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Managed realignment at Tollesbury

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Management R&D Programme

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C.J.Reading, R.A.Garbutt, C.W.Watts, P.Rothery,
A.Turk, M.Yates, C.Boffey, J.Saunders & M.Wolters

Statement of use: This report describes research completed at the Tollesbury managed re-alignment site between 2003 and 2008. It will be of use to any organisation intending to create managed re-alignment sites in the future.

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Research contractor:
Center for Ecology and Hydrology
CEH Wallingford, Benson Lane,
Crowmarsh Gifford, Wallingford
Oxon. OX10 8BB. UK

C. J. Reading (cjr@ceh.ac.uk)

Defra project officer:
Paul Murby
Defra

paul.murby@DEFRA.GSI.GOV.UK

Publishing organisation
Department for Environment, Food and Rural Affairs
Flood Management Division,
Ergon House,
Horseferry Road
London SW1P 2AL

Tel: 020 7238 3000 Fax: 020 7238 6187

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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, and reported in 2002 (Reading et al., 2002). During 2007, the final year of a 5 year monitoring programme, research was completed on sediment accretion and invertebrate colonisation by ecologists from the Centre for Ecology & Hydrology (CEH) and on soil/sediment strength and stability by Rothamsted Research.

Invertebrate colonisation

- The total number of invertebrate species recorded from within the Tollesbury managed realignment site (n=21) was higher than in the marsh (n=16).

- The mean density, per sample, of all but one of the species common to all eight sites was highest in those from the managed realignment site.

- There was a gradient, between the upper and lower shore levels, in the mean number of species found per sample, with the highest numbers occurring in the lower shore samples.

- After an initial high rate of increase in the total number of species found at Tollesbury, each year between 1995 and 1998, the rate declined between 1998 and 2007.

Sediment accretion studies

- Accretion on the Old Hall and Tollesbury saltmarshes, adjacent to the Tollesbury managed realignment site, continued at a rate of 3-4mm/year. There was no significant difference in the rates of change before and after the creation of the Tollesbury managed realignment site.

- Within the realignment site the accretion rate during 2006/07 (9.6mm) showed a decrease over that reported for 2005/06 (11.2mm). Since 1996 there has been a steady decline in the annual rate of sediment accretion of 1.6mm (0.6-2.1mm).

Saltmarsh monitoring

- Between 1995 and 2007 there were significant changes in the frequency of occurrence of some plant species in the saltmarshes adjacent to the realignment site they were not correlated with the creation of the realignment site.

- By 2007 13 ha of the 21 ha realignment site were covered by saltmarsh vegetation that comprised 21 plant species. The upper elevations of the realignment site were dominated by *Puccinellia maritime* whilst the lower elevations were dominated by *Salicornia europaea* agg. and *Spartina anglica*.

Soil studies

- Sediment strength and stability were measured during early September 2003 and early September 2007, over five different vegetation zones and along three transects within the managed realignments site at Tollesbury during its continued development as a saltmarsh and sediment ecosystem.

- Within the site, saltmarsh plants were found on sediments with shear strengths ranging from 5 to 70 kPa with both *Salicornia europaea* and *Spartina anglica* occurring over this entire range. Greater species diversity occured where the sediment was stronger than 30 kPa, but there were no significant plant communities where shear strength fell below 5 kPa.

- The colonisation of the lower elevation vegetation zones (c & d) in 2007 by *Spartina anglica* was associated with a reduction in shear strength and stability of the surface sediments compared with 2003 when *Salicornia europaea* was dominant. However, where *Spartina anglica* colonised the mud flat (zone e), strength and stability both increased.

- Creeks formed once the weak rapidly accreting sediment exceeded a critical depth of 20 – 30 cm on top of the much stronger underlying agricultural soil.

- The lower extent of the *Salicornia europaea* extended along the faster draining, stronger (up to 18 kPa) and more stable creek margins. There was some evidence that these plants may contribute to higher sediment strength. In 2007 the colonisation by *Spartina anglica* of the creek margins we characterised in 2003 resulted in the disappearance of these creeks. We found little evidence of significant creek formation in areas where *Spartina anglica* dominated.

GENERAL INTRODUCTION

As part of its Flood and Coastal Defence research programme, Defra, the Department for Environment, Food and Rural Affairs 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 saltmarsh 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 saltmarsh biotopes.

It was also crucially important to determine the effects on the adjacent creeks and saltmarshes 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 saltmarsh 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 saltmarsh plants and inter-tidal invertebrates were still occurring, albeit at a much reduced rate than previously. Continued low level 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 (now Rathamsted Research) was sub-contracted, by CEH, to do the soil monitoring (years 1 & 5).

This report is the final report detailing research done between 2003 and 2007 and views the results in context with those obtained during the earlier projects (1995-2002).

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

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CHAPTER 1

COLONISATION OF THE TOLLESBURY MANAGED REALIGNMENT SITE BY INTERTIDAL ANIMALS.

C.J. READING[1], R.A. GARBUTT[2] & G.M. JOFRÉ[1]

1 - Centre for Ecology & Hydrology, CEH Wallingford, Benson Lane, Crowmarsh Gifford, Wallingford, Oxon. OX10 8BB. UK cjr@ceh.ac.uk
2 - Centre for Ecology & Hydrology, CEH Bangor, Environment Centre Wales, Deiniol Road, Bangor. LL57 2UW. UK

1.1 SUMMARY

1 The intertidal invertebrates present within the Tollesbury realignment area and in an adjacent area of existing marsh were surveyed between the 2-4th October 2007.

2 Seven sites within the realignment area, corresponding to those identified in the five previous annual surveys (1995 - 2001), were sampled for intertidal invertebrates. Nine core samples (15cm deep x 10cm diameter) were taken from each and from an additional site on the existing marsh giving a total of 72 samples.

3 The invertebrates present in each sample were identified to species (in most instances) and counted.

4 A total of 22 species of invertebrates were identified from the 8 sites. Of these, 16 occurred in the marsh and 21 in the realignment area. With the exception of *Gammarus* all of the species found in the marsh samples were also found in the 'realignment' samples.

5 With the exception of *Crangon vulgaris* the mean density, per sample, of the 11 invertebrate species that occurred in all 8 sample sites was highest in the realignment area.

6 Between 2004 and 2007 significant increases were observed in the density of four of the most common species (*H. ulvae, M. balthica, E. longa, Diptera* maggots) within the realignment area. Significant increases in the density of these four species were also found between 1995 and 2007 within the realignment area.

7 Overall, during the 12 years between 1995 and 2007 significant increases in the mean number of species per sample were recorded in 5 sites (3, 4, 5, 6, 7) within the re-alignment area.

8 Maps showing the distribution of each species occurring at all the 8 sites were drawn.
These suggest that many of the intertidal invertebrates present within the realignment area may now have reached a 'plateau' in the number of sites at which they occur.

1.2 INTRODUCTION

Although the original monitoring proposals for the realignment experiment were confined to the vegetation, it was realised that the invertebrate fauna was an essential component of the pre- and post-inundation communities and should, therefore, also be monitored, particularly as their response to habitat changes could be expected to be much more rapid than that of vegetation.

Additionally, the invertebrate fauna colonising the site during, and following, its transition from a terrestrial to an intertidal biotope will comprise many species that are important as food for shore birds. As the range and abundance of these invertebrate species may be reflected in the range and abundance of bird species attracted to the site it is therefore important that the link between the two be determined so that the most appropriate guidance can be given regarding the future management of the site.

To these ends the intertidal invertebrate fauna of the realignment site was surveyed for the first time in October 1995 (Reading 1996). This survey produced a 'baseline' of information about the intertidal invertebrates present within the realignment area from which changes could be measured. Subsequent surveys were completed in the October of 1996 (Reading 1997), 1997 (Reading 1998), 1998 (Reading 1999), 2001 (Reading 2002) and 2004 (Reading 2005). The results of the seventh and final annual survey (October 2007) are reported here with changes in the invertebrate faunas of the realignment area and existing marsh between all seven surveys being highlighted. This work was funded by the Conservation and Woodlands Policy Division of Defra (formerly MAFF) under the joint Defra / Environment Agency flood and coastal erosion risk management R&D programme.

1.3 SITE DESCRIPTION

Prior to August 1995 the realignment site at Tollesbury was an area of approximately 21 hectares of agricultural land bounded to the north and east by an existing sea wall and to the south and west by a new embankment (Map 1.1). Prior to the construction of the new sea defences behind the existing sea wall, the area was dissected by a stream flowing west to east and entering the saltmarsh through a sluice. Once the new embankment was completed and the existing sea wall breached, the sluice was permanently sealed off and the stream diverted to leave the site via the breach.

To the north of the stream the land was left fallow prior to inundation resulting in a field of overgrown clover and thistles. To the south of the stream the land was sub-divided into three sections (replicates R1, R2, R3) and within each section the land was further sub-divided into four roughly parallel strips. Within each replicate the strips were treated in four ways: left as stubble following the last harvest, ploughed, allowed to grow rye-grass and 'cultivated', (using a cultivator pulled behind a tractor).

Within the study area, 7 sites were identified from which invertebrate core samples were taken and these were compared with samples taken from one site outside the study area (Map 1.1).

Site 1 : ('Ditch') The 'borrow' dyke to the south of the northern sea wall was filled in with top soil from the study area. Although compacted and firm enough to walk on it was, nevertheless, less firm than in previous years with significant amounts of fine

	mud having settled on it. During the first 5 years it was, for the most part, covered in pools at low water. Its mean height was 1.0-1.5m above Ordnance Datum (O.D.). By 2007 the pools had been largely replaced by a drainage channel. The substrate was comprised of relatively unconsolidated fine sediments.
Site 2 : (‘Lower clover’)	This was an area previously left fallow (clover/thistle field) prior to inundation and had a height not exceeding 1m above O.D. At low water it was largely covered by surface water. The areas closest to the main drainage channel were scoured of soft sediments leaving a firm compacted substrate that was greater in area than in 1996. The amount of fine mud overlaying this hard basal layer increased in depth as the distance from the main drainage channel increased.
Site 3 : (‘Upper clover’)	This area was similar to site 2 (i.e. clover/thistle) except that it occurred at a higher level with a height mostly in excess of 1.25m above O.D. Although much of this area drained at low water parts did remain covered by surface water. This area was covered in approximately 13-34cm. of fine mud.
Sites 4-7: (‘Vegetation plots’)	Each of the four ‘treatments’ (see above) were represented by one strip of land in each of the three replicates for each site. Each strip sloped down the shore from the new embankment (approx. 2.5m above O.D.), to the south of the study area, north to the stream (approx. 1.25-1.5m above O.D.). At the southern end of these strips the land drained completely at low water whilst at the northern end the strips remained covered in surface water. The land sloped down from R1 to R3 and from the new sea wall above R1-3 towards the draining stream. Thus, the mid and lower levels of sites 4-7 were wetter and muddier than the upper levels and the mid and lower levels of R3 were much muddier than those of R2 or R1. The lower levels of R3 (sites 4-7) resembled soft intertidal mudflat similar to that found outside the realignment area. Saltmarsh (*Salicornia europaea*, *S. ramosissima*) had developed on the upper levels of each replicate. By 2007 the lowest parts of these sites was covered in 10-35cm of fine mud.
Site 8 : (‘Marsh’)	To provide a baseline from which to compare the intertidal invertebrate fauna within the study area with that outside, an area of intertidal mud flat within the marsh to the east of the existing sea wall was selected. This comprised very fine sediments which drained well at low water.

1.4 METHODS

Nine 10cm diameter core samples were taken from each of the eight sites (Map. 1.1). At sites 2, 3 and 8 they were taken in the form of a 3x3 grid whilst at site 1 they were taken in the form of a line transect. In each of the four vegetation treatment areas (sites 4-7) three samples were taken in each treatment of each replicate such that for any given treatment there were, overall, nine samples in the form of a grid with three taken near the top of the shore (upper), three at the mid shore level (mid) and three at the lowest level of the shore (lower). The depth to which each sample was taken was determined by the hardness of the substrate such that full depth cores (15cm) were taken in sites 1 (ditch) and 8 (marsh) whilst in sites 2-7 they were taken to varying depths up to 15cm. Examination of the substrate at those sites where full depth core samples could not be taken revealed that it was too compacted to allow intertidal invertebrates to colonise below the soft surface layers.

Samples were sieved on site using a 0.5mm (500µm) brass sieve and the sieved part of each sample preserved in 5% formal saline. All animals (except oligochaetes) were identified to genus and most to species. The number of individuals of each species/sample was recorded.

Data analysis was done using one-way analysis of variance in MINITAB.

1.5 RESULTS

1.5.1 Distribution of species

Twenty two (22) invertebrate species were found in the 72 samples taken from the 8 sampling areas at Tollesbury (Table 1.1, Maps 1.2-1.23). Of these, three molluscs, the gastropod *Hydrobia ulvae* and the bivalves *Abra tenuis*, and *Scrobicularia plana*; three errant polychaetes *Eteone longa*, *Nephtys hombergi*, and *Nereis diversicolor*; one sedentary polychaete *Pygospio elegans*; Oligochaetes; two crustaceans *Carcinus maenas* and *Crangon vulgaris* and diptera maggots occurred in all 8 sampling areas. These species were also the most widely distributed invertebrates, occurring in 19-70 (26-97%) of the core samples. The bivalve *Macoma balthica*, was also abundant, occurring in 7 of the sampling areas and 24 (33%) of the core samples. Six (6) of the species were found in just one sample area.

Sixteen (16) of the 22 invertebrate species identified, were found in the marsh samples (site 8) and 21 in the realignment samples (sites 1-7). *Gammarus sp.* was the only invertebrate species that occurred solely in the marsh samples (site 8). Within the realignment area the 7 sites divided into two groups as defined by the number of invertebrate species found within them. Sites 1, 2, 6 & 7 each had 11-13 species whilst sites 3, 4 & 5 each had 15-16 species.

There was no significant difference between the mean numbers of species found per sample in each of the four treatments (sites 4-7). With the exception of site 3, the mean numbers of species found in samples from sites within the realignment area (1, 2, 4, 5, 6 & 7) were all significantly lower ($p \leq 0.036$) than those found in the marsh samples (site 8). However, within the realignment area (sites 1-7), the mean numbers of species found in samples from sites 3, 4 & 5 were not significantly different whilst the mean number of species found in samples from site 3 was significantly higher ($p \leq 0.039$) than those found in samples from sites 1, 2, 6 & 7. Interestingly, there were no significant differences in the mean numbers of species found in samples from sites 4 and 5, and the other sites within the realignment area (Table 1.2).

Within sites 4-7 where samples were taken from the upper, mid and lower shore levels in each replicate significantly fewer species per sample were recorded from the upper shore than from either the mid or lower shore (Table 1.3). There was no significant difference in the mean number of species found per sample between the mid and lower shore levels.

1.5.2 Density of species

The relative abundance of the 18 invertebrate species found in 2007 in the marsh (site 8) and re-alignment area (sites 1-7) is shown in Table 1.1. The most abundant invertebrate in both areas was *H. ulvae* with a mean density of 63.9 individuals per sample (8,136/m^2) on the marsh compared with 196.4 per sample (14,362/m^2) in sites 1-7 (range/site: 0-67,864/m^2). The other ten species occurring at all 8 sites were *Abra tenuis* with a mean sample density of 5.2 (662/m^2) in the marsh and 11.9 (1,515/m^2) in sites 1-7 (range/site: 0-16,170/m^2), *Scrobicularia plana* with a mean sample density of 1.3 (165/m^2) on the marsh and 1.2 (147/m^2) in sites 1-7 (range/site: 0-1273/m^2), *Eteone longa* with a mean sample density of 1.6 (204/m^2) in the marsh and 1.0 (122/m^2) in sites 1-7 (range/site: 0-637/m^2), *Nephtys sp.* with a mean sample density of 1.6 (204/m^2) on the marsh and 1.0 (127/m^2) in sites 1-7 (range/site: 0-891/m^2), *N. diversicolor* with a mean sample density of 1.2 (153/m^2) on the marsh and 2.8 (353/m^2) in sites 1-7 (range/site: 0-2,674/m^2), *Pygospio elegans* with a mean sample density of 6.3 (802/m^2) on the marsh and 2.8 (351/m^2) in sites 1-7 (range/site: 0-3,692/m^2), *Oligochaetes* with a mean sample density of 70.9 (9,027/m^2) on the marsh and 79.5 (10,124/m^2) in sites 1-7 (range/site: 0-95,748/m^2), *Carcinas maenas* with a mean sample density of 0.8 (102/m^2) on the marsh and 0.5 (60/m^2) in sites 1-7 (range/site: 0-509/m^2), *Crangon vulgaris* with a mean sample density of 12.6 (1,604/m^2) on the marsh and 4.0 (506/m^2) in sites 1-7 (range/site: 0-4,074/m^2), *Diptera* maggots with a mean sample density of 0.1 (13/m^2) on the marsh and 0.6 (80/m^2) in sites 1-7 (range/site: 0-509/m^2).

1.5.3 Comparing the results of the 1995, 1996, 1997, 1998, 2001, 2004 and 2007surveys

1.5.3.1 Species number and distribution

The total number of intertidal invertebrate species found within the realignment area in 2007 was 21, and with the exception of 2004 (18 species), represents an increasing and significant ($p=0.046$, $r^2 = 58.1\%$, $n = 7$) trend in the species diversity of the study area since 1995 (Fig. 1.1). With the exception of the gastropod *Litorina littorea*, that was found for the first time in 2007, the overall composition of mollusc species recorded (5) was essentially similar to that found in previous years. The number of locations where each species occurred also followed the same trend as in the previous three surveys (1998, 2001 & 2004) with *H. ulvae* being the most abundant gastropod and *A. tenuis* being the most abundant bivalve. *H. ulvae* was the only species that occurred at all sites during each of the six survey years since 1995 and over the same period increased its overall distribution from 74% of samples (n=53) in 1995 to 100% (n=72) in 2004 (Table 1.4). Similarly *M. balthica* was found at two sites (11 samples) in 1995 and all eight sites (30 samples) in 2004, though not in site 1 in 2007. Over the ten years since 1995 the distribution of *M. balthica* was greatest in 2001 (44 samples) and fell back to 1997 levels in 2007. The distribution of *A. tenuis* also peaked in 2001 (62 samples) and returned to similar levels as those found in 1998 (45 samples) in 2007. The relatively large bivalve, *S. plana*, was found each year and the number of sites at which it occurred increased from one in 1995 to all eight in 2004 and 2007. The number of samples in which it was found has also increased steadily from 16 in 2001 to 34 in 2004, showing a continued trend towards an increase in its distribution since 1995. Although the number of sites, and samples, containing *C. edule* both increased between 1995 and 2004, they declined back to 1998 levels in 2007. Its overall density and distribution has remained relatively low.

During 2007 a total of eight annelid species were found in the eight sites and, with the exception of 1995 (6 species) was essentially similar to that found in previous years (nine in 1996, 1997 & 2001, eight in 1998 and seven in 2004). With the exception of *Spio filicornis*, which was again absent from all samples in 2007, as in the three previous surveys, all the species found in 1995 were also found during subsequent surveys. One errant polychaete, *Phyllodoce maculata*, which was found at very low densities within the realignment area in 1997 and 1998, but was absent in

2001, was again present at a very low density in one lower shore sample in 2007 (Table 1.4, Map 1.10). Oligochates continued to be found at all eight sites though their distribution in 2007 (59 samples) was slightly lower than in 2004(63 samples).

The shore crab (*Carcinus maenas*) continued to increase its distribution within the study area and was found in all eight sites in 2007 and in 19 samples, an increase of 12 samples over 2004 (Table 1.4).

Dipteran maggots were again relatively widespread in 2007 and continued to an increase in the number of sites, and total number of samples, in which it was found compared with previous years (Table 1.4).

The number of species common to all 8 sites increased from a minimum of two in 1995 to eleven in 2007. One species (*M. balthica*) occurred at seven of the eight sites in 2007 (Table 1.4). Overall, the distribution of many species, in terms of the total number of samples in which they were found, increased, or remained relatively constant in 2007 compared with 2004 (Table 1.4) continuing the trend for increasing colonisation over time. In each of the seven years of survey, the gastropod (*H. ulvae*) has consistently remained the most common and widespread invertebrate. It has also been recorded from progressively more samples in each survey to the point where it was recorded from every sample in 2001 and 2004 though not in 2007 (Table 1.4). Three bivalve molluscs and four annelids are also worthy of note. Although *A. tenuis* has continued to occur in all eight sites, the total number of samples in which it was found decreased between 2001 and 2007 suggesting a slight decrease in its overall distribution. However, the decline between 2004 and 2007 was small and almost certainly not significant. The Baltic telling *M. balthica* also occurred in fewer sites and fewer samples overall on 2007 compared with both 2004 and 2001 suggesting that this may be a declining trend. The opposite was true for *S. plana*, which was found in all eight sites and in more samples in 2007 than in 2004. This species has shown a continued trend for range expansion within the study area since 1995. The apparent decline in the distribution of the rag worm, *N. diversicolor*, between 1997 and 2004 was not continued into 2007 when it was found in slightly more samples than in 2004 (Table 1.4). The smaller *E. longa* that showed a decline in its distribution within the study area between 2001 and 2004 increased its range in 2007, occurring in 31 samples compared with 28 in 2004. The distribution of *Nephtys sp.* in 2007 showed no change over 2004 or since about 1998.

The total numbers of species recorded in each of the eight sites during each survey are shown in Fig. 1.2. The total number of intertidal species recorded within the realignment area, increased at two sites (3 & 5) between 2004 and 2007, decreased at one site (1) and remained unchanged at four sites (2, 4,6 & 7). The numbers of species found in each of the seven sites, within the realignment area, were all equal to or less than (range=11-15) than the number found in the marsh samples (n=16). Overall, the eight sites fell into two groups. The first comprised of sites 3, 4, 5 & 8, all with either 15 or 16 species. The second group comprised of sites 1, 2, 6 & 7, all with between 11-13 species.

The mean number of species recorded for each sample within the eight sites is shown in Table 1.5a where differences between years at each site are presented. Between 2004 and 2007 there were two significant changes ($p>0.05$) in the mean number of species per sample at sites 5 and 8. Overall, during the 12 years between 1995 and 2007 significant increases ($p<0.05$) in the mean number of species per sample were recorded in five of the re-alignment sites (sites 3, 4, 5, 6 & 7; Table 1.5b).

One of the original aims of the annual surveys was to determine the length of time required for farmland to become indistinguishable from established intertidal mud-flat in terms of its invertebrate fauna. This was done by comparing the numbers of species occurring in the marsh (site 8) with the individual sites within the managed realignment area (Fig. 1.3). Over the 12 years since inundation by sea-water, in 1995, the number of 'marsh species' that have been recorded from within the realignment area has shown an overall increase that was relatively rapid between 1995 and 2001 and then much slower until 2007 when there was another apparent rapid increase. The mean number of species, per site (n=7), within the managed realignment area was also compared with the mean number of species within the marsh (Fig. 1.4). This showed a relatively stable situation within the marsh between 1995 and 2007 whilst within the realignment area there was a rapid increase over the first four surveys (1995-1998) followed by a less rapid increase between 1998 and 2007. The data suggest that although there appears to be relative stability in the number of species occurring in the marsh the number of species occurring within the realignment area is still increasing, albeit at a much reduced rate, and may exceed that of the marsh in the future.

The mean numbers of invertebrate species found/sample during each survey at each site are shown in Fig. 1.5. Taken individually, each of the sites within the realignment area, with the exception of site 3, showed a relatively steady increase in the number of species found in them between the first and last surveys. However, there was an overall tendency for the rate of increase to slow down during the latter years. Also, the total number of species found in each of the realignment sites, with the single exception of site 3, remained below that of the marsh (site 8). At site 3, there was a rapid increase in the number of species found between 1995 and 1998 followed by a relatively 'steady state'. When the samples from the seven realignment sites were analysed together (sites 1-7 in Fig. 1.5), for comparison with the marsh site it is clear that, overall, the mean number of species/sample within the realignment site is still lower than that of the marsh site.

The invertebrate sample data were also analysed with respect to shore level (Fig. 1.5). These data do not include the samples from site 1 which were not subdivided by shore level as the site ran parallel to the sea wall. The mean number of invertebrate species found in upper, mid and lower shore samples has increased steadily throughout the study period (1995-2007). This increase was highest in the mid and lower shore samples between 1995 and 1998, after which the rate of increase slowed down. The rate of increase in the upper shore samples was highest between 1995 and 2001 before slowing down. During the first three surveys (1995-1997) the mean number of invertebrate species found in the upper, mid and lower shore samples from sites 2-7 were all significantly ($p<0.0001$) lower than that found in the marsh. In the surveys of 1998, 2001 and 2004 there was no significant ($p>0.05$) difference between the mid and lower shore samples from sites 2-7 and the marsh whilst there remained significant ($p<0.03$) differences between the upper samples from sites 2-7 and the marsh. In contrast, there were significant ($p<0.05$) differences in the number of invertebrate species found in the upper and lower shore samples from sites 2-7 and the marsh in 2007 but not between the mid shore samples and the marsh. As might be expected, the mean number of invertebrate species/sample in sites 2-7 showed a gradient between upper and lower shore levels with the lowest values occurring in samples from the top of the shore and the highest values from those at the bottom of the shore. Overall, the pattern of annual fluctuations in the mean number of invertebrate species per sample from sites 2-7 and site 8 were similar between 1998 and 2007.

