of levels so that early warning of changes can be detected at both local and nations levels. This is considered in detail in succeeding sections.

8. Monitoring and surveillance options

8.1 Objectives of monitoring

Setting baselines

Monitoring can perhaps best be described as the determination of change, and change can only be measured if accurate baselines have been established. A distinction must be made between the baselines for monitoring and the baselines for management. The occurrence of change is determined from the monitoring data by comparing data collected after a set period of time with the initial data set; if there is a statistically significant difference then change is said to have occurred. That is, change is considered in relation to two points within the period of monitoring. It is not generally possible to make tests for the occurrence of significant change with data pre-dating the application of that monitoring regime.

Management is concerned with the manipulation of the vegetation towards a particular target, and this target may relate either to the situation at the start of the monitoring or at some earlier starting point. To use terrestrial grassland as an example, if it is observed that there is some scrub invasion into the grassland then it could well be appropriate to set up a programme of monitoring to see if the scrub is spreading. At some later date the monitoring data could be examined to see if significant changes had occurred (significant differences between the data at that point and the original data). If this were the case then a suitable management regime could be imposed but this would normally be targeted at returning the vegetation to the situation existing before the scrub invasion. In other situations it might be appropriate to set a vegetation state or condition in the future to act as the trigger for, or starting point of, management action.

Even though there is this important distinction between the baselines for monitoring and management the criteria on which monitoring baselines are set must cover the criteria on which management decisions are to be made. In practice it is desirable to ensure that the baselines for monitoring are more precise and more comprehensive than the anticipated management criteria. It is better to have some extra data on which to base decisions than to try to extrapolate from partial or inadequate data.

The setting of baselines for monitoring has to be considered from the point of view of the full range of species and communities which are known to occur within the area under consideration. A prerequisite for a successful monitoring programme is the existence of a comprehensive survey of the whole area. The detailed monitoring can then be tailored to ensure that, as well as covering the area as a whole, there is adequate coverage of areas with particularly high or unusually low rates of change.

Defining rates of change

Rates of change can be assessed by comparing two sets of data separated by a given period of time. However, for practical and economic reasons whole populations are rarely recorded. Instead samples are taken of the whole, and thus decisions have to be made with regard to the efficiency of the sampling and the variation between the sample mean and the true mean for each monitoring event. In practice this means that the setting up of the baseline monitoring programmes requires careful consideration to ensure that there will always be a greater level of accuracy between the true mean and the sample mean than that required for the accuracy of the monitoring itself. Achieving this would normally be a matter of taking appropriate statistical advice, but it may be appropriate to make some comments here which apply specifically to saltmarshes and saltmarsh vegetation.

Decisions also have to be made on whether to use permanent quadrats or to re-sample each year. This is partly a statistical matter to be decided in relation to the nature of the likely data sets, but for saltmarshes there are practical considerations. Generally the statistical objections to permanent quadrats are outweighed by practical advantages of the approach, but the sensitivity of saltmarshes to damage by trampling also needs to be taken into consideration. Even annual visits to fixed sample points can cause visible changes to the vegetation. Additionally the dynamic nature of saltmarshes can often make it very difficult to relocate the quadrat markers (although the use of accurate GPS positioning systems in conjunction with metal detectors to locate hidden or lost markers can be of considerable help in this respect).

Cyclical and directional change

Even when it is clear there have been significant changes, it is important to determine which, if any, relate to permanent directional change and which are simply part of natural cyclical fluctuations and therefore in the longer term of only limited significance. This may, at first, appear to be a relatively simple question to answer but the many interactions between the natural processes of regular cyclic changes in the vegetation pattern and cyclical and other changes in climatic parameters make defining the magnitude and direction of change difficult. For saltmarshes these issues also need to be considered in relation to physico-chemical impact from the accretion and/or erosion of sediment on the marsh surface. It is also important to recognise that the distinction between areas showing significant changes in the long term and those areas where the changes are cyclical may be a question of the distinction between change in space and change in time. With the progressively changing saltmarsh environment it is also possible for regular cyclical changes to acquire gradually an element of directionality. Thus what may be dismissed over a period of a few years as an exclusively cyclical phenomenon may over a longer period have to be recognised as making up a permanent change.

Practical monitoring objectives

In respect of management, the objectives of monitoring have to be the detection of permanent change with the greatest reliability at the lowest possible cost. This definition of change has to apply to the whole management area and not just that covered by sampling. The detection of change is needed to determine when an appropriate management regime should be applied and to assess if the desired objectives of that regime have been fulfilled.

As well as monitoring the plant or animal species and communities to be conserved, it will usually also be highly desirable to monitor the environmental factors most likely to influence change. Very often such environmental factors may be crucial in distinguishing the nature of the observed changes as well as contributing to decisions on the appropriateness of any new management strategy which may be applied.

8.2 Techniques used

Field methods

The size of quadrat used is of particular importance. Many of the commonest saltmarsh plant communities show several scales of pattern and it may be difficult to accommodate all of them. There is nearly always a conflict between the size of quadrat and the number it is possible to record within the practical limits of time and cost. Nested quadrats can often be very effective but it may also be worth considering the use of two radically different sizes of quadrats. For example, to detect the spreading of individual shoots making up clumps of *Limonium* the use of 250 mm quadrats might be appropriate, but to detect the changes in the balance between areas dominated by *Puccinellia* and *Atriplex* within the same community a quadrat size of 4 metres might be appropriate. In other cases it might be worth considering the use of rectangular quadrats rather than square ones, as rectangular quadrats can often be effective in the recording of vegetation where a pattern is found at different scales.

The largest scale of pattern is that shown by the different major areas of saltmarsh such as pioneer marsh and lower marsh and most workers would instinctively sample each of these areas separately. However, there may be recognisable subdivisions within these major areas and often the sampling errors can be considerably reduced by the process of 'stratified random sampling'. In this method the subdivisions within an area are identified and sampled separately, thus avoiding the situation where, purely by chance, a disproportionately large number of the random quadrats falls within a particular vegetation type, thus leaving other vegetation types under-sampled.

The actual methods of recording will largely be determined by practical considerations relating to the nature of data to be collected, the time available and the level of accuracy needed. Careful thought must always be given to the ease of application of a particular method both at the time of initiating the process and in the future as both the communities and the environmental circumstances change. Techniques which are efficient and easy to apply under the community conditions at the start of monitoring may become both inefficient and laborious at some time in the future. Changes in techniques during a period of monitoring always carry the risk of creating difficulties for the later interpretation of the data.

The Environment Agency is developing remote sensing techniques for marine SAC monitoring. Remote sensing is considered to offer the only realistic means of monitoring change in land cover over wide spatial scales, and it allows the collection of accurate digital maps for inter-annual comparison. Ground-based methods, whilst highly accurate in small areas, require intrepolation to cover the full extent of the coastal zone, which introduces inaccuracies. Ground cover types can be identified from remotely sensed imagery using a technique known as digital image classification. The Environment Agency has demonstrated the use of remotely sensed data to map environmental habitats in the coastal environment, particularly in the intertidal zone. These techniques are capable of distinguishing saltmarsh, algae and bare mud, in addition to water and terrestrial vegetation.

Automated monitoring

The advances in modern technology may make it possible to automate ecological monitoring, a method which is thought to be both cost-effective and objective. These assumptions need to be examined carefully for a number of reasons. Careful consideration needs to be given to the reliability of the automated system and the provision of adequate forms of back-up against both the failure of equipment and human error. The prevailing conditions in a saltmarsh – water, weather, salinity and difficulties of terrain (soft mud, creeks, etc.) – are likely to test both electronic equipment and its human operators. The benefits which arise from the objectivity of automated methods have to be set against the implications which can arise from the lack of flexibility of automated systems compared with the ability of an experienced observer to detect unexpected incipient changes in a wide range of parameters. The greatest advantage of automated methods is undoubtedly the ability to acquire comprehensive and complete long-term data sets and thus to detect the occurrence of the episodic, and therefore unexpected and largely unpredictable events which are very often the determining factors in saltmarsh processes. The use of such systems also allows results to be presented in digitised form for use in a GIS application. The display of data in this form is essential for efficient management of dynamic coastal habitats.

At present there are very few systems which have been developed for automated recording of physical processes and few of these can be directly applied (installed) in the saltmarsh environment without considerable modification requiring specialist electronic and technical expertise. This is in marked contrast to commercially available monitoring equipment that is capable of functioning unattended for very long periods in the harsh conditions of the deep ocean.

Data analysis and presentation

It is important from the statistical viewpoint to design any monitoring programme with the desired end-objectives clearly in view with regard to the analysis of the data, the way that the data will be handled and analysed and the eventual presentation of the data. There are often communication difficulties between ecologists who design the collection of monitoring data, those who analyse the data and the resource managers who subsequently make the decisions on the application of management techniques. The presentation of data with the optimum use of graphs and diagrams can be of considerable help in this respect as can the use of presentation techniques such as Powerpoint™. It must always be remembered that whatever impressive techniques of data presentation are used they can only be as good as the original data.

A further important point is that while the monitoring programme may be producing a number of distinct data sets the data itself should always be considered as a whole. Changes in individual parts of saltmarshes often have implications for other parts of the system. This is true for saltmarshes even more than in many other habitats and the procedures for data handling and presentation must take this into account.

8.3 Application of techniques

Operational monitoring

The practical application of monitoring consists of more than just the annual or more frequent applications of the monitoring programme. Most ecologists are familiar with the variations that can occur from year to year in the timing of seasonal changes. However, this is a notable deficiency in the development of any methods for setting the timing of an annual recording or the annual components of recording in relation to the conditions prevailing in a particular year. On the one hand, if it was desired to record details of the spring germination patterns of many saltmarsh seeds, it would also be necessary to adjust the timing of the operation to the conditions prevailing in each year of the exercise. The same approach should also be applied to all the other processes which vary in timing from year to year. One the other hand, if it is necessary to conduct the monitoring at a fixed date each year, thought must be given to the possibility of adjusting the data to reduce or remove this possible source of error.

It is also worth giving thought to whether the monitoring needs to be applied every year. If, for example, a lower marsh community is going to take 40 years to develop into a middle marsh community, it might be considered that annual monitoring is unnecessary and monitoring at intervals of two, three or more years may be adequate. In other cases it may be beneficial to have a form of dual-level monitoring, with the recording aimed at detecting major changes being carried out each year but making a more detailed record at every second or third year.

With much ecological work going out to contract it is also necessary to ensure either that the same personnel carry out the work each time or, preferably, that the methodology is sufficiently rigorous to cover any problems which might be caused by changes in staff. The continuous availability of the same person to carry through a long programme of monitoring cannot be taken for granted. The special nature of saltmarsh recording and the conditions under which the recording will be carried out give added emphasis to the need to ensure uniformity and continuity even with changes in operators.

A further point here is the desirability of conducting at least a preliminary analysis of the data as soon as possible after collection. This will ensure that any errors or omissions can be detected when there is still the possibility of putting them right before there have been any changes in the communities or the conditions.

Provision of information

Reference has already been made to the benefits of using an experienced operator in picking up background information; this can make all the difference when it comes to the interpretation of monitoring data sets. Special preparations for the collection, recording and processing of this information should be considered to be an integral part of a monitoring programme. In practical terms this may be quite difficult not only in the collection of such information but also as its interpretation is likely to have a strong subjective element. The importance of the provision of information from a variety of sources can be invaluable when assessing long-term change. Anecdotal evidence can be extremely useful – for example, the reports of large turves of saltmarsh vegetation scoured by ice on the estuary bed at West Mersea; the historic use of Bob Hall’s marsh at

Wells, Norfolk for sheep grazing, or information on the extent of the cutting of samphire at Stiffkey. However, the accuracy of this qualitative data needs to be carefully assessed when being used for monitoring or management purposes.

Recording of techniques used

The importance of the standardisation of the techniques used in the practical application of saltmarsh monitoring has already been described but it is also important that these methods are adequately described and documented. A distinction must be made here between the requirements imposed in the writing of the 'methods' section of a scientific paper and the level of information necessary to ensure that the working methods could be adequately repeated at the same site on a later date, or equally to ensure that the information was complete and adequate for the methods to be tried elsewhere.

Matters that need to be considered under this point also include adequate information on the location and positioning of the quadrats and information on the format and storage of the data itself, as well as the compilation and storage of supporting environmental data.

8.4 Assessment of success

Long-term monitoring

Assessing the adequacy of the long-term monitoring of saltmarshes depends both on the quality standards applied in the collection and storage of the data and on the adequacy of this data in providing the answers needed for effective saltmarsh management. It is important that the same standards are used to assess the effectiveness and validity of the methods used for monitoring saltmarsh change as for the monitoring of the management regimes which are being applied to those marshes.

