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MANAGED REALIGNMENT AT TOLLESBURY

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EXECUTIVE SUMMARY

This report presents the combined results of a continued programme of research into the ecology of the 'managed realignment' site at Tollesbury, Essex, on the east coast of the UK. The results should, therefore, be viewed in conjunction with those from the earlier work that was started in 1995 when the area was first exposed to inundation by sea-water. During 2005, the third year of a 5 year monitoring programme (2003-2008), research was completed on sedimentation rates and plant distributions within the realignment site and the adjacent salt marshes by specialists from the Centre for Ecology & Hydrology (CEH).

The results obtained during 2005 show that:

- Accretion on the Old Hall and Tollesbury salt marshes, adjacent to the Tollesbury managed realignment site, continued at a rate of 3-4mm/year thereby maintaining their position in the tidal frame.

- The overall accretion rate within the Tollesbury managed realignment site continued to slow down from a mean rate of 23.1mm/year between 1995 and 2001, to a mean rate of 10.7mm/year between 2002 and 2005.

- There continue to be changes in the frequency of plant species occurring within the Tollesburt managed realignment site, ten years after it was first re-exposed to tidal inundation, with common glasswort (*Salicornia europaea* agg.) expanding its range and dominating the vegetation.

- Common cord grass (*Spartina anglica*) increased in its frequency of occurrence, within the Tollesbury managed realignment site, from 35.9% in 2003 to 57.9% in 2005.

- Common salt marsh grass (*Puccinellia maritima*) continued to increase in frequency, within the Tollesbury managed realignment site, from 14.6% in 2003 to 20.5% in 2005, forming a narrow band along the base of the counter wall on the southern edge of the site.

- There was a 25% decline in the frequency of sea purslane (*Atriplex portulacoides*) between 1994 and 2005 on salt marshes adjacent to the Tollesbury managed realignment site.

GENERAL INTRODUCTION

As part of its Flood and Coastal Defence research programme, Defra, the Department for Environment, Food and Rural Affairs (formerly the Ministry of Agriculture, Fisheries and Food) commissioned a study of the managed realignment of sea defences at Tollesbury, Essex. This study was a full-scale experiment in which new sea defences, in the form of low embankments, were constructed behind the existing sea wall and surrounding approximately 21ha of low-lying agricultural land adjacent to Tollesbury Creek. Following the completion of the new sea defences, the existing sea wall was breached on 4 August 1995 and the enclosed area of agricultural land behind it exposed to tidal inundation for the first time in at least 150 years.

It was expected that exposure of the agricultural land to seawater would result in the accumulation of silt and, in the long-term, the establishment of its associated intertidal invertebrate fauna and salt marsh vegetation. This multidisciplinary project involved, initially, only studies of the vegetation and hydrology of the site. It was also realised that as the habitat within the study area changed from terrestrial to intertidal it would inevitably result in a change in the invertebrate fauna from one characteristic of agricultural and marginal biotopes to one characteristic of intertidal or salt marsh biotopes.

It was also crucially important to determine the effects on the adjacent creeks and salt marshes of setting back the sea defence. Therefore, detailed studies of those areas immediately adjacent to the breach were also undertaken.

This programme of research was initiated in 1995 and followed on from previous work at the site, by the Institute of Terrestrial Ecology (ITE*), which started in October 1993. The biological monitoring of both the realignment site and adjacent marshes was the responsibility of ITE, studies of changes in soil structure within the flooded area were done by the Silsoe Research Institute, and the hydrology of both the breach and adjacent creeks was undertaken by HR Wallingford Ltd.

In 1997, Defra authorised the continuation of the research for a further five years and also approved additional research on the role of invertebrates in the establishment of salt marsh plants. This work was the responsibility of the Queen Mary and Westfield College Department of Biological Sciences. At the same time, responsibility for the overall running and co-ordination of this multi-disciplinary research was given to ITE. The results of this 5 year multi-disciplinary research programme were reported to Defra in March 2002 (Reading *et al.*, 2002).

In 2003, Defra authorised a further 5 years (2003-2008) of continued, but reduced, monitoring at Tollesbury as it was recognised that changes in sediment accretion rates and the colonisation of the realignment area by salt marsh plants and inter-tidal invertebrates were still occurring, albeit at a much reduced rate than previously. Continued monitoring of the changes in soil structure was also authorised. CEH was given overall responsibility for the extended project and for monitoring sediment accretion (annually), botanical (years 1, 3 & 5) and invertebrate (years 2 & 5) aspects of the work whilst the Silsoe Research Institute was sub-contracted, by CEH, to do the soil monitoring (years 1 & 5).

* In 2000 the Institute of Terrestrial Ecology (ITE) became the Centre for Ecology and Hydrology (CEH).

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CHAPTER 1

BOTANICAL AND SEDIMENT MONITORING OF THE TOLLESBURY MANAGED REALIGNMENT SITE AND ADJACENT SALT MARSHES

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1 SUMMARY

This report presents the results of botanical and sedimentation monitoring at the Tollesbury realignment site and adjacent marshes for 2005. This monitoring forms part of a larger study investigating the changes in soil characteristics and ecology of the site, over time, from terrestrial farmland to intertidal salt marsh and mudflat.

The Old Hall and Tollesbury marshes adjacent to the realignment site continued to accrete vertically (3–4mm year^{-1}). These rates are typical for salt marshes in the Greater Thames area and the marshes appear to be well able to maintain their position in the tidal frame despite projected mean eustatic sea level rise.

There is continued evidence of a slow down in sedimentation rates within the managed realignment site. The mean rate of accretion from 1995 to 2001 was 23.1mm year^{-1} and from 2002 to 2005, 10.7mm year^{-1}. The reduced rate of accretion is thought to be a function of increasing elevation within the site over time and the subsequent reduction in inundation frequencies. However, other factors such as changes in sediment supply, tidal regime or compaction under increasing sediment load might also account for the differences.

Ten years after the site was first re-exposed to tidal inundation in 1995 there continue to be changes in species frequency. Common glasswort (*Salicornia europaea* agg.) continued to dominate the vegetation, expanding its range and colonising previously unvegetated areas of the site. Common cord grass (*Spartina anglica*) increased in frequency from a mean of 35.9% in 2003 to 57.9% in 2005. Although *S. anglica* could be found as individual plants on the mud flat, there were no extensive patches below the main vegetated zone, defined by the lower limits of the *S. europaea* agg. distribution.

Common salt marsh grass (*Puccinellia maritima*) continued to increase in frequency forming a distinctive, narrow band at the foot of the counter wall on the southern edge of the site. The *P. maritima* dominated community contained many of the plant species found on the adjacent natural marshes.

Sea purslane (*Atriplex portulacoides*) declined by 25% between 1994 and 2005 on the marshes adjacent to the managed realignment site. Although the reasons for this are unclear there are several possible causes such as a natural cycle of maturation and decline of the species, changes in inundation frequency or an increase in the frequency of storms. *S. anglica* increased in frequency from 1.5% to 13.9% during the same period. Again the reasons for this

are unclear, although it has been suggested that *S. anglica* may profit from certain climate change scenario's or may simply be colonising the gaps left by the die-back of *A. portulacoides*.