Similarly, comparisons between the mean number of species found in samples from the upper, mid and lower shore levels of sites 4-7 (treatments) for 1995, 1996, 1997, 1998, 2001, 2004 and

2007 are shown in Table 1.6. The mean number of species found in the upper shore samples from sites 4-7 increased annually with the greatest difference occurring between 1995 and 2004 ($p<0.0001$). Although increases between consecutive surveys were also found for the mid and lower shore levels they were not all significant between consecutive years. Nevertheless, highly significant increases ($p<0.0001$) in the mid and lower shore samples were found between 1995 and 2007.

1.5.3.2 Density of species

A comparison of the mean number of individuals of 5 of the most abundant invertebrate species found in samples from all 7 sites inside the realignment area and the marsh site for 1995, 1996, 1997, 1998, 2001, 2004 & 2007 are shown in Table 1.7a&b respectively. In the realignment area (sites 1-7) no significant ($p>0.05$) increases were found in any of the 5 species between 2004 and 2007. In contrast, there was a significant ($p=0.016$) decrease in the density of *H. ulvae* between 2004 and 2007. Between 1995 and 2007 the density of all the species, except *N. diversicolor*, increased significantly ($p<0.01$). Following a significant increase in the density of *N. diversicolor* between 1995 and 1997 their density is now significantly lower than in 1996/97 but, nevertheless, appears to have stabilised over the last four surveys (1998, 2001, 2004 & 2007). The density of *diptera* larvae has remained relatively constant and low since 1996.

In the marsh samples, the pattern of change in the density of the 5 invertebrate species reflected that found within the realignment area. Between 1995 and 2007 the densities of *M. balthica* and *N. diversicolor* both declined significantly ($p<0.05$) whilst in the realignment area they either increased significantly (*M. balthica*; $p=0.007$) or showed no significant change (*N. diversicolor*; $p>0.05$).

1.6 DISCUSSION

With the exception of one small area in the north-east of the Tollesbury realignment site which contained a large number of experimental areas, core samples were obtained from most of the realignment site allowing the distribution of colonising intertidal invertebrates to be roughly mapped. The results show that the areas being colonised are generally those that are lowest on the shore. This was not unexpected as these areas are the ones covered for the longest time by sea water at high tide and also the ones that have the highest rates of accretion by fine 'muddy' sediments which many intertidal estuarine invertebrates prefer/require.

In common with previous surveys (1995, 1996, 1997, 1998, 2001 & 2004) all except one (*Gammarus sp.*) of the species found within the marsh site in 2007 were also found in the realignment area (Reading 1996, 1997, 1998, 1999, 2002, 2005). Some additional invertebrate species e.g. the molluscs: *L. littorea* and *C. edule*; the crustacean: *P. varians*; the insect: *Coleoptera* larvae; the nemertine and the anemone, were found in the realignment area but not in the marsh, perhaps reflecting the greater habitat diversity of the realignment area sites compared with that of the marsh site. In addition, more species were found in the realignment area in 2007 (21) than in the marsh (16). During the twelve years since 1995 the number of species found in the marsh samples has fluctuated between 11 and 16 with the least fluctuation (n=11-13) between 1995-2004. In contrast the number of invertebrate species found in the realignment area was initially low (n=14) but then increased and appears to have stabilised at between 18 and 21. Diversity, as measured by the number of different species present, remains greater within the realignment area than in the marsh and probably reflects the greater diversity of sediment/substrate types and elevation levels within the area compared to outside. Alternatively, the greater diversity may be the result of an increased probability of finding more species due to the larger number of samples taken from within the realignment area compared with the marsh.

Although the number of species recorded from each of the sites (1-7) within the realignment area is now very similar to that for the marsh their distribution is ‘patchy’, as illustrated by the mean number of species per sample from each site (Fig. 1.4). This patchy distribution is probably the result of differences in rates of accretion of soft sediments within the realignment area, with high rates on the lower shore and lower rates, or scouring of soft sediments, on the upper shore and areas close to the breach (site 2). The association between high levels of soft sediment accretion on the lower shore and higher numbers of invertebrate species and higher densities of many of these species is demonstrated by the data shown in Fig. 1.6. The particularly high total number of species found in site 3 is probably due to the large area of this site resulting in a more varied habitat structure than that found in the marsh. Overall, the lower shore levels within the realignment area are more similar to the marsh than the upper shore levels.

The continuing trend for species common to both the realignment area and the marsh to occur at higher densities in the realignment area than in the marsh has continued into 2007. This is probably the result of a combination of the structure of the substrate within the realignment area and the time elapsed since the sea wall (and the flooding of the area) was breached and is an indication of the rate at which the realignment area is transforming into intertidal mud flat through the deposition of fine sediments. In 1998 this was particularly noticeable at the lower levels of sites 2, 3, 4-7 whilst in 2001 this effect was also apparent at mid shore levels. In 2004 it was noticeable on most the upper shore, particularly amongst the colonising saltmarsh, which had extended its downshore range significantly since 2001. The accretion of fine sediments on all levels of the shore was very marked in 2007, as was the continued downshore progress of the saltmarsh. Much of the realignment area is now not visibly different from many saltmarshes and intertidal mudflats found elsewhere in the UK though it still lacks the creek systems found in the mature saltmarsh outside the realignment site.

As a result of the baseline survey carried out during October 1995 it has been possible to monitor and quantify the changes in the intertidal invertebrate fauna of the realignment area from the subsequent invertebrate surveys completed during the October of 1996, 1997, 1998, 2001, 2004 and 2007. The mean numbers of invertebrate species found in samples from within the realignment site are continuing to rise, albeit at reduced rates compared with the first three years following initial inundation of the area, but, in 2007, were still below that of the marsh samples. This process of change is likely to continue for a number of years, its rate being determined largely by the degree to which sediment accretion continues to occur within the realignment area and the rate at which the saltmarsh extends downshore. As the sediment levels within the realignment area rise it is likely that the area of saltmarsh will increase and the area of intertidal mud flat decrease. The loss of intertidal mudflat will reduce the feeding/roosting area available for wading birds at low water and this is likely to be reflected in a decline, over time, in the number and/or species diversity of birds using the area.

The October 2007 survey of the managed realignment area at Tollesbury, Essex is the seventh, and final, survey planned to monitor the rate of colonisation of the area, following tidal inundation (1995), by intertidal invertebrates. As the length of time, since the sea wall was first breached (1995), increases, it is likely that the rate of colonisation of the realignment area, by intertidal invertebrates, will continue to decline and that the density of successful colonisers within the realignment area will increase.

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1.8 REFERENCES

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1.9 APPENDIX 1.1

Tables 1.1 – 1.7

Table 1.1 Mean number of individuals/sample of each intertidal invertebrate species in each of the areas sampled at Tollesbury, Essex, in October 2007.

SPECIES		SITE								
		1	2	3	4	5	6	7	8	**TOTAL SITES**
	MOLLUSCS									
1	*Hydrobia ulvae*	137.9	86.6	165.4	98.6	159.4	80.0	62.0	63.9	**8**(70)
2	*Littorina littorea*	-	-	-	0.1	-	-	-	-	**1**(1)
3	*Abra tenuis*	0.8	0.3	11.0	11.1	7.1	35.8	17.2	5.2	**8**(43)
4	*Cerastoderma edule*	-	0.1	0.2	0.1	-	-	-	-	**3**(4)
5	*Macoma balthica*	-	0.3	2.0	2.8	0.4	3.7	0.9	0.8	**7**(24)
6	*Scrobicularia plana*	0.3	0.2	2.1	1.2	0.9	2.2	1.2	1.3	**8**(34)
	ANNELIDS									
7	*Ampharete grubei*	-	-	0.2	0.1	-	-	-	0.1	**3**(4)
8	*Eteone longa*	0.9	0.6	0.2	1.8	1.8	1.3	0.1	1.6	**8**(31)
9	*Phyllodoce maculata*	-	-	0.1	-	-	-	-	0.1	**2**(2)
10	*Nephtys sp.*	0.3	0.1	2.7	0.8	1.2	1.1	0.8	1.6	**8**(31)
11	*Nereis diversicolor*	7.3	2.0	0.1	1.3	2.8	3.8	2.1	1.2	**8**(43)
12	*Pygospio elegans*	2.8	0.3	6.2	1.8	0.7	7.2	0.3	6.3	**8**(32)
13	*Cirratulid sp.*	-	-	-	0.2	0.1	-	-	1.7	**3**(6)
14	*Oligochaetes*	21.1	219.2	123.0	53.7	51.8	74.8	13.0	70.9	**8**(59)
	CRUSTACEANS									
15	*Carcinus maenas*	0.1	0.7	0.2	0.9	0.1	0.2	0.3	0.8	**8**(19)
16	*Crangon vulgaris*	4.8	2.4	9.3	1.7	2.8	1.6	5.2	12.6	**8**(56)
17	*Palaemonetes varians*	-	-	0.3	-	-	-	-	-	**1**(3)
18	*Gammarus sp.*	-	-	-	-	-	-	-	0.1	**1**(1)
	OTHER									
19	*Diptera* : maggots	0.8	1.0	0.1	0.9	0.7	0.7	0.2	0.1	**8**(26)
20	*Coleoptera larvae*	-	-	-	-	0.1	-	-	-	**1**(1)
21	*Nemertine*	-	-	-	-	0.1	-	-	-	**1**(1)
22	*Anemone sp.*	-	-	-	-	-	-	0.2	-	**1**(2)
	TOTAL SPECIES	**11**	**13**	**16**	**16**	**15**	**12**	**13**	**16**	
Mean	No. species/sample	5.0	5.6	8.8	6.9	7.1	6.3	5.9	9.2	

Nos. in parenthesis are the total number of samples in which a species was found (Total=72)

Table 1.2 Differences between the mean number of species per sample (in parenthesis) for each site (Table 1.1) at Tollesbury, Essex, in October 2007.

	Site 2 (5.56)	Site 3 (8.78)	Site 4 (6.89)	Site 5 (7.11)	Site 6 (6.33)	Site 7 (5.89)	Site 8 (9.22)
Site 1 (5.00)	t=-0.53 NS DF=16	**t=-4.09 P=0.001 DF=16**	t=-1.61 NS DF=16	t=-2.04 NS DF=16	t=-1.07 NS DF=16	t=-0.68 NS DF=16	**t=-4.49 P=<0.001 DF=16**
Site 2 (5.56)	-	**t=-3.73 P=0.002 DF=16**	t=-1.19 NS DF=16	t=-1.59 NS DF=16	t=-0.65 NS DF=16	t=-0.26 NS DF=16	**t=-4.17 P=0.001 DF=16**
Site 3 (8.78)	-	-	t=1.88 NS DF=16	t=1.99 NS DF=16	**t=2.24 P=0.039 DF=16**	**t=2.50 P=0.030 DF=11**	t=-0.62 NS DF=16
Site 4 (6.89)	-	-	-	t=-0.20 NS DF=16	t=0.43 NS DF=16	t=0.73 NS DF=16	**t=-2.29 P=0.036 DF=16**
Site 5 (7.11)	-	-	-	-	t=0.66 NS DF=16	t=0.98 NS DF=16	**t=-2.47 P=0.025 DF=16**
Site 6 (6.33)	-	-	-	-	-	t=0.31 NS DF=16	**t=-2.62 P=0.019 DF=16**
Site 7 (5.89)	-	-	-	-	-	-	**t=-2.85 P=0.016 DF=11**

NS = Non-significant (P>0.05)

Table 1.3 Differences between the mean number of species per sample (in parenthesis) for upper, mid and lower shore levels in sites 4-7 at Tollesbury, Essex, in October 2007.

	Mid (sites 4-7) (Mean = 7.67)	Lower (sites 4-7) (Mean = 7.50)
Upper (sites 4-7) (Mean = 4.50)	**t = -3.68 P = 0.001 DF = 22**	**t = -3.59 P = 0.002 DF = 22**
Mid (sites 4-7) (Mean = 7.67)	-	t = 0.16 NS DF = 22

NS = Non-significant (P>0.05)

Table 1.4 Total number of sites and samples from Tollesbury, Essex, in which each intertidal invertebrate species was recorded for the years 1995, 1996, 1997, 1998, 2001, 2004 & 2007. Total number of samples taken each year = 72.

SPECIES	1995		1996		1997		1998		2001		2004		2007	
	No. Sites	No. Samples	No. Sites	No. Samples	No. Sites	No. Samples	No. Sites	No. Samples	No. Sites	No. Samples	No. Sites	No. Samples	No. Sites	No. Samples
Hydrobia ulvae	8	53	8	58	8	65	8	69	8	72	8	72	8	70
Littorina littorea	-	-	-	-	-	-	-	-	-	-	-	-	1	1
Retusa obtuse	1	1	-	-	-	-	1	2	1	2	-	-	-	-
Abra tenuis	-	-	-	-	-	-	8	45	8	62	8	45	8	43
Cerastoderma edule	1	1	1	1	2	2	5	5	5	13	7	17	3	4
Macoma balthica	2	11	8	30	8	24	8	38	8	44	8	30	7	24
Mya arenaria	-	-	3	11	8	34	-	-	-	-	-	-	-	-
Nucula sp.	-	-	1	1	-	-	-	-	-	-	-	-	-	-
Scrobicularia plana	1	9	5	15	6	11	6	10	7	16	8	31	8	34
Ampharete grubei	-	-	3	9	2	3	5	9	6	10	2	2	3	4
Arenicola marina	-	-	1	2	-	-	-	-	1	1	-	-	-	-
Cirratulid sp.	-	-	4	12	3	7	3	10	3	4	-	-	3	6
Eteone longa	3	14	7	18	6	11	7	20	8	39	8	27	8	31
Mellina cristata	-	-	-	-	-	-	-	-	1	1	-	-	-	-
Nephtys hombergi	4	12	2	5	6	15	7	33	8	32	8	28	8	31
Nereis diversicolor	8	40	8	63	8	63	8	48	8	46	8	40	8	43
Phyllodoce maculata	-	-	-	-	1	2	1	1	-	-	1	1	2	2
Pygospio elegans	7	34	5	14	4	11	6	12	5	16	7	31	8	32
Spio filicornis	3	14	2	10	3	4	-	-	-	-	-	-	-	-
Oligochaetes	2	13	3	13	2	15	3	19	8	54	8	63	8	59
Carcinus maenas	3	3	1	1	3	3	2	2	2	2	5	7	8	19
Crangon vulgaris	3	5	2	2	1	2	2	2	1	1	-	-	8	56
Palaemonetes varians	-	-	-	-	-	-	-	-	-	-	-	-	1	3
Cyathura carinata	-	-	-	-	-	-	-	-	1	2	-	-	-	-
Gammarus sp.	1	1	-	-	-	-	1	3	-	-	1	1	1	1
Coleoptera larvae	-	-	-	-	-	-	1	1	-	-	2	2	1	1
Diptera : chironomids	5	8	-	-	-	-	-	-	-	-	-	-	-	-
Diptera : maggots	5	11	8	24	8	18	7	14	7	22	7	23	8	26
Collembola sp.	-	-	-	-	-	-	-	-	-	-	1	1	-	-
Nemertine	-	-	-	-	1	3	3	4	1	2	4	6	1	1
Anemone sp.	-	-	-	-	-	-	-	-	-	-	-	-	1	2

Table 1.5a Comparisons between the mean number of species per sample for each site (Table 1) at Tollesbury, Essex between October 1995 and October 2007. Standard errors of the mean are shown in parenthesis.

	Mean 1995	Comparing 1995-1996	Mean 1996	Comparing 1996-1997	Mean 1997	Comparing 1997-1998	Mean 1998	Comparing 1998-2001	Mean 2001	Comparing 2001-2004	Mean 2004	Comparing 2004-2007	Mean 2007
Site – 1 Ditch	3.67 (0.47)	t = -1.10 NS DF = 15	4.44 (0.53)	t = 2.17 **P = 0.046** DF = 15	2.67 (0.62)	t = 0.90 NS DF = 15	3.44 (0.60)	t = -3.40 **P = 0.004** DF = 15	6.56 (0.69)	t = 1.59 NS DF = 15	4.78 (0.88)	t = -0.19 NS DF = 16	5.00 (0.78)
Site – 2 Lower clover	4.00 (0.55)	t = -0.80 NS DF = 15	4.67 (0.62)	t = 0.89 NS DF = 13	4.00 (0.41)	t = 0.0 NS DF = 14	4.00 (0.60)	t = -2.47 **P = 0.028** DF = 13	6.67 (0.90)	t = 1.38 NS DF = 14	5.11 (0.68)	t = -0.45 NS DF = 16	5.56 (0.71)
Site – 3 Upper clover	2.89 (0.31)	t = -1.84 NS DF = 15	3.67 (0.29)	t = -2.36 **P = 0.036** DF = 12	5.11 (0.54)	t = 3.51 **P = 0.003** DF = 15	8.00 (0.62)	t = 0.15 NS DF = 13	7.89 (0.39)	t = 0.36 NS DF = 15	8.11 (0.48)	t = -0.96 NS DF = 16	8.78 (0.49)
Site – 4 Stubble	1.67 (0.55)	t = -1.74 NS DF = 15	3.22 (0.70)	t = 0.0 NS DF = 13	3.22 (0.46)	t = 0.92 NS DF = 13	4.00 (0.71)	t = -0.62 NS DF = 15	4.67 (0.82)	t = 0.68 NS DF = 15	5.56 (1.00)	t = -1.00 NS DF = 16	6.89 (0.87)
Site – 5 Ploughed	1.67 (0.41)	t = -2.17 **P = 0.047** DF = 15	2.89 (0.39)	t = -0.49 NS DF = 11	3.33 (0.82)	t = 0.43 NS DF = 14	3.78 (0.62)	t = -1.39 NS DF = 15	5.00 (0.62)	t = 0.53 NS DF = 15	4.56 (0.56)	t = -2.92 **P = 0.010** DF = 16	7.11 (0.68)
Site –6 Rye grass	1.44 (0.53)	t = -1.44 NS DF = 14	2.78 (0.76	t = -0.93 NS DF = 14	3.67 (0.58)	t = 0.59 NS DF = 15	4.22 (0.74)	t = -1.08 NS DF = 15	5.44 (0.85)	t = 0.63 NS DF = 15	6.22 (0.89)	t = -0.08 NS DF = 16	6.33 (0.97)
Site – 7 Cultivated	1.78 (0.40)	t = -1.00 NS DF = 14	2.44 (0.53)	t = -1.27 NS DF = 15	3.44 (0.58)	t = 1.19 NS DF = 15	4.44 (0.60)	t = -1.19 NS DF = 15	5.56 (0.71)	t = 0.11 NS DF = 15	5.67 (0.71)	t = -0.18 NS DF = 16	5.89 (1.05)
Site – 8 Marsh	8.78 (0.36)	t = 2.14 **P = 0.054** DF = 12	7.89 (0.20)	t = 1.92 NS DF = 12	7.11 (0.35)	t = -1.05 NS DF = 13	6.67 (0.24)	t = -1.41 NS DF = 9	7.67 (0.67)	t = 0.15 NS DF = 10	7.56 (0.29)	t = -2.79 **P = 0.013** DF = 16	9.22 (0.52)

X_m = mean; DF = degrees of freedom; NS = Non-significant (P>0.05)

Table 1.5b Comparisons between the mean number of species per sample for each site (Table 1) at Tollesbury, Essex between October 1995 and October 2007. Standard errors of the mean are shown in parenthesis.

	Comparing 1995-1997	Comparing 1995-1998	Comparing 1995-2001	Comparing 1995-2004	Comparing 1995-2007
Site – 1 Ditch	t = 1.28 NS DF = 14	t = -0.29 NS DF = 15	t = 3.46 **P = 0.004** DF = 14	t = -1.11 NS DF = 12	t = -1.46 NS DF = 16
Site – 2 Lower clover	t = 0.0 NS DF = 14	t = 0.0 NS DF = 15	t = 2.53 **P = 0.025** DF = 13	t = -1.27 NS DF = 15	t = -1.73 NS DF = 16
Site – 3 Upper clover	t = -3.58 **P = 0.004** DF = 12	t = 7.34 **P <0.001** DF = 11	t = 10.06 **P <0.001** DF = 15	t = -9.09 **P <0.001** DF = 13	t = -10.11 **P <0.001** DF = 16
Site – 4 Stubble	t = -2.15 **P = 0.048** DF = 15	t = 2.49 **P = 0.025** DF = 15	t = 2.94 **P = 0.012** DF = 13	t = -3.28 **P = 0.007** DF = 12	t = -4.96 **P <0.001** DF = 16
Site – 5 Ploughed	t = -1.83 NS DF = 11	t = 2.85 **P = 0.014** DF = 13	t = 4.47 **P = 0.001** DF = 13	t = -4.19 **P = 0.001** DF = 14	t = -6.90 **P <0.001** DF = 16
Site –6 Rye grass	t = -2.84 **P = 0.013** DF = 15	t = 3.05 **P = 0.009** DF = 14	t = 3.99 **P = 0.002** DF = 13	t = -4.60 **P = 0.001** DF = 13	t = -4.42 **P <0.001** DF = 16
Site – 7 Cultivated	t = -2.36 **P = 0.033** DF = 14	t = 3.56 **P = 0.003** DF = 13	t = 4.53 **P = 0.001** DF = 12	t = -4.68 **P = 0.001** DF = 12	t = -3.58 **P = 0.005** DF = 10
Site – 8 Marsh	t = 3.29 **P = 0.005** DF = 15	t = -4.87 **P < 0.001** DF = 13	t = -1.46 NS DF = 12	t = 2.61 **P = 0.020** DF = 15	t = -0.70 NS DF = 16

X_m = mean; DF = degrees of freedom; NS = Non-significant ($P>0.05$)

Table 1.6 Comparing the mean number of species per sample for Upper, Mid and Lower shore levels in sites 4-7 at Tollesbury, Essex, between October 1995 and October 2007.

Shore level	1995	Comparing 1995-1996	1996	Comparing 1996-1997	1997	Comparing 1997-1998	1998	Comparing 1998-2001	2001	Comparing 2001-2004	2004	Comparing 2004-2007	2007
Upper	X_m = 0.83 n = 12 SD = 0.72	t = -0.67 NS DF = 19	X_m = 1.08 n = 12 SD =1.08	t = -1.38 NS DF = 21	X_m = 1.67 n = 12 SD = 0.98	t = -0.47 NS DF = 20	X_m = 1.83 n = 12 SD = 0.72	t = -3.24 **P = 0.006** DF = 14	X_m = 3.58 n = 12 SD = 1.73	t = 0.15 NS DF = 16	X_m = 3.67 n = 12 SD = 0.89	t = 1.70 NS DF = 22	X_m = 4.50 n = 12 SD = 1.45
Mid	X_m = 1.75 n = 12 SD =1.48	t = -2.98 **P = 0.0071** DF = 21	X_m = 3.42 n = 12 SD =1.24	t = -1.34 NS DF = 19	X_m = 4.25 n = 12 SD = 1.76	t = -1.22 NS DF = 21	X_m = 5.08 n = 12 SD = 1.56	t = -0.64 NS DF = 21	X_m = 5.50 n = 12 SD =1.62	t = 0.0 NS DF = 21	X_m = 5.50 n = 12 SD = 1.88	t = 2.33 **P = 0.029** DF = 22	X_m = 7.67 n = 12 SD = 2.61
Lower	X_m = 2.50 n = 12 SD =1.31	t = -2.63 **P = 0.016** DF = 21	X_m = 4.00 n = 12 SD =1.48	t = -0.63 NS DF = 20	X_m = 4.33 n = 12 SD = 1.07	t = -2.97 **P = 0.008** DF = 82	X_m = 5.42 n = 12 SD = 0.67	t = -1.46 NS DF = 12	X_m = 6.42 n = 12 SD =2.27	t = 0.92 NS DF = 21	X_m = 7.33 n = 12 SD = 2.61	t = 0.16 NS DF = 22	X_m = 7.50 n = 12 SD = 2.51

Shore level	Comparing 1995-1997	Comparing 1995-1998	Comparing 1995-2001	Comparing 1995-2004	Comparing 1995-2007
Upper	t = -2.37 **P = 0.028** DF = 20	t = -3.41 **P = 0.0025** DF = 22	t = -5.09 **P <0.0001** DF = 14	t = -8.60 **P <0.0001** DF = 21	t = -7.87 **P <0.0001** DF = 16
Mid	t = -3.76 **P = 0.0012** DF = 21	t = -5.35 **P <0.0001** DF = 21	t = -5.90 **P <0.0001** DF = 21	t = -5.42 **P <0.0001** DF = 20	t = -6.83 **P <0.0001** DF = 22
Lower	t = -3.74 **P = 0.0012** DF = 21	t = -6.85 **P <0.0001** DF = 16	t = -5.16 **P <0.0001** DF = 17	t = -5.74 **P <0.0001** DF = 16	t = -6.12 **P <0.0001** DF = 16

X_m = mean; SD = standard deviation; DF = degrees of freedom; NS = Non-significant ($P>0.05$)

Table 1.7a Comparison between the mean number of individuals per sample of 5 of the most abundant invertebrate species found within the realignment area (‘set-back’: sites 1-7) between 1995 and 2007.