In order for the methods of saltmarsh monitoring to be fully effective in the long term, there is a real need for the methods to have a sufficient degree of built-in flexibility to enable them to cope with any changes that may occur during the intended period of monitoring. This will apply not only to the magnitude of the changes which may occur within the zone or community being monitored but also to changes in the boundaries of the zones.

Assessment of achievement of objectives

The first and probably the least significant aspect of the achievement of success in any monitoring programme is the actual assembly and compilation of the data set collected during the period of monitoring. The key measure is the attainment of specific objectives, preferably the objectives that were set before the initiation of the monitoring programme. The criteria in the determination of the achievement of success must themselves be statistically rigorous and at the same time be related to specific management aims and requirements. As well as determining whether defined changes have occurred or not, there must also be sufficient information to enable sound decisions to be made on the selection and application of the appropriate management regimes. It is important to note that monitoring change is primarily aimed at providing the information needed for effective management, though it can also have its own intrinsic value.

Updating management plans

The formulation of a management plan and its implementation coupled with a programme of monitoring is the appropriate way of ensuring the effective management of saltmarsh plant and animal communities. However, the aim of monitoring is to ensure that the management regimes are appropriate and applied in the optimum way in the prevailing circumstances. This can only be fully achieved if the management plans are constantly kept under review in the light of the information flowing from the monitoring programme itself.

It may be helpful to note that recent developments both in our understanding of the functioning of saltmarsh ecosystems and in computer software are leading to some very interesting possibilities for the future regarding the integration of monitoring and management knowledge. Difficulties have been experienced in the utilisation of recent advances in the modelling of saltmarsh processes, particularly in the integration of the data and understanding that can be gained from the various individual models. There are also problems in the collection and assimilation of the large amounts of research data on saltmarsh ecology and management which appear annually.

Possibilities for the integration of the various sources of information and the application of the various saltmarsh modelling studies are indicated by the EUROSAM Decision Support System. This was the end product of the EUROpean SAltmarsh Management study involving participants from the UK, the Netherlands and France which was recently completed. The EUROSAM Decision Support System is a management tool for European saltmarshes, which was constructed by Brown and Cox (2001) and comes on a CD complete with its own software. At present it is very much a prototype but it clearly indicates some exciting possibilities for the development of fully integrated computer-based management systems in the not too distant future. The most significant development is the possibility of the functional integration of a wide range of saltmarsh process models and the application of the results to practical saltmarsh management in a predictive model.

9. Management experience

9.1 Aims of management

Need for defined target setting

The aim of management is to maintain an ecosystem or complex of ecosystems according to specific guidelines; but of course part of the process is setting these guidelines. The guidelines may relate to the area as it is now or as it was at some specified time in the past, or they may relate to the overall state of those ecosystems in a much wider area. The ecologist should be able to say what a site is like at the present, what it was like at a specific time in the past or indeed how it compares with other similar sites in the area. He or she may be able to say what changes could be achieved by the various management options which are available, but over and above that strategic conservation decisions will have to be made before specific targets can be set.

The setting of targets is very important because they are the means whereby the effectiveness of management regimes can be judged. In general, the more specific the targets are the easier it will be to assess management success. Nevertheless it will often also be true that the more specific the targets are the less likely that they will be met in full.

In areas like saltmarshes which are dynamic and can sometimes change quite quickly the targets that are set may well represent conditions quite different from those prevailing at the starting point. Therefore some form of environmental assessment may be needed to verify that the desired objectives have been achieved. It may not always be possible to verify the achievement of management success simply by the presence of desired species and communities. The status and functioning of these communities may also form part of the process of the verification of success: this will be considered in detail later.

Provision and dissemination of information

The key to the process of target setting is the collection and dissemination to all concerned of reliable and up-to-date information on the extent and distribution of key species and communities together with information on their functional interactions. While most of this information is generally available for the area of concern, it is also needed on a regional or national scale so as to assess overall status and not simply that of one small area.

Generally in the UK there is good general information on the overall distribution of saltmarsh habitats, but the extent of detailed information that is available is very varied. Clear guidelines and a detailed framework have been established for those areas given special status under the European Union Habitats and Birds Directives as part of the establishment of a network of conservation areas to be known as ‘Natura 2000’. A good example of the processes involved and the detail required can be seen from ‘Essex Estuaries European Marine Site’, published by English Nature in June 2000. This lays down an excellent framework for the provision and dissemination of the information needed for the setting of management targets and conservation objectives. It also includes detailed advice on habitat sensitivity and management operations. The success achieved in this document was not only due to the work that went into its compilation;

it also reflects the very large research effort that had already been put into the study of saltmarshes in the Essex area. It reflects too the willingness of a wide range of other users of the coastal zone to participate in the various initiatives aimed at co-ordinating the many varied interests in the coastal zone.

The establishment of the Essex Estuaries European Marine Site was followed up by the development of CHaMPS or Coastal Habitat Action Plans to provide the framework for the management of European or Ramsar sites which are located on dynamic coastlines. The CHaMPS programme contains a section on compiling the inventory of features of sites, the setting of conservation objectives, the identification of features that can and can not be retained together with an assessment of the maintenance of site integrity. What it does not address, however, is the maintenance of ecological function as described by Wigand *et al*. (2001). The broader implications of the effects of coastal defence policies and natural processes on habitat conservation within these areas have recently been reviewed by Lee (2001), who describes the various difficulties which will have to be faced during the coming 50 years and goes on to describe a possible management framework.

While the initiatives described above provide a clear framework for the way ahead in certain specific, designated areas, these initiatives by no means cover the whole of the UK. Despite the Essex Estuaries European Marine Site being an area where the long-established research background greatly facilitated the compilation of the wide range of necessary information, difficulties were still experienced in compiling the documentation. Although great efforts are being made by the conservation agencies in other parts of the UK, there are still wide areas for which the detailed information just does not exist. In the more remote parts of the UK the basic site information is still far from complete and the additional information needed for the prediction of change and for effective conservation management is scant. The provision of information on the functional role of the many different coastal ecosystems has scarcely been addressed. The importance of the acquisition of this information is not just of relevance to the management of these sites but is likely to have a range of implications for the management of UK sites as a whole.

The use of the NVC system in the descriptions of vegetation needed for management plans does provide a uniform standard for the whole country but there are difficulties. In Essex, for example, within two NVC units 16 sub-communities can also be recognised as units of vegetation. While these sub-communities are clearly of less significance than the parent communities, management is concerned with the detection and manipulation of change; the sub-units could give the first signs of the onset of change. The NVC classification recognises that in parts of Scotland and Northern Ireland there is less than adequate coverage and thus the classification has to be regarded as provisional.

Formulation of management plans

The framework for the formulation of management plans has been addressed by the documentation previously referred to: in particular, the UK Marine SACs Project and the Living with the Sea Project, which includes CHaMPS (see www.english-nature.org.uk). Thus it need not be repeated here. There are, however, a number of points which need to be emphasised. First, a framework would be based on the best information available at the time the strategy was drawn up and thus would need periodically to be updated in the light of increases in scientific and technical knowledge. This would include, for example, the provision of tests for the maintenance of habitat function as well as overall habitat integrity. Secondly, the management plans should take in the widest possible range of individuals and bodies whose activities take place within or have an impact on the coastal zone. Thirdly, it could be beneficial for full consideration to be given to the development, assessment and utilisation of new technology such as the latest advances in IT and dedicated decision support systems. Finally, it is important that individual area management plans are fully integrated not only in respect of the various different sites and habitats within their own areas but also on regional, national and international scales.

Assessment of achievement of objectives

The assessment of the achievements of objectives depends on the setting of precise and clear targets in the first place. It also depends on the setting of suitable criteria upon which to judge success or failure. The development of new ways of judging these criteria can be further improved by formulating ways of ranking and integrating these criteria, thus going beyond the level of subjective judgements regarding individual criteria (Short *et al.*, 2000).

Need for management plan updates

During the implementation of management plans information will be acquired which may affect the validity of the management plan or of the criteria being used to judge success. Wider ecological changes may in the longer term have implications for particular management strategies. Not only do management plans need to be responsive to changing conditions and circumstances but there also need to be appropriate mechanisms for the regular review and updating of management plans at the local, regional and national levels. Provision for the effective exchange and sharing of information from the full range of monitoring and research activities in saltmarsh habitats is an essential part of this process. There may also be occasions when problems encountered during management or the assessment of management success or failure indicate the need for gathering further information or targeted research to clarify particular issues.

9.2 Management techniques

Management options

Management options range from doing nothing to large-scale habitat creation or re-creation. However, both these options will be considered separately and will not be discussed further at this point. Broadly, there are two aspects to habitat community or species management: control or prevention of unfavourable influences, and the introduction or encouragement of favourable influences.

It is basic to any management system that any unfavourable influences, such as trampling, pollution and/or eutrophication, the effects of habitat damage and disturbance, will be prevented or at the very least minimised. What is also needed is to ensure that the effects of any unavoidable residual levels of potentially damaging activities are carefully monitored with the feedback of this information to adjust the ways in which these activities are controlled.

Positive management, on the other hand, involves the encouragement and manipulation of influences favourable to the development of desired objectives. There is a range of possible management options regarding saltmarsh vegetation. These include the cutting or grazing of vegetation, the encouragement or control of individual species, and the regeneration of the successional sequence by lowering of the marsh surface through turf-cutting. There is also the possibility of the direct control of individual species which are having or could have an unfavourable influence on saltmarsh communities.

Control of public access

The right of the public to wander on saltmarshes has long been taken for granted, but as well as there being circumstances when it has to be controlled on safety grounds there are two areas for concern. These relate to the susceptibility of saltmarshes to damage from trampling and to the possible disturbance of nesting birds in the summer and wintering wildfowl. Even small numbers of pedestrians can disturb roosting and nesting birds. The identification of areas sensitive to disturbance and/or trampling should be undertaken to assess whether access has damaging effects, and where necessary the provision of information on adverse impacts and limited or re-routed access may be acceptable.

Saltmarsh erosion control

The question of erosion control can be subdivided into two: limitation of surface damage such as trampling, and measures used to limit the large-scale erosion of the marsh as a whole. The effects on the vegetation of trampling can be reduced by the use of a geotextile fabric secured to the marsh surface. Most of the fabrics available are of a relatively fine mesh and thus can only be applied directly to the soil surface with the vegetation regenerating through the fabric. Their value thus lies in the repair of areas which have lost their vegetation cover as a result of damage from excessive trampling. The semi-rigid plastic fabrics with apertures of a few centimetres can often be used on top of existing (short) vegetation and can rapidly be incorporated in the litter layer, substantially increasing the resistance of the area to trampling. This approach can also be used in the short term when it is desirable to minimise the damage caused by the passage of people or equipment for a particular management or research operation.

The control of erosion near the seaward edge of the marsh is more complex. The existence of such damage will be evident in areas of bare ground, in reduced vegetation cover near the marsh edge or in the form of an actively eroding cliff edge to the marsh. The control of saltmarsh erosion under these conditions can only be achieved by reducing the wave energy which is causing the erosion. The direct use of any protective barrier applied to the marsh edge is only likely to give very limited protection in the short term. There are however a number of other possibilities for erosion control in the long term. One lies in the establishment (or re-establishment) of new pioneer marshes further seaward, though if the present marsh edge is eroding significantly this is unlikely to prove possible. The introduction of sufficient quantities of fresh sediment into the system in the critical area just beyond the marsh edge has been shown to be effective at West Mersea and Hamford Water, in Essex. At another site in Essex the use of sunken barges filled with gravel to provide an offshore wave break has also proved relatively successful, at least in the medium term. It must always be borne in mind that the underlying reason for these forms of erosion is environmental changes which mean that the position the marshes are in is no longer sustainable and that natural process are tending towards the development of a more stable configuration.

Recording of management techniques used

Various management techniques have been described and many of them are well documented. The practical application of any given management technique almost inevitably encounters a range of problems specific to that use of the technique. For that reason alone it is important that full records are kept of the techniques used, of difficulties encountered in their application and of the success or otherwise of the final outcome. Reference has already been made to the benefits of regularly updating any programme of management and the recording of the full details of the management techniques used is a vital part of this. The matter is also important because the lessons learnt in one situation may have implications for the use of the techniques elsewhere.

Resolving management conflicts

Where incidence of damaging activities cannot be eliminated or where a justifiable activity, such as research or even management itself, is causing or may cause habitat damage, then it is necessary to decide how best the impact can be absorbed. For example, wildfowling, bird-watching, research and even management will probably involve damage from trampling to gain access to the part of the marsh where the activity will take place. Consideration will then need to be given to whether there are alternative routes which will result in less damage, whether it is preferable for there to be a higher level of damage to a specific area or lower levels of damage over wider areas, or whether damage can be reduced by particular measures such as the provision of special reinforced walkways. The latter solution would probably be the most appropriate one in situations where the threats are only short-term in duration.