2 INTRODUCTION

This report presents the results of botanical and sedimentation monitoring at the Tollesbury managed realignment site and adjacent marshes for 2005. This monitoring forms part of a larger study investigating the changes in soil characteristics and ecology of the site over time from terrestrial farmland to intertidal salt marsh and mudflat. The work forms the continuation of a programme of research, initially commissioned by MAFF in 1993, to remove some of the uncertainties surrounding the creation of intertidal habitats on agricultural land (Boorman, Garbutt et al. 1997; Reading, Gray et al. 2002).

Broadly speaking the research to date has shown that, with relatively minimal pre-treatment and/or management of the area, allowing tidal ingress through a simple, relatively small breach of the existing sea wall, onto low-lying agricultural land will quickly produce intertidal mudflats which are colonised by salt marsh plants. However, the future development of the site remains unclear, with two potential alternative states predicted. First, the coming years may see the development of a salt marsh plus mudflat, and of a creek system draining them, as accretion of sediments raises the low lying unvegetated areas to elevations suitable for plant growth. Alternatively, changes in the sediment supply, or failure to develop an adequate drainage system of creeks, may produce a long-standing, waterlogged mudflat low in the tidal frame and fringed by relatively static salt marsh vegetation. These alternative states have quite different consequences for the exploitation of the site by fish and birds. Continued long term monitoring is therefore essential if the full value of the scheme, both in delivering its objectives and in providing insights into the problems of salt marsh restoration and the optimal design features of realignment sites, are to be realised.

3 Monitoring sedimentation rates within the realignment site and adjacent salt marshes.

3.1 Introduction

Sedimentation rates within the Tollesbury realignment site were measured to answer uncertainties about the ability of the site to retain sediment. Sedimentation rates of the existing salt marshes, adjacent to the realignment site, were also monitored in an attempt to detect any changes in sedimentation rates that could be attributed to the breaching of the sea wall. Garbutt (2005) reported evidence of a slow down in the rate of increase in accretion rates within the site, whereas rates on the adjacent salt marshes remained relatively constant (3.7mm pa for Old Hall marshes and 4.7mm pa for Tollesbury marshes) with no detectable effect due to the breach of the sea wall.

3.2 Methods

Changes in the bed level of the marsh were measured using a network of 2m wide sediment transects. Measurements were recorded to the nearest millimetre and taken at fixed positions along each transect relative to an aluminium bar placed across a pair of permanent points at either end of each transect. Recording took place on the Old Hall marshes (on the north side of Old Hall Creek) from May 1993, and on the Tollesbury marshes (adjacent to the experimental site) from April 1994.

Sediment transects were located in the vegetated areas of the marshes dominated by a mosaic of sea-purslane (*Atriplex portulacoides*) and common salt marsh-grass (*Puccinellia maritima*). Elevations for the sediment transects ranged from 2.33m to 2.59m ODN (mean = 2.47m ODN) on the Old Hall marshes and 2.38m to 2.75m ODN (mean = 2.54m ODN) on the Tollesbury marshes.

Before the sea wall was breached in August 1995, a further 20 sediment transects were positioned at random within the experimental site (Figure 1). Data from these transects were recorded regularly from September 1995 onwards. Elevations for the sediment transects ranged from 1.22m to 1.71m ODN (mean = 1.36m ODN).

In April 1999, five additional sediment transects were set up inside the site. One was positioned in each of the three original fields, in the southern half of the site, on the high ground close to the new sea wall (transects 21, 22 and 23) where common glasswort (*Salicornia europaea agg.*) occurred at high densities. Two were placed near the breach in the original sea wall, one either side of the cut channel (transects 24 and 25). These areas were thought to be eroding and were not covered by the 20 transects already in place.

3.3 Results

The mean accretion rates for the Old Hall and Tollesbury marshes continued to show linear increases (Figures 2 & 3). Whilst year on year rates are variable, mean annual accretion rates of 3.2mm year^{-1} (r^2=96.5%, p<0.0001) for the Old Hall marshes and 4.5mm year^{-1} (r^2=97.9%, p<0.0001) for the Tollesbury marshes were constant (Table 1), and unchanged since the last survey in 2004 (Garbutt 2005).

There was continued evidence of a reduction in sedimentation rates within the site. Figure 4 shows a plot with mean accretion rates for the site split into two data series with fitted regression lines (the gap between the data series (winter/spring 2001/2002) was due to the end of one CEH contract and the start of the current contract). The rate of accretion differs significantly between the two data series ($F_{1, 49}$ = 36.85, p<0.001). The mean rate of accretion for data series ‘a’ is 23.1mm year^{-1} and for data series ‘b’ 10.7mm year^{-1}.

Evidence was found of a slowdown in the rate of increase in sedimentation within the managed realignment site (Figure 5, a quadratic model was used which accounts for simple curvature in the data (r^2=99.2%, p-value for quadratic effect <0.001). Table 2 shows estimated annual sedimentation rate by year since recording started using the quadratic equation (y = 31.31 -1.547 year).

Figure 6 shows the change in bed level at the 20 transects within the experimental site between their original elevation (pre-breach) and October 2005. A locally weighted scatter plot smoother (Lowess line) has been added to summarise the trend in the data. Most transects are situated below an elevation of 1.4m ODN, which reflects the low-lying nature of the site. The greatest increases in the surface level occurred on the transects below this elevation. As transect elevation increased, the change in bed level decreased. The change in bed level for individual transects are shown in Table 3.

Of the five additional sediment transects set up in 1999 transects 21, 22 and 23 all showed small linear increases in bed level (1.5mm, 3.4mm and 1.9mm respectively). Of the transects closest to the breach, transect 24 continued to erode (mean rate = -7.4mm $year^{-1}$) at a similar rate as previously recorded. Since April 2004 the mudflat surface at Transect 25 started to accrete sediment at a mean rate of 28.3mm $year^{-1}$ where previously it was eroding at -15.2mm $year^{-1}$ (Figure 7). The increased rate was due to the encroachment of accreting sediment from the south of the transect.

3.4 Discussion

The Old Hall and Tollesbury marshes continued to accrete vertically (between 3 – 4mm $year^{-1}$). These rates are typical for salt marshes of the Greater Themes area (van der Wal & Pye 2004) and the marshes appear to be well able to maintain their position in the tidal frame despite projected mean eustatic sea level rise.

Mean sedimentation rates continued to slow down within the realignment site. Allen (1990) developed a model that predicts an elevation-time curve for mudflat/marsh growth where sediment build up rises steeply during the early stages but thereafter flattens off very rapidly. The detailed form of the curve depends on the balance between several parameters (sediment supply, tidal regime, compaction under sediment load etc). The rate of minerogenic sedimentation is determined chiefly by the tidal and fine-sediment regimes and is expected to be a decreasing function of mudflat elevation. This can be observed within the site where there was the broadly expected inverse relationship between initial mudflat elevation and sedimentation rates. As the surface level builds up, sedimentation rates will slow as sediment supply is reduced by lower inundation frequencies.