Species	‘Set-back’						
	1995	1996	1997	1998	2001	2004	2007
Hydrobia ulvae	X_m = 12.59 n = 63 SD = 19.81	X_m = 23.21 n = 63 SD = 36.62	X_m = 45.37 n = 63 SD = 60.02	X_m = 123.1 n = 63 SD = 128.2	X_m = 102.2 n = 63 SD = 83.2	X_m = 196.4 n = 63 SD = 240.5	X_m = 112.8 n = 63 SD = 124.1
Macoma balthica	X_m = 0.03 n = 63 SD = 0.018	X_m = 1.19 n = 63 SD = 2.80	X_m = 1.19 n = 63 SD = 2.63	X_m = 6.14 n = 63 SD = 10.33	X_m = 3.73 n = 63 SD = 5.72	X_m = 2.02 n = 63 SD = 3.84	X_m = 1.44 n = 63 SD = 3.99
Eteone longa	X_m = 0.09 n = 63 SD = 0.29	X_m = 0.22 n = 63 SD = 0.52	X_m = 0.11 n = 63 SD = 0.32	X_m = 0.68 n = 63 SD = 1.27	X_m = 1.27 n = 63 SD = 1.75	X_m = 0.71 n = 63 SD = 1.18	X_m = 0.95 n = 63 SD = 1.45
Nereis diversicolor	X_m = 1.59 n = 63 SD = 2.26	X_m = 22.35 n = 63 SD = 16.52	X_m = 15.94 n = 63 SD = 12.57	X_m = 2.56 n = 63 SD = 4.27	X_m = 2.51 n = 63 SD = 4.51	X_m = 1.95 n = 63 SD = 2.93	X_m = 2.78 n = 63 SD = 4.66
Diptera : maggots	X_m = 0.16 n = 63 SD = 0.51	X_m = 0.73 n = 63 SD = 1.26	X_m = 0.36 n = 63 SD = 0.75	X_m = 0.24 n = 63 SD = 0.59	X_m = 0.46 n = 63 SD = 0.89	X_m = 0.59 n = 63 SD = 1.04	X_m = 0.62 n = 63 SD = 0.94

Species	‘Set-back’						
	Comparing means 1995-1996	Comparing means 1996-1997	Comparing means 1997-1998	Comparing means 1998-2001	Comparing means 2001-2004	Comparing means 2004-2007	Comparing means 1995-2007
Hydrobia ulvae	t = -2.02 **P = 0.05** DF = 95	t = -2.50 **P = 0.014** DF = 102	t = -4.36 **P <0.0001** DF = 87	t = 1.09 NS DF = 106	t = 2.94 **P <0.004** DF = 76	t = 2.45 **P = 0.016** DF = 92	t = -6.33 **P <0.0001** DF = 65
Macoma balthica	t = -3.27 **P = 0.002** DF = 62	t = 0.0 NS DF = 123	t = -3.69 **P = 0.0004** DF = 69	t = 1.62 NS DF = 96	t = -1.97 **P <0.051** DF = 108	t = 0.82 NS DF = 124	t = -2.81 **P = 0.007** DF = 62
Eteone longa	t = -1.68 NS DF = 98	t = 1.44 NS DF = 102	t = -3.47 **P = 0.0009** DF = 69	t = -2.16 **P = 0.033** DF = 112	t = -2.09 **P <0.039** DF = 108	t = -1.01 NS DF = 124	t = -4.59 **P <0.0001** DF = 67
Nereis diversicolor	t = -9.88 **P <0.0001** DF = 64	t = 2.45 **P = 0.016** DF = 115	t = 8.00 **P <0.0001** DF = 76	t = 0.06 NS DF = 123	t = -0.82 NS DF = 106	t = -1.19 NS DF = 104	t = -1.82 NS DF = 89
Diptera : maggots	t = -3.33 **P = 0.001** DF = 82	t = 1.98 NS DF = 100	t = 1.06 NS DF = 117	t = -1.65 NS DF = 107	t = 0.73 NS DF = 121	t = -0.18 NS DF = 124	t = -3.41 **P = 0.001** DF = 96

X_m = mean; SD = standard deviation; DF = degrees of freedom; NS = Non-significant ($P>0.05$)

Table 1.7b Comparison between the mean number of individuals per sample of 5 of the most abundant invertebrate species found within the Marsh (site 8) between 1995 and 2007.

Species	Marsh						
	1995	1996	1997	1998	2001	2004	2007
Hydrobia ulvae	X_m = 141.6 n = 9 SD = 103.1	X_m = 63.67 n = 9 SD = 23.07	X_m = 142.7 n = 9 SD = 65.4	X_m = 189.6 n = 9 SD = 148.2	X_m = 180.9 n = 9 SD = 73.0	X_m = 161.7 n = 9 SD = 104.1	X_m = 63.9 n = 9 SD = 36.7
Macoma balthica	X_m = 5.67 n = 9 SD = 4.61	X_m = 1.33 n = 9 SD = 1.80	X_m = 0.56 n = 9 SD = 0.88	X_m = 3.22 n = 9 SD = 2.77	X_m = 1.67 n = 9 SD = 0.87	X_m = 1.11 n = 9 SD = 0.78	X_m = 0.78 n = 9 SD = 1.39
Eteone longa	X_m = 1.44 n = 9 SD = 1.24	X_m = 1.78 n = 9 SD = 1.56	X_m = 1.0 n = 9 SD = 1.41	X_m = 0.22 n = 9 SD = 0.44	X_m = 1.33 n = 9 SD = 1.12	X_m = 0.22 n = 9 SD = 0.44	X_m = 1.56 n = 9 SD = 2.24
Nereis diversicolor	X_m = 3.78 n = 9 SD = 2.39	X_m = 8.78 n = 9 SD = 9.20	X_m = 5.78 n = 9 SD = 5.67	X_m = 3.00 n = 9 SD = 1.41	X_m = 2.44 n = 9 SD = 3.36	X_m = 1.78 n = 9 SD = 1.64	X_m = 1.22 n = 9 SD = 2.28
Diptera : *maggots*	X_m = 1.22 n = 9 SD = 1.79	X_m = 0.33 n = 9 SD = 0.71	X_m = 0.33 n = 9 SD = 0.50	X_m = 0.22 n = 9 SD = 0.67	X_m = 1.00 n = 9 SD = 1.12	X_m = 0 n = 9 SD = 0	X_m = 0.11 n = 9 SD = 0.33

Species	Marsh						
	Comparing means 1995-1996	Comparing means 1996-1997	Comparing means 1997-1998	Comparing means 1998-2001	Comparing means 2001-2004	Comparing means 2004-2007	Comparing means 1995-2007
Hydrobia ulvae	t = 2.21 NS DF = 8	t = -3.42 **P = 0.008** DF = 9	t = -0.87 NS DF = 10	t = -0.16 NS DF = 11	t = -0.45 NS DF = 14	t = 2.66 **P = 0.026** DF = 9	t = 2.13 NS DF = 9
Macoma balthica	t = 2.63 **P = 0.02** DF = 10	t = 1.16 NS DF = 11	t = -2.75 **P = 0.023** DF = 9	t = -1.61 NS DF = 9	t = -1.43 NS DF = 15	t = 0.63 NS DF = 16	t = 3.05 **P = 0.014** DF = 9
Eteone longa	t = -0.50 NS DF = 15	t = 1.11 NS DF = 15	t = 1.58 NS DF = 9	t = 2.77 **P = 0.02** DF = 10	t = -2.77 **P = 0.02** DF = 10	t = -1.75 NS DF = 8	t = -0.13 NS DF = 16
Nereis diversicolor	t = -1.58 NS DF = 9	t = 0.83 NS DF = 13	t = 1.43 NS DF = 8	t = -0.46 NS DF = 10	t = -0.54 NS DF = 11	t = 0.59 NS DF = 16	t = 2.32 **P = 0.034** DF = 16
Diptera : *maggots*	t = 1.39 NS DF = 10	t = 0.0 NS DF = 14	t = 0.40 NS DF = 14	t = 1.79 NS DF = 13	-	-	t = 1.83 NS DF = 16

X_m = mean; SD = standard deviation; DF = degrees of freedom; NS = Non-significant (P>0.05)

1.10 Appendix 1.2

Figures 1.1 – 1.6

Fig 1.1 Total number of invertebrate species recorded at Tollesbury each year

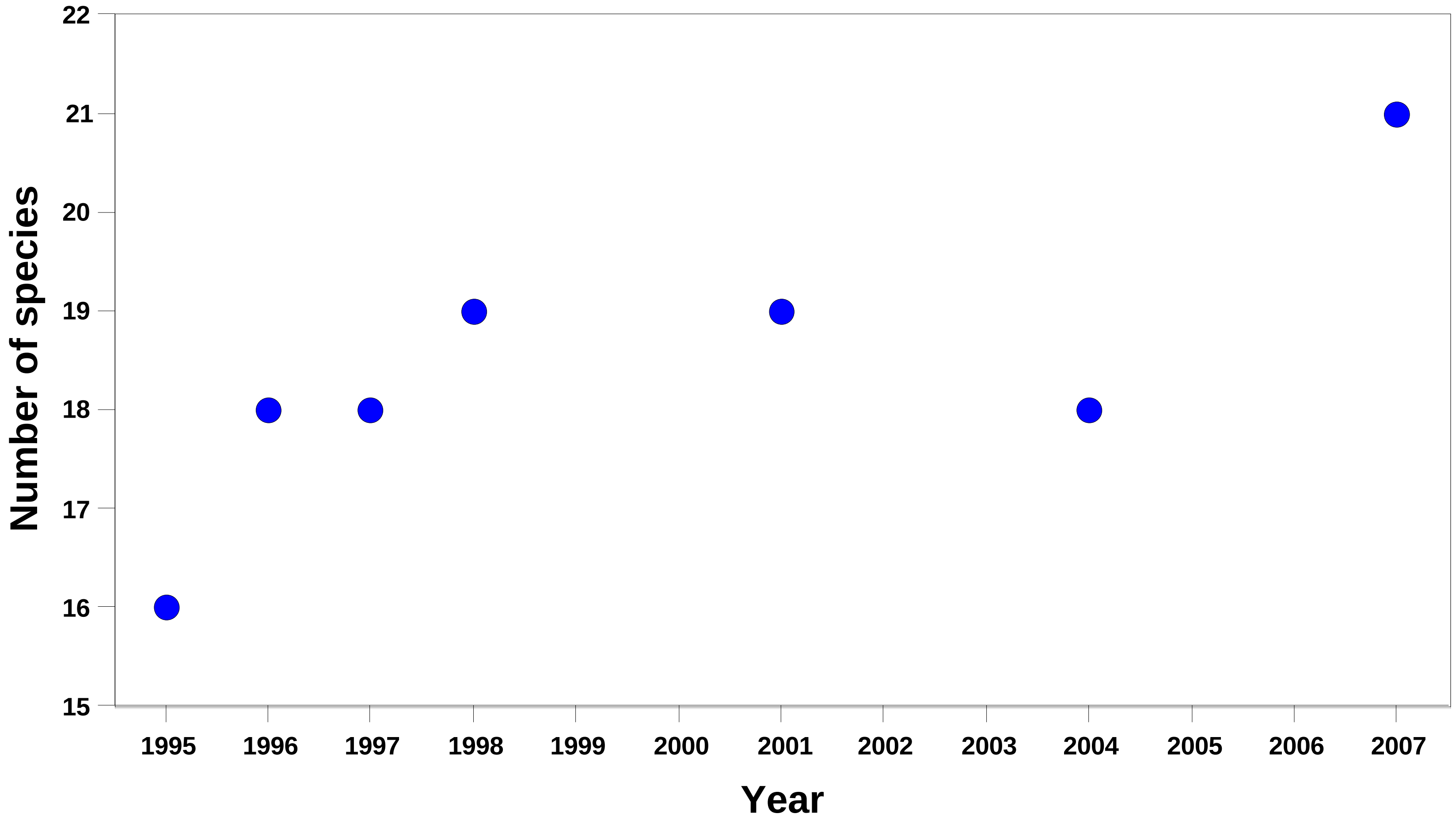
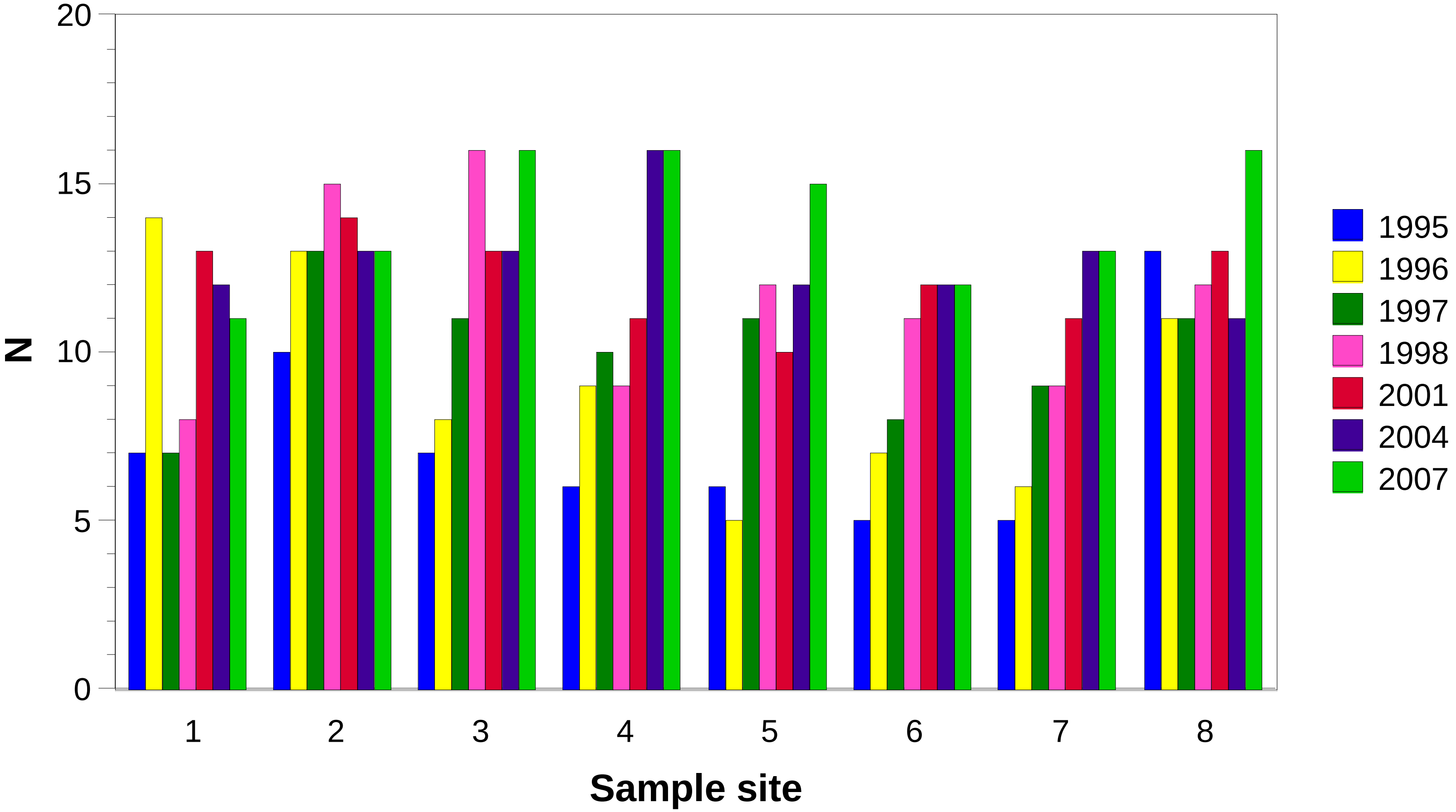
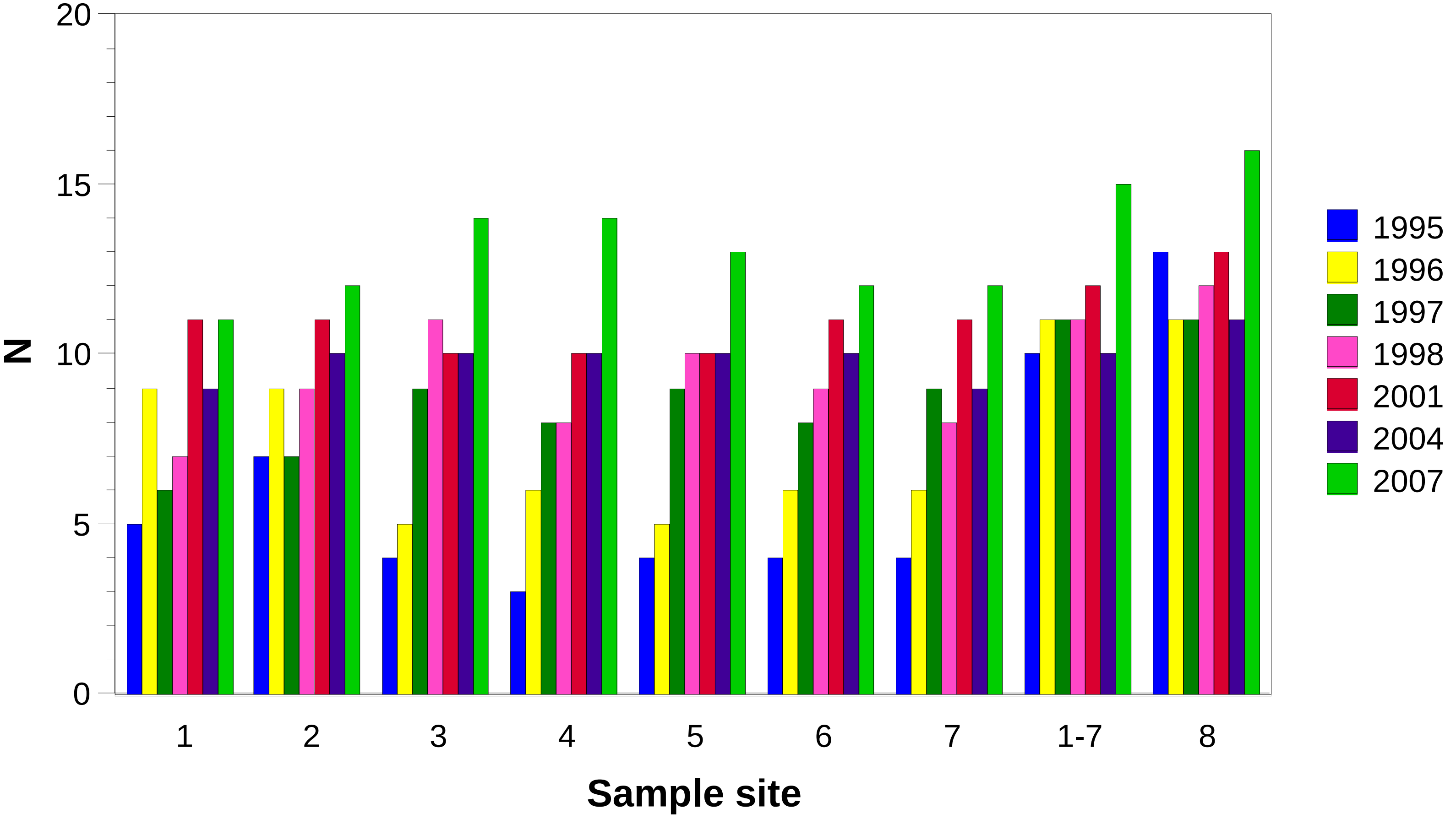


Fig 1.2 Total number of species recorded in each of the 8 sample sites in 1995, 1996, 1997, 1998, 2001, 2004 and 2007.



1 : Ditch 2 : Lower clover 3 : Upper clover 4 : Stubble 5 : Ploughed 6 : Rye grass 7 : Cultivated 8 : Marsh

Fig 1.3 Number of species recorded in sites 1-7 in 1995, 1996, 1997, 1998, 2001, 2004 and 2007 that also occurred in the marsh (site 8).



1 : Ditch 2 : Lower clover 3 : Upper clover 4 : Stubble 5 : Ploughed 6 : Rye grass 7 : Cultivated 8 : Marsh

Fig 1.4 Mean number of species/site (+/- SD) within the Tollesbury managed re-alignment site (blue : sites 1-7) compared with outside the site (red : site 8) for 1995, 1996, 1997, 1998, 2001, 2004 and 2007.