Integration of management techniques

The formulation of management techniques is generally done on the basis of providing an answer to specific problems. The integration of the various management techniques is not simply a matter of avoiding any direct conflicts, although that in itself is a matter of importance. Rather the integration of management techniques provides an opportunity for linking the management to the ecosystems as a whole. Just as the saltmarsh ecosystems are interlinked to many of the adjoining ecosystems, optimum management success is most likely to be achieved if the various management techniques are themselves integrated. For example, the presence of grazing animals on the marsh will not only affect the species composition of the vegetation but will also affect the litter layer. Birds on the marsh will be affected by changes in the nature of the vegetation and breeding, grazing and roosting birds will be affected differently. Changes in the litter as well as changes in the vegetation will affect the export of organic matter from the marsh and this will in turn affect the invertebrates feeding on this organic matter. The other point about the integration of management techniques is that there may be considerable practical and cost benefits in their integrated application.

Wider management implications

The formulation of techniques for the conservation management of saltmarsh naturally gives priority to conservation criteria; but many if not all marshes have multiple uses and functions. It is therefore necessary as far as possible to take this into account in the formulation and use of management plans. The benefits from this can be indirect, such as the avoidance of conflicts between different users, but there is also the potential for direct benefits. For example, if a marsh has a high value for coastal defence as well as conservation this will increase the support base for ensuring its long-term survival. Ensuring the saltmarsh is fully functional with regard to the outward fluxes of organic matter not only affects the health of the saltmarsh but has implications for intertidal and sub-tidal invertebrate populations and hence fisheries. The growing numbers of local coastal zone management groups provide useful foci for the further development of this type of approach.

9.3 Management of saltmarsh vegetation

Vegetation management

The one area where cutting is still likely to have a continued role is in the commercial utilization of the extensive reed beds which spread down into brackish conditions in a number of areas. The management of reed beds is best considered on its own merits and there are not likely to be wider implications here for saltmarsh management.

The saltmarsh species whose management has received the most attention is undoubtedly *Spartina anglica*, but the threat this poses is now less than in the early years of its spread. It is still a common colonist of mudflats but its survival and persistence into later saltmarsh communities is generally limited. There is also a range of established methods for its control (Adam, 1990) as well as methods for discouraging the die-back of *Spartina* (Johnson, 2000) in areas where this is considered to be desirable.

It has also been recorded that in areas used for grazing the vigorously growing *Juncus maritimus* has been controlled by burning or cutting and by the use of chemical herbicides. However, this has only been done on a limited local scale and the practice does not appear to be widespread.

Use of grazing animals

Various animals may graze marshes. In many areas there is winter grazing by wildfowl. There are practical difficulties in controlling this form of grazing, particularly as the wildfowl themselves may be of conservation interest and are generally considered to make a positive contribution to the overall biodiversity. Goose grazing is generally restricted to those areas where the vegetation is sufficiently short for the geese to be able to see approaching predators and which are characterised by having a very distinctive short dense sward. The species composition of such swards is generally less diverse than that of adjoining ungrazed areas but this results from the combined effects of grazing and trampling. The latter impact is sometimes sufficient to result in local patches of bare mud, at least during the winter months, but these areas are generally recolonised as the geese usually leave before the onset of the main growing season. While goose grazing is not generally considered to be vital for the maintenance of species diversity, it is possible to increase the levels of grazing by making the areas more attractive to the geese; this is achieved by cutting the taller vegetation that could provide cover to predators. Rabbit and hares have also been observed grazing saltmarshes, and hares in particular often graze at considerable distances from the dry land. Wild deer graze the Highland marshes, particularly in the winter. The impact of grazing by these animals, however, is limited in its impact.

The maintenance of the typical vegetation associated with many marshes in the north-west of England is the result of use of the marshes over centuries for grazing farm stock, particularly sheep. The species composition as well as the overall appearance of the vegetation in these areas has been strongly affected by this grazing. Recent trends in agriculture and changes in agricultural practice threaten the maintenance of this traditional practice. If the trend is not reversed then large-scale changes over the coming decades are likely (Adam, 1990). As well as the direct removal of green shoots by the grazing animals, grazing also reduces the build-up of the surface litter layer. Adam (1990) points out that this could favour species diversity but this is only likely to be of overall significance at low grazing densities. At higher grazing intensities the impact of trampling may well outweigh any benefits of the control of the coarser vegetation. Shrubby plants like *Atriplex* are particularly vulnerable to this form of damage, as are species such as *Limonium* whose buds, sticking up above the soil surface, are sensitive even to low trampling intensities. Conversely, the bare patches created by these low trampling intensities also provide the open habitats needed for the persistence of pioneers such as *Salicornia* or *Suaeda* species and for low-growing marsh species such as *Spergularia* or *Cochlearia*.

The potential benefits of grazing are probably at their greatest in some of the transitional saltmarsh zones where tall-growing species tend to dominate the vegetation and lead to the development of rather species-poor communities. Nevertheless even there it is often worth considering whether grazing is the best option or whether cutting would be more appropriate. Haymaking has been practised on saltmarshes both in Europe and America in the past but is rarely practised in Britain. There is only limited evidence on the benefits of cutting saltmarsh vegetation for hay (Adam, 1990), but it is a way of controlling the coarse vegetation characteristic of the higher marsh levels and some trials have been conducted of its conservation value (Hurford, 1994). The main difficulties in the application of cutting as a management technique are likely to be the high cost and considerable practical difficulties in mechanising the operation. It must also be noted that the risk of disturbance to breeding birds would limit the times when cutting or grazing could be conducted.

Saltmarsh regeneration

The cutting of turves for the establishment of high-quality specialist lawns has been an established use of marshes in the north-west of England for many years. The area for turf cutting is prepared beforehand by a programme of weed control and mowing. The turves are then cut mechanically and generally regeneration of the vegetation cover is left to natural processes. This provides an ideal habitat for a wide range of ephemerals and bryophytes and as such contributes to the overall biodiversity of the area (Adam, 1990). The turves that are harvested in these circumstances are cut with quite a thin layer of soil from the high marsh. There is little change therefore in the level of the cut areas and no major change in the tidal regime and thus in the saltmarsh succession.

Turf cutting has been used in the Netherlands for the regeneration of dune slack plant communities and saltmarsh communities. Here much thicker turves are cut and the level of the soil surface is significantly lowered. This increases the inundation frequency and effectively accelerates an earlier stage in the saltmarsh succession. There are practical difficulties involved in this operation and with the difficulties of mechanising the operation it is difficult to see that it could have widespread application. Nevertheless with the combined effects of lowering the marsh surface and creating open spaces for plant colonisation it would be worth considering as a possible technique for use in specific circumstances.

9.4 Effects of non-management

Can nature be relied on?

Given that saltmarshes have survived many thousands of years in the complete absence of management it is reasonable to ask whether nature can be relied upon to ensure their continued survival. In many respects and in certain circumstances this is undoubtedly true. Saltmarshes are not like grassland which eventually develops into woodland. While in the early stages marshes can develop quite quickly, their subsequent development is progressively slower with almost imperceptible rates of accretion on the highest marshes which are only covered by the occasional spring tide. The episodic occurrence of the most severe storm ensures that periodically the whole saltmarsh system is subjected to the processes of erosion and regeneration. Even changes in sea level have been accommodated by the erosion of the seaward edges of the marsh and its gradual displacement landwards eventually to reach a new stable equilibrium.

What then has changed that means nature can no longer be relied upon? The first thing is that marshes are very much less extensive now than they were formerly. This can be seen in the extent of the low-lying land inside the present sea walls. Because so many marshes have disappeared there is an ever-increasing need to ensure the survival of those which remain. But much more serious is the extent to which these sea walls are acting as a complete barrier to the natural readjustment of saltmarshes as a response to ever-rising sea levels. The reduction in the number and extent of saltmarshes in Britain is also significant with regard to the increasing isolation of one saltmarsh system from the next. The plants of an individual saltmarsh may form stable populations despite the site's isolation, but all the birds and many of the other animals move from marsh to marsh and are thus dependent on the relative continuity of this chain of habitats, a chain that is increasingly threatened by the loss of individual marshes.

Probably the most important factor in favour of positive management is the acceleration of the rate of change that has taken place of recent years. As well as the increase in the rate of habitat destruction and the increases in the various direct human impacts on the marshes, the onset of climate change and sea level rise are causing changes at rates well above those to which nature can respond. The increasing isolation of marshes means that it is increasingly difficult for species to move between marshes as circumstances change. Even in those areas where human activities are not interfering with the natural responses of saltmarshes to rising sea levels we can no longer be sure that these responses will be able to keep pace with accelerations in the rates of change. All this points to the real need to ensure that the necessary management techniques are ready and available when natural processes are no longer capable of coping with the pressures mankind is placing on saltmarshes.

Long-term implications

Predictions of climate change and sea level rise have been considerably refined in recent years, but there is still more information on trends than there is on the actual details of any new equilibrium which may become established. In these circumstances it is difficult for there to be long-term management targets as these may well have to be adjusted to the prevailing environmental conditions. Emphasis will have to be placed on the conservation of as many as possible of the characteristic species and communities of saltmarshes. This clearly indicates the importance of having as complete a set of baselines as possible on the present situation regarding the distribution and extent of the saltmarsh flora and fauna and of the functional relationship of the various components. If management is to succeed in the long term it must also be sustainable and this implies that it must have an appropriate degree of flexibility. The early detection of change either in the environment or in the saltmarsh itself is of little benefit if the management system can not respond to accommodate these changes.

9.5 Saltmarsh creation

Aims of saltmarsh creation

The aim of saltmarsh creation will generally be to replace areas of this habitat where it was lost previously or to create it nearby. However, the primary aim of saltmarsh creation is to provide saltmarsh in those areas where its presence and function can be of economic, social or environmental benefit. The economic benefits relate particularly to the role of saltmarshes in flood defence, in providing a living and largely self-repairing wave break. They also relate to other economic functions such as wildfowling or amenity as well as to the way in which saltmarshes contribute to the functioning of other habitats of economic importance. The environmental benefits principally relate to the conservation of the saltmarsh habitat itself and to the conservation of a wide range of associated species of animals and plants. It is important to develop the right relationships with the local community and local interests when saltmarsh creation is contemplated as it may be viewed as ‘giving in to the sea’ (Myatt-Bell *et al.*, 2002). Providing full information on the necessity for and benefits of any scheme can significantly reduce local community conflict.

Creation of saltmarsh from terrestrial habitats

There are several different ways in which saltmarsh can be created and the details of these will depend on the starting points as well as the methods being used. Saltmarshes can be re-created from terrestrial habitats by lowering the surface of the habitat so that tidal inundation can result in the generation of new areas of saltmarsh. Saltmarsh can also result from the removal of barriers to tidal inundation of low-lying areas with terrestrial plant communities by breaching or removing sea walls. Saltmarshes can also be created by building up the levels of intertidal areas to a level, in relation to the tide, at which vegetation can become established. Within these three broad categories there is a wide range of more detailed options.

In Britain the commonest form of saltmarsh creation has been the realignment of sea walls, by setting back the sea wall, so that areas within the sea wall which had, over the centuries, been converted to agricultural land could once again develop the protective cover of saltmarsh vegetation. This process has been progressively called ‘managed retreat’, ‘managed realignment’, or simply and rather confusingly ‘set back’, as it involved the setting back of the sea wall and the adoption of a more landward line of defence. The preferred term is generally considered to be ‘managed realignment’, that is, adopting a more sustainable line of defence.

The initial motivation for saltmarsh creation has been economic. This is because it was difficult to justify the maintenance of a particular length of sea wall when the value of the land protected was less or only marginally greater than the cost of wall repairs and maintenance. Even though this approach has indicated extensive possibilities for managed realignment on these grounds alone, the incorporation of elements of the other economic benefits of saltmarshes would extend this further. In various circumstances there can also be important indirect economic benefits from marsh creation. For example, the extent of marshes in the middle section of an estuary is likely to affect the extent of flooding in the upper estuary. While the economic picture of the cost/benefits of an individual managed realignment may be relatively simple (Spurgeon, 1998), the economic analyses become far more difficult if attempts are made to assess the situation on a whole estuary basis. The ideal situation for managed realignment is where there is high ground behind the area to be opened to tidal flooding, as in these circumstances no new wall will be needed; this results in big savings in the total cost.