Garbutt and Wolters (2004) noted that the period of lower deposition within the site coincided with the creation of the 78ha Abbotts Hall realignment site (breached in October 2002) to the north of the Tollesbury realignment site and marshes, and separated from them by the Old Hall RSPB reserve. It is worth reiterating that, whilst it is not possible to correlate the creation of the Abbotts Hall realignment with the decline in sedimentation rates at the Tollesbury site, the coincidence highlights an important issue. Experience from Tollesbury and other realignments have shown that such sites act as 'sinks' for sediment. It may be possible that the creation of successive realignment sites could impact on the sediment budget within an estuary by taking sediment out of the system. This would reduce severely a) the ability of existing intertidal habitats to adjust to relative sea level rise by increasing elevation, and b) the ability of the surface level within realignment sites to reach elevational equilibrium with adjacent areas.

The potential scale, and the design and siting, of particular schemes remain fairly contentious issues, with some stakeholder disputes remaining unresolved with disagreement about the wider impact of such schemes. For example, Pethick (1993) and Townend and Pethick (2002) argue that breach retreats can lead to erosion of the outer estuary channel, further threatening flood defence embankments and intertidal habitat. Monitoring hydrologic, physical and biological processes on an estuary wide scale may, therefore, be necessary if the reaction of the estuary to the realignment of its boundaries is to be better understood.

4 Monitoring the development of salt marsh within the realignment site

4.1 Introduction

After six years of tidal inundation the development of salt marsh within the realignment site reached its predicted extent (down to mean high water neap tides), covering approximately 6ha of the 21ha site (Garbutt, Myhill et al. 2002). However, the marshes that developed were immature, dominated by pioneer vegetation, with annual changes in the abundance and species richness of salt marsh plants colonising the site. Continued monitoring is necessary to assess the time scales involved in the establishment of salt marsh communities on former agricultural soils that reflect those of semi-natural reference sites.

4.2 Methods

A transect 20 metres wide and 125 metres long was laid out in each of three fields within the realignment site, starting from the foot of the new seawall and extending down the slope into the unvegetated mudflat. Fields were numbered 1-3 from the west to the east. Each transect was divided into 2500 cells of $1m^2$ and in each cell presence and percentage cover were recorded for each species. Recording was first undertaken in September 1997, the second year after the breach and repeated annually until 2001. Under the present contract the three transects will be recorded every other year (i.e. 2003, 2005 and 2007). CEH funded the recording in the interim period between contracts in 2002.

The vegetation of the site was described using the standard methodology for the survey and description of British Plant Communities (Rodwell 2000). Five 2x2m quadrats were used to record presence and estimated percentage cover of plant species in areas of homogeneous vegetation. The vegetation were compared with all other British vegetation types described by the *National Vegetation Classification* (NVC) using the Tablefit computer programme (Hill 1996).

A list of scientific and common names for salt marsh plants (Stace 1997) is provided in Appendix 3.

4.3 Results

Ten years after the site was first re-exposed to tidal inundation there continue to be changes in species frequency (Table 4). *S. europaea* agg. has continued to dominate the vegetation and expanded its range, colonising previously unvegetated areas of the site (Figure 8). *P. maritima* has increased in frequency becoming the dominant species at the highest elevations of the site. In addition to the species recorded on the transects, a single sea-arrow grass (*Triglochin maritima*) plant was observed in the site for the first time in 2005.

The largest rise in frequency was by common cord grass (*Spartina anglica*), which increased from a mean of 35.9% across the three transects in 2003 to a mean of 57.9% in 2005. *S. anglica* was recorded at all elevations within the transects from the foot of the new sea wall down to the mud flat. Although it was found, as individual plants on the mud flat, there were no extensive patches below the main vegetated zone, defined by the lower limits of the *S. europaea* agg.

The *NVC* survey showed that there were two distinct vegetation communities within the realignment site with a narrow transition community separating them (Table 5).

SM13 – *Puccinellia maritima* salt marsh

This lower-middle level salt marsh community is dominated by *P. maritima* (cover typically 90%) with a variety of associated species (7-8 species/quadrat), though *S. europaea* agg. is the only other constant. Other species include individual plants of sea lavender (*Limonium vulgare*), low growing bushes of *A. portulacoides* and scattered plants of greater sea-spurrey (*Spergularia media*). The nationally scarce, perennial glasswort (*Sarcocornia perennis*) was also associated with this community. The vegetation was generally closed, with little bare mud or surface water at low tide. The *P. maritima* salt marsh occupied a narrow zone at the foot of the new sea wall on the southern edge of the site.

SM8 – *Salicornia* salt marsh

The *Salicornia* marsh was the dominant community of the realignment site where *S. europaea* agg. and *S. anglica* were both constants at a ratio of around 80/20% cover. Apart from the transition to mud flat there was little exposed mud and standing water was rare. *S. anglica* formed large stands in some areas, a result of vegetative spread. No other species were recorded in this community.

4.4 Discussion

The SM13 - *Puccinellia maritima* salt marsh was a distinctive feature of the realignment site and contained many of the plant species found on the adjacent natural marshes. Whilst there were still significant changes in the frequency of some species the results show that, given time and a local source of propagules, a range of species appropriate to the elevation of the site can colonise naturally and form distinct and recognisable communities.

The extensive nature of the SM8 *Salicornia* salt marsh and the high frequency of *S. europaea* agg in the three transects reflects the sites elevation, being low in the tidal frame. In the adjacent estuary the marsh edges are predominantly cliffed, with *S. europaea* agg restricted to the edge of creeks. The community within the site represents one of the most extensive examples of the type in the region. The future of the *Salicornia* salt marsh is uncertain however. The frequency of *S. anglica* continued to increase in 2005 becoming established at all levels of the site. The successful establishment and spread of *S. anglica* throughout the UK during the last century was largely due to the species perennial life history and the existence of a zone of mud flat formally unoccupied by native salt marsh plants – a vacant niche (Gray, Benham et al. 1990). The rapid spread of *S. anglica* within the site is probably also due to the same reasons. The mudflats within the Tollesbury realignment site are sparsely vegetated, dominated by annual *Salicornia*, providing ideal conditions for the invasion of *S. anglica*.

Extensive stands of *Salicornia* are rare in estuaries with abundant *S. anglica* (Adam 1990). If the increases in *S. anglica* continue, as appears likely, it could represent the dominant vegetation type. The expansion of this species within the site raises important issues for the creation of other realignment sites, particularly those which are commissioned as part of compensatory measures for loss of intertidal habitat elsewhere. Careful consideration should be given, in such cases, to the objectives and success criteria of individual schemes and the quality of habitat created.

5 Monitoring changes in vegetation frequency on the salt marshes adjacent to the realignment site

5.1 Introduction.

Detailed monitoring of the vegetation on the marshes adjacent to the realignment site was carried out annually, between 1994 and 2001, to determine whether any changes to the vegetation composition that occurred during this period could be attributed to the creation of the realignment site (Garbutt, Myhill et al. 2002). Whilst there were significant increases in the frequency of certain species and decreases in others, the changes detected could not be related to the creation of the realignment site. It is possible that the changes were reflecting regional trends or that change as a result of the realignment was not detectable in the time scale of the monitoring programme to date. Monitoring of the salt marsh vegetation was therefore continued in 2003 and 2005, and will be repeated in 2007. After the final year of monitoring in 2007 the data will be re-analysed to determine if the breach is having an effect on the species composition of the marshes adjacent to the Tollesbury realignment site.