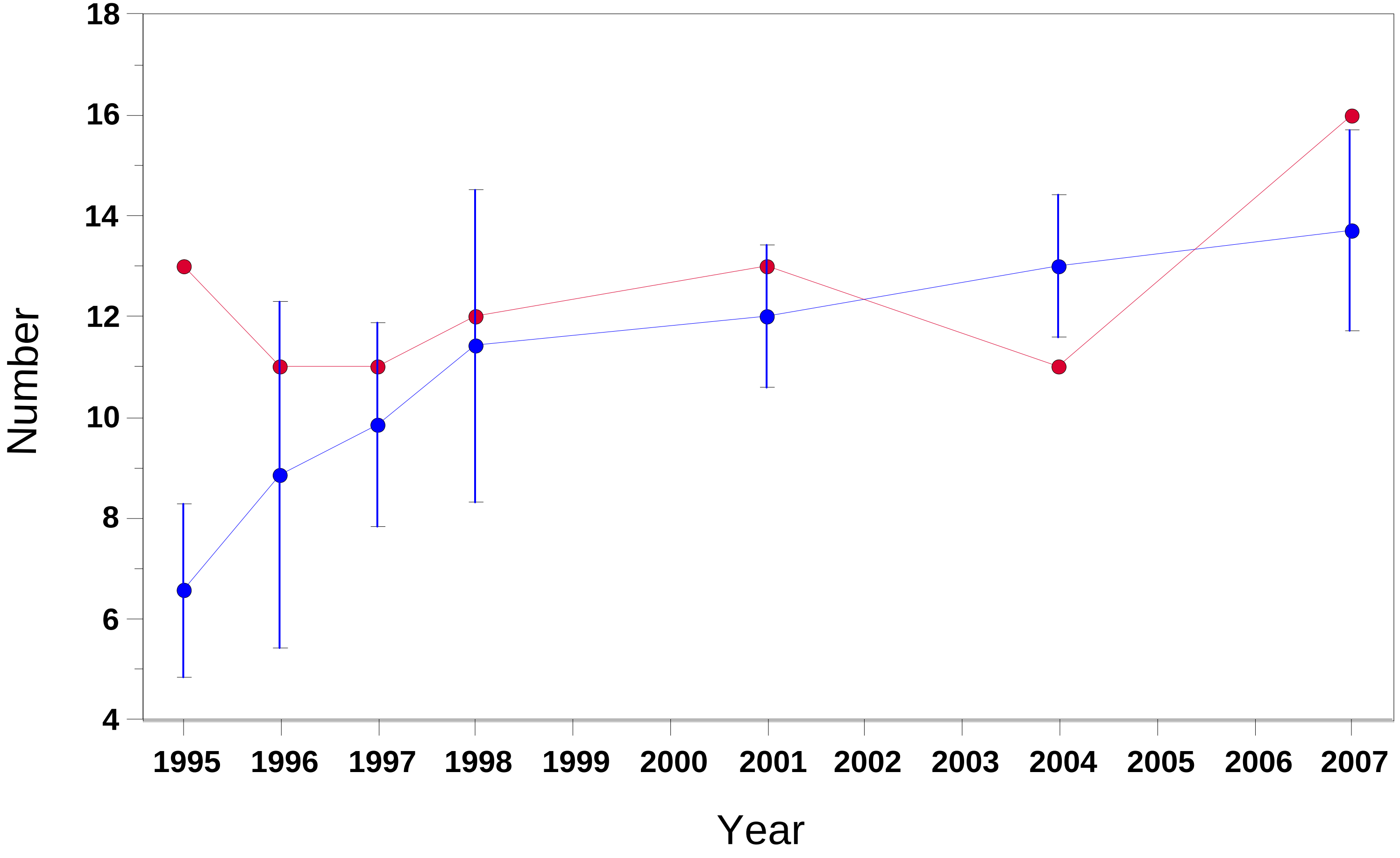


Fig 1.5 Annual variation in the mean number of species/sample at sites 1-8

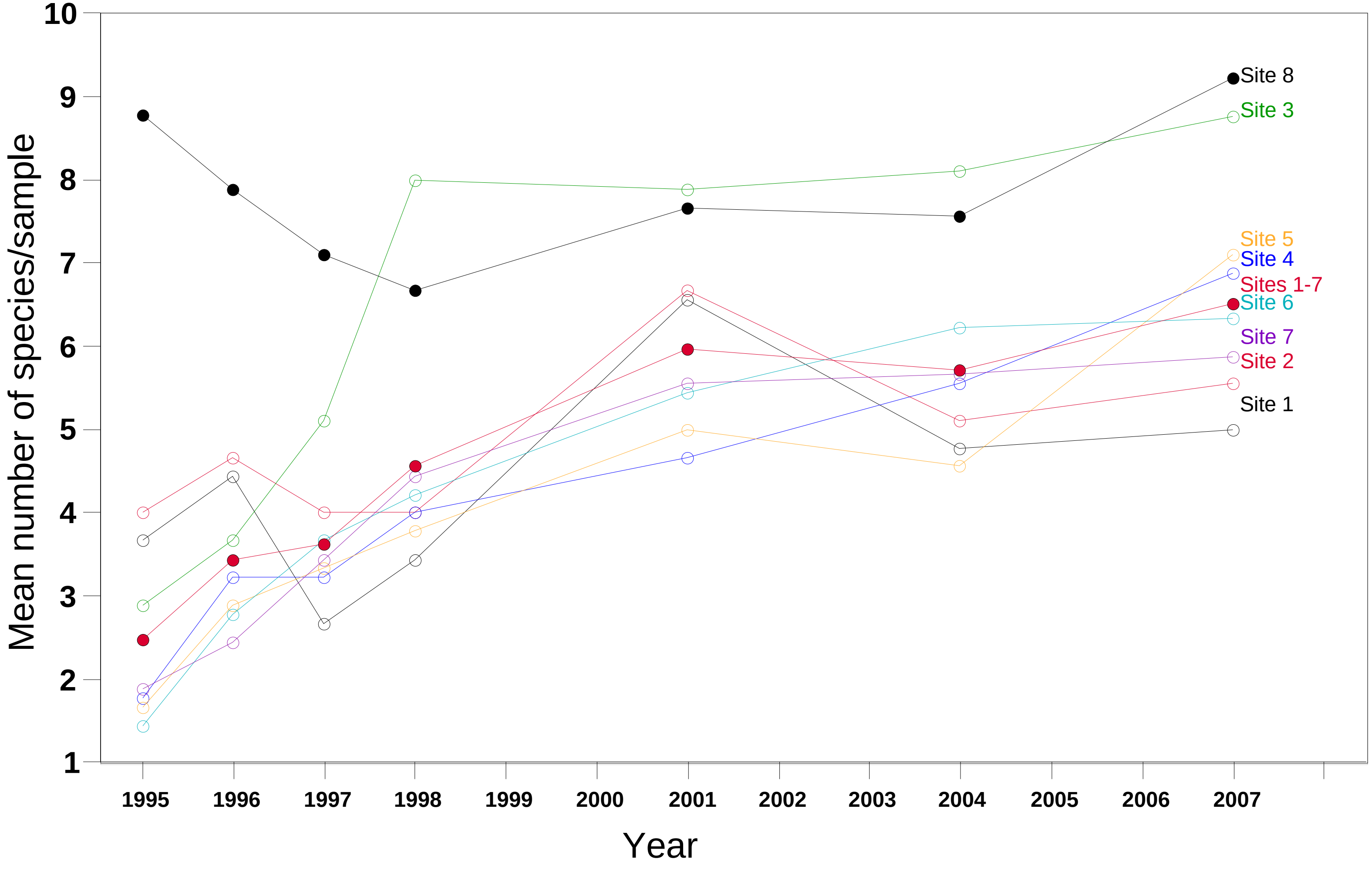
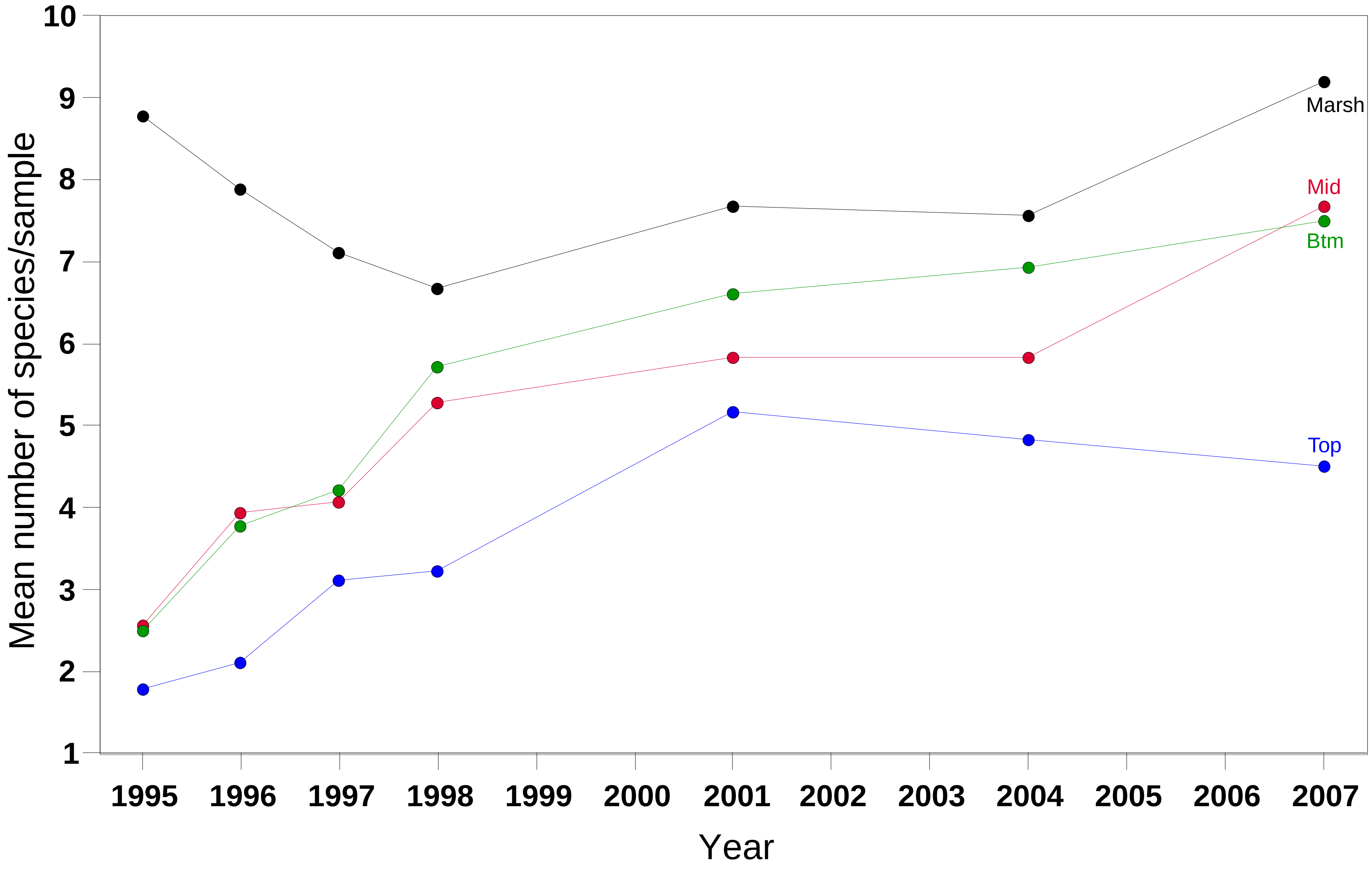
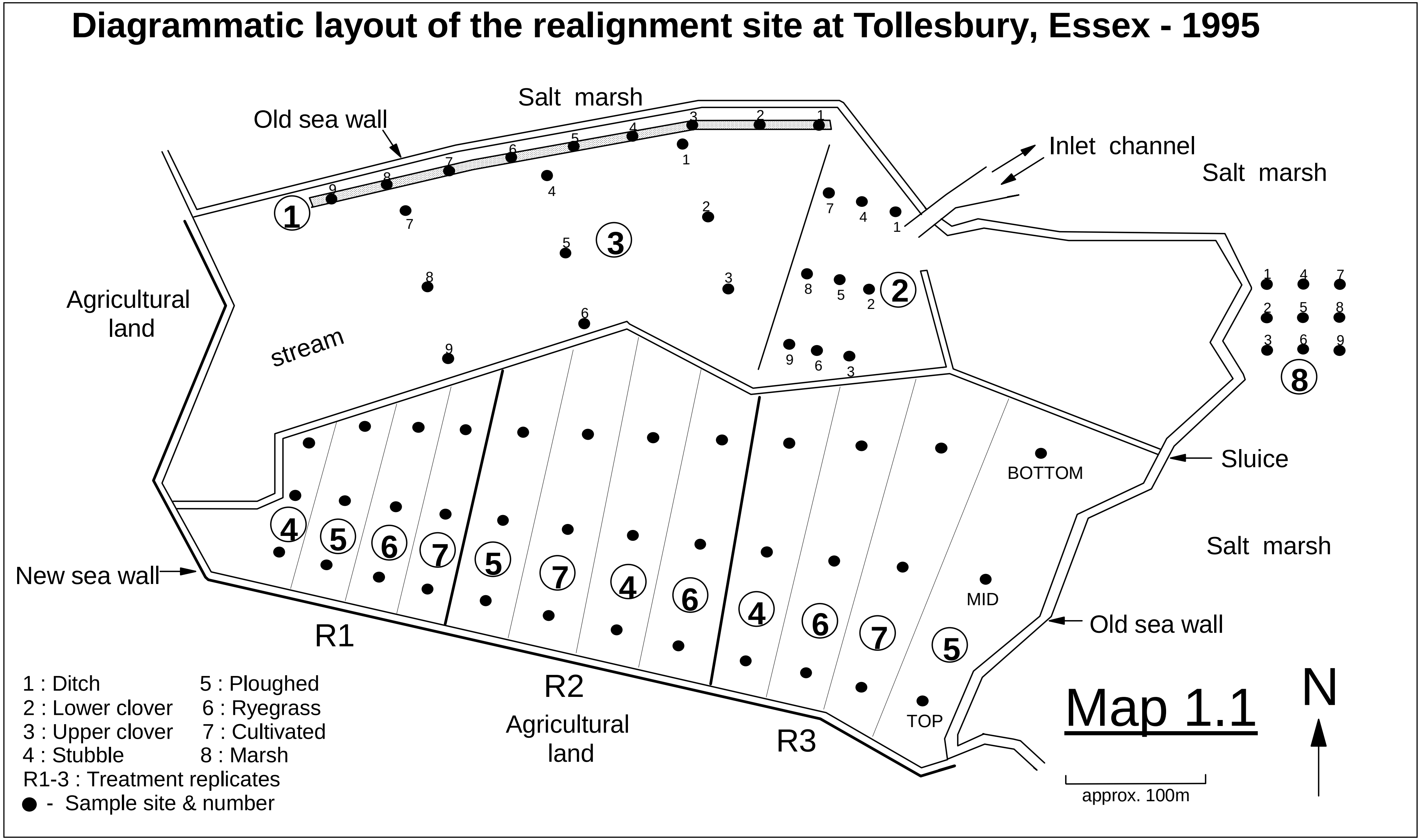


Fig 1.6 Annual variation in the mean number of species/sample at Top, Middle & Bottom shore levels (sites 2-7) and in the Marsh (site 8) between 1995 and 2007.



1.11 Appendix 1.3

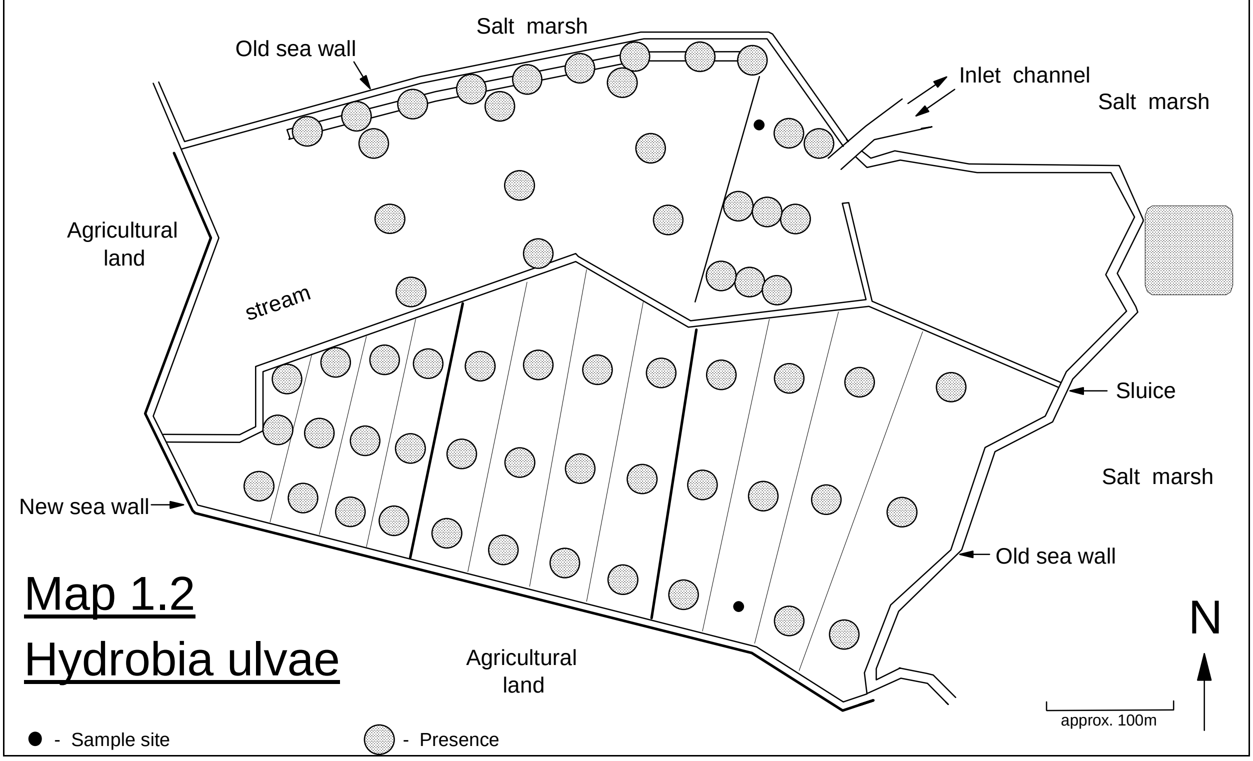
Maps 1.1 – 1.23



Diagrammatic layout of the realignment site at Tollesbury, Essex - 1995

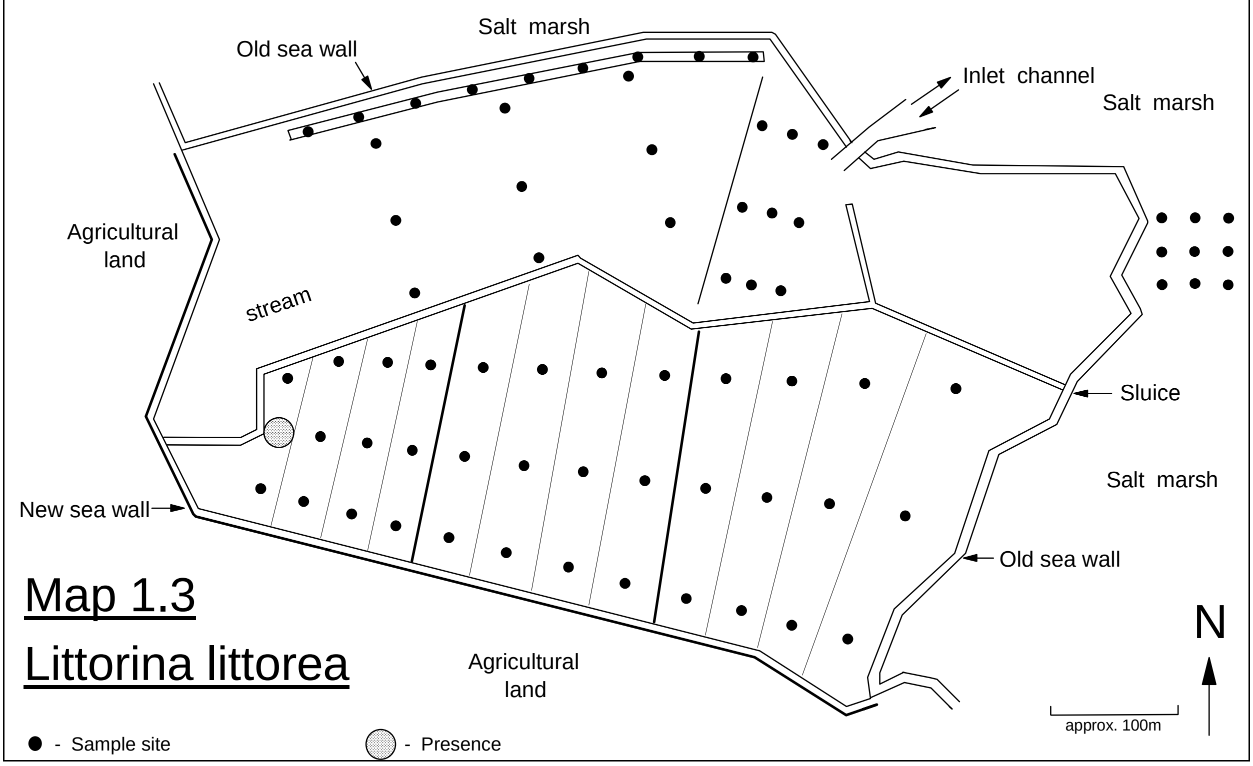
Map 1.1

Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex



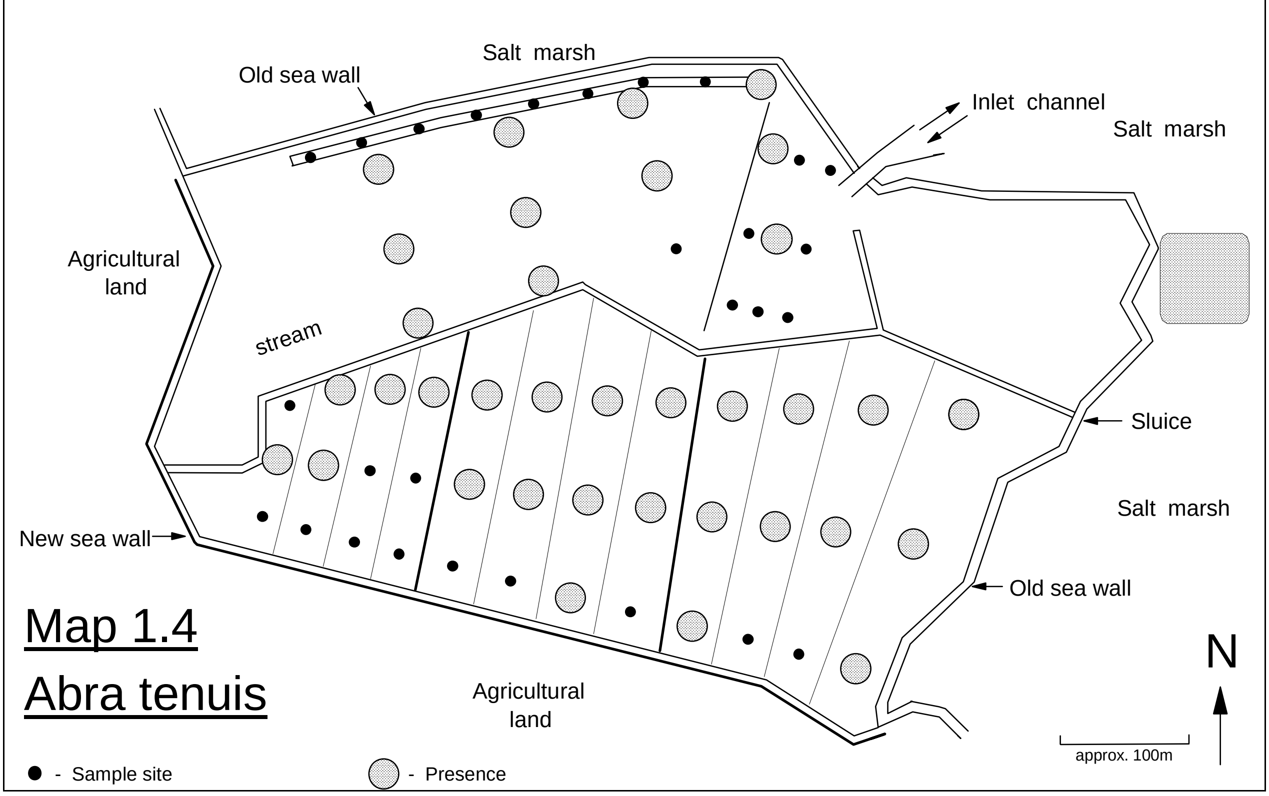
Map 1.2
Hydrobia ulvae

Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex



Map 1.3
Littorina littorea

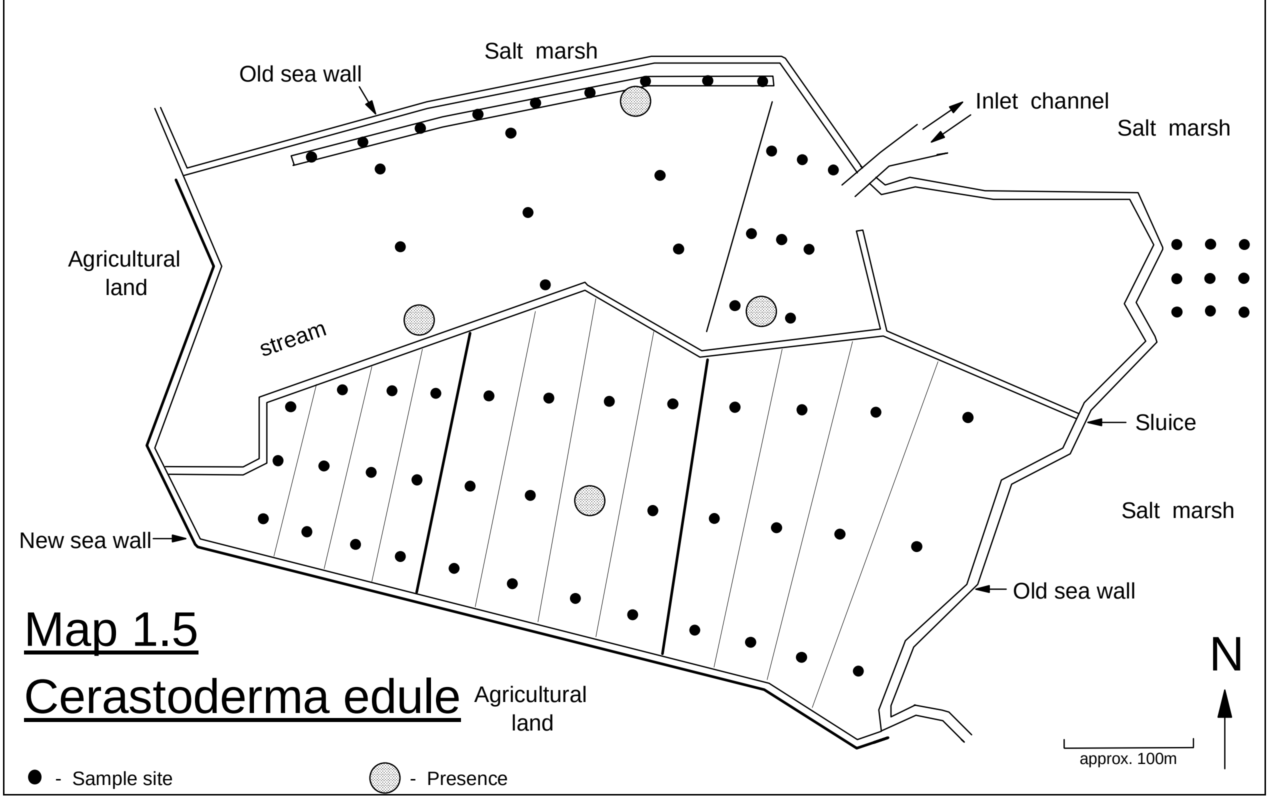
Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex



Map 1.4
Abra tenuis

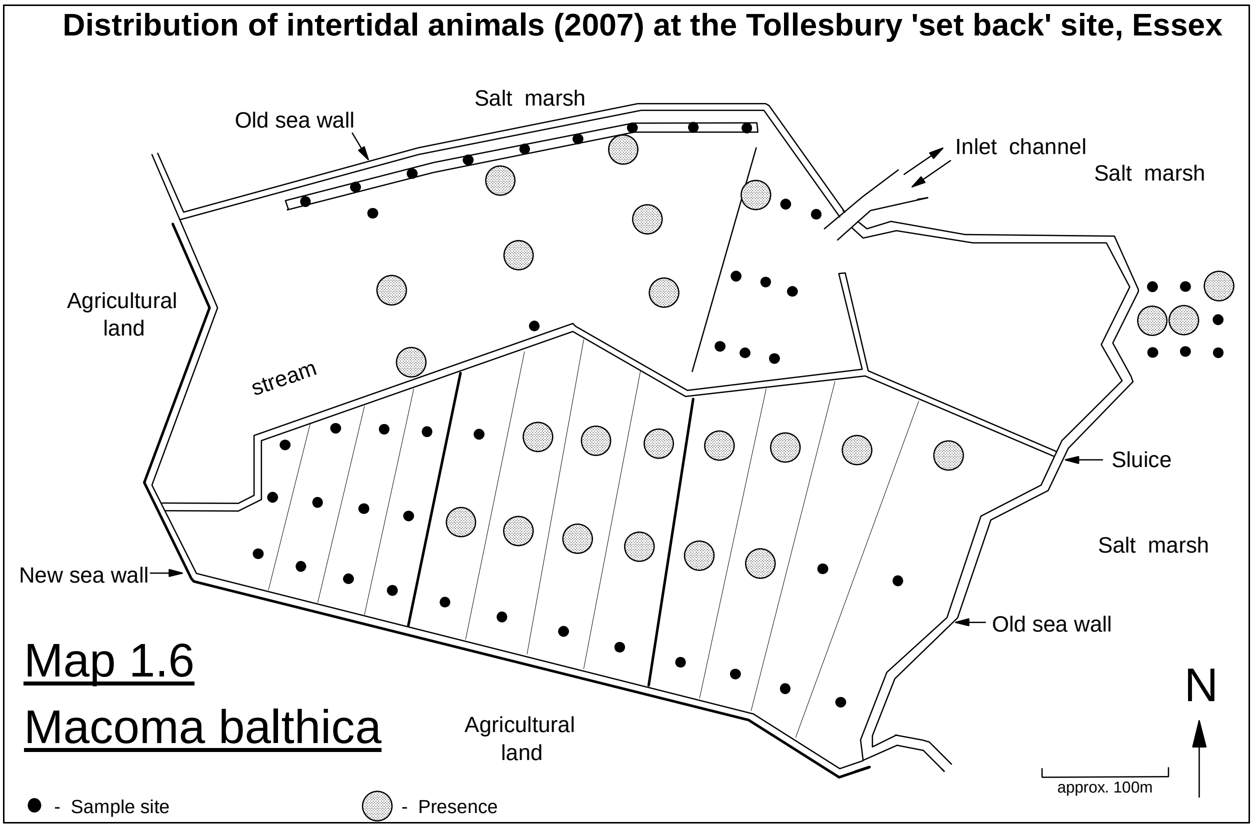
● - Sample site ○ - Presence

Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex



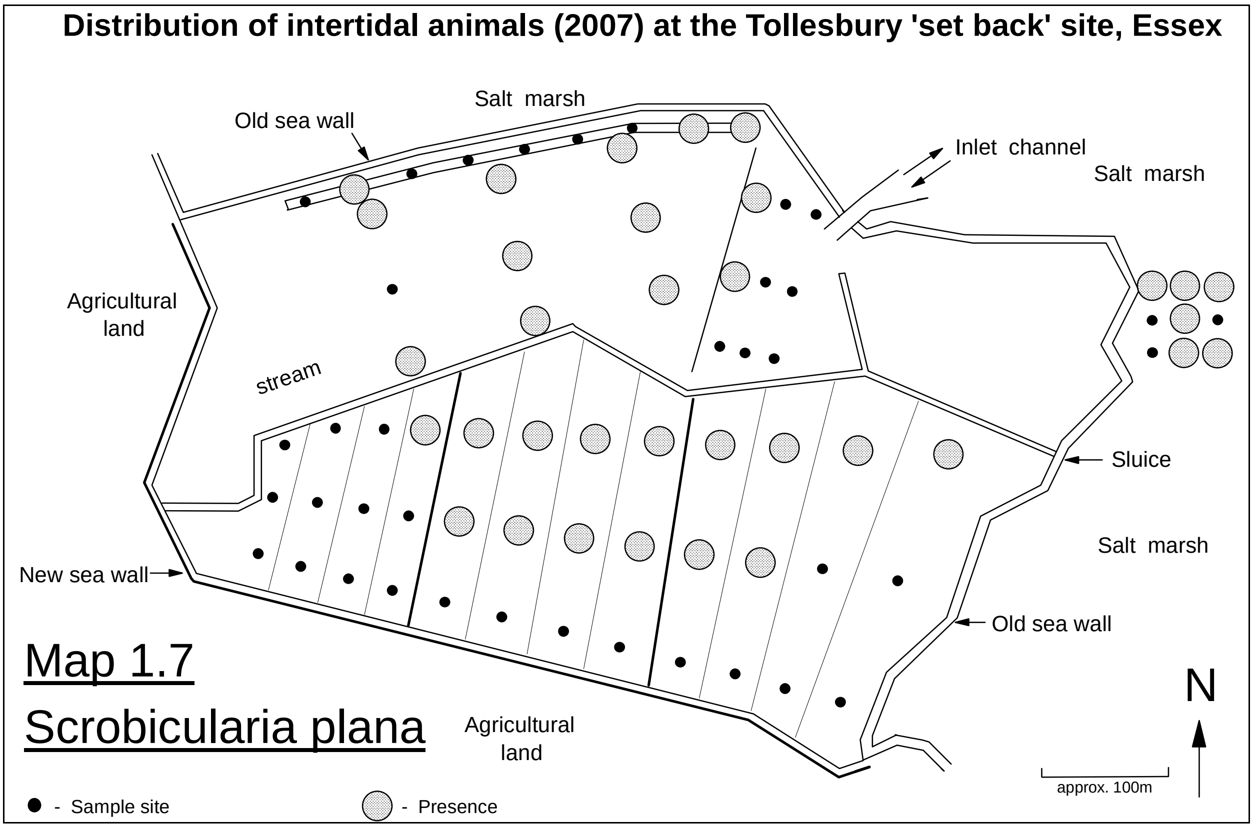
Map 1.5
Cerastoderma edule

● - Sample site ○ - Presence



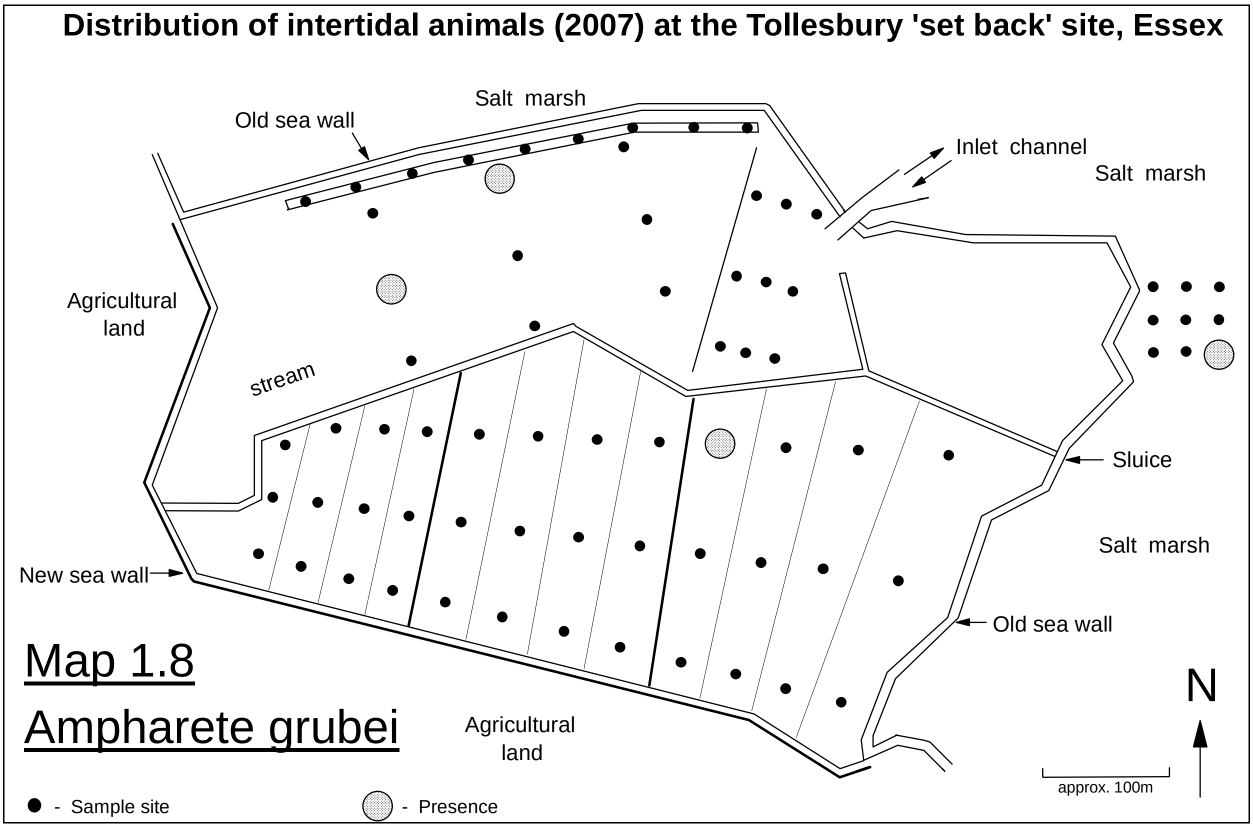
Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex

Map 1.6 Macoma balthica



Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex

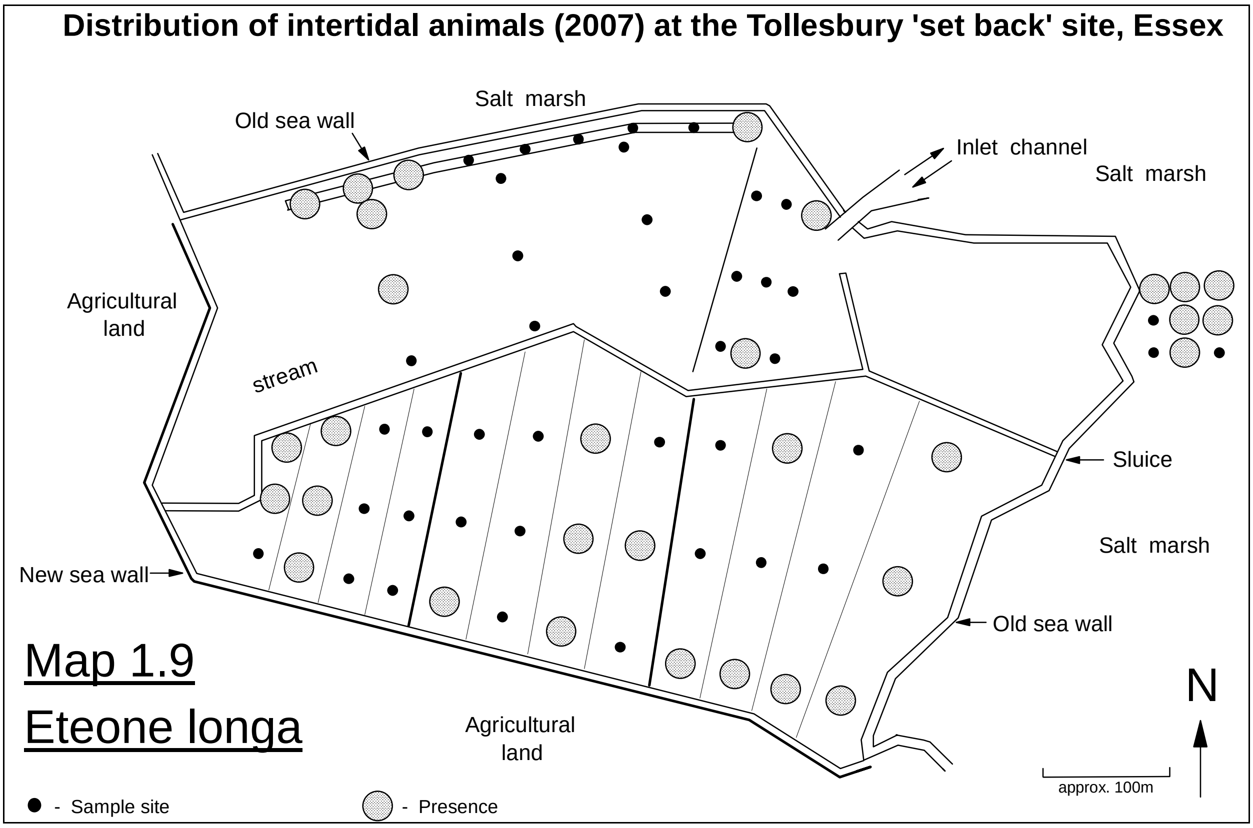
Map 1.7 Scrobicularia plana



Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex

Map 1.8

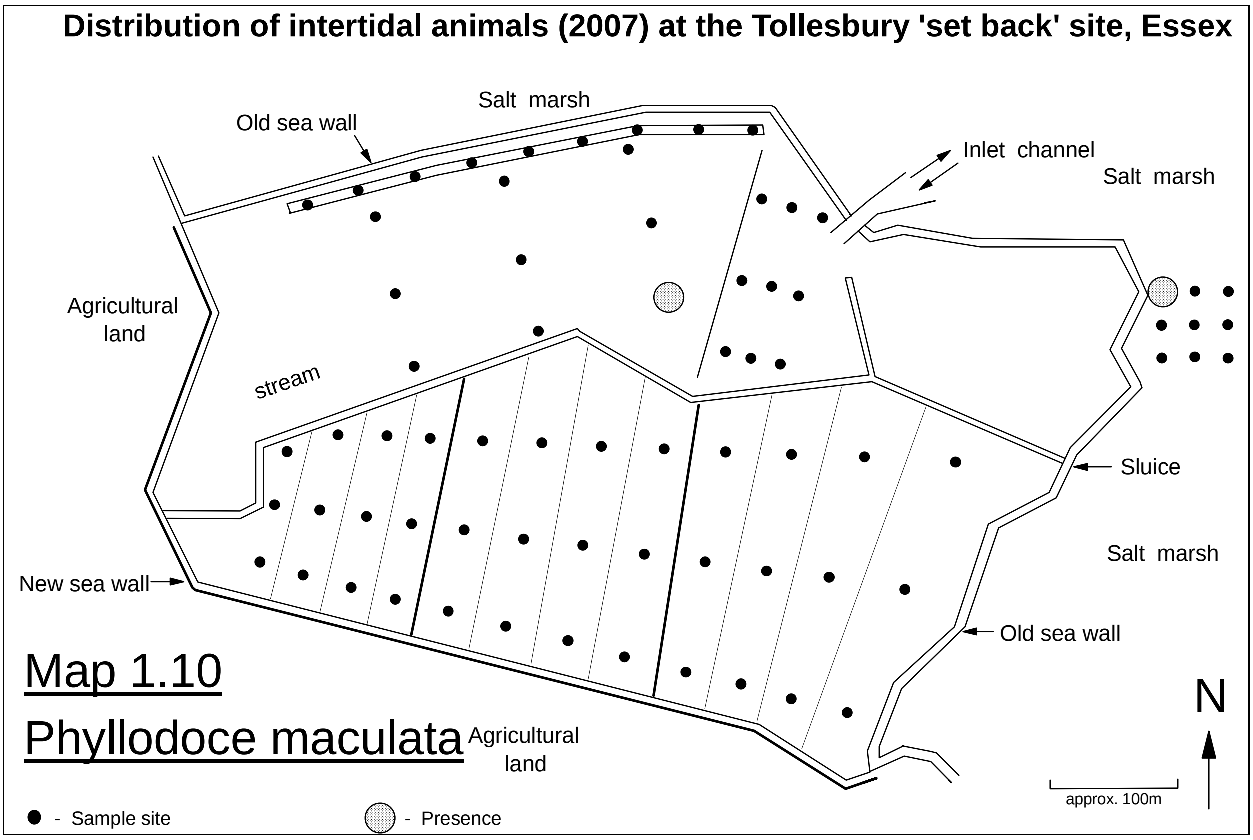
Ampharete grubei



Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex

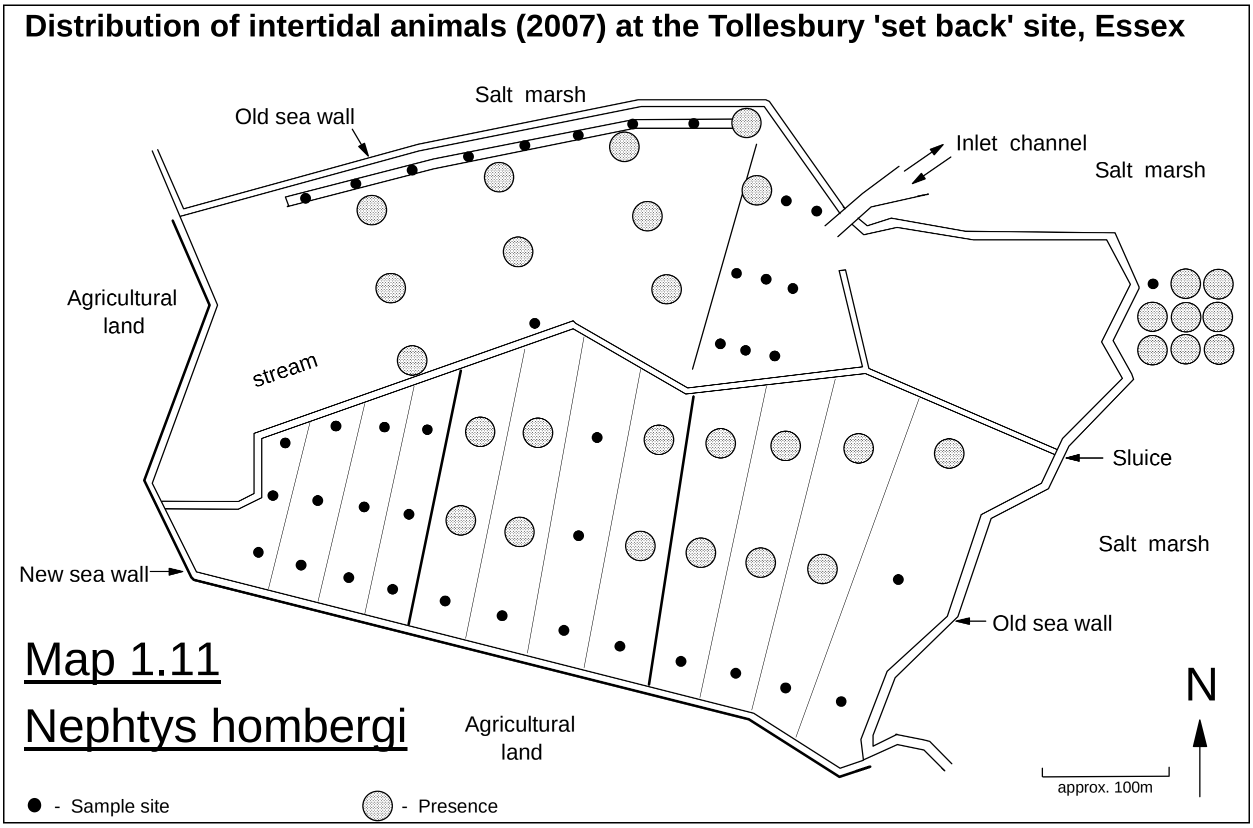
Map 1.9

Eteone longa


Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex

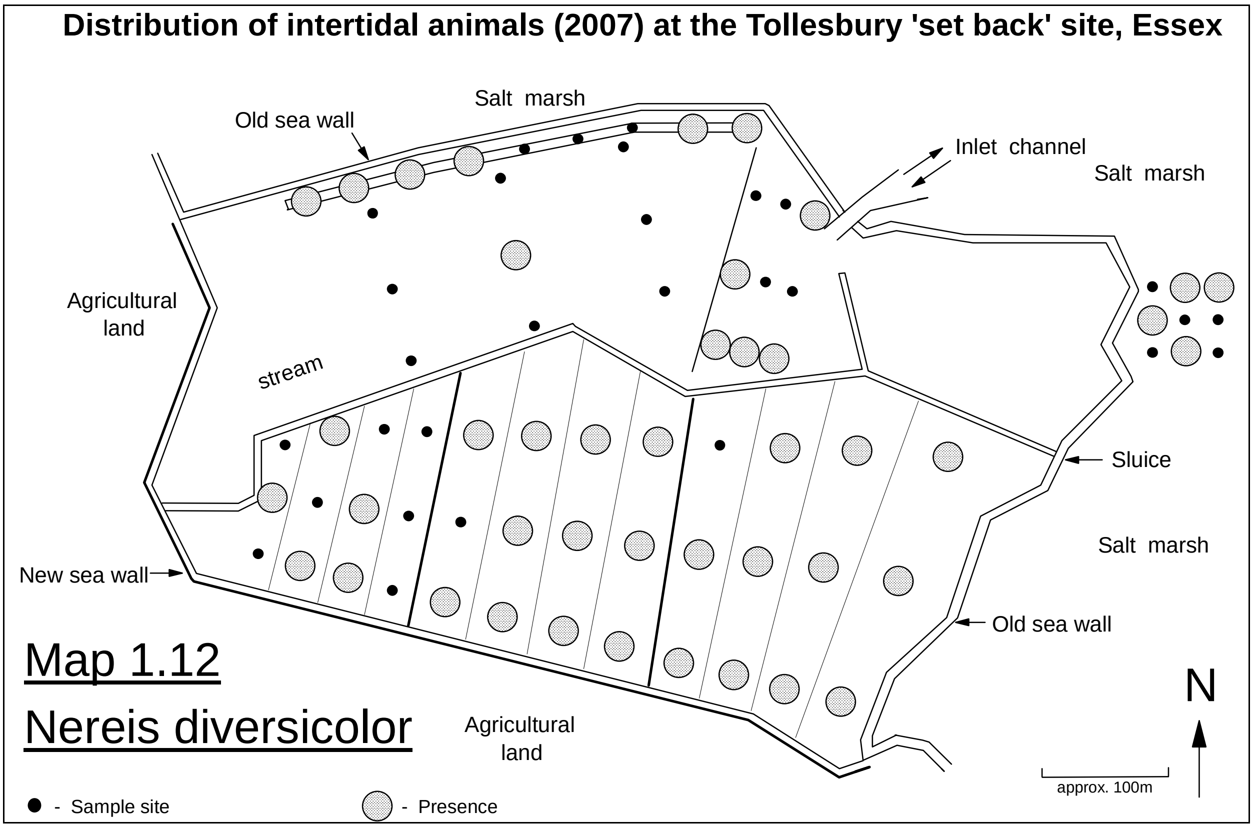
Map 1.10

Phyllodoce maculata


Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex

Map 1.11

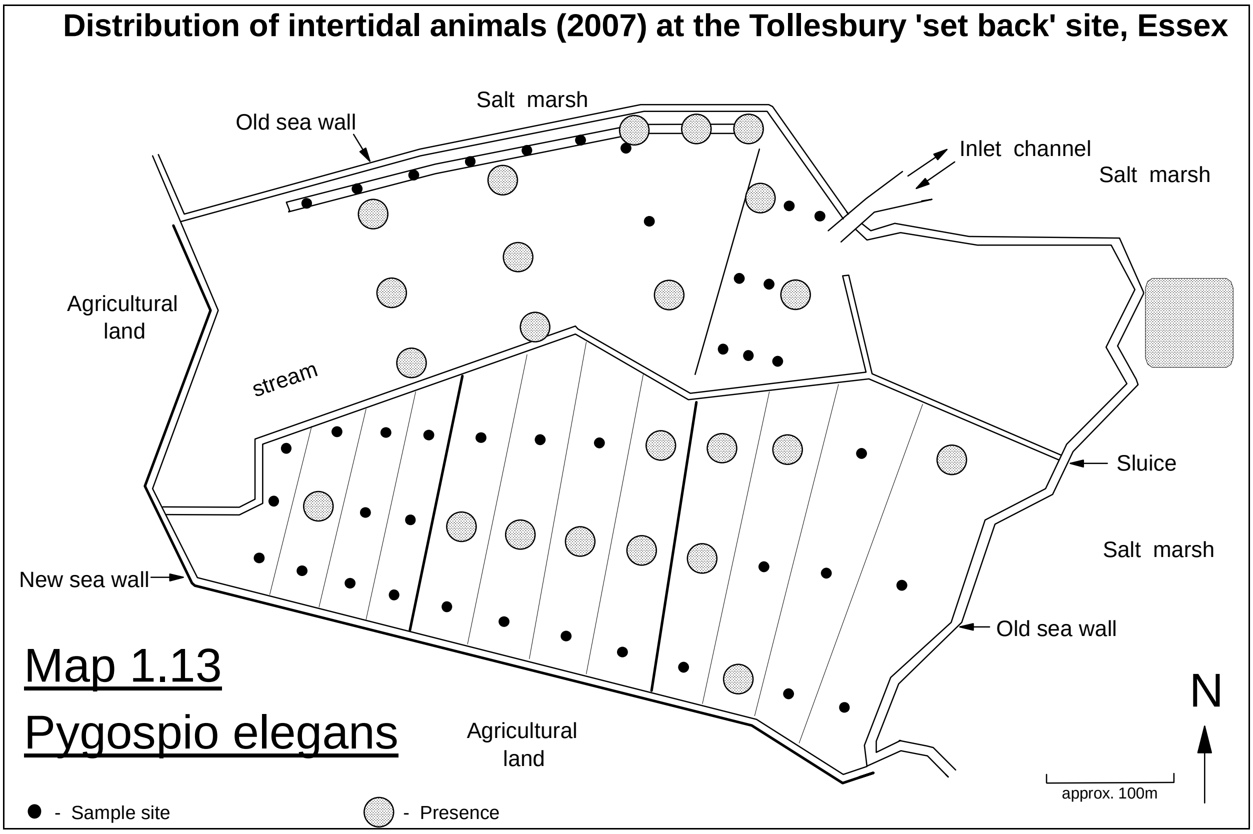
Nephtys hombergi



Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex

Map 1.12

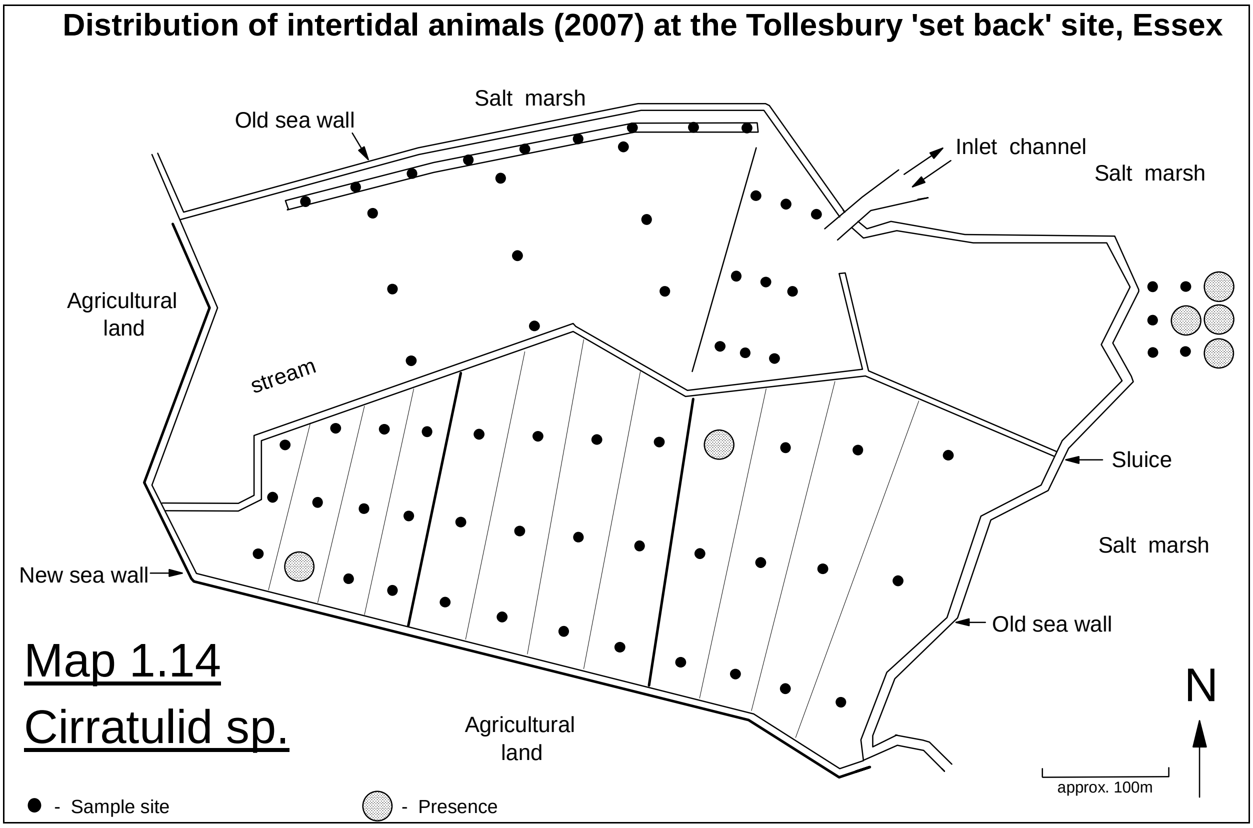
Nereis diversicolor



Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex

Map 1.13

Pygospio elegans



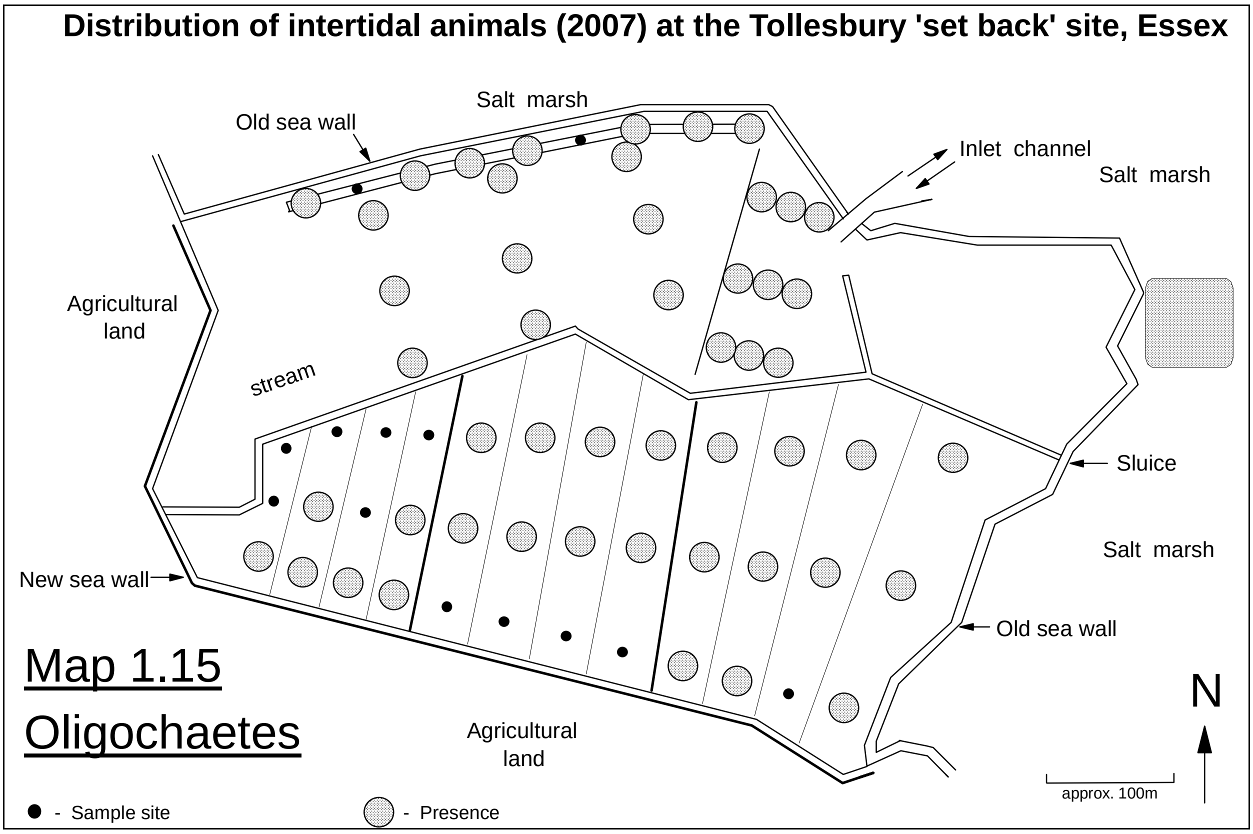
Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex

Map 1.14

Cirratulid sp.

● - Sample site

○ - Presence



Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex

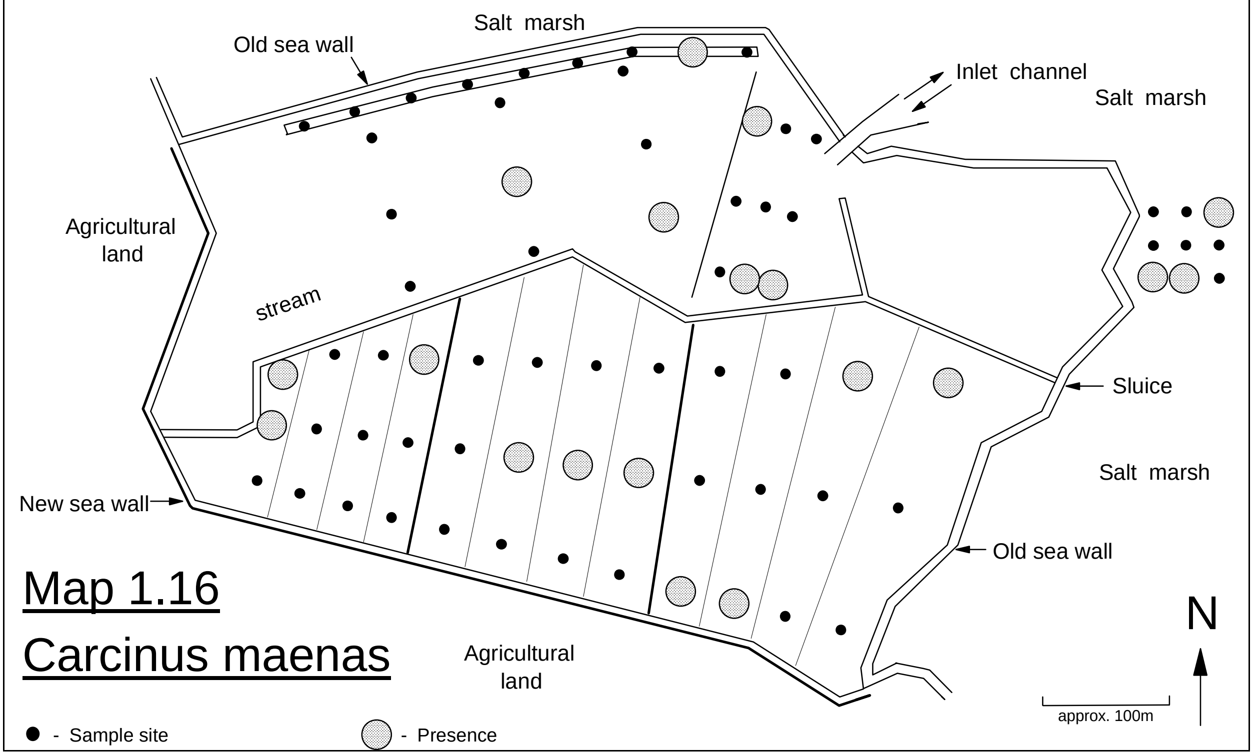
Map 1.15

Oligochaetes

● - Sample site

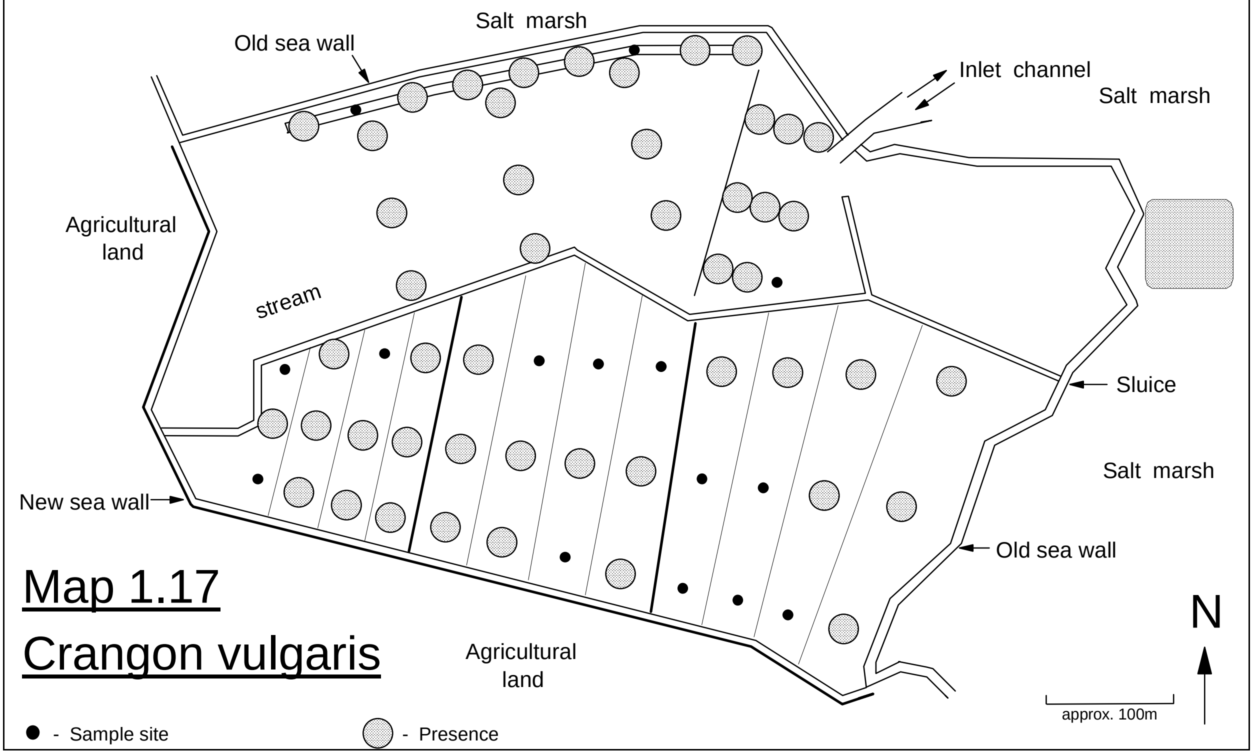
○ - Presence

Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex

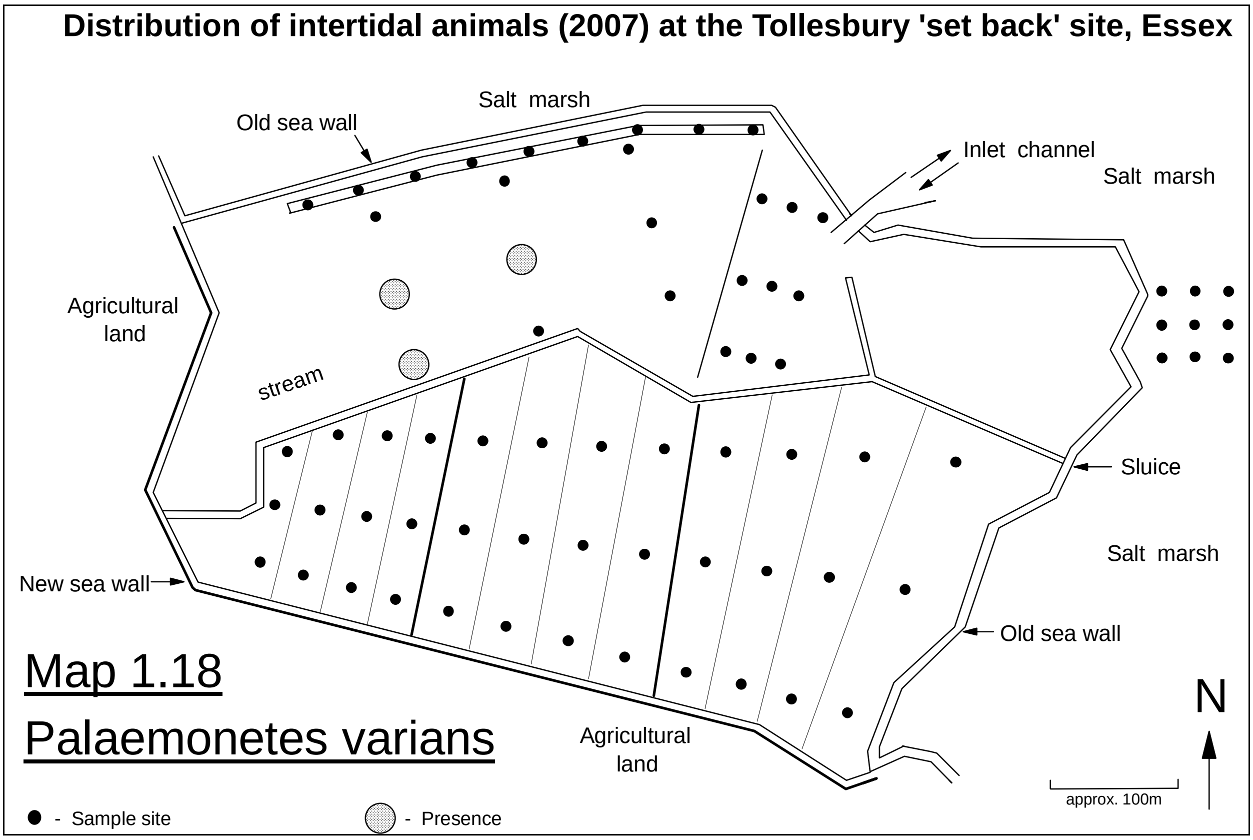


Map 1.16
Carcinus maenas

Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex



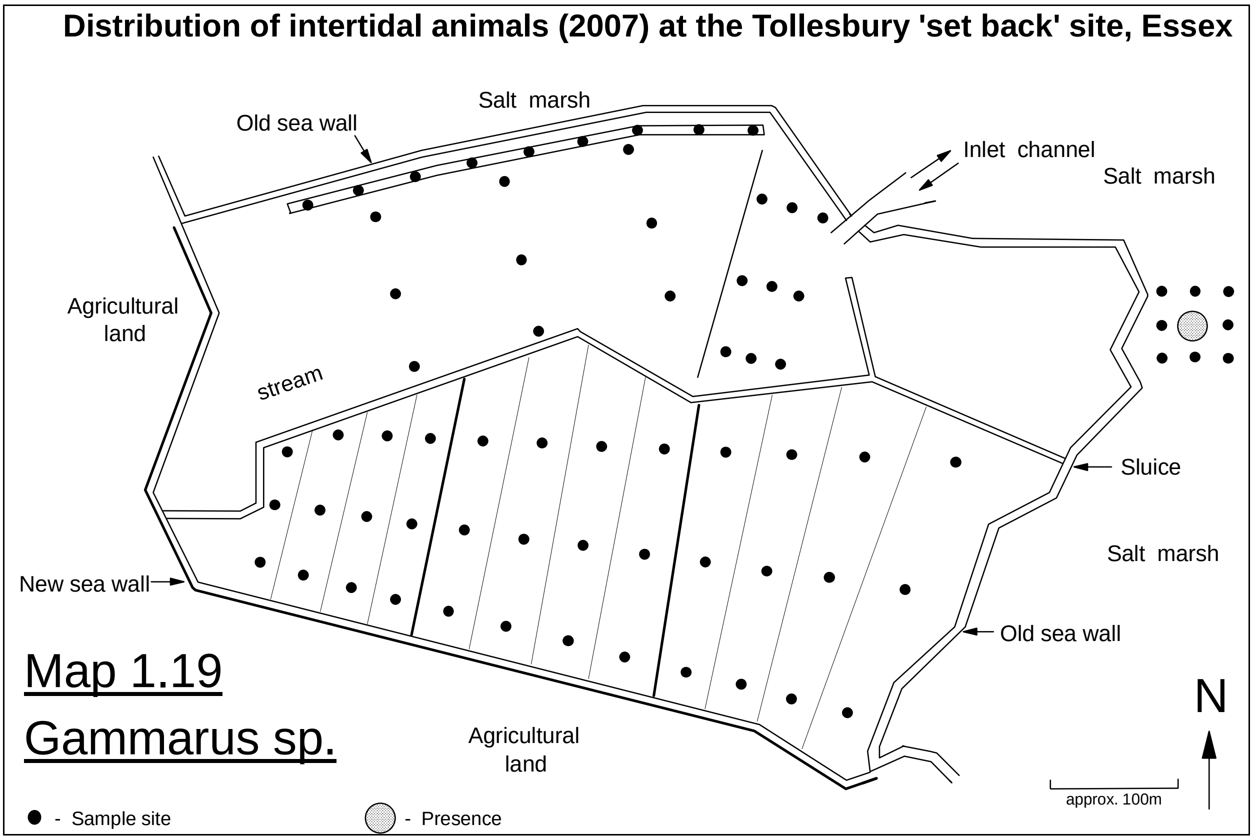
Map 1.17
Crangon vulgaris



Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex

Map 1.18

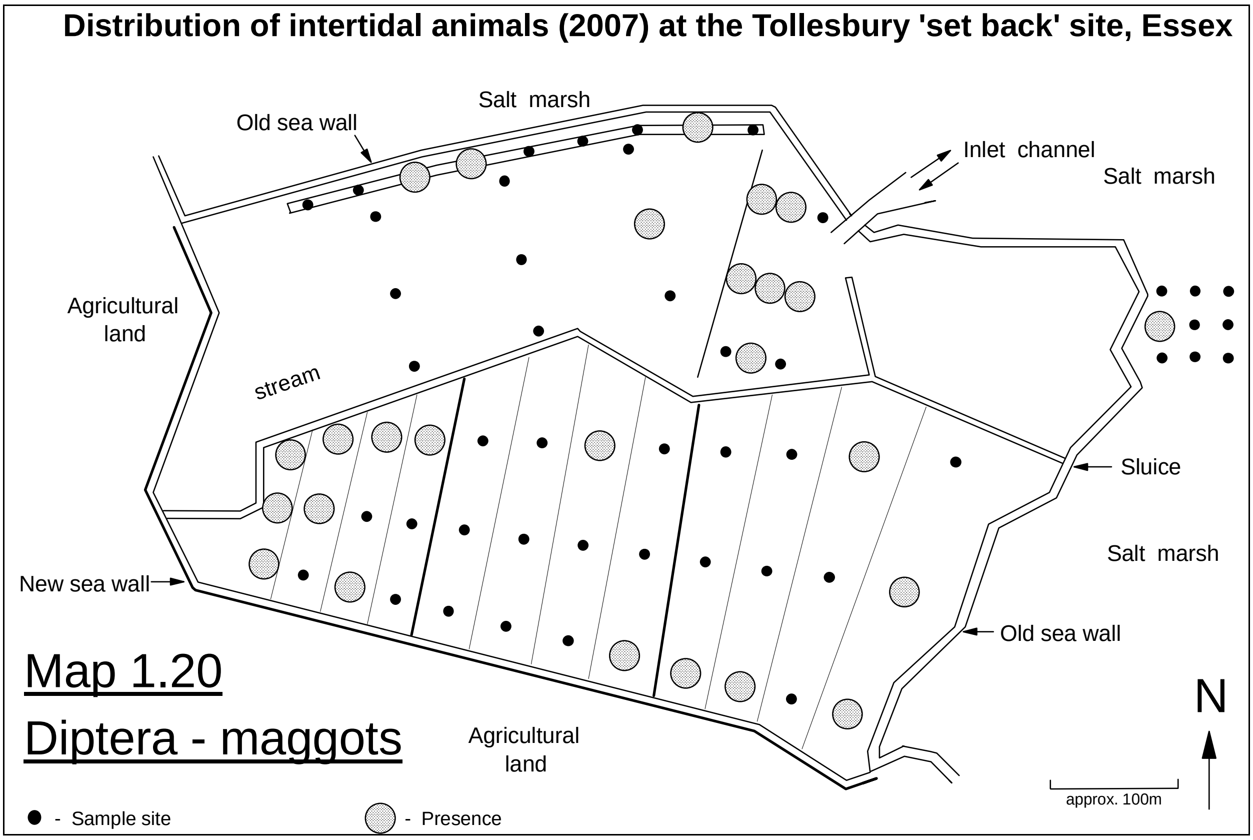
Palaemonetes varians



Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex

Map 1.19

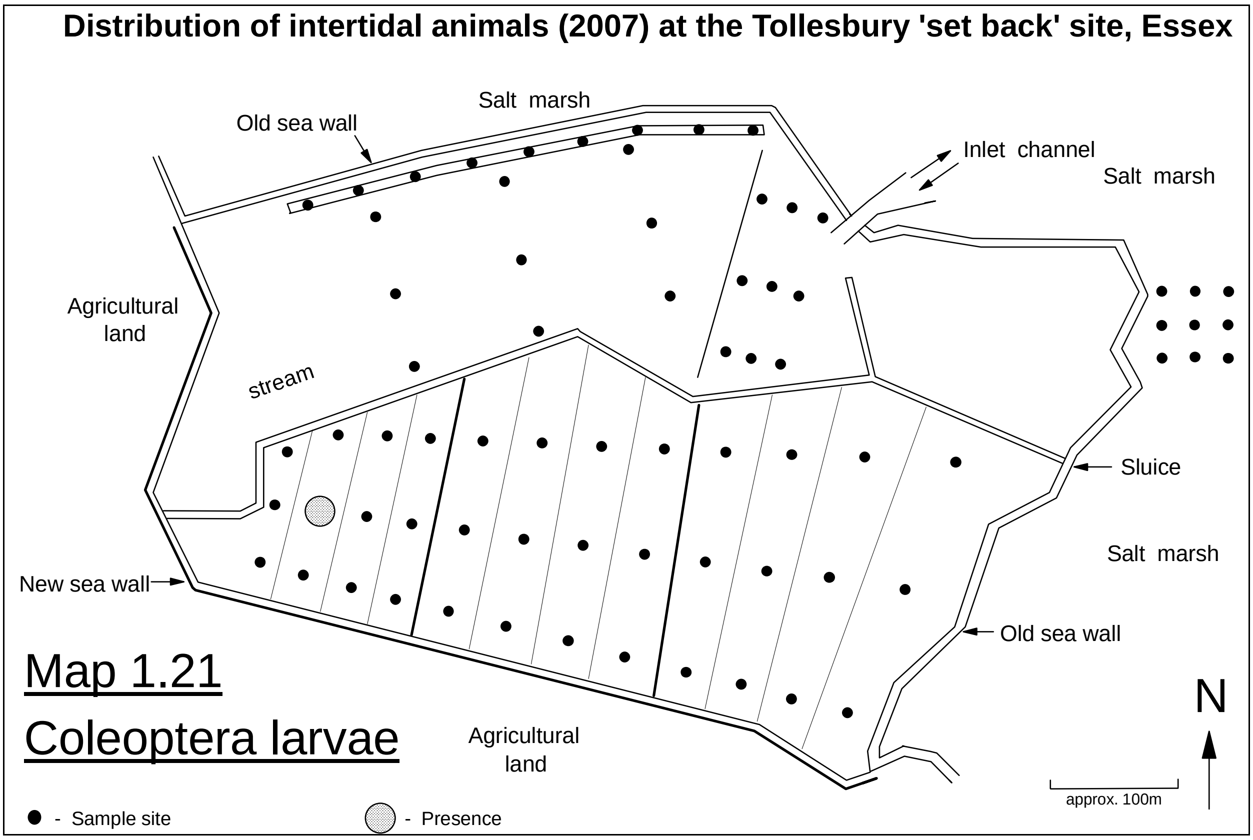
Gammarus sp.



Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex

Map 1.20

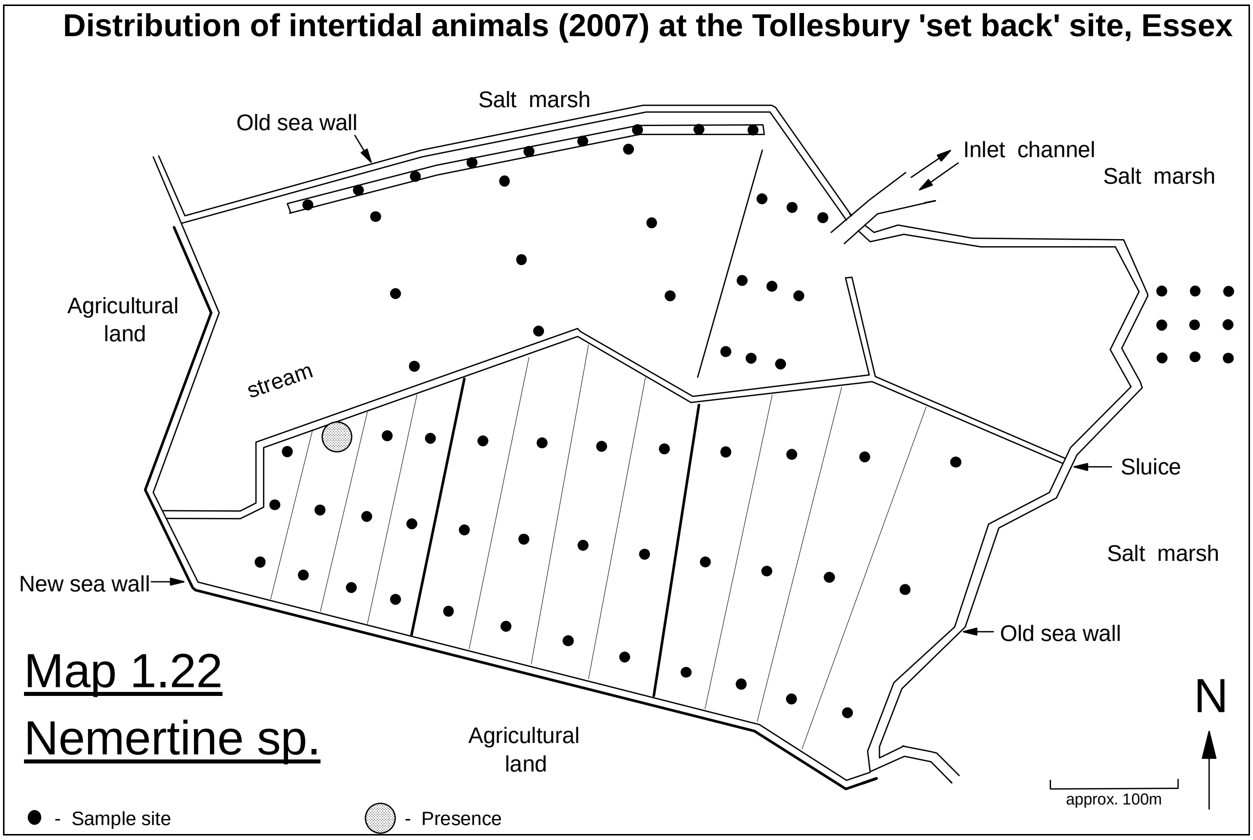
Diptera - maggots



Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex

Map 1.21

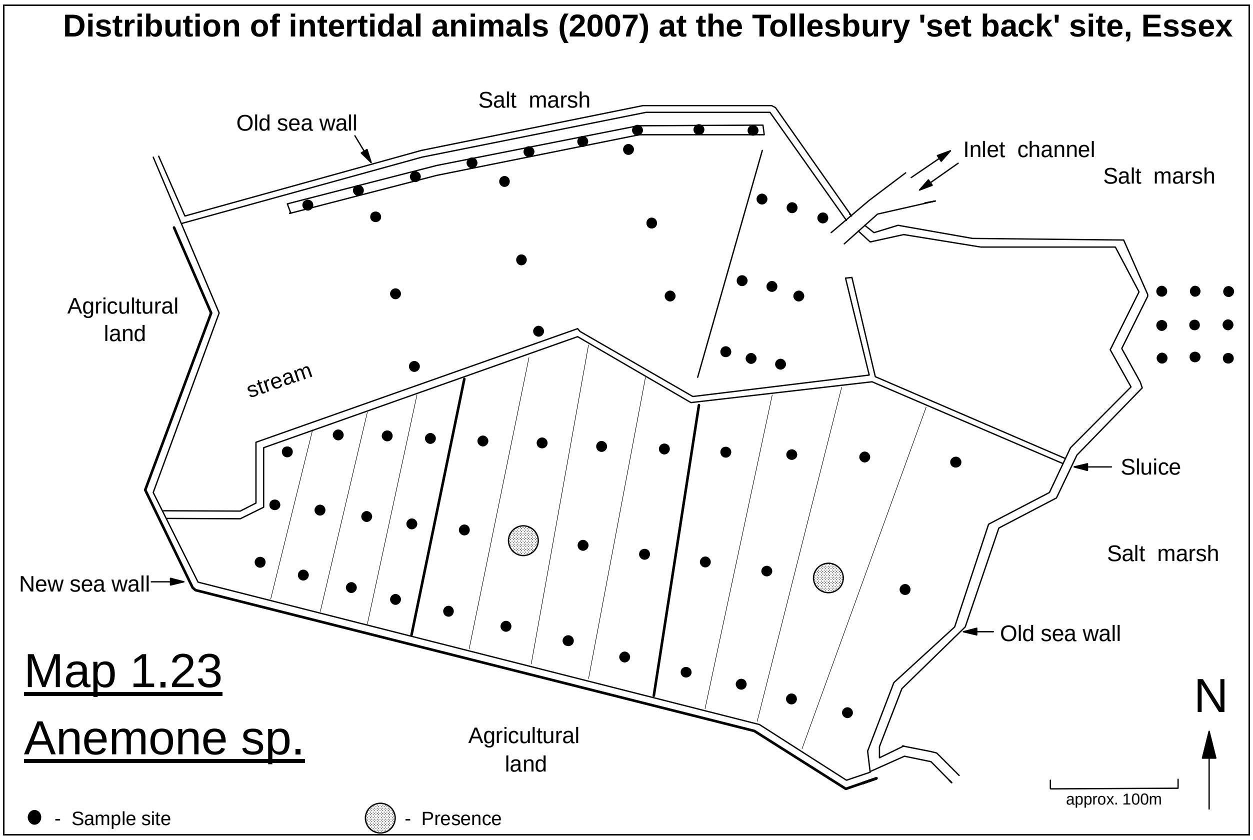
Coleoptera larvae



Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex

Map 1.22

Nemertine sp.



Distribution of intertidal animals (2007) at the Tollesbury 'set back' site, Essex

Map 1.23

Anemone sp.

CHAPTER 2

BOTANICAL AND SEDIMENT MONITORING OF THE TOLLESBURY MANAGED REALIGNMENT SITE AND ADJACENT SALTMARSHES

R.A..GARBUTT[1], C.J. READING[2], A.TURK[3], M.YATES[3] & P. ROTHERY[3]

1- Centre for Ecology and Hydrology, CEH Bangor, Environment Centre Wales, Deiniol Road, Bangor, Gwynedd, LL57 2UW, UK. ag@ceh.ac.uk
2- Centre for Ecology & Hydrology, CEH Wallingford, Benson Lane, Crowmarsh Gifford, Wallingford, Oxon. OX10 8BB. UK
3- Centre for Ecology & Hydrology, Monks Wood, Abbots Ripton, Huntingdon, Cambs. PE28 2LS. UK

2.1 SUMMARY

This report presents the results of botanical and sediment monitoring at the Tollesbury managed realignment site and adjacent marshes in 2007. The 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 mud flat.

Throughout the monitoring programme, the mean change in the bed level of the Old Hall and Tollesbury salt marshes remained constant, at around 3mm year^{-1} and 4mm year^{-1} respectively. There was no significant difference between the rates of change before and after the creation of the managed realignment site.

Initial rates of accretion within the managed realignment site were linear and relatively high at 21mm year^{-1}. Since 2003, there was evidence of a slow down in the build up of sediment within the realignment site. The reduction in sedimentation was thought to be a function of increasing elevation within the site over time and subsequent reduction in inundation frequency and sediment supply. The long-term consequences of sediment infilling are predicted to be an increase in the area of the site suitable for colonisation by plants and a reduction in water storage capacity.

Over the fourteen years species frequency was measured on the natural marshes adjacent to the managed realignment site, most plants showed some degree of change. There was no evidence to suggest that the creation of the managed realignment site was the cause of this change. Pre- and post-breach differences appear to be part of longer-term trends.

Approximately thirteen hectares of the 21 ha Tollesbury managed realignment site were covered in saltmarsh vegetation by 2007. Up to 2007 a total of 21 species of saltmarsh plant recorded within the site. All species were typical of the region and included the nationally scarce *Inula crithmoides*, *Spartina maritima* and *Suaeda vera*. Several plant species growing on the marshes adjacent to the site, at low frequency, were not present within the site, even though, in the highest areas, the elevation was suitable. This was thought to be due to the low frequency of seeds and a dense cover of *Puccinellia maritima* within the realignment site, excluding other species.

The majority of the vegetated area of the realignment site was dominated by *Spartina anglica*, in 2007. The establishment of *Spartina*, early in the development of saltmarsh within managed realignment sites, gives the regenerate marshes a very different starting point to that of natural marshes, and may affect the eventual outcome of creation efforts. The expansion of this species within the site raises important issues for the creation of other realignment sites, particularly those commissioned as part of compensatory measures for loss of intertidal habitat elsewhere.

2.2 INTRODUCTION

This report presents the final results from botanical and sedimentation monitoring at the Tollesbury managed realignment site and adjacent marshes, Essex, UK. The monitoring formed 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 mud flat. The work was a 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).

The Tollesbury study area is located on a side arm of the Blackwater estuary on its north shore (TL 960 110). Earth embankments back the marshes, some lengths of which are re-enforced with concrete blocks to repair erosion damage. Brushwood groins have been used to halt erosion of the saltmarsh in some areas. The marshes are mature and dissected by a dendritic creek system, where saltpans are common. The marsh edge is cliffed and there are areas of mud mounds. The vegetation communities are dominated by mid marsh flora. Pioneer and lower marsh flora are generally restricted to creek edges. Upper marsh and transition communities are rare. The mean tidal range for Bradwell, the nearest reference point for the Blackwater estuary, is 4.7m on spring tides and 3.0m on neap tides. Mean high water springs (MHWS) are 2.60m O.D.N (MHWN) and mean high water neaps are 1.50m O.D.N (Pye and French 1993).

In August 1995, a breach was made in the sea defences at Tollesbury and reclaimed land, previously under cultivation, was exposed to tidal inundation for the first time in over 150 years. Tidal inundation was limited to the 21ha site by the construction of a counter wall, built on the 3m contour. The elevation of the site ranged from 0.90m O.D.N to 3.00m O.D.N before flooding, although most was less than 2.00m O.D.N. Apart from a channel cut from an existing drainage ditch to the breach, no other engineering work was undertaken on the site.

A list of scientific and common names for saltmarsh plants used in this report is provided in Appendix 2.1.

2.3 MONITORING SEDIMENTATION PATTERNS WITHIN THE REALIGNMENT SITE AND ADJACENT SALTMARSHES

2.3.1 Introduction

The effect of compaction and dewatering on embanked marsh sediments, coupled with rising sea level, has accentuated the differences between reclaimed land and nearby salt marshes in south east England. In many cases differences of 1.0 to 1.5 m between the reclaimed land surface and adjacent marshes exist (Pethick and Burd 1995). Unless the surface elevation of low-lying realignment sites is raised over time by natural sedimentary processes, or raised artificially using imported sediment, low-lying mud flat is likely to persist. Sedimentation within the Tollesbury realignment site was measured to test the ability of the site to retain sediment and raise the low-lying areas of the site to an elevation suitable for saltmarsh plants to colonise. Sedimentation rates of the existing salt marshes, adjacent to the realignment site, were also monitored in an attempt to detect any changes that could be attributable to the creation of the managed realignment site.

2.3.2 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. Recordings were taken 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. Measurements were taken monthly up to 1998, bimonthly up to 2000 and then in April and September to 2007.

Sediment transects on the Old Hall and Tollesbury marshes were located in vegetated areas, dominated by a mosaic of *Atriplex portulacoides* (sea-purslane) and *Puccinellia maritima* (common saltmarsh-grass). Elevations of 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 collected monthly from September 1995 to 1998, bimonthly up to 2000 and then in April and September to 2007. Elevations of these 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 in areas thought to be eroding, and were not covered by the 20 transects already in place. 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). Two sediment transects were placed near the breach in the sea wall, one either side of the cut channel (transects 24 and 25). Data from these transects were collected in April and September to 2007.

The changes in bed level are described using linear regression analysis. For differences between pre- and post breach rates, a t-test was used.

2.3.3 Results

Throughout the monitoring programme, the mean change in the bed level of the Old Hall and Tollesbury salt marshes remained constant, at around 3mm year^{-1} and 4mm year^{-1} respectively (Figures 2.2 & 2.3). There was no significant difference between rates of change before and after the creation of the managed realignment site.

Initial rates of accretion within the managed realignment site were linear and relatively high at 21mm year^{-1}(Garbutt & Wolters 2004). Since 2003, there was evidence of a slow down in the build up of sediment within the realignment site (Figure 2.4). Table 2.1 shows the estimated annual change in bed level, by year, since recording started, based on the quadratic equation, smoothing out the variation, fitted to the data in Figure 2.4.

Most transects used to measure changes in the bed level of the managed realignment site are situated below an elevation of 1.4m ODN, reflecting the low-lying nature of the site. The greatest increases in the surface level occurred on the transects below this elevation (Figure 2.5; Table 2.2). As transect elevation increased, the amount of sediment deposited over the pre-inundation land surface decreased. Transects 6, 7 and 9 show smaller rates of change than might be predicted by their elevation, as a result of greater water velocities around the breach, restricting deposition.

Of the five additional sediment transects set up in 1999 transects 21, 22 and 23 all showed small linear increases in bed level of between 1-3mm year^{-1}. Since April 2005 the mudflat surface at Transect 24 started to accrete sediment at a mean rate of 11mm year^{-1} where previously it was eroding at -8mm year^{-1}. Since April 2004 the mudflat surface at Transect 25 started to accrete sediment at a mean rate of 20mm year^{-1} where previously it was eroding at -15mm year^{-1} (Figure 2.6).

2.3.4 Discussion

The Old Hall and Tollesbury salt marshes showed a constant rate of vertical accretion throughout the 14 years of recording (at around 3 – 4mm year^{-1}). These rates are typical for salt marshes in the Greater Thames area (van der Wal & Pye 2004), and the marshes appear to be able to maintain their position in the tidal frame, despite projected mean eustatic sea level rise. There was no evidence that the creation of the managed realignment site had any effect on sediment deposition on the marshes adjacent to the site.

There is evidence that the amount of sediment being deposited over the managed realignment site is reducing over time. This response was predicted by Allen (1990) who developed a model that predicted an elevation-time curve for mudflat/marsh growth where sediment build up rises steeply during the early stages but thereafter flattens off. 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 sediment accretion 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 sediment accretion rates. As the surface level builds up, the amount of sediment deposited over the site will slow as sediment supply is reduced by lower inundation frequencies. In time, the surface of the site would be expected to build up to a level equivalent to that of the adjacent natural marshes. Around the breach area within the Tollesbury site, the mud flats developed a ‘ridge/runnel’ morphology (see transects 24 and 25). Water leaving the site flows through the runnels, rather than as a sheet flow as happened in the early stages of the sites development. This resulted in additional deposition on the ridges and into the formerly eroding area, close to the breach.

The build up of sediment allowed more areas of the site to be colonised by saltmarsh vegetation as the elevation increased. Sediment infilling will have a long-term impact on the future of the site, both for the conservation interest and flood defence. First, there has been a reduction in the area of mud flat and this will have consequences for feeding and roosting birds that use the site. Second, in 2007 there was transition from mud flat, through pioneer to low and mid marsh vegetation communities within the site. This is uncommon in the Essex region where most salt marshes are cliffed on their seaward edge leading to a scarcity of pioneer communities. However, if deposition continues, as expected, there will be a gradual infilling of the site up to the level of the surrounding marshes with the consequent loss of the pioneer/low marsh communities. This can be observed at the many ‘accidental’ breach sites in Essex where sea walls have been breached by storm events in the past (e.g. the storms of 1953). The present level of the marshes regenerated within these sites is comparable to that of the adjacent natural marshes and is dominated by monotone climax vegetation (Burd, 1992). If the Tollesbury site responds in a similar way to the ‘accidental’ breach sites it is possible that site infilling would not only lead to a reduction in vegetation diversity but may also lead to a reduction in the water storage capacity. This process is, of course, an entirely expected response to the reintroduction of tidal flooding to low lying reclaimed land, but is worth reiterating to emphasise that sediment management is key to the long term sustainability of coastal systems.

2.4 MONITORING CHANGES IN VEGETATION FREQUENCY ON THE SALTMARSHES ADJACENT TO THE REALIGNMENT SITE

2.4.1 Introduction

At the outset of the Tollesbury project, there was concern that small scale breaching of the sea wall, rather than the whole scale removal of the embankment, would increase the tidal prism without any compensatory increase in the cross-sectional area of the estuarine channel and subsequently lead to erosion of existing salt marshes (Boorman 1997; Townend and Pethick 2002). Detailed monitoring of the vegetation on the natural marshes, adjacent to the realignment site, was carried out to determine whether any changes detected in vegetation composition could be attributed to the creation of the managed realignment site (Garbutt et al. 2002).

There were 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 community type is Puccinellia maritima salt marsh, typically the SM13c sub-community, which often forms a mosaic with the *A. portulacoides* salt marsh. The *Puccinellia* salt marsh is species rich and forms one of the most distinctive British saltmarsh communities, especially when *Limonium vulgare* (sea lavender) and *Armeria maritima* (sea pink/thrift) are in flower and small plants of *Salicornia* spp. (common glasswort) and *Suaeda maritima* (annual sea blite) turn red in the summer months.

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*). *Puccinellia maritima* can occur at its upper limits.

2.4.2 Methods

Permanent quadrats were used at two scales, 5m x 5m and 1m x 1m, to ensure that an adequate area of the salt marshes adjacent to the site were sampled and that recording was done in sufficient detail to pick up fine-scale changes in the vegetation (Figure 2.7). Forty $5m^{-2}$ quadrats were used, each sub-divided into twenty five 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 $5m^{-2}$ quadrats. The $1m^{-2}$ quadrats were each sub-divided into 100 0.1m x 0.1m cells. Recording took place in July 1994-2001, 2003, 2005 and 2007. The 1994 and 1995 surveys took place before creation of the managed realignment site. The species present within each cell were recorded and their mean percentage frequency calculated. Change in frequency (post breach – pre breach) was measured and analysed using a one-sample t-test of zero change.

Garbutt et al. (2002) used several physical parameters to test for changes in plant frequency resulting from the creation of the managed realignment site. This analysis was repeated using all data up to 2007. A GIS was used to derive values for some of the explanatory variables used in the analyses; distance of each quadrat to breach, sea wall, and to the nearest creek of a given minimum width. Spearman et al (2002) showed that after an initial period of morphological adjustment, most creeks feeding the realignment site had stabilised by 2001. Change in species frequency, in relation to bathymetric change between 1994 and 2000, and change in creek cross-sectional area (CSA) was also analysed.

2.4.3 Results

Over the fourteen years of the study species frequency was measured on the natural marshes adjacent to the managed realignment site and most plants showed some degree of change. *Sarcocornia perennis* (perennial glasswort), *Spergularia media* (greater sea-spurrey), *Aster tripolium*, *Limonium vulgare* all increased in frequency (Tables 2.3 and 2.4). *Spartina anglica* (common cord grass) increased from 1.5% in 1994 to 18.2%, in 2007, in the 5m x 5m quadrats. *Atriplex portulacoides* decline in frequency from a high of 73.7% in 1994 down to 49.2%, in 2007, in the 1m x 1m quadrats. The cover of mud and algae (>10%) was highly variable throughout the monitoring period.

Tables 2.5 and 2.6 show the correlation between botanical change in the $1m^2$ and $25m^2$ quadrats (post- minus pre-breach) in relation to elevation, distance from breach, distance to creeks of varying widths, bathymetric change between 1994 and 2000 and change in cross-sectional area (CSA). Certain species show a correlation with some variables, such as *A. portulacoides* with breach distance in the $1m^2$ quadrats. However, no clear trends appear between botanical changes and any of the explanatory variables.

2.4.4 Discussion

Whilst there were changes in the frequency of saltmarsh plant species growing on the Tollesbury marshes, there was no evidence to suggest that the creation of the managed realignment site was the cause. Pre- and post-breach differences appear to be part of longer-term trends. The decline in the frequency of *A. portulacoides* appears to have occurred on a regional (Essex wide) scale and is not confined to the Tollesbury marshes. 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 saltmarsh 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 saltmarshes 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 *Spartina* is interesting and not easily explained. In the upper marsh, at Tollesbury, *P. maritima* would be expected to be competitively dominant. It may simply be that *Spartina* is colonising the gaps left by *A. portulacoides*. Alternatively, Gray and Mogg (2001) postulated that *Spartina* is able to profit from higher temperatures, particularly in early spring, and may be able to out-compete *P. maritima* and other salt marsh species. Either way, the increase in *Spartina* and decline in *A. portulacoides* in the upper marsh poses questions about the long- term stability of the saltmarsh communities and their ecology.

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. The data probably show the population dynamics and natural variability of saltmarsh plant communities over time, in response to interactions between different species and external physical drivers. As the lower limit of salt marsh is defined by tolerance to physical factors, such as salinity, and the upper limit by competition, plant communities of saltmarshes usually represent a fluctuating equilibrium with the intertidal environment (Adam 1990). As plants die, others will replace them, either from the same or different species. Over time, the abundance of different species may vary, but overall composition should remain stable, if the physical parameters remain constant. The balance between sedimentation and erosion primarily determines this. Whether the increasing frequency of *Spartina* into the system alters this balance, and the natural dynamics of the plant communities, is uncertain. The results of the monitoring programme show that the interactions between saltmarsh plants and their environment are complex and, without monitoring the physical environment simultaneously, are often difficult to explain.

2.5 MONITORING THE DEVELOPMENT OF SALTMARSH WITHIN THE REALIGNMENT SITE

2.5.1 Introduction

As part of the initial research programme at Tollesbury, saltmarsh plants, seeds and turfs of saltmarsh vegetation were planted or sown on the site to assess whether a rapid cover of vegetation could be established, prior to natural colonisation (Garbutt et al. 2006). Establishment of the introduced plants and seeds was poor, and it was recommended that managed realignment sites in low energy environments, located near natural marshes should be left to regenerate naturally. Experience from other sites around the UK has confirmed this and found that, in most cases, natural plant colonisation within managed realignment sites is rapid (less than 5 years). Because of the relative newness of the method, however, there were still uncertainties around the timescale needed for plant assemblages, that resemble natural communities, to develop, if at all. The Defra funded research at Tollesbury represents the longest systematic monitoring scheme for a managed realignment site in the UK, and aimed to answer this.

2.5.2 Methods

A permanent 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 (Figure 2.8). 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 the species presence was recorded (Figure 2.9). Recording was first undertaken in September 1997, the second year after the breach, and repeated annually until 2003, and then again in 2005 and 2007. CEH funded the recording in 2002; an interim period between contracts. A paired t-test was used to compare difference in species frequency between years.

Vegetation data from three elevations along each of the vegetation transects were used to describe the development of plant communities within the realignment site, over time. Three elevational zones were used (zone 1: 1.25m +MHWN; zone 2: 0.50m +MHWN; zone 3: MHWN) to represent typical vegetation communities of the region. Mean high water neap tide (MHWN) is at 1.50m ODN. The data from a 20m row of 1m x 1m cells in each transect were combined to give a frequency value for each species, from 1997 to 2007, at the three elevations. The vegetation were compared with all other British Plant Communities as described by the National Vegetation Classification (NVC; Rodwell 2000) using the Tablefit computer programme (Hill 1996).

Because the natural saltmarshes, adjacent to the realignment site, are cliffed at the seaward edge and backed by earth embankments, the full zonational range of saltmarsh plants is restricted. To compare the plant communities of the realignment site over their full elavational range, data from Boorman (1992) were used.

2.5.3 Results

In 2007, twelve years after the Tollesbury realignment site was first re-exposed to tidal inundation, approximately 13ha of the 21ha site was covered by saltmarsh vegetation. Thirteen species were recorded within the monitoring transects (Table 2.7) and 21 species were recorded over the whole site (appendix 2.1). *Inula crithmoides* (golden samphire), *Spartina maritima* (small cord grass), *Suaeda vera* (shrubby sea blite) and *Triglochin maritima* (sea arrow grass) were also recorded growing within the site. There continued to be changes in plant species frequency, up to 2007. *P. maritima* increased in frequency year on year, becoming the dominant species at the highest elevations of the site. *Salicornia europaea* agg. and *Spartina anglica* dominated the vegetation, expanding their range to colonise previously unvegetated areas of the site (Figure 2.10). *S. anglica* was first recorded within the site in 1997, where it remained at a low frequency until 2001. From 2001, there was a rapid expansion of *Spartina* across all levels of the site where, by 2007, the frequency was 65%.

The NVC analysis showed that there were two distinct vegetation communities within the realignment site, by 2007 (Figure 2.11).

2.5.3.1 Zone 1: 2.75m ODN

SM13 – *Puccinellia maritima* saltmarsh - 96% goodness of fit to the NVC

The *Puccinellia* saltmarsh occupied a narrow zone at the foot of the new sea wall, on the southern edge of the site, in 2007. This mid level salt marsh community was dominated by *P. maritima* (cover typically 90%) with a variety of associated species (7-8 species/quadrat), though *S. europaea* agg. was the only other constant. Other species included 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. At the upper limits of this community, there was very little sediment deposition. The plants at this level were growing in the pre-inundation, agricultural substrate, with only a thin veneer of marine sediment covering the surface.