The conservation benefits of saltmarsh creation are clear in the sense that it provides a way of replacing lost habitat, but there are two concerns here which need to be addressed. The first is the need for caution in assessing the degree to which natural saltmarshes can be replaced by created marshes. The second is that as yet there are no agreed frameworks for the assessment of the economic value of natural habitats. In fact, generally when such estimates are made they are often based on the cost of replacement, leading to circular arguments without really addressing the real problem of assessing the degree to which functions have been restored. This matter is now receiving some attention from two viewpoints. The first evaluates the functional integrity of saltmarshes from a determination of the extent to which they provide key ecosystem services (Wigand *et al.*, 2001), by developing 'success criteria' for restored habitats (Short *et al.*, 2000). The second assesses the extent to which there is 'ecological equivalence' between natural and created areas (Strange *et al.*, 2002). The relative success achieved in the creation of saltmarsh in the UK in respect of the provision of habitat for birds has recently been summarised (Atkinson *et al.*, 2001). The authors concluded that 'the creation of new habitats … provides the opportunity to recreate historically lost habitats', but they expressed caution that there were still large gaps in the knowledge about habitat restoration.

In a number of areas in Essex where saltmarsh had regenerated naturally following the failure of the sea wall, there was optimism that saltmarshes could be recreated simply by breaching the sea wall. In practice this was accompanied by modelling studies to ensure that there were no unfavourable damaging effects occurring on the sites or in adjoining habitats. The success of the first scheme at Northey Island, on the Blackwater Estuary (Dagley, 1995) seemed to confirm this view that breaching the sea wall would lead to the rapid development of new saltmarsh habitat.

Subsequent large-scale schemes for the creation of saltmarsh following managed realignment were not quite as successful in respect of the achievement of vegetation cover (Boorman *et al.*, 1997). It was clear that natural colonisation only occurred at levels equivalent to that of higher marsh and that the speed of recolonisation of the lower marsh levels was much slower, with only a limited degree of success even after seven years. It was also significant that even in areas situated at a level equivalent to that of quite high marsh the processes of revegetation followed the course of succession normally found in the lower marsh.

It appeared that the development of vegetation on these areas newly exposed (or re-exposed) to tidal inundation was not solely dependent on the existence of areas at levels equivalent to that of the existing marshes outside the sea wall. An increasing body of evidence pointed to the various ways in which the soils on land reclaimed for agriculture had to develop and change before the growth of saltmarsh plant could become possible. The soils found in areas of low-lying farmland inside the sea walls have changed very considerably from those that existed when the area was originally saltmarsh. When managed realignment takes place the creation of saltmarshes involves soils which have undergone a wide range of physical and chemical changes, some of which are irreversible (Hazelden *et al*., 2001). These soils when flooded with salt water still show much higher soil density and decreased porosity and are relatively unsuitable for colonisation by saltmarsh plants. The increased density and cohesiveness of these soils also form a barrier to the development of a new creek system. The rapid drainage of an area as the tide ebbs is of considerable importance for the establishment of saltmarsh plants as any drying of the soil will increase its stability and thus facilitate seed establishment.

However, these problems associated with the soil conditions following inundation are partly solved by the deposition of fresh sediment following the breaching of the sea wall. Following the flooding at Tollesbury in 1995 there has been a mean annual increase in the surface level of 24.9 mm (Reading *et al*., 2001). This indicates that there is now an average of 174mm of fresh sediment over the site although this varied considerably at different points within the site. Nevertheless it does mean that there should be an adequate depth of soil for plant establishment and growth across most of the site. At the higher levels the establishment of saltmarsh plants has been generally successful, with 12 species becoming established in the first five years. Plant establishment has been far less successful at lower levels and there is a considerable difference in the lower limit of pioneer species such as *Salicornia* within the site and in the adjoining natural marshes.

The reasons for this are not clear but the mobility of the new sediments and the need for the adequate development of the soil microflora are likely to be important factors. The microflora of saltmarsh soils play an important role in soil process (Burke *et al*., 2002), in the breakdown of organic matter and in the fluxes of plant mineral nutrients; certain saltmarsh plants also have mycorrhizal associations (Rozema *et al*., 1986). It has been shown that the mycorrhizal associations can affect the flooding tolerance of pioneer species such as *Aster* (Huiskes, 2001, Carvahlo *et al*., 2001). It would thus be reasonable to assume that the lack of these organisms would inhibit the processes of saltmarsh development (Boorman, 1999). It has also been suggested that the activities of soil fauna may be restricting plant establishment (Gerdol and Hughes, 1993, Hughes, 1999 and Emmerson, 2000). The authors considered that the activities of *Corophium volutator* and *Nereis diversicolor* could significantly reduce plant establishment, particularly in the pioneer zone, and suggested that management action might be necessary for the successful establishment of vegetation.

The consolidation of the often very mobile sediments which are deposited following the breaching of the sea wall are important for the establishment of vegetation (French *et al*., 1995). The first stage in this process is the development of an adequate drainage system to accelerate the speed with which the water can be removed. Given the high density and lack of porosity in the underlying old agricultural soils, this drainage will have to be largely through surface runoff. The early re-establishment of a system of creeks does not occur naturally 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. There is evidence that there are benefits in accelerating artificially the natural development of an effective drainage system (Boorman, 1999, Dixon *et al.*, 1998).

Saltmarsh creeks also help to dissipate tidal energy (Pethick, 1992) but they are an often neglected component in the design of saltmarsh creation schemes (Reed *et al.*, 1999). There are many complex interactions between the deposition of sediment and the development of saltmarsh creeks and these need to be taken fully into account in the design of schemes for saltmarsh creation. The morphometry of natural saltmarsh creek systems is often complex (Zeff, 1999) but the restoration of saltmarshes demands that creek functionality be adequately restored. It is at present not clear how far a natural creek system has to be constructed as part of the saltmarsh creation process or to what extent its development can be initiated artificially and its subsequent development left to natural processes. Given that surface variations which existed in the agricultural soils at North Fambridge are still visible in the form of wide creeks one hundred years and 1.2 metres of sediment later, it is possible that the creation of a new creek system may not require the excavation of a full-depth system across the marsh and that more modest efforts at the start of the project may provide the trigger necessary for subsequent creek development.

It is an important part of saltmarsh creation that the project is monitored carefully at all stages. Early warning of unforeseen changes and difficulties will greatly facilitate any corrective management that is needed. This monitoring should include the collection of data on physical (weather and tidal patterns), geomorphological (changes in creek morphology and sediment fluxes in and adjacent to the site) and biological parameters. Even before a saltmarsh creation project through managed re-alignment is started it is important to establish through hydrodynamic modelling whether there are likely to be any unfavourable changes of erosion or accretion in adjoining areas. For example, in the case of the Tollesbury project concern was expressed about the possibility of re-mobilised sediment affecting oyster lays some distance down the main creek or indeed the access channel to a nearby marina.

The question of the adequacy of the sources of seed available for recolonisation needs also to be taken into account. In many cases where there are large areas of natural saltmarsh nearby this is not likely to be a problem, but where this is not the case consideration needs to be given to the possible supplementation of an inadequate natural supply. Sowing seed and planting both young plants and turves of saltmarsh vegetation was tried at Tollesbury. In the short term the use of turves of vegetation proved to be more effective than planting small plants or sowing seed, which had a relatively low success in all but the highest areas. Natural colonisation has now largely supplanted the local successes achieved by sowing and planting, although some of the original plants are still surviving. In view of the way that soil conditions appeared to limit natural colonisation it is perhaps not surprising that the plants that were introduced fared little better. In the future it might be better to postpone planting or sowing until the conditions within the area have become more suitable for plant establishment and growth and also to be more selective in choosing areas for these introductions. The comments above relating to the improvement of soil conditions through ways of accelerating creek development should perhaps be taken into consideration when plans are being made for the introduction of saltmarsh plants.

It was noted above that the most successful natural recolonisation, at a site in Essex following wall failure, was at a relatively high level, equivalent to the upper saltmarsh zone outside the sea wall, and there was little lower marsh vegetation (Burd, 1995). This has been confirmed by current experience in saltmarsh creation in the area, and raises the question of whether it might be possible to increase the general level of the area to facilitate plant colonisation.

This approach has been standard practice in the United States for the past 30 years and it is reported from Louisiana that over 1400 hectares of marshes have been created in this way (Turner and Streever, 2002). It is reported that the unintentional development of wetlands on dredged material predates this considerably. The critical factor in the creation of wetlands using dredge spoil is the supply of large quantities of clean (*i.e.* non-polluted) sediment. The normal source of the sediment will be dredge spoil and it is unlikely that it would ever be economically viable to use material from other sources given the very large quantities needed. It should be noted that the successful American experience relates to the creation of new 'wetlands' and this term, even when qualified with the word 'coastal', includes both salt water and fresh water tidal marshes. The marshes created in Louisiana have generally been left to develop a vegetation cover by natural processes, while in Texas sowing and planting has been extensively used. It has been reported that generally planting has been more effective than sowing. It has also been reported that diverse plant communities have developed even when only one or a few species have been planted (Turner and Streever, 2002). It is generally acknowledged that unless there are good natural sources of seed locally, planting or sowing will be needed.

The standard methods of unloading dredged sediment will not generally be adequate to create the desired morphological features and some local adjustments to the positioning of the sediment are often needed. This is regarded as particularly important when it is desired to incorporate specific features such as tidal creeks and tidal pools. Because of the extra, often innovative work and associated costs which will be involved, methods to be used to create these features need to be considered at the design stage.

The placing of the dredged material has proved to be a key part of the successful creation of new marshes. The various dredged materials will consolidate at different rates and to different extents under different conditions. The weight of the placed sediment will often cause settlement of the underlying material, the natural bottom below the dredged material. Precise engineering methods have had to be used to determine the final elevations critical for the establishment and survival of the plant cover. Another technique which has also been adopted is the use of bunds to confine areas of semi-mobile sediment; the material is then allowed to de-water naturally. This is, however, a slow process and nothing can be done in the area until it is achieved. The positioning and in particular the degree of exposure of any created sites is also of key importance. Exposed situations have to be avoided and even in semi-exposed sites some form of wave protection may be needed.

The extensive and successful creation of marshes using dredge spoil has depended on the availability of sufficient quantities of the right material. The sediment obviously must not contain any toxic substances which might impede marsh development or be released into the wider environment. The material not only has to be of a suitable particle size but it also has to be of an appropriate density. Some dredged material has a density only slightly greater than that of water; this would be unsuitable for the creation of wetlands as it could very easily be eroded. Even with the relatively abundant supply of dredged sediment from major waterways the creation of new marshes using this supply of material is estimated at around $40,000 (£25,000) per hectare; however, the majority of this figure relates to the costs of the dredging itself.

In the UK dredged material has been use to decrease erosion at the edges of the marsh. There are clearly possibilities for the creation of marshes using dredged material but the main limiting factor is the availability of suitable material. There are far fewer large-scale dredging operations than in the US and much of the material which is available is contaminated in one way or another. It could be argued that using lightly contaminated material to form the base for a future saltmarsh might be justified, in the sense that the contamination would be more isolated from the environment than would be the case if it were to be dumped elsewhere at sea. Nevertheless any such use of contaminated material would require the utmost caution. It might be possible to acquire clean sediment by the use of dedicated dredging operations but then the project would be subject to the high costs of the order referred to above.

Even if the large-scale use of dredged material is not possible because of the unavailability of the very large quantities needed, smaller quantities have proved to be useful in the rehabilitation of marshes deteriorating rapidly through the combined effects of rising sea levels and exposure. In Louisiana a technique has recently been developed in which the marsh is restored by spraying on a thin layer of dredged material. The material was applied at rates that the emergent vegetation (*Spartina alterniflora*) could withstand; although the vegetation was initially damaged by the sediment deposition it subsequently recovered and grew well (Ford *et al.*, 1999). The quantities which were applied were only marginally higher than those which could result from natural accretion during a storm.

An unusual technique which has been developed for the creation of wetlands is the so-called bay bottom terracing. In this method bottom sediment is used to create a series of banks and terraces which can then be planted with *Spartina* or other emergent marsh species. These terraces act as baffles to wave action and facilitate the trapping of sediment, so filling up the cells created by the baffles. Eventually the terraces themselves develop into marshes similar to those created by the use of dredged materials.

A further method of wetland creation which has been developed and extensively adopted in northern Europe is the so-called Schleswig-Holstein method using brushwood groynes to reduce wave action and to trap sediment (Kamps, 1962). The whole system of groynes forms an extensive sedimentation field. This method was used originally to create new areas for agriculture but it has subsequently been adopted and modified for the creation of marsh (Ford *et al.*, 1999). The use of fences to trap sediment can also be of benefit on a rather smaller scale. A sediment fence was used in the pioneer zone of marshes in a Venice lagoon; it significantly increased sediment accretion and appeared to improve the cover in the pioneer vegetation (Scarton *et al.*, 2000).