There are two distinct vegetation zones on the salt marshes adjacent to the experimental site, referred to in this report as ‘upper’ and ‘lower marsh’, which in a wider context correspond to mid/low and pioneer salt marsh. There are two dominant vegetation communities on the upper salt marsh. The first community is *Atriplex* (*Halimione*) *portulacoides* salt marsh (coded as SM14 under the *National Vegetation Classification*, Rodwell 2000). At Tollesbury this is typically the *Puccinellia maritima* sub-community (SM14c) which is widespread, forming large stands of often species poor vegetation. The second more diverse community is *Puccinellia maritima* salt marsh, typically the SM13c sub-community (*Limonium vulgare-Armeria maritima*), which often forms a mosaic with the *Atriplex portulacoides* salt marsh.

The rayless aster (*Aster tripolium* var. *discoideus*) salt marsh (SM11) dominates the lower marsh and often forms a mosaic with annual *Salicornia* salt marsh (SM 8). SM11 occurs mainly on the edges of creeks or on mud mounds at Tollesbury and is species poor, usually only occurring with *Salicornia* and annual sea-blite (*Suaeda maritima*). *P. maritima* can occur at its upper limits.

5.2 Methods

Permanent quadrats were used at two scales, 25m^2 and 1m^2, to ensure an adequate area of the marshes were sampled and that recording was done in enough detail to pick up fine-scale changes in the vegetation. Recording took place in July 1994-2001, 2003 and 2005, and will take place once more in 2007. Forty 25m^2 quadrats were used, each sub-divided into 25 1m x 1m cells. The species present within each of these cells were recorded and their mean percentage frequency calculated. Quadrats were randomly located.

Sixty 1m^2 quadrats were used to monitor small-scale changes in the frequency of plant species, forty of which were located in the south west corner of the 25m^2 quadrats. The 1m^2 quadrats were each sub-divided into 100 0.1m x 0.1m cells. The species present within each cell were recorded and their mean percentage frequency calculated.

5.3 Results

There were notable increases in the mean frequency of *T. maritima*, *S. media* and *Suaeda maritima* between 2003 and 2005 in the $5m^{-2}$ quadrats of the upper marsh (Table 6). The increase in *S. maritima* was reflected in the $1m^{-2}$ quadrats, although not in *T. maritima*, which showed a small decline (Table 7). The mean frequency of *A. portulacoides* continued to be significantly less than when recording first started at both quadrat scales. After being totally absent in 2003 the mean frequency of algae recorded in both the $5m^{-2}$ and $1m^{-2}$ quadrats recovered to 22.0% and 26.9% respectively in the lower marsh quadrats. *S. anglica* continued to increase in mean frequency up to its highest recorded level in 2005 (13.9%) in the upper marsh $5m^{-2}$ quadrats (Table 6). All other species were within previously observed or expected ranges.

5.4 Discussion

The decline in the frequency of *A. portulacoides* over the recording period appears to have occurred on a regional (Essex wide) scale and not confined to the Tollesbury marshes (Garbutt, Myhill et al. 2002). There are several possible reasons for this decline such as a natural cycle of maturation and decline, changes in inundation frequency or an increase in the frequency of storms. A. *portulacoides* is usually confined to well-drained, aerobic soil environments such as the edges of creeks. It is known that seedlings and young plants cannot tolerate water logging and standing water can kill mature plants (Chapman 1950). It is estimated that the total salt marsh loss, in Essex, between 1973 and 1998 exceeds 1,000 hectares (CGP 2000), equivalent to approximately 40ha per year. Between 1973 and 1998 the Blackwater estuary alone lost 196.6ha (22.3%) of its existing salt marshes which has been attributed to changes in wind and wave climate (van der Wal and Pye 2004). It is possible that, even if the marsh surface is able to maintain its position in the tidal frame in the face of rising sea levels, the physical effects of greater wave action over marshes may be detrimental.

The expansion of *S. anglica* is interesting and not easily explained. At the elevation in the upper marsh, at Tollesbury, where it has been recorded, *P. maritima* would be expected to be competitively dominant. Gray and Mogg (2001) considered the competitive responses of *S. anglica* and *P. maritima* under elevated temperatures and CO_2 in the context of climate change. They postulated that if *S. anglica* is able to profit from higher temperatures, particularly in early spring, it may be able to out-compete *P. maritima* and other salt marsh species. Gray and Mogg (2001) concluded, however, that *S. anglica* would increase its latitudinal range under increased temperatures and CO_2 levels and that *P. maritima* would increase its elevational range (downwards) at individual sites. Nevertheless, the increase in *S. anglica* in the upper marsh poses interesting questions about the long term stability of the salt marsh communities and their ecology.

To date, the results of the monitoring programme show that the interactions between salt marsh plants and their environment are complex and, without monitoring the physical environment simultaneously, are often difficult to explain. Garbutt, Myhill et al. (2002) concluded that whilst there were significant increases in the frequency of certain species and decreases in others, the changes detected could not be related to the creation of the realignment site. This analysis will be repeated after the final year of monitoring in 2007.