While the approaches to marsh development described have all previously involved either the creation of a marsh on an area at a suitable level in relation to the tide or building up an area to that level, it is also possible to re-create saltmarshes when the whole area has been industrially developed. The best example of what can be achieved here is at the site of the 2000 Olympic Games in Sydney. The Homebush Bay wetlands consisted of a mosaic of saltmarsh and mangroves on the Paramatta River but these had reduced in area by over 50% during the last 60 years. The sites had been occupied by a variety of developments including an abattoir and a waste dump. A programme of rehabilitation is now under way which includes cutting a new canal to restore tidal flooding (Burchett *et al.*, 1998). The programme involves not only this remedial work but also the creation *de novo* of wetlands where they had been entirely obliterated over 50 years by the dumping of waste and of dredged material.

Enhancement of natural marsh development

The possible use of thin layers of sediment to enhance natural marsh development has already been referred to. In sites where managed realignment is not an option (*e.g.* the Lymington/Keyhaven marshes, Hampshire) there may well be the possibility of taking measures to introduce artificial wave breaks to protect the vulnerable edges of the marshes. It may prove feasible to place dredged material immediately in front of the marsh, thus minimising wave action. It may also be possible to increase the vigour of the growth of saltmarsh plants by improving creek systems and thereby the soil drainage (Johnson, 2000). While these measures may tip the balance overall in favour of accretion rather than erosion it is very likely that such benefits will only be short-term and thought should be given to finding solutions which are sustainable in the long term, even when this may involve more expensive and more radical solutions. This is not to say that short-term solutions cannot be of considerable importance locally.

Successional processes in created marshes

Theoretically, once the pioneer communities have been re-established it might be expected that the saltmarsh would follow the normal processes and reflect the selected reference sites. In the US mitigation agreements involving millions of dollars have been based on the assumption that damage to habitats will be compensated for fully over a period of 5–10 years (Zedler and Callaway, 1999). Monitoring at a 12-year-old marsh creation site has shown that this is not the case and that the targets set are unlikely to be achieved in the near future. It is suggested that functional maturity often takes much longer to achieve than the restoration of the plant communities themselves. The authors further suggest that some of the predictions of the time needed are inaccurate as they are be based on research involving short-term data from pulse-driven ecosystems. It is necessary to recognise that functional equality may rarely be achievable and that the mitigation value of a replacement habitat may be less than previously thought. This needs to be considered when saltmarsh creation is suggested to compensate for habitat loss.

Management of created marsh

The management of the created marsh will clearly need to be related to the standard management procedures for the type of habitats which were created originally and for those which may be expected to develop in the future. There is also the need to ensure that any undesired changes are detected at the earliest opportunity and appropriate measures taken wherever necessary. The setting of clear management targets is particularly important and it is important that both short-term and long-term targets be set. While it is probable that the long-term targets are the most important, well-chosen short-term targets can provide evidence about the extent to which management is likely to succeed in relation to the critical long-term targets. The comments made earlier about the importance of the regular updating of saltmarsh management plans apply even more to created marshes, which hopefully will be subject to changing conditions and management requirements on the path to the desired end objectives.

The restoration of biodiversity is particularly important in habitat creation as developing communities may appear to be developing on satisfactory lines yet some of the characteristic species may still be poorly represented or completely lacking. Targeted species management programmes may have to be set up to ensure the optimum restoration of biodiversity.

10. Gaps and requirements for further research

10.1 Meeting threats to saltmarsh survival

Assessment of low-level pollutant damage

A range of studies has shown that a number of pollutants occur in saltmarsh sediments. These include agricultural and industrial chemicals which at high levels are known to affect a range of biota both plants and animals. Toxicological studies have generally concentrated on the study of effects of these chemicals at levels at which they kill the target organisms or at levels at which they have significant acute toxic effects on non-target organisms. Much less information is available on possible long-term low-level effects on saltmarsh plants and animals or on the fact that some chemicals can affect a wider range of organisms than indicated in the scientific literature. For example, there have been extensive studies into the effects of TBT on oysters and other invertebrates but little attention has been paid to the observation that it can also inhibit the growth of some saltmarsh plants. Herbicide residues can be found in some saltmarsh soils but virtually no information exists on the effect of low levels of these chemicals in the long term.

A review of pollutants occurring at low levels in the saltmarsh environment and experimental work conducted into possible effects on saltmarsh biota at these levels would address the questions raised above.

Quantification of impact of sea level rise

The possible effects of sea level rise have been interpreted in terms of the effects a given rise is likely to have on the saltmarsh zonation and the plant communities growing at the different levels. These predictions need to be quantified and refined both from the angle of providing better information on the zonation of species and communities and on the interpretation of likely rates of erosional changes in the marshes. Information is also needed on likely rates of change in sea level and on the ability of saltmarsh vegetation and geomorphological processes to adapt to these rates of change.

The development of a predictive model to interpret the effect of different rates of change in sea level on specific saltmarsh systems and marsh morphology and the ability of individual components of the saltmarsh vegetation to respond would be a useful tool for quantifying the impacts of sea level rise.

10.2 Maintaining saltmarsh structure and function

Impact of sea level rise on marsh function

There has been quite a volume of work recently on various aspects of saltmarsh function, including both internal marsh fluxes of organic matter, sediment and nutrients and the fluxes of these material between the saltmarsh and adjacent communities and ecosystems. Some work has been done to investigate the effects of environmental factors on these marsh functions but at present there is little specific information on the likely overall effects of sea level rise on saltmarsh function and on ecosystem interactions.

A desk study into possible effects of sea level rise on the functional relationships of saltmarsh and adjoining communities could assist understanding on this topic and would define the specific research needed to acquire the information for the development of a predictive model.

Classification of saltmarsh vegetation

The NVC provides a sound overarching system for the classification of British saltmarsh vegetation, although further work is required on certain types which have not been adequately described (see Rodwell *et al.*, 2000). In some instances the system lacks the detailed sub-classifications needed for fully effective monitoring and management of saltmarsh vegetation, although such distinctions may not always be appropriate for a national classification such as this. There also needs to be some further work to determine whether the NVC provides adequate coverage of the vegetation of Scottish saltmarshes.

A re-examination of the NVC saltmarsh classification would be beneficial, with emphasis on the development and refinement of the sub-units, particularly of the commoner vegetation communities. Further NVC surveys of the saltmarshes of Scotland and Northern Ireland, and a review of the NVC classification of saltmarsh communities, would be helpful to this subject.

Regeneration of vegetation structure

Various authors have referred to the importance of the maintenance of the saltmarsh vegetation structure, and thus the regeneration of vegetation structure is important both in degraded and newly created marshes. The architecture of saltmarsh vegetation will affect plant species diversity through its effect on regeneration niches. It will also affect fluxes of organic matter and sediment in and out of the saltmarsh and the utilisation of the marsh by different bird and animal species.

A desk study to define more fully the nature of the problem and the research that is needed would be beneficial.

10.3 Saltmarsh Creation and Management

Soil treatments to improve plant establishment

The provision of a suitable environment for the germination and establishment of saltmarsh plants is the key to successful saltmarsh creation. Both the substrate and the level at which it is located determine the establishment of vegetation. Any hindrance to the rapid establishment of vegetation cover greatly increases the risk of serious erosion. Central to this is a better understanding of the interactions involved in the processes whereby non-saline arable soils change to biologically active saltmarsh substrates and the impact of changing soil conditions on the germination and establishment of saltmarsh plant species.

Research to consider the definition of the optimum soil state for germination and establishment, the determination of the implications of differing tidal regimes and the quantification of the impact of different sedimentation rates could help improve plant establishment rates.

The influence of buried soil horizons on saltmarsh development

Following managed retreat and saltmarsh creation, the old agricultural soil often remains as a dense, hard layer on top of which new sediment accumulates. This layer almost certainly hinders the drainage and hence slows the rate at which the overlying sediment dries out. It is more dense and less permeable than the natural saltmarsh sediment. Also it is stronger than the natural sediment and this will affect the way creeks develop in it. At North Fambridge, some of the creeks have firm wide bases where the old agricultural soil forms the creek bed. The nature of any buried soil horizons could have significant implications for saltmarsh creation.

Research into the physical and biological effects of buried old soil horizons and their possible influences on saltmarsh development could be of assistance.

Accelerated succession

It has been noted that even at high levels in relation to the tide the course of plant colonisation usually follows the normal primary saltmarsh succession. In created saltmarshes the development of the full range of saltmarsh plant communities is no longer dependent on the time required for sediment accretion to build the marsh up to the appropriate level for that community, but general successional changes are slow. Given that the target is the regeneration of a full range of plant and animal communities, management techniques which could accelerate this process would be particularly helpful.

A comparative assessment could be made, by examining the scientific literature and existing saltmarsh creation schemes, of the rates of succession in natural and created saltmarshes. From this suggestions could be made for innovative ways in which saltmarsh succession might be accelerated and specific experimental trials initiated.

Site drainage and creek establishment

Various references have been made to the importance of drainage in saltmarsh creation and of the role of the creek system in the restoration of full saltmarsh function, including its ability to absorb wave energy during storms. A number of suggestions have already been put forward as to how this could best be achieved, but as yet there have been no trials on any of the methods. The possibilities vary from incising a rudimentary creek system right through to the excavation of a creek system, modelled by computer, at some later stage in the saltmarsh creation process.

An investigation into possible ways of enhancing side drainage and the development of an efficient creek system would help address these issues. Desk studies could be followed by a trial of promising methods in conjunction with current and future marsh creation schemes.

Resolution of conflicts in saltmarsh creation

While the technology and practice of saltmarsh creation is developing well, relatively little attention has been paid to the resolution of some of the conflicts. There needs to be a broad assessment of the nature and extent of these conflicts which include hostility to change, suspicion regarding wider environmental consequences and doubts about the chances of success. Public attitudes, both in areas where saltmarsh creation has already taken place, and in other places where the possibilities have not even been considered, need to be taken into consideration as well as those of parties directly affected.

A field survey involving both ecologists and sociologists, and a parallel desk study to identify key problems and to suggest how conflicting interests could be reconciled, would be appropriate to address this issue.

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12. Appendices

Appendix 1. Summary list of saltmarsh plant communities according to the NVC (from Rodwell, 2000, pp. 499–500)

SALTMARSH AND SEA-CLIFF VEGETATION

SPARTINETEA MARITIMAE R. Tx. In Beeftink 1962
Pioneer vegetation of perennial cord-grasses on intertidal mud and sand

SPARTINETALIA MARITIMAE Conrad 1935

Spartinion maritimae Conrad 1952
SM4 *Spartina martima* saltmarsh community
Spartinetum maritimae (Emb. Et Regn. 1926)
Corillion 1953
SM5 *Spartina alterniflora* saltmarsh community
Spartinetum alterniflorae Corillion 1953
SM6 *Spartina anglica* saltmarsh community
Spartinetum anglicae Corillion 1953 corr.
Géhu et Géhu-Franck 1984

THERO-SALICORNIETEA (Pignatti 1953) R. Tx. in R. Tx. et Oberdorfer 1958
Pioneer communities of annual glassworts, seablite or other halo-nitrophiles on tidal mudflats

THERO-SALICORNIETALIA Pignatti 1953 em. R. Tx. 1954 ex T. Tx et Oberdorfer 1958
Pioneer communities of annual glassworts and seablite on tidal mudflats

Thero-Salicornion stricta Br.-Bl. 1933 em. T. Tx. 1950 in Tx. et Oberdorfer 1958
SM7 *Arthrocnemum perenne* saltmarsh community
SM8 Annual *Salicornia* saltmarsh community *Salicornietum europaeae*
Warming 1906
SM9 *Suaeda maritima* saltmarsh community *Suaedetum maritimae*
(Conrad 1935) Pignatti 1953

JUNCETEA MARITIMI R. Tx. et Oberdorfer 1958
Usually closed swards on the silt and sand of coastal and inland saltmarshes and on sea cliffs

GLAUCO-PUCCINELLIETALIA Beeftink et Westholff 1962

Puccinellion maritimae Christiansen 1927 em. Tx. 1937
Communities of the lower pats of saltmarshes, generally inundated by spring tides
SM10 Transitional low-marsh vegetation
SM11 *Aster tripolium* var. *discoideus* saltmarsh community
SM12 Rayed *Aster tripolium* stands
SM13 *Puccinellia maritima* saltmarsh community *Puccinellietum maritimae*
(Warming 1906) Christiansen 1927

Puccinellio maritimae-Spergularion salinae Beeftink 1965
Ephemeral communities in saline habitats, coastal and inland, with disturbance or moisture regime

SM23 *Spergularia marina-Puccinellia distans* saltmarsh community
Puccinellietum distantis Feekes (1934) 1945

Armerion maritimae Br.-B1 et De Leeuw 1936
Perennial communities of the upper parts of saltmarshes, rarely inundated by spring tides

SM14 *Halimione portulacoides* saltmarsh community
Halimionetum portulacoidis (Kuhnholtz-Lordat 1927) Des Abbayes et Corillion 1949
SM16 *Festuca rubra* saltmarsh community
Juncetum gerardii Warming 1906
SM17 *Artemisia maritima* saltmarsh community
Artemisietum maritimae Hocquette 1927
SM18 *Juncus maritimus* saltmarsh community
SM19 *Blysmus rufus* saltmarsh community
Blysmetum rufi (G.E. et G. Du Rietz 1925) Gillner 1960
SM20 *Eleocharis uniglumis* saltmarsh community
Eleocharitetum uniglumis Nordhagen 1923
SM21 *Suaeda vera-Limonium binervosum* saltmarsh community
SM22 *Halimione portulacoides –Frankenia laevis* saltmarsh community
Limonio vulgaris-Frankenietum laevis Géhu et Géhu-Franck 1975
SM25 *Suaeda vera* saltmarsh community
Elmyo pycnanthi-Suaedetum verae (Arénes 1933) Géhu 1975
SM26 *Inula crithmoides* stands

Halo-Scirpion (Dahl et Hada 1971) Den Held et Westhoff 1969 nom. Nov.
Vegetation of flushed depression in upper saltmarsh

SM15 *Juncus maritimus-Triglochin maritima* saltmarsh community

Silenion maritimae Malloch 1971
Closed swards of perennial on sea-cliff tops and ledges little splashed by salt-spray

MC2 *Armeria maritima-Ligusticum scoticum* maritime crevice community
MC3 *Rhodioloa rosea-Armeria maritima* maritime cliff-ledge community
MC8 *Festuca rubra-Armeria maritima* maritime grassland
MC9 *Festuca rubra-Holcus lanatus* maritime grassland
MC10 *Festuca rubra-Plantago* spp. maritime grassland
MC11 *Festuca rubra-Daucus carota* ssp. *Gummifer* maritime grassland
MC12 *Festuca rubra-Hyacinthoides non-scripta* maritime cliff community

SAGINETEA MARITIMAE Westhoff, van Leeuwen et Adriani 1962
Ephemeral vegetation with winter annuals on bare or disturbed saltmarsh muds and sand, periodically wettened by saline waters

SIGINETALIA MARITIMAE Westhoff, van Leeuwen et Adriani 1962
Atlantic and Mediterranean ephemeral vegetation in saline habitats

Sagionion maritimae Westhoff, van Leeuwen et Adriani 1962

SM27 Ephemeral saltmarsh vegetation with *Sagina maritima*

CRITHMO-LIMONIETEA Br.-Bl. In Br.-Bl. Et al. 1952
Open communities of crevices on rocky sea-cliffs much splashed by salt spray

CRITHMO-ARMERIETALIA MARITIMAE Géhu 1968

MC1 *Crithmum maritimum-Spergularia rupicola* maritime crevice community
MC4 *Brassica oleracea* maritime cliff-ledge community

Appendix 2. List of saltmarsh sites in the UK with their areas (from Burd, 1989, Appendix 8.7)

Site Name	County	Area (ha)
The Wash	Lincolnshire	3384.8
Burry Inlet	Llanelli and W. Glamorgan	2121.26
River Ribble	Lancashire	1912.0
Moricambe Bay	Cumbria	1190.16
Blackwater	Essex	1102.85
Wells to Blakeney	Norfolk	1051.67
Dee Estuary	Cheshire	1026.1
Dee Estuary	Clwyd	871.18
Hamford Water	Essex	863.27
Carnforth	Lancashire	852.75
Mersey Estuary	Cheshire	838.31
The Wash	Norfolk	776.8
North Lincolnshire Coast	Lincolnshire	771.35
Medway	Kent	754.46
Chichester Harbour	Sussex	709.93
Poole Harbour	Dorset	696.93
Holme to Gun Hill	Norfolk	687.16
River Lune	Lancashire	676.85
Colne	Essex	670.56
River Leven	Cumbria	592.23
Roach & Foulness	Essex	590.52
Rockcliffe Marsh	Cumbria	564.72
Caerlaverock (Solway)	Nithsdale	563.4
Wigtown Bay (Solway)	Wigtown	553.28
Burgh Marsh	Cumbria	524.01
Tywyn Gwendraeth	Llanelli and W. Glamorgan	513.8
Keyhaven – Lymington	Hampshire	505.9
Duddon Sands	Cumbria	488.22
Bridgwater Bay	Somerset	485.06
Humber Estuary – North Shore	Humberside	467.66
River Deben	Suffolk	461.3
Afon Dyfi	Ceredigion	430.89
Swale	Kent	413.82
Dengie	Essex	404.84
Thames North	Essex	376.91
Chichester Harbour	Hampshire	366.9
Morfa Harlech and Traeth Bach	East Gwynedd	347.04
Tay Estuary (North Shore)	Perth and Kinross	326.47
Cockerham and Pilling	Lancashire	303.23
River Wyre	Lancashire	293.63
Crouch	Essex	292.38
River Ribble	Merseyside	272.0
South Walney	Cumbria	241.46
Taw and Torridge Estuary	Devon	239.0
Afon Taf	Carmarthan	238.23
River Kent	Cumbria	231.53
Hythe – Calshot	Hampshire	225.1
Scolt Head Island	Norfolk	224.86
Afon Mawddach	East Gwynedd	219.0
Dee Estuary	Wirral	210.71
Kirkconnell Merse (Solway)	Nithsdale	205.28
Morrich More (Dornoch Firth)	Ross and Cromarty	200.5
River Beaulieu	Hampshire	184.56
Portsmouth Harbour	Hampshire	181.2
Humber Estuary – South Shore	Humberside	180.2
Bridgemarsh Island	Essex	175.9

Lindisfarne Mainland	Northumberland	175.71
Lynher Estuary	Cornwall	175.26
Blakeney Point	Norfolk	162.96
River Alde	Suffolk	162.8
Stour South	Essex	159.73
Crymlyn Burrows and Neath Estuary	Llanelli and W. Glamorgan	159.01
Ravenglass	Cumbria	158.0
Afon Tywi	Carmarthen	146.73
Priestside Bank (Solway)	Nithsdale	145.52
Culbin	Nairn	142.72
Stour North	Suffolk	136.84
River Ore	Suffolk	129.7
Butley River	Suffolk	124.0
Foryd Bay	West Gwynedd	123.0
Carew and Cresswell	Preseli and S. Pembroke	122.02
Newtown Harbour	Isle of Wight	120.0
River Orwell	Suffolk	118.79
Findhorn Bay	Moray	118.05
Orfordness	Suffolk	116.5
Afon Dyfi	East Gwynedd	115.97
Lydney to Sedbury	Gloucestershire	112.91
Tyninghame Shore	East Lothian	112.1
Malltraeth Sands	West Gwynedd	110.76
Afon Conwy	East Gwynedd	105.25
Langstone Harbour	Hampshire	100.2
Tong/Melbost Sands (Lewis)	Western Isles	96.0
Fal Estuary Complex	Cornwall	93.45
Slimbridge	Gloucestershire	91.8
River Hamble	Hampshire	88.73
Tay Estuary (South Shore)	North East Fife	86.76
Nigg Bay (Cromarty Firth)	Ross and Cromarty	84.25
Grangemouth to Alloa	Falkirk	83.12
Uskmouth	Gwent	82.09
Skibo (Dornoch Firth)	Sutherland	80.0
Caldicot to Magor	Gwent	78.75
Auchencairn, Orchardton (Solway)	Stewartry	78.32
Thames South	Kent	77.67
Aberlady Bay	East Lothian	77.08
Northwick	Avon	76.83
Beauly Firth	Inverness	75.5
Loch Carron (L. Carron)	Ross and Cromarty	73.32
Tamar Estuary	Cornwall	71.02
Gibraltar Point	Lincolnshire	66.64
Exe Estuary	Devon	66.52
Traeth Melynog	West Gwynedd	66.48
Yar Estuary	Isle of Wight	66.42
Pembrey Burrows	Llanelli and W. Glamorgan	66.23
Tamar Estuary	Devon	64.74
Beddmanarch to Cymyran	West Gwynedd	62.97
Greenmerse & Kelton (Solway)	Nithsdale	62.0
River Stour	Kent	62.0
Eastern Cleddau	Preseli and S. Pembroke	61.77
Carnforth	Cumbria	61.55
Rampside	Cumbria	60.49
Culbin	Moray	60.28
Western Cleddau	Preseli and S. Pembroke	60.25
Loch Beg (Mull)	Argyll and Bute	60.0
Montrose Basin	Angus	58.011
Rough Firth (Solway)	Stewartry	56.96
Southwick (Solway)	Nithsdale	56.12
Rye Harbour	Sussex	54.4

Morfa Dyffryn	East Gwynedd	53.74
Peterstone Great Wharf	Gwent	52.46
Chesil and the Fleet	Dorset	51.46
Gruinart (Islay)	Argyll and Bute	50.56
Dornoch Point (Dornoch Firth)	Sutherland	50.5
River Dee (Solway)	Stewartry	50.08
Christchurch Harbour	Dorset	49.8
Camel Estuary	Cornwall	49.47
Annan (Solway)	Annandale and Eskdale	49.4
North Walney	Cumbria	48.75
Tay Estuary (North Shore)	Dundee	47.65
Crinan (Jura Sound)	Argyll and Bute	47.28
Afon Teifi	Ceredigion	45.44
Whiteness Head	Nairn	44.8
Littleton	Avon	44.21
River Clyde, W. (Firth of Clyde)	Dumbarton	44.08
Dornoch Firth – South (Dornoch Firth)	Ross and Cromarty	43.79
Thornwell to Portskewett	Gwent	42.62
River Clwyd	Clwyd	42.52
Eling and Bury Marshes	Hampshire	41.16
Bridgend (Islay)	Argull and Bute	40.4
Northton (S. Harris)	Western Isles	39.5
Traigh Eachkamish (Baleshare)	Western Isles	37.5
Pembroke River	Preseli and S. Pembroke	37.49
Pegwell Bay	Kent	37.2
Conon Islands (Cromarty Firth)	Ross and Cromarty	36.77
Illeray (Baleshare)	Western Isles	35.75
River Tavy	Devon	35.0
Carse Bay (Solway)	Nithsdale	34.72
Clevedon	Avon	34.67
Chittening	Avon	34.33
Axe Estuary	Devon	34.25
Cowpen Marsh	Cleveland	34.16
Pagham Harbour	Sussex	33.3
Dingwall Bay (Cromarty Firth)	Ross and Cromarty	33.08
Holy Island	Northumberland	33.03
Tay Estuary (South Shore)	Perth and Kinross	32.72
Eden Estuary	North East Fife	31.91
Lodmoor	Dorset	31.56
Crabhall Saltings	Preseli and S. Pembroke	31.49
Traeth Coch	West Gwynedd	31.25
Inverscaddle Bay (L. Linnhe)	Lochaber	30.85
Beauly Firth	Ross and Cromarty	30.5
Irvine (Ayr)	Kyle and Carrick	30.04
Alness – Dalmore (Cromarty Firth)	Ross and Cromarty	30.04
Gretna – Redkirk (Solway)	Annandale and Eskdale	30.0
Balconie Point (Cromarty Firth)	Ross and Cromarty	30.0
Nonach (L. Alsh)	Skye and Lochalsh	29.84
Portbury Wharf	Avon	29.7
Cardiff	Mid and South Glamorgan	29.44
Daugleddau	Preseli and S. Pembroke	29.26
Havergate Island	Suffolk	29.2
Loch Paible (N. Uist)	Western Isles	29.0
Fleet Bay (Solway)	Stewartry	28.12
Shepperdine	Avon	27.84
Lamby	Mid and South Glamorgan	27.81
Ringdoo Sands (Solway)	Wigtown	27.2
Manxman's Lake (Solway)	Stewartry	26.68
Back Saltings (Lewis)	Western Isles	25.75
River Avon	Devon	25.53
Rumney Great Wharf	Mid and South Glamorgan	25.22