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7 Appendix 1

Figures 1 – 8

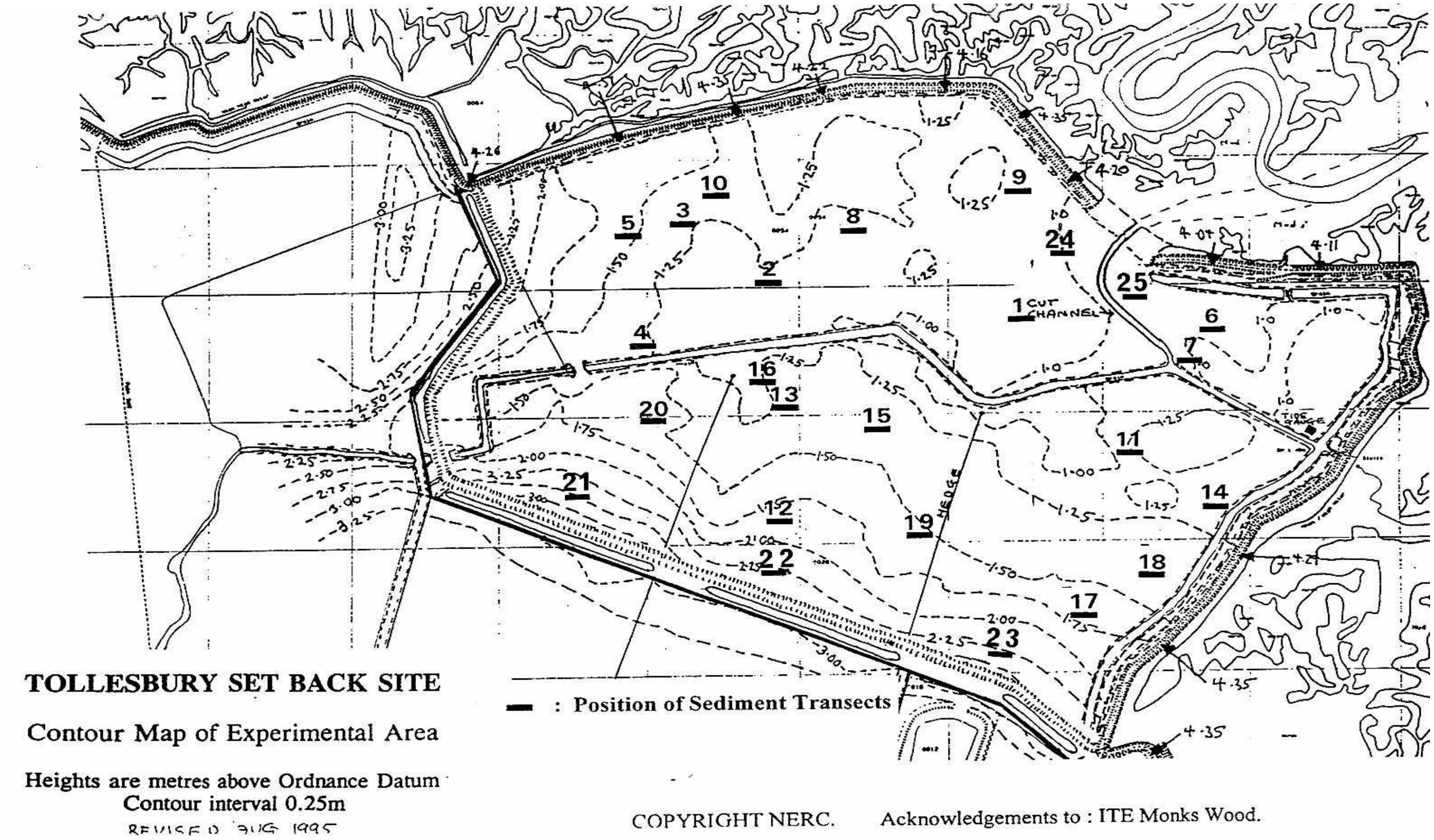

Figure 1. Position of the sediment transects within the managed realignment site at Tollesbury.

Figure 2. Mean sedimentation rates (n=12) for the Old Hall salt marshes, between May 1993 and October 2005. Mean rate is 3.2mm $year^{-1}$; regression equation: mean accretion = - 1.588 + 0.008858 day; r^2=96.5%, p<0.0001).

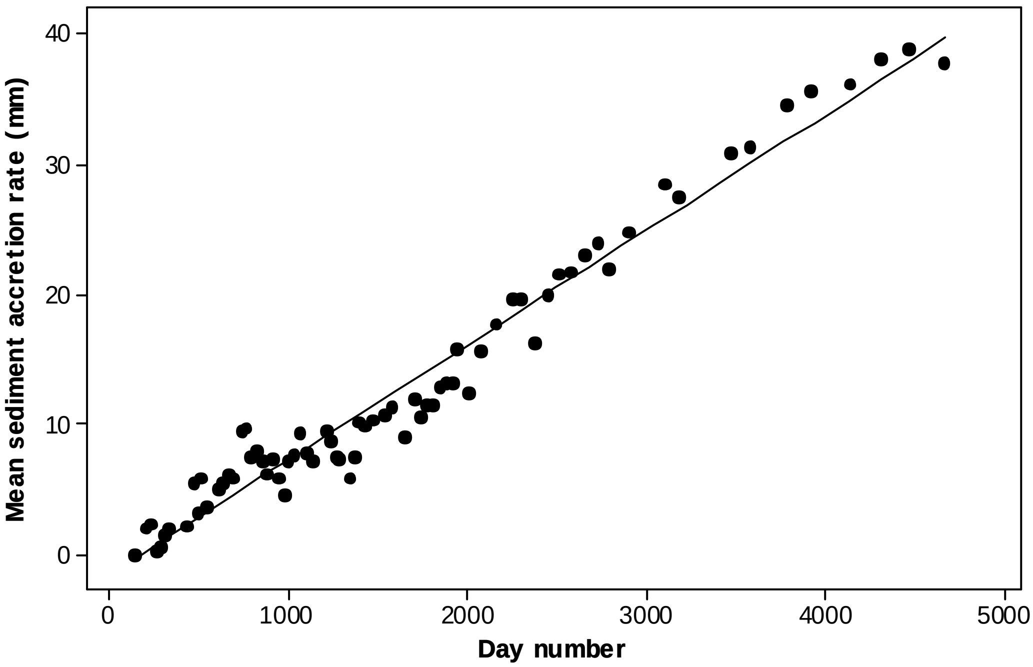

Figure 3. Mean sedimentation rates (n=16) for the Tollesbury salt marshes, between April 1994 and October 2005. Mean rate is 4.5mm $year^{-1}$; regression equation: mean accretion = -8.852 + 0.01242 day; r^2=97.9%, p<0.0001).

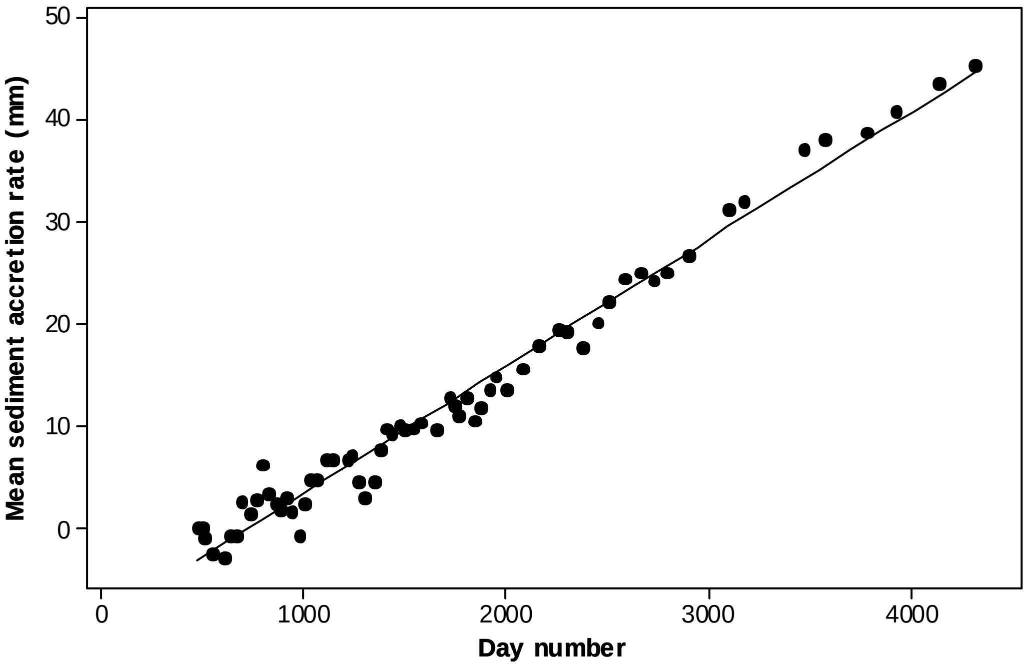

Figure 4. Mean sedimentation rate within the realignment site with fitted regression line through data series 'a' (August 1995 to September 2001) and data series 'b' (July 2002 to October 2004). The estimated mean rate of accretion for data series 'a' is 23.1mm $year^{-1}$ and for data series 'b' 10.7mm $year^{-1}$.