Dart Estuary	Devon	25.0
Torridon (Upper L. Torridon)	Ross and Cromarty	24.68
Camusrory (L. Nevis)	Lochaber	24.0
Alnmouth	Northumberland	23.78
An Seilean (Lorn)	Argyll and Bute	23.63
Berkeley	Gloucestershire	22.94
East Seilebost (S. Harris)	Western Isles	22.52
Broadwater	East Gwynedd	22.49
Spey Bay	Moray	22.2
Head of Loch Creran (Lorn)	Argyll and Bute	21.4
Traeth Dulas	West Gwynedd	21.23
Erme Estuary	Devon	20.75
The Gannel	Cornwall	20.25
Loch Caolisport (Jura Sound)	Argyll and Bute	20.24
Loch Feochan (Lorn)	Argyll and Bute	20.12
Cosheston Pill	Preseli and S. Pembroke	20.02
Otter Estuary	Devon	19.25
Croe Bridge (L. Duich)	Skye and Lochalsh	19.16
Hayle Estuary	Cornwall	19.0
Sand Bay	Avon	18.87
River Clyde, E. (Firth of Clyde)	Dumbarton	18.48
Munlochy Bay (Moray Firth)	Ross and Cromarty	18.2
Woodspring Bay	Avon	17.89
Kinlochmoidart (Moidart)	Lochaber	17.4
Barrisdale Bay (L. Hourn)	Skye and Lochalsh	17.28
Little Loch Broom	Ross and Cromarty	16.96
Dornock (Solway)	Annandale and Eskdale	16.72
Browhouses (Solway)	Annandale and Eskdale	16.4
Holy Loch (Firth of Clyde)	Argyll and Bute	16.32
Loch Harport (L. Bracadale)	Skye and Lochalsh	16.17
Loch Don Saltmarsh (Mull)	Argyll and Bute	16.12
Strathbeg	Banff and Buchan	15.91
Oxwich	Llanelli and W. Glamorgan	15.51
River Ogmore	Mid and South Glamorgan	15.25
E. Kentra Bay (Moidart)	Lochaber	15.24
Kishorn (L. Kishorn)	Ross and Cromarty	15.2
Caol Spit (L. Linnhe)	Lochaber	15.13
Loch Laich (Lorn)	Argyll and Bute	15.12
Knock-Cuien (N. Uist)	Western Isles	14.75
Balblair (L. Fleet)	Sutherland	14.72
Warkworth	Northumberland	14.54
Sandy Haven Pill	Preseli and S. Pembroke	14.5
Kilchoan (L. Sunart)	Lochaber	14.28
Sleek of Tarty	Gordon	14.02
S. Kentra Bay (Moidart)	Lochaber	13.89
King’s Quay	Isle of Wight	13.8
St John’s Lake	Cornwall	13.6
Medina Estuary	Isle of Wight	13.56
Nairn E.	Nairn	13.5
Achnahaird Bay (Rubha Coigeach)	Ross and Cromarty	13.48
Milnfield Merse (Solway)	Annandale and Eskdale	13.28
Udale Bay (Cromarty Firth)	Ross and Cromarty	13.02
Teign Estuary	Devon	13.0
Awre to Purton	Gloucestershire	12.56
Loch Sligachan (Sligachan-Broadford)	Skye and Lochalsh	12.4
Lag Gorm (Baleshare)	Western Isles	12.0
Vallay (Vallay)	Western Isles	11.75
Brean Down and Uphill Cliff	Somerset	11.7
Loch Sunart Head (L. Sunart)	Lochaber	11.64
N. Kentra Bay (Moidart)	Lochaber	11.61
Nith (Solway)	Nithsdale	11.52

Pool Roag (L. Bracadale)	Skye and Lochalsh	11.49
Glenmore (L. Sunart)	Lochaber	11.05
Inveran – Carbisdale (Dornoch Firth)	Sutherland	11.0
Tywyn Gwendraeth	Carmarthen	10.93
Wick River	Caithness	10.92
Rumney Great Wharf	Gwent	10.87
Bonar Bridge (Dornoch Firth)	Sutherland	10.8
Kirkton (L. Alsh)	Skye and Lochalsh	10.4
Kinlocheil (L. Linnhe)	Lochaber	10.21
Newport Saltings	Preseli and S. Pembroke	10.19
Glencoe (L. Linnhe)	Lochaber	10.12
Mersey Estuary	Merseyside	10.08
Balgarva (S. Uist)	Western Isles	10.0
Loch Slapin (Eishort/Slapin)	Skye and Lochalsh	9.8
West Seilebost (S. Harris)	Western Isles	9.75
Eilean Cuithe Nam Faidh (S. Uist)	Western Isles	9.75
River Cuckmere	Sussex	9.65
River Adur	Sussex	9.65
Oldbury	Avon	9.49
Loch Stornoway (Jura Sound)	Argyll and Bute	9.4
Gramsdale/Uachdar (Benbecula)	Western Isles	9.25
Dunstaffnage (Lorn)	Argyll and Bute	9.16
Glenelg (Glenelg)	Skye and Lochalsh	9.08
Loch Broom (L. Broom)	Ross and Cromarty	9.04
Long Nanny	Northumberland	9.0
Waulkmill Bay (Mainland)	Orkney	9.0
Budle Bay	Northumberland	9.0
Lochailort	Lochaber	8.92
Glen Luce (Solway)	Wigtown	8.88
Afon Dyfi	Montgomery	8.87
Beachley	Gloucestershire	8.86
Cocklemill Bay	North East Fife	8.82
Traeth Lafan	West Gwynedd	8.67
Uphill	Avon	8.66
Loch Fyne (L. Fyne)	Argyll and Bute	8.44
River of Wester	Caithness	8.25
East Aberthaw	Mid and South Glamorgan	8.12
Castle Stuart Bay	Inverness	8.0
Liniclate (Benbecula)	Western Isles	8.0
Loch Ainort (Sligachan-Broadford)	Skye and Lochalsh	7.82
Kyle of Tongue (Kyle of Tongue)	Sutherland	7.64
Shiel Bridge (L. Duich)	Skye and Lochalsh	7.58
Loch A'Choire (L. Linnhe)	Lochaber	7.57
Loch na Dal (Sleat)	Skye and Lochalsh	7.4
Loch Melfort (Jura Sound)	Argyll and Bute	7.36
Portishead	Avon	7.31
Cata Sand (Sanday)	Orkney	7.3
Kinlochteacuis (L. Sunart)	Lochaber	7.29
Carinish (N. Uist)	Western Isles	7.28
Skelbo (L. Fleet)	Sutherland	7.25
Borgie Mouth (Torrisdale Bay)	Sutherland	7.25
Sands of Forvie and Foveran Burn	Gordon	7.25
Auchalick Bay (L. Fyne)	Argyll and Bute	7.25
Loch Portree (Portree)	Skye and Lochalsh	7.21
Tayport	North East Fife	7.0
Islay Saltmarshes (Islay)	Argyll and Bute	6.96
Cambusmore (L. Fleet)	Sutherland	6.92
Benbecula Aerodome (Benbecula)	Western Isles	6.75
The Strand (Colonsay)	Argyll and Bute	6.68
Kinlochhourn (L. Hourn)	Lochaber	6.68
Ruel Estuary (Firth of Clyde)	Argyll and Bute	6.64

Loch Striven (Firth of Clyde)	Argyll and Bute	6.6
Torduff Point (Solway)	Annandale and Eskdale	6.59
Linne Mhuirich (Jura Sound)	Argyll and Bute	6.52
Stakeness	Banff and Buchan	6.51
Garvan (L. Linnhe)	Lochaber	6.47
Finiskaig (L. Nevis)	Lochaber	6.45
Little Sea (Sanday)	Orkney	6.4
Hinton	Gloucestershire	6.39
Loch Eyre (L. Snizort)	Skye and Lochalsh	6.38
Inverie Bay (L. Nevis)	Lochaber	6.36
Clett-Feora (N. Uist)	Western Isles	6.25
Loch Eynort	Skye and Lochalsh	6.21
Rubha Ardnish (Sligachan-Broadford)	Skye and Lochalsh	6.15
Traeth Lafan	East Gwynedd	6.09
The Mound (L. Fleet)	Sutherland	6.04
Langass (N. Uist)	Western Isles	6.0
Grenitote (N. Uist)	Western Isles	6.0
Eilean Uaine (Moidart)	Lochaber	6.0
East and West Looe Rivers	Cornwall	5.99
Black Devon/Clackmannan Pow	Clackmannan	5.99
Gualan (S. Uist)	Western Isles	5.75
Bayhead (N. Uist)	Western Isles	5.75
Kyle of Durness	Sutherland	5.68
Castletown Marshes	Tyne and Wear	5.55
Inversanda (L. Linnhe)	Lochaber	5.52
Seannabhaile/Gearradubh (Grimsay)	Western Isles	5.5
Slumbay (L. Carron)	Ross and Cromarty	5.48
Ardura (Mull)	Argyll and Bute	5.36
Attadale (L. Carron)	Ross and Cromarty	5.16
Traigh Bad na Baighe (L. Laxford)	Sutherland	5.0
Bridge of Waithe & Cumminess (Mainland)	Orkney	4.87
Kinlochleven (L. Linnhe)	Lochaber	4.74
Opinan	Ross and Cromarty	4.72
Ardmore Point (Firth of Clyde)	Dumbarton	4.56
Helford River	Cornwall	4.5
Kingsbridge Estuary	Devon	4.5
Torridon House (Upper L. Torridon)	Ross and Cromarty	4.44
Howbeg (S. Uist)	Western Isles	4.25
Eilean Dubh (L. Eriboll)	Sutherland	4.25
Kinnaber Links	Angus	4.23
Strathkanaird (L. Broom)	Ross and Cromarty	4.2
Whiteness Head	Inverness	4.2
Kyle (L. Alsh)	Skye and Lochalsh	4.18
Baltasound (Unst)	Shetland	4.1
Newton of Ardtoe (Moidart)	Lochaber	4.09
Bay of Suckquoy (Mainland)	Orkney	4.07
Avonmouth	Avon	4.05
Broadford Bay (Sligachan-Broadford)	Skye and Lochalsh	4.04
Coul Links (L. Fleet)	Sutherland	4.0
St Cyrus	Kincardine and Deeside	4.0
Ythan	Gordon	3.92
Lunan Burn	Angus	3.9
Seaton Sluice	Northumberland	3.9
Camas na Croise (L. Linnhe)	Lochaber	3.89
Ardelve (L. Alsh)	Skye and Lochalsh	3.87
Loch Dunvegan (L. Dunvegan)	Skye and Lochalsh	3.87
Kylesmorar (L. Nevis)	Lochaber	3.83
Milford Haven, Neyland, Westfield	Preseli and S. Pembroke	3.75
Kilninver (Lorn)	Argyll and Bute	3.68
Gleann Aoistail (Jura)	Argyll and Bute	3.6
Ardentiny (Lorn)	Argyll and Bute	3.6

Dalrannoch (Lorn)	Argyll and Bute	3.56
Invernaver (Torrisdale Bay)	Sutherland	3.5
Melvich	Sutherland	3.5
Loch Craignish (Jura Sound)	Argyll and Bute	3.44
Loch Beag (L. Bracadale)	Skye and Lochalsh	3.44
Quoys (Hoy)	Orkney	3.4
Willington Gut	Tyne and Wear	3.36
Pow Burn (Ayr)	Kyle and Carrick	3.36
Isleornsay (Sleat)	Skye and Lochalsh	3.29
Dervaig (Mull)	Argyll and Bute	3.28
Oyce of Quindry (S. Ronaldsay)	Orkney	3.2
Loch Greshornish (L. Snizort)	Skye and Lochalsh	3.09
Culross Shore	Dunfermline	3.04
Lama Ness Oyce (Sanday)	Orkney	3.0
Pwllheli	West Gwynedd	3.0
The Ouse, Veantrow Bay (Shapinsay)	Orkney	3.0
Loch Sheigra (L. Inchard)	Sutherland	3.0
Loch Gealavat, Callanish (Lewis)	Western Isles	3.0
Arisaig (S. Morar)	Lochaber	3.0
Menai Straits	West Gwynedd	2.98
Bunacaimb (S. Morar)	Lochaber	2.97
Loch Snizort Head (L. Snizort)	Skye and Lochalsh	2.84
Whitehouse Bay (Jura Sound)	Argyll and Bute	2.84
River Fowey	Cornwall	2.78
Lochan na Leobaig (Eddrachillis Bay)	Sutherland	2.76
Ardheisker/Horisary (N. Uist)	Western Isles	2.75
Swarsquoy (Mainland)	Orkney	2.73
Toscaig (Applecross)	Ross and Cromarty	2.72
Tain Golf Course (Dornoch Firth)	Ross and Cromarty	2.7
Loch Aline	Lochaber	2.68
Tor Ness & Quivals Creek (Sanday)	Orkney	2.65
Oyce of Isbister (Mainland)	Orkney	2.6
Lottle Ayre (Hoy)	Orkney	2.6
Rhosneigr	West Gwynedd	2.51
Creag Bheag (L. Fleet)	Sutherland	2.5
Martin’s Haven	Preseli and S. Pembroke	2.5
River Yealm Complex	Devon	2.46
Balure of Shian (Lorn)	Argyll and Bute	2.44
Kinkell Harbour to Craig Hartle	North East Fife	2.4
Mill Sand (Mainland)	Orkney	2.36
Strontian (L. Sunart)	Lochaber	2.34
Reiff (Rubha Coigeach)	Ross and Cromarty	2.32
Mill Bay (Hoy)	Orkney	2.3
Arlingham	Gloucestershire	2.29
Ullapool (L. Broom)	Ross and Cromarty	2.28
Cuil Bay (L. Linnhe)	Lochaber	2.26
Angle Bay	Preseli and S Pembroke	2.25
Loch Carloway (Lewis)	Western Isles	2.25
Nostie (L. Aish)	Skye and Lochalsh	2.21
Kennetpans	Clackmannan	2
Brodick Bay	Cunninghome	2
Gartnagrenach Bay (Jura sound)	Argyll and Bute	2.15
Fassfern (L. Linnhe)	Lochaber	2.03
Lossiemouth	Moray	2.02
Rhiconich (L. Inchard)	Sutherland	2.0
Fraserburgh Bay	Banff and Buchan	2.0
Myre Bay (S. Walls, Hoy)	Orkney	2.0
Berrow Dunes	Somerset	1.98
Reraig Bay (L. Kishorn)	Ross and Cromarty	1.96
Camascross (Sleat)	Skye and Lochalsh	1.96
Uig (L. Snizort)	Skye and Lochalsh	1.95

Rubha Raonuill (L. Nevis)	Lochaber	1.92
Poolewe (L. Ewe)	Ross and Cromarty	1.92
The Ouse, Finstown (Mainland)	Orkney	1.91
Swanbister Bay (Mainland)	Orkney	1.81
Tokavaig (Eishort/Slapin)	Skye and Lochalsh	1.8
Torsa (Jura Sound)	Argyll and Bute	1.8
Sallachan Point (L. Linnhe)	Lochaber	1.78
The Ayre, North Bay (Hoy)	Orkney	1.75
Ceann nan Clachan (S. Vallay Strand)	Western Isles	1.75
Bun Nathrach (L. Linnhe)	Lochaber	1.73
Bay of Tuquoy (Westray)	Orkney	1.7
Saltness (Hoy)	Orkney	1.7
Loch na H'Airde	Skye and Lochalsh	1.68
Duirinish (L. Alsh)	Skye and Lochalsh	1.68
Garderhouse, Seli Voe (Mainland)	Shetland	1.68
Applecross Bay (Applecross)	Ross and Cromarty	1.6
Dales Voe, Delting (Mainland)	Shetland	1.59
Badachro (L. Gairloch)	Ross and Cromarty	1.56
Loch Treaslane (L. Snizort)	Sky and Lochalsh	1.54
Loch Scresort (Rhum)	Lochaber	1.53
Afon Ffraw	West Gwynedd	1.5
Ceann A'Baigh (S. Vallay Strand)	Western Isles	1.5
Barraglom (Lewis)	Western Isles	1.5
Morfa Harlech and Traeth Bach	West Gwynedd	1.42
Loch Creran (Lorn)	Argyll and Bute	1.36
Stronchreggan (L. Linnhe)	Lochaber	1.35
Wyng Strand (S. Walls, Hoy)	Orkney	1.35
Black Rock Marsh, Otters Wick (Sanday)	Orkney	1.3
Eilanreach (Glenelg)	Skye and Lochalsh	1.28
Loch Ardbhair (Eddrachillis Bay)	Sutherland	1.25
Afon Ystwyth and Rheidol	Ceredigion	1.25
Abersoch	West Gwynedd	1.24
Fernaig (L. Alsh)	Skye and Lochalsh	1.2
Balmacara (L. Alsh)	Skye and Lochalsh	1.2
Garliestone (Solway)	Wigtown	1.12
Uig Sands	Western Isles	1.0
Glenluig (Moidart)	Lochaber	1.09
Boddin Point to Scurdie Ness	Angus	1.053
Grange Burn	Falkirk	1.05
Loch Eishort (Eishort/Slapin)	Skye and Lochalsh	1.04
Loch Caroy (L. Bracadale)	Skye and Lochalsh	1.01
Vadill, Head of Whiteness Voe (Mainland)	Shetland	1.0
Sandi Sand (Mainland)	Orkney	1.0
Canna Harbour (Canna)	Lochaber	1.00
Loch Grimersta (Lewis)	Western Isles	1.0
Oyce of Rennibister (Mainland)	Orkney	1.0
Camas na Sgianadin (Sligachan-Broadford)	Skye and Lochalsh	0.98
Cleastrain Strand, Mootaig (Mainland)	Orkney	0.98
Loch Erghallan (L. Dunvegan)	Skye and Lochalsh	0.97
Three Mile Water (L. Linnhe)	Lochaber	0.95
Erbusaig (L. Alsh)	Skye and Lochalsh	0.91
Fishnish Bay (Mull)	Argyll and Bute	0.88
Dury Voe (Mainland)	Shetland	0.85
Buddon Burn	Angus	0.841
Kilmaronag Island (Lorn)	Argyll and Bute	0.84
Afon Teifi	Preseli and S. Pembroke	0.83
Mullock Bay (Solway)	Stewartry	0.81
Logie Head	Banff and Buchan	0.8
Gairloch Sands (L. Gairloch)	Ross and Cromarty	0.76
Plockton (L. Aish)	Skye and Lochalsh	0.76
Loch Nedd (Eddrachillis Bay)	Sutherland	0.75

Little Loch Roag (Lewis)	Western Isles	0.75
Ore Bay (Hoy)	Orkney	0.75
An Cruinn-Leum (L. Gairloch)	Ross and Cromarty	0.72
Shieldaig Lodge Hotel (L. Gairloch)	Ross and Cromarty	0.72
Deveron Mouth	Banff and Buchan	0.7
Ardvasar (Sleat)	Skye and Lochalsh	0.69
Culdie (Applecross)	Ross and Cromarty	0.68
Glencripesdale (L. Sunart)	Lochaber	0.66
Fife Ness	North East Fife	0.653
Portree (Portree)	Skye and Lochalsh	0.65
Lagg Bay (Jura)	Argyll and Bute	0.64
Lyrawa Bay (Hoy)	Orkney	0.63
Dales Voe, Lerwick (Mainland)	Shetland	0.58
Charleston (L. Gairloch)	Ross and Cromarty	0.56
Barns Ness Coast	East Lothian	0.55
Crail to Anstruther	North East Fife	0.533
Barry Burn	Angus	0.52
Don Mouth	Aberdeen	0.51
Tarbert Bay (Jura)	Argyll and Bute	0.5
Weaver’s Bay (L. Laxford)	Sutherland	0.5
Rhian Burn (Kyle of Tongue)	Sutherland	0.5
Loch Eriboll (L. Eriboll)	Sutherland	0.45
River Kerry (L. Gairloch)	Ross and Cromarty	0.44
Burravoe, Busta Voe (Mainland)	Shetland	0.4
Brae (Mainland)	Shetland	0.4
Aros (Mull)	Argyll and Bute	0.4
Trowie Loch, Garth (Mainland)	Shetland	0.4
River Avon	Falkirk	0.39
Housetter (Mainland)	Shetland	0.38
Effirth, Bixter Voe (Mainland)	Shetland	0.37
Gluss Voe (Mainland)	Shetland	0.37
Inverasdale (L. Ewe)	Ross and Cromarty	0.36
Boatsromm Voe, Lunna Ness (Mainland)	Shetland	0.35
East of Ness of Bixter (Mainland)	Shetland	0.35
Leon, Loch of Queyfirth (Mainland)	Shetland	0.33
Hamna Voe (Yell)	Shetland	0.33
East Head, Portsoy	Banff and Buchan	0.31
Haggrister (Mainland)	Shetland	0.31
Foula Wick, Olna Firth (Mainland)	Shetland	0.3
Rattray Bay	Banff and Buchan	0.3
Dalgety Bay	Kirkcaldy	0.263
Spinningdale (Dornoch Firth)	Sutherland	0.25
Afon Aeron	Ceredigion	0.25
Lunderton	Banff and Buchan	0.24
Pittullie (Rosehearty)	Banff and Buchan	0.21
Balmedie	Gordon	0.2
East Burrafirth, Aith Voe (Mainland)	Shetland	0.2
Main Ayre, Loch of Queyfirth (Mainland)	Shetland	0.2
Aultbea (L. Ewe)	Ross and Cromarty	0.2
Vidlin (Mainland)	Shetland	0.19
Laxo, Dury Voe (Mainland)	Shetland	0.19
Ose (L. Bracadale)	Skye and Lochalsh	0.17
South Voxter, Gon Firth (Mainland)	Shetland	0.17
Aith, Aith Voe (Mainland)	Shetland	0.15
Head of Weisdale Voe (Mainland)	Shetland	0.13
Bridge of Twatt, Bixter Voe (Mainland)	Shetland	0.13
Cullivoe (Yell)	Shetland	0.12
Houb, Sullom (Mainland)	Shetland	0.12
Houb, Fugla Ness (Mainland)	Shetland	0.11
Gutcher (Yell)	Shetland	0.11
Goldcliff	Gwent	0.1

Tresta (Mainland)	Shetland	0.1
Black Burn to Abercorn Burn	West Lothian	0.094
River Ugie	Banff and Buchan	0.08
Reed Point	Berwickshire	0.07
St Andrew's Harbour	North East Fife	0.07
Elie Ness	North East Fife	0.05
Forth Bridge	Edinburgh	0.032
Dunbar Gold Course	East Lothian	0.03
Balmerino Shore	North East Fife	0.025
Black Burn	West Lothian	0.02
Black Ness	Falkirk	0.012
Chapel Ness	North East Fife	0.011
Carlingheugh Bay & Meg's Craig	Angus	0.01

Appendix 3. Distribution of major saltmarsh sites and NVC classes of saltmarsh vegetation in Northern Ireland in decreasing order of site area (information from P. Corbett)

Name of Site	**County**	**Map Reference***	**Marsh Area (ha)**	**No. of NVC units**
Strangford Lough	Down	J355365	75	15**
Lough Foyle	Londonderry	C260439	62	9**
Larne Lough	Antrim	J346398	28	8**
Carlingford Lough	Down	J324314	26	13
Bann Estuary	Londonderry	C280435	24.1	9**
Outer Ards	Down	J364348	10	12
Murlough	Down	J342337	8.5	5
Ballycastle Coalfield	Antrim	D313441	1	–
Ballymacormick Point	Down	J354384	1	9
Carrickarade	Antrim	D306445	1	–
Giant's Causeway and Dunseverick	Antrim	C296445	1	5***
Outer Belfast Lough	Antrim/Down	J345385	1	–
Rathlin Island	Antrim	D315451	<1	–
Ballyquintin Point	Down	J363346	<1	7
Killard	Down	J363344	<1	7
Doagh	Londonderry	C270438	<1	1
Benone and Umbra	Londonderry	C237437	<1	1
Mourne Coast	Down	J337325	<1	4

Notes
* Based on the Irish National Grid.
** Includes the unassigned community where there has been extensive secondary colonisation by *Spergularia media*.
*** Includes a variant of SM16b (*Juncus gerardii* sub-community) with *Schoenus nigricans*.

Appendix 4. List of saltmarsh creation sites in the UK (from Atkinson *et al*., 2001)

Name	County	Habitat
Orplands	Essex	Saltmarsh
Tollesbury	Essex	Saltmarsh
Northey Island	Essex	Saltmarsh
Abbotts Hall	Essex	Saltmarsh
Havergate Island	Essex	Saltmarsh
Trimley	Essex	Saltmarsh/Mudflat
Horsey Island	Essex	Saltmarsh/Mudflat
Cobmarsh Island	Essex	Saltmarsh/Mudflat
Old Hall Point	Essex	Saltmarsh/Mudflat
Tollesbury Wick	Essex	Saltmarsh/Mudflat
Wallasea Island	Essex	Saltmarsh/Mudflat
Pewet Island	Essex	Saltmarsh/Mudflat
Blaxton Meadow, Saltram	Devon	Saltmarsh
Seal Sands	Teeside	Mudflat
Thornham Point	Hants	Saltmarsh
Chalkdock Point	Hants	Saltmarsh
Bleadon Marsh	Somerset	Saltmarsh