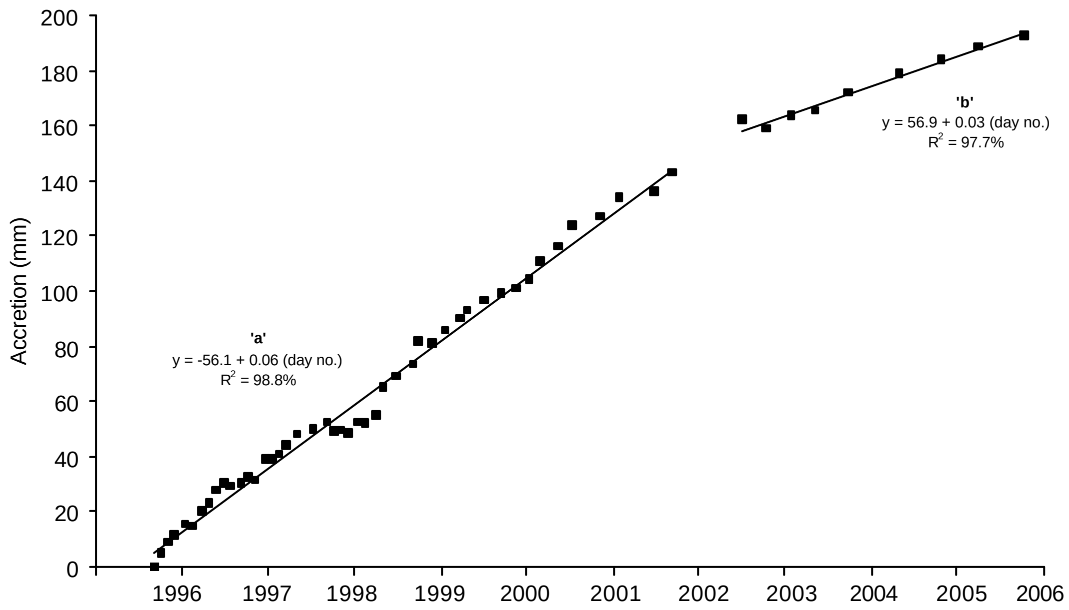

Figure 5. Mean sedimentation rate (n=20) within the Tollesbury managed realignment site between 1995 and 2005. Line shows fitted quadratic model (Mean = - 42.42 + 0.05530 day; r^2=99.2%, *p*-value for quadratic effect <0.001).

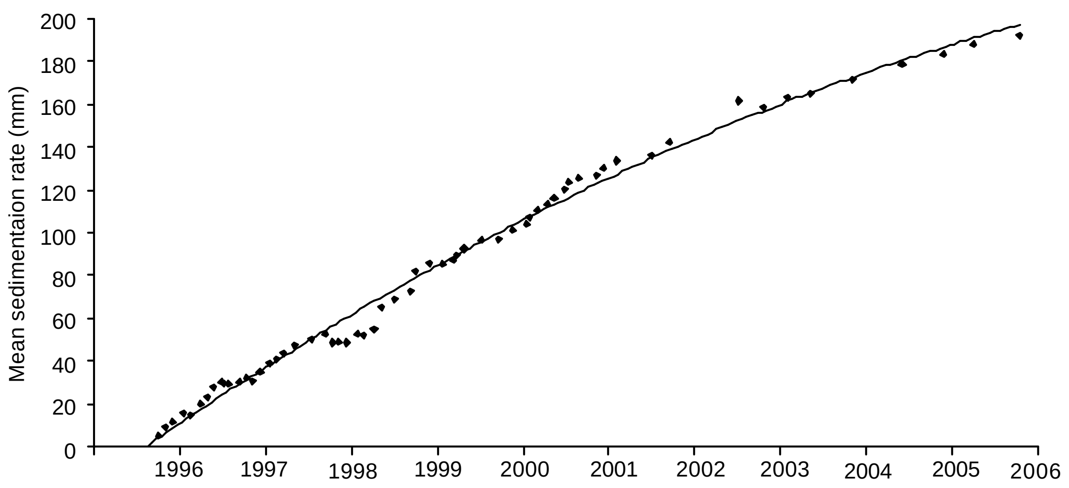

Figure 6. Depth of sediment over pre-inundation land surface in October 2005 at sediment transects 1-20 within the experimental site. Lowess smoother line is shown to indicate underlying trend.

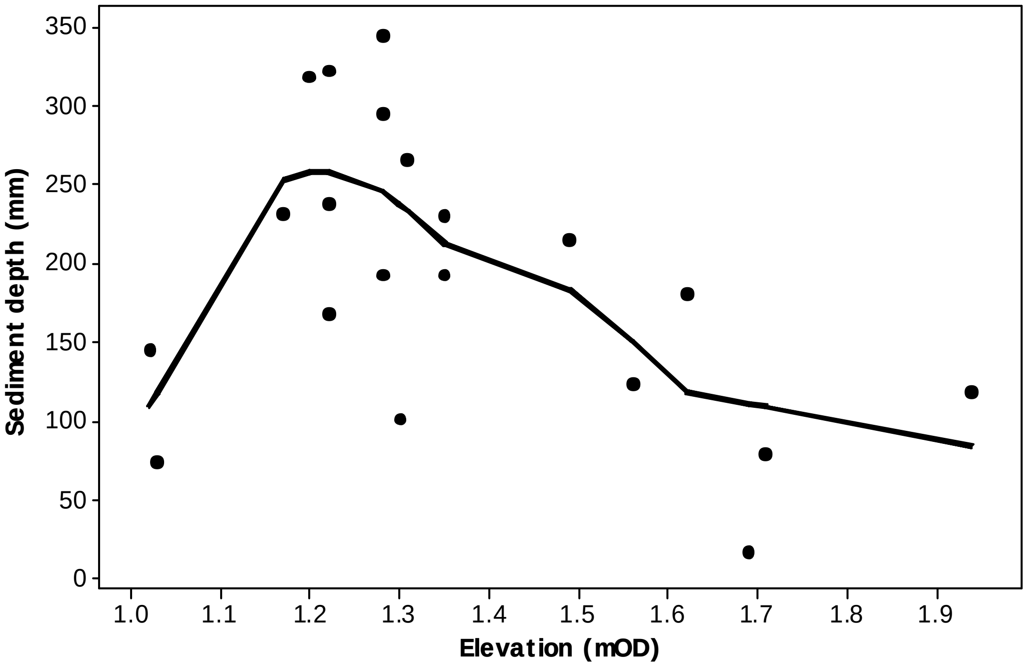

Figure 7. Change in bed level at five additional sediment transects within the managed realignment site. Transects 21, 22, 23 were situated in the highest parts of the site, whilst transects 24 and 25 were close to the breach.

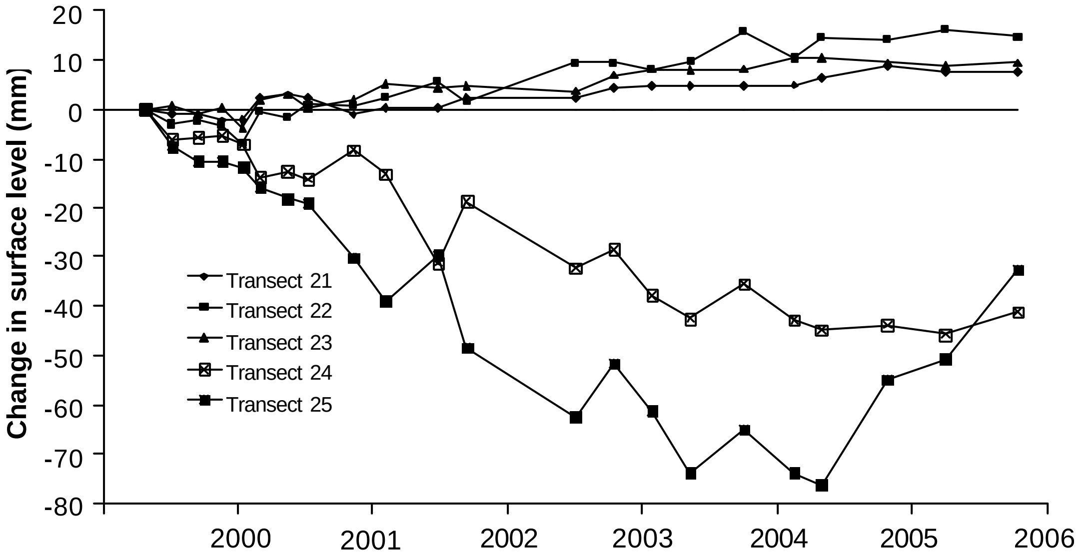

Figure 8. Looking north into the Tollesbury managed realignment site from the counter wall. The *Puccinellia maritima* (common salt marsh grass) in the foreground occupies a narrow band of marsh at the foot of the wall. The rest of the vegetation is dominated by *Salicornia europaea* agg. (common glasswort) and *Spartina anglica* (common cord grass). *Salicornia europaea* agg. can be seen encroaching onto the mud flats.

8 Appendix 2

Tables 1 – 7

Table 1. Mean change in the bed level (mm) of the Old Hall and Tollesbury marshes and the experimental site, over twelve month periods, commencing August 1993.

	1993-1994	1994-1995	1995-1996	1996-1997	1997-1998	1998-1999	1999-2000	2000-2001	2001-2002	2002-2003	2003-2004	2004-2005	Mean annual rate (s.e.)
Old Hall	2.3	1.6	0.8	3.3	4.2	3.6	5.9	5.1	3.2	3.8	2.1	0.1	3.2 (0.08)
Tollesbury	-	3.1	1.6	7.4	3.9	4.0	5.8	7.1	5.6	2.5	4.5	1.4	4.5 (0.08)
Site	-	-	30.0	21.0	20.2	25.6	27.8	15.1	21.3	8.3	12.3	9.4	-

NB. The sea wall was breached in August 1995.

Table 2. Estimated annual sedimentation rate, by year, since recording started within the Tollesbury managed realignment site using the quadratic equation (y = 31.31 -1.547 year; r^2=99.2%; p <0.001).

Year	Slope (mm/year)
1	26.7
2	25.1
3	23.6
4	22.0
5	20.5
6	18.9
7	17.4
8	15.8
9	14.3
10	12.7

Table 3. Depth of sediment over the pre-inundation land surface at sediment transects within the managed realignment site at Tollesbury in October 2005.

Transect	Depth (mm)	Transect	Depth (mm)
1	167.9	11	322.0
2	237.2	12	117.5
3	295.1	13	343.5
4	192.9	14	231.8
5	122.4	15	214.7
6	73.9	16	229.9
7	145.0	17	17.0
8	318.2	18	192.9
9	100.3	19	180.4
10	265.8	20	79.3

Table 4 Mean percentage frequency (s.e.) of species recorded over three transects within the realignment site at Tollesbury. For differences between 2003 and 2005 frequencies a paired t-test was used: - * $p < 0.05$; ** $p < 0.01$; *** $p<0.001$.

	1997	1998	1999	2000	2001	2002	2003	2005	Difference 2005-2003
Salicornia europaea	15.6	57.5	66.5	63.2	58.4	58.3	55.7	66.8 (0.5)	***
Suaeda maritima	0.5	19.4	13.9	13.5	11.2	10.8	8.0	8.2 (0.3)	ns
Sarcocornia perennis	0.01	0.5	0.3	1.4	1.4	1.8	3.1	2.0 (0.1)	***
Spartina anglica	0.01	0.1	0.3	1.9	5.2	18.2	35.9	57.9 (0.4)	***
Spergularia marina		1.5	1.5	2.4	2.5	2.5	0.5	-	ns
Puccinellia maritima		1.0	2.9	5.4	7.8	12.2	14.6	20.5 (0.4)	***
Atriplex portulacoides		0.3	0.9	0.8	1.3	1.3	1.3	2.7 (0.1)	*
Aster tripolium		0.3	0.9	2.5	3.8	5.7	5.5	9.7 (0.2)	**
Atriplex littoralis		0.2	-	0.3	0.4	-	0.01	-	ns
Limonium vulgare			0.4	0.7	1.0	1.3	1.1	1.5 (0.1)	ns
Cochlearia anglica			0.1	-	-	0.1	0.03	-	ns
Spergularia media				0.5	1.3	2.8	2.8	5.7 (0.2)	ns
Elytrigia atherica					0.2	0.6	0.7	1.3 (0.1)	ns
Hordeum marinum					0.2	0.1	-	-	-
Atriplex prostrata					0.01	-	-	-	-
Beta maritima						0.01	-	0.03 (0.01)	ns

Table 5. British Plant Communities recorded on the Tollesbury managed realignment site, 2005. The vegetation were compared with all other British vegetation types described by the *National Vegetation Classification* (NVC) using the Tablefit computer programme (Hill 1996).

SM13 - *Puccinellia maritima* salt marsh (96% Fit)

	Frequency	% cover
Puccinellia maritima	V	1
Salicornia europaea	V	0.7
Suaeda maritima	IV	0.1
Spartina anglica	III	89.7
Aster tripolium	III	5.7
Spergularia media	III	2.3
Atriplex portulacoides	I	0.1
Limonium vulgare	I	2
Number of samples	5	
Mean no. of species/sample	7 (7-8)	

SM8 - *Salicornia* salt marsh (81 % Fit)

	Frequency	% cover
Salicornia europaea	V	80
Spartina anglica	V	20
Number of samples	5	
Mean no. of species/sample	2 (2)	

Table 6 Means (s.e.) of percentage frequency data in 25 m^2 quadrats on upper (n=30) and lower (n=10) marsh at Tollesbury. Species occurring with a frequency of less than 5.0 % at the maximum are excluded. For differences between pre- and post-breach frequencies a paired t-test was used; * p < 0.05; ** p < 0.01; *** p<0.001. There was no monitoring in 2002 and 2004.

Species	Marsh Type	1994	1995	**Breach**	1996	1997	1998	1999	2000	2001	2003	2005	Mean difference (post-pre breach)
Limonium vulgare	Upper	64.8	68.5		71.5	69.7	70.9	72.8	72.0	69.9	71.2	75.3 (5.8)	5.0 (1.9)*
	Lower	-	-		-	-	-	-	-	-	-	-	-
Plantago maritima	Upper	14.7	13.3		14.9	13.1	12.4	13.7	16.7	15.2	12.7	13.7 (3.8)	0.1 (1.1)
	Lower	-	-		-	-	-	-	-	-	-	-	-
Sarcocornia perennis	Upper	10.7	21.7		27.7	30.7	23.7	30.0	23.7	22.1	22.5	30.8 (5.2)	10.2 (2.1)***
	Lower	-	-		-	-	-	-	-	-	-	-	-
Triglochin maritima	Upper	44.9	51.6		51.2	51.9	52.5	51.3	54.3	52.7	49.6	61.5 (13.3)	4.9 (1.9)*
	Lower	-	-		-	-	-	-	-	-	-	-	-
Spergularia media	Upper	40.8	38.1		36.3	37.9	36.8	43.9	45.1	50.3	47.9	66.0 (13.0)	6.0 (2.6)*
	Lower	-	-		-	-	-	-	-	-	-	-	-
Spartina anglica	Upper	1.5	2.0		2.0	3.6	4.3	3.9	4.5	5.9	9.9	13.9 (3.7)	4.3 (1.1)***
	Lower	-	-		-	-	-	-	-	-	-	-	-
Puccinellia maritima	Upper	96.3	99.2		99.9	99.3	99.2	98.8	97.5	95.6	92.7	92.8 (3.6)	-0.8 (1.3)
	Lower	8.0	11.2		7.2	5.6	7.2	4.8	5.2	4.8	2.8	0.4 (0.4)	-4.9 (1.9)*
Atriplex portulacoides	Upper	90.8	90.5		90.0	89.7	84.4	75.1	80.8	80.8	66.0	66.0 (7.4)	-10.1 (2.7)***
	Lower	8.0	6.8		3.6	5.6	3.6	2.4	4.0	4.0	0.8	2.4 (1.7)	-4.1 (3.2)
Aster tripolium	Upper	39.7	38.4		39.7	38.4	44.7	52.4	58.3	57.5	61.3	59.6 (6.2)	12.4 (2.6)***
	Lower	59.2	58.0		56.8	54.0	47.2	53.6	54.8	56.4	50.8	50.8 (12.1)	-5.5 (2.2)*
Suaeda maritima	Upper	72.7	80.4		86.7	87.5	84.1	82.3	68.1	62.7	73.1	94.1 (11.8)	3.2 (2.7)
	Lower	52.0	50.0		54.0	60.0	44.0	36.0	16.8	20.8	22.8	46.4 (9.2)	-13.4 (4.0)**
Salicornia europaea	Upper	60.1	75.3		86.1	88.3	87.6	82.5	87.5	91.2	87.9	84.8 (6.0)	19.3 (4.3)***
	Lower	96.0	96.0		98.0	96.4	94.8	92.0	90.0	88.8	90.4	96.4 (2.1)	-2.7 (1.3)
Algae >10%	Upper	1.7	0.8		0.3	11.1	15.9	18.0	12.1	27.2	5.2	16.7 (6.1)	11.5 (3.4)**
	Lower	21.2	27.2		58.4	80.8	45.2	47.6	51.2	27.2	0.0	22.0 (12.5)	17.4 (10.2)
Mud >10%	Upper	2.4	0.9		8.1	9.2	10.8	14.8	19.7	8.3	40.3	25.7 (6.6)	15.5 (3.3)***
	Lower	73.2	91.6		93.6	98.8	96.8	97.6	100	100	100	100 (0)	16.0 (5.7)*

Table 7 Means (s.e.) of percentage frequency data in 1 m^2 quadrats on upper (n=43) and lower (n=17) marsh at Tollesbury. Species occurring with a frequency of less than 5.0 % at the maximum are excluded. For differences between pre- and post-breach frequencies a paired t-test was used: - * p < 0.05; ** p < 0.01; *** p<0.001. There was no monitoring in 2002 and 2004.

Species	Marsh Type	1994	1995	**Breach**	1996	1997	1998	1999	2000	2001	2003	2005	Mean difference (post-pre breach)
Atriplex portulacoides	Upper	73.7	66.1		69.0	64.6	58.3	50.1	53.2	50.0	42.5	46.7 (5.5)	-15.5 (2.8)***
	Lower	-	-		-	-	-	-	-	-	-	-	-
Limonium vulgare	Upper	21.5	22.1		24.6	25.4	25.9	28.2	29.7	31.3	31.5	30.1 (5.6)	6.7 (2.5)*
	Lower	-	-		-	-	-	-	-	-	-	-	-
Puccinellia maritima	Upper	86.3	84.5		80.7	80.6	76.9	81.6	81.3	80.7	77.0	73.7 (5.7)	-6.0 (1.5)***
	Lower	-	-		-	-	-	-	-	-	-	-	-
Triglochin maritima	Upper	16.5	17.6		17.5	17.4	17.6	18.7	18.4	18.4	17.7	15.5 (4.1)	0.6 (1.2)
	Lower	-	-		-	-	-	-	-	-			
Aster tripolium	Upper	10.5	10.4		9.77	10.5	10.8	17.0	14.4	15.9	20.3	18.3 (3.5)	4.3 (1.4)**
	Lower	22.5	21.2		19.1	22.5	16.5	16.9	21.9	17.9	15.7	17.7 (6.9)	-3.7 (2.0)
Salicornia europaea	Upper	30.0	38.1		51.6	51.1	47.3	51.2	55.2	55.4	59.1	55.9 (5.8)	19.6 (3.6)***
	Lower	64.2	61.8		65.5	72.7	60.1	53.5	49.3	57.1	60.2	67.7 (9.2)	-2.2 (4.1)
Suaeda maritima	Upper	43.1	42.9		53.2	47.4	37.7	30.3	15.0	18.2	27.3	39.5 (4.3)	-9.3 (2.6)***
	Lower	12.3	5.9		11.4	14.9	9.7	7.4	3.4	2.7	4.0	11.4 (6.7)	-1.0 (2.7)
Algae >10%	Upper	5.1	10.0		10.9	30.7	26.5	20.1	12.6	13.7	11.2	16.7 (4.4)	10.2 (3.0)***
	Lower	19.8	33.8		40.8	81.3	65.8	51.1	47.6	45.2	0.0	26.9 (10.)	18.0 (7.1)*
Mud >10%	Upper	3.7	10.8		19.0	19.2	6.3	7.1	13.9	10.7	32.9	19.5 (4.1)	8.9 (2.5)***
	Lower	86.9	86.9		80.9	85.1	65.2	90.1	91.8	92.7	58.7	99.5 (0.3)	-3.9 (4.6)

9 Appendix 1.3

Scientific and common names of salt marsh plants (nomenclature follows Stace, 1997).

Scientific names	**Common names**
Aster tripolium	Sea aster
Atriplex littoralis	Grass-leaved orache
Atriplex portulacoides	Sea-purslane
Atriplex prostrata	Spear-leaved orache
Beta maritima	Sea beet
Cochlearia anglica	English scurvy-grass
Elytrigia atherica	Sea couch
Hordeum marinum	Sea barley
Limonium vulgare	Common sea-lavender
Puccinellia maritima	Common salt marsh-grass
Salicornia europaea	Common glasswort
Sarcocornia perennis	Perennial glasswort
Spartina anglica	Common cord-grass
Spergularia marina	Lesser sea-spurrey
Spergularia media	Greater sea-spurrey
Suaeda maritima	Annual sea-blite