2.5.3.2 Zone 2: 2.00m ODN

SM6 – *Spartina anglica* saltmarsh – 90% goodness of fit to NVC

Spartina saltmarsh was the dominant vegetation community of the Tollesbury site in 2007. This pioneer saltmarsh community was characterised by tall tussocks of *Spartina anglica* (cover typically 70%) with a constant under story of *Salicornia europaea* agg. and bare mud. Up to 2005, the vegetation of this zone was dominated by SM 8, *Salicornia* salt marsh, where *Spartina* had a cover of only 20%.

At the boundary with the SM13, *Puccinellia* saltmarsh, *Suaeda maritima* and *Puccinellia maritima*, in association with *Spartina* and *Salicornia europaea* agg., formed a narrow transition zone between the two major communities of the site.

2.5.3.3 Zone 3: 1.50m ODN

SM6 – *Spartina anglica* salt marsh - 70% goodness of fit to NVC

Spartina was not recorded at this elevation until 2005, where it occurred as single plants or small tussocks. By 2007, the number of *Spartina* plants at this level remained sparsely scattered, although the individual tussocks recorded in 2005 had expanded.

Figure 2.12 shows the vegetation communities of the Tollesbury managed realignment site in 2007, and the natural saltmarshes of the region (after Boorman 1992). By 2007, the plant communities of the site were not as diverse as the natural marshes of the region, at similar elevations, and differed in species composition. It appears that the plant communities of the realignment site occupy a zone higher than that of the equivalent natural marsh community. For example, the *Puccinellia/Atriplex* dominated community of the natural marshes occupies a zone between 2.35-2.75m ODN. Within the realignment site, the *Puccinellia/Atriplex* dominated community was recorded at 2.35-3.00m ODN

2.5.4 Discussion

Approximately thirteen hectares of the 21 ha Tollesbury managed realignment site were covered in saltmarsh vegetation by 2007. There were 17 species of saltmarsh plant recorded within the site, up to 2007. All species were typical of the region and included the nationally scarce *Inula crithmoides*, *Spartina maritima* and *Suaeda vera*. Some species recorded in the monitoring on the natural marshes were not recorded with in the managed realignment site, however. *Armeria maritima*, *Festuca rubra*, *Juncus maritimus*, *Juncus gerardii*, *Plantago maritima* and *Seriphidium maritimum* all grow on the marshes adjacent to the site, at low frequency, but were not present within the site, even though, in the highest areas, the elevation was suitable.

The lack of certain species within the site could be a function of either unsuitable abiotic conditions, their relative scarcity in the local species pool leading to a low abundance of seeds, or a lack of dispersal ability for individual species. Despite the potential for long-distance transport of propagules by tidal water, there is a predominance for local dispersal in coastal settings (Huiskes et al., 1995). In a study of seed dispersal into the Tollesbury site, Wolters et al. (2005) found that the seeds of saltmarsh plants are predominantly dispersed over short distances, and colonisation of de-embankment sites probably occurs via stepping-stones. Wolters et al. (2005) recorded seeds of *Festuca rubra* and *Plantago maritima* within the site, where these species were not recorded as adult plants. The areas of the site that were at a suitable elevation to support the less frequent species were dominated by a closed sward of *Puccinellia maritima*, providing few gaps for other species to colonise. In addition to the potential scarcity of seeds entering the site, the vigorous growth of *Puccinellia maritima* is likely to out-compete other species.

Within the Tollesbury site, *Salicornia europaea* agg. grew down to its expected lower limit (MHWN), fulfilling the predicted extent of salt marsh development. However, it appears that the plant communities of the realignment site occupy a zone higher than that of the equivalent natural saltmarsh community, at a similar elevation. Garbutt et al. (2006) found that the lower elevational limit of saltmarsh plants within the realignment site were, on average, 0.19m higher that those of the adjacent natural marshes, after six years of tidal inundation. Watts et al. (2003) found that the newly accreted sediments within the site were characterised by high water content, low dry bulk density and low resistance to erosion. This has considerable implications for the development of vegetation, as waterlogged sediments are important in determining the lower limits of plants in the tidal frame and the course of vegetation succession.

By 2007 the majority of the vegetated area of the realignment site was dominated by *Spartina anglica*. The sparsely vegetated mudflats that typify the early phases of saltmarsh development within realignment sites provide ideal conditions for the establishment of this invasive species. *Spartina* can drastically alter the sedimentary and drainage characteristics of its surroundings leading to the creation of waterlogged and anoxic soils (Doody 1984). Whilst *Spartina* is now currently accepted as an integral part of the flora of European saltmarshes (Lacambra et al. 2004), the presence of this species in the early stages of saltmarsh restoration may be less desirable. The establishment of *Spartina*, early in the development of saltmarsh within managed realignment sites, gives the regenerate saltmarshes a very different starting point to that of natural saltmarshes, and may affect the eventual outcome of creation efforts. 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.

The Tollesbury managed realignment project has been successful in regenerating saltmarsh vegetation on formerly reclaimed, agricultural land. This has been achieved by the natural colonisation of plants from the local species pool. The site supports three nationally scarce species and two recognisable British saltmarsh plant communities. However, several species of plant that would be expected to be present, as predicted by their elevation were lacking. In addition, these plant communities are less diverse and dominated by one species, *Puccinellia maritima* or *Spartina anglica*. The results presented here should not be interpreted as a failure of managed realignment to create saltmarsh that matches natural conditions, but as a cautionary note that in fact, restoration efforts may never fully replace natural wetland functions. Whether saltmarshes regenerated within managed realignment sites are any less valuable for nature conservation in their own right should be considered. It may be that from a functional aspect regenerated marshes are not that different from natural systems, although this remains untested.

2.6 Acknowledgements

Laurie Boorman was the principal investigator for this project from its conception until 1996, writing the methodologies for the sedimentation measurements, botanical monitoring and reports. Dave Barratt, Dave Myhill, Jayne Mann, Mineke Wolters, Caroline Boffey and Pete Nuttall helped with the botanical recording. Mick Yates and Tony Turk helped with sediment recording. Peter Rothery provided statistical support throughout the project.

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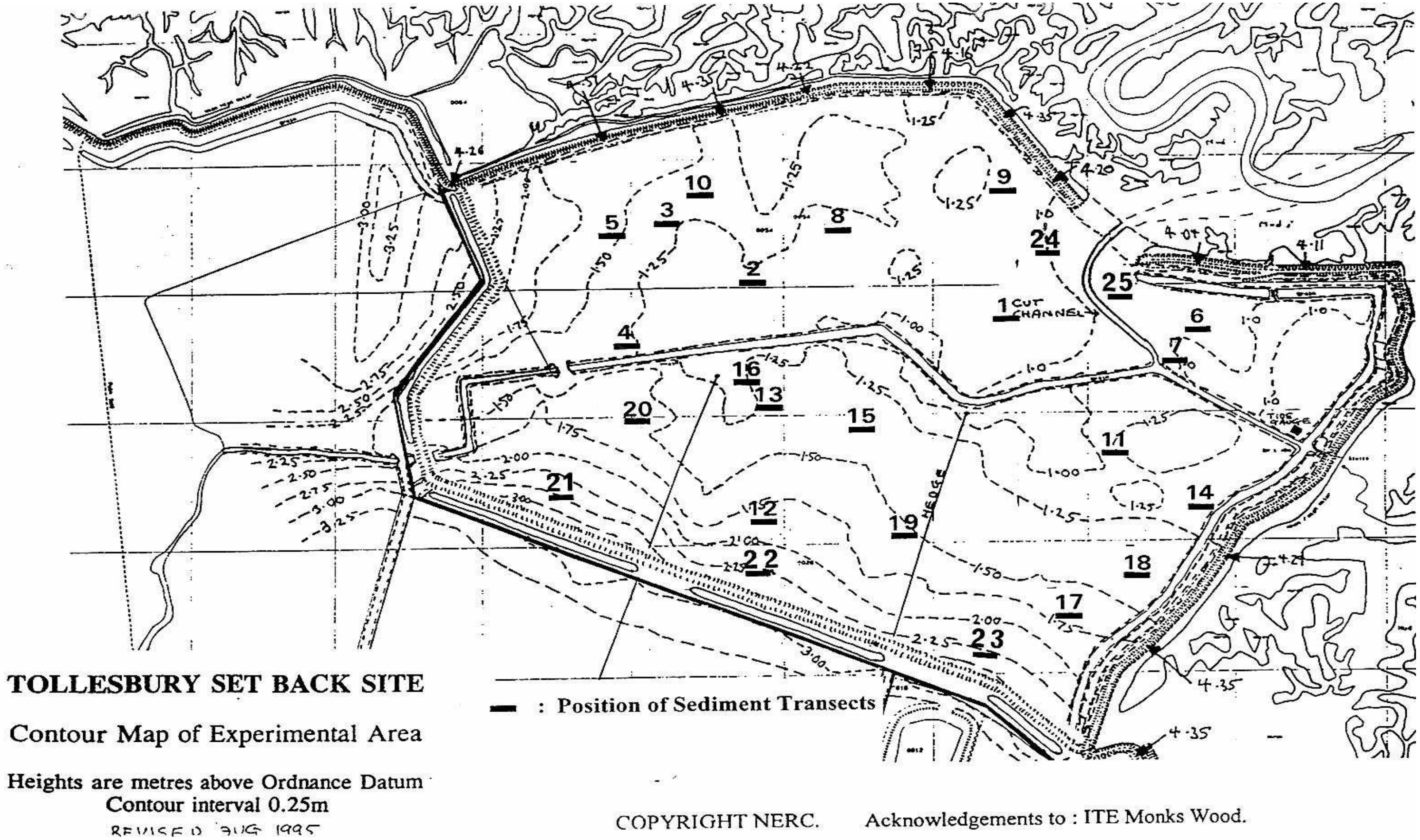
2.8 Appendix 2.1

Scientific and common names of saltmarsh plants recorded within the Tollesbury managed realignment site (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
Inula crithmoides	Golden samphire
Limonium vulgare	Common sea-lavender
Puccinellia maritima	Common salt marsh-grass
Salicornia europaea	Common glasswort
Sarcocornia perennis	Perennial glasswort
Seriphidium maritimum	Sea wormwood
Spartina anglica	Common cord-grass
Spartina maritima	Small cord-grass
Spergularia marina	Lesser sea-spurrey
Spergularia media	Greater sea-spurrey
Suaeda maritima	Annual sea-blite
Suaeda vera	Shrubby sea-blite
Triglochin maritima	Sea arrow-grass

2.9 Appendix 2.2

Figures 2.1 – 2.11



TOLLESBURY SET BACK SITE

Contour Map of Experimental Area

Heights are metres above Ordnance Datum
Contour interval 0.25m
REVISED AUG 1995

▬ : Position of Sediment Transects

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Figure 2.1 Position of the sediment transects within the managed realignment site at Tollesbury.

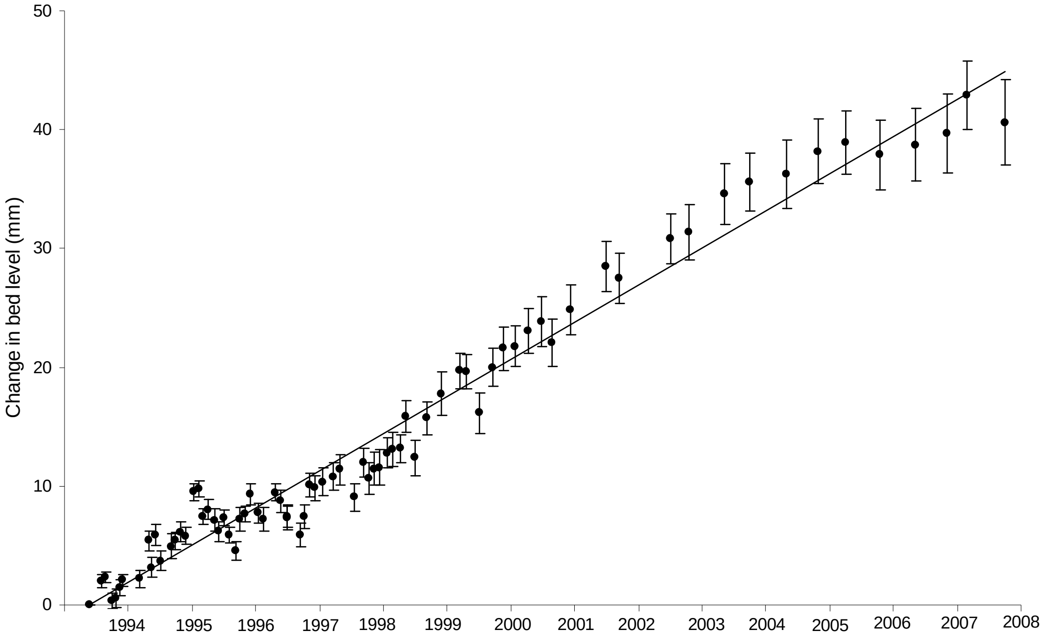


Figure 2.2 Mean sedimentation (n=12) for the Old Hall salt marshes between May 1993 and October 2007 with best fit line. Mean rate is 3.1mm year^{-1} (regression equation: $y = -1.136 + 0.008529$ day; r^2=97.1%, $p<0.001$).

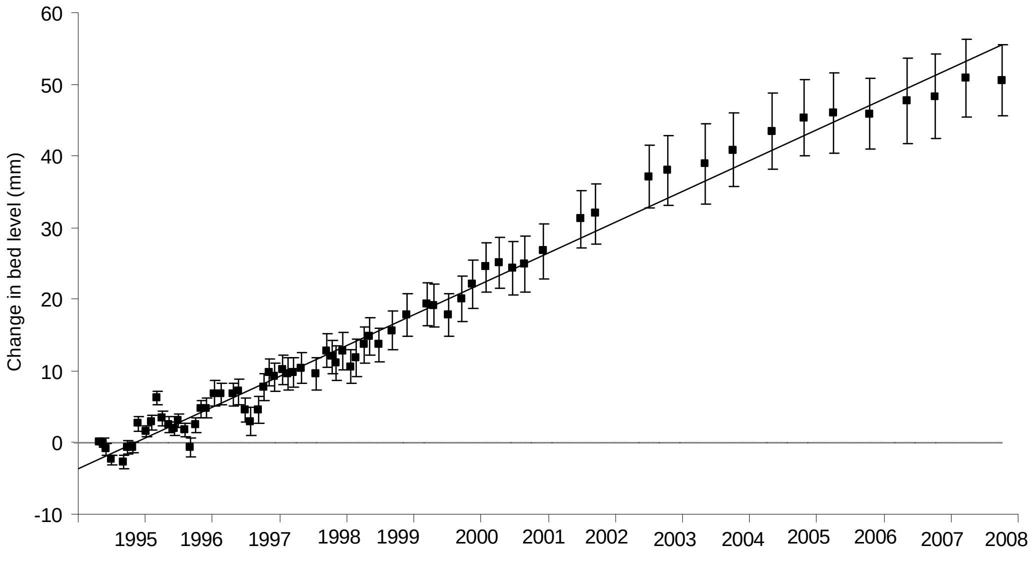


Figure 2.3 Mean sedimentation (n=16) for the Tollesbury salt marshes between April 1994 and October 2007 with best fit line. Mean rate is 4.2mm year^{-1} (regression equation: $y = -7.505 + 0.01162$ day; r^2=97.9%, $p<0.001$).

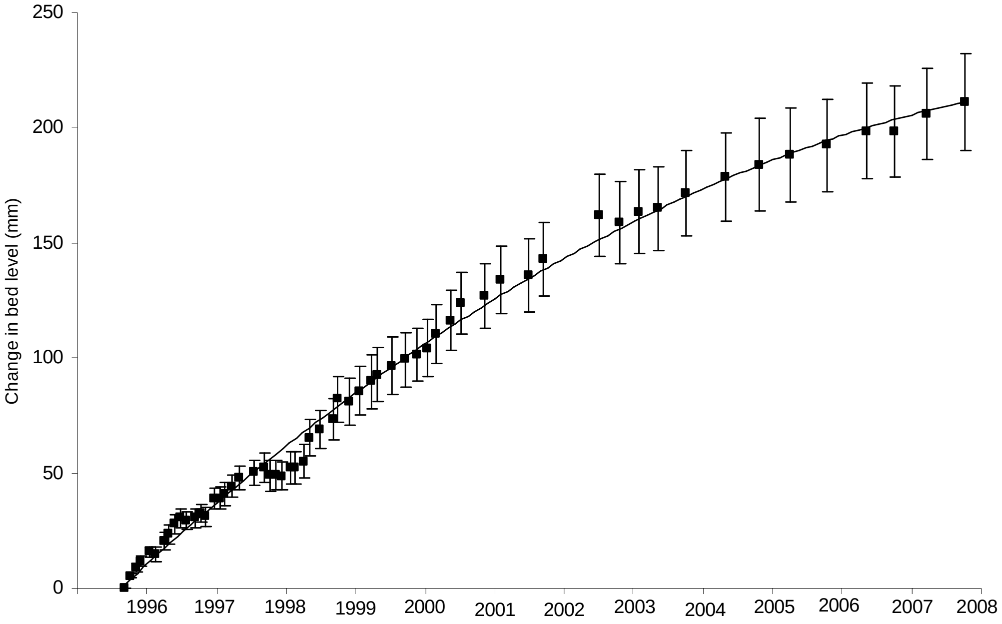


Figure 2.4 Mean sediment accretion (n=20) within the Tollesbury managed realignment site between 1995 and 2007. Line shows fitted quadratic model used to account for the simple curvature in the data (y = -14.85 + 0.07650 day - 0.000006 day2; r^2=99.2%, p-value for quadratic effect <0.001).

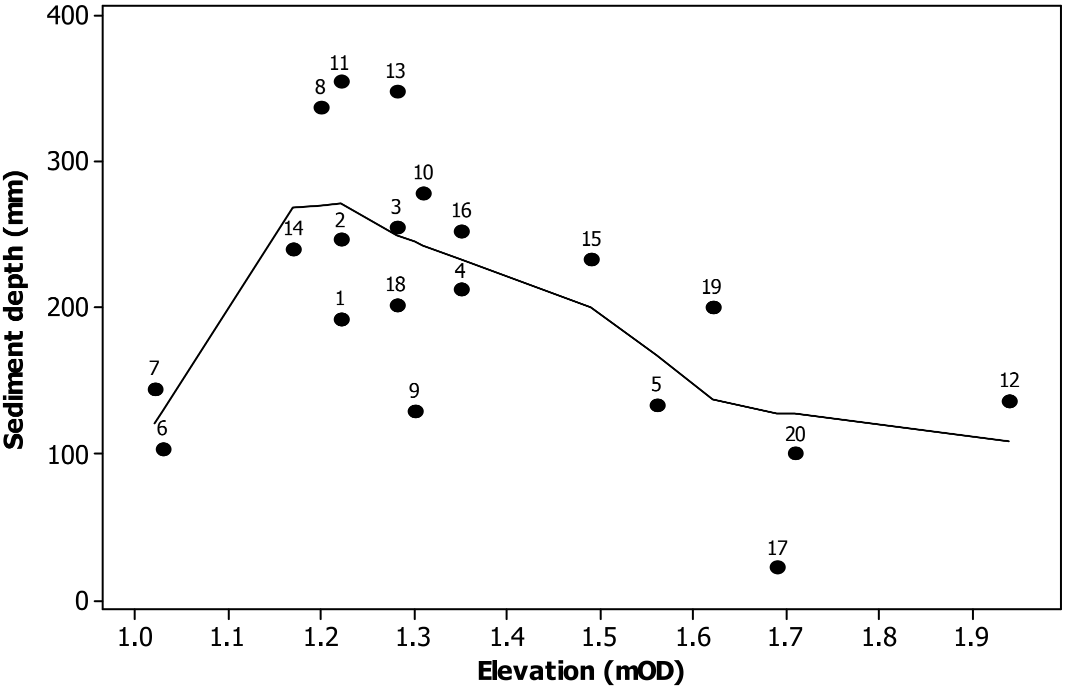


Figure 2.5 Depth of sediment over pre-inundation land surface in October 2007 at sediment transects 1-20 within the experimental site. Lowess smoother line is shown to indicate underlying trend.

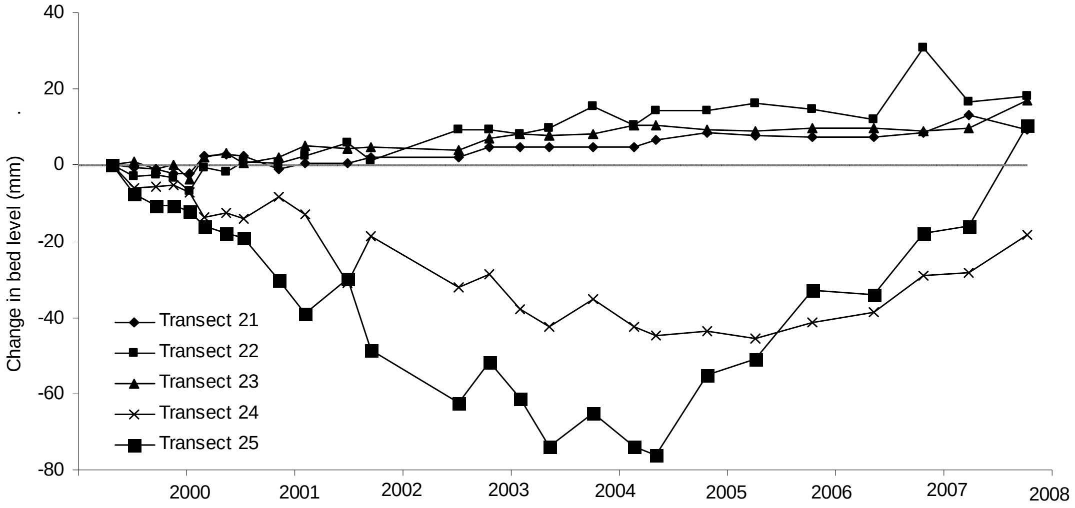
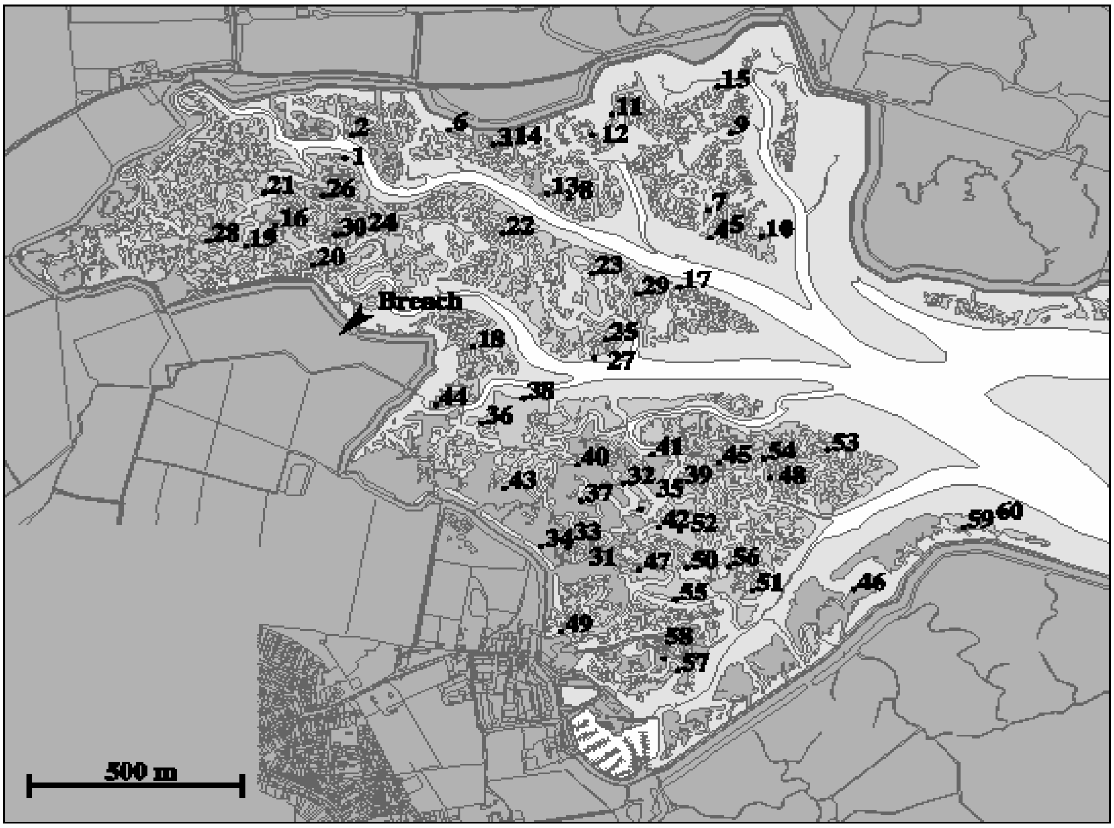


Figure 2.6 Change in bed level at five additional sediment transects within the managed realignment site. Transects 21, 22, 23 were situated in the highest parts of the site, whilst transects 24 and 25 were close to the breach.



Based upon the Ordnance Survey Land-Line® digital map data with the permission of The Controller of Her Majesty's Stationery Office. ©Crown Copyright.

Figure 2.7 Map of the Tollesbury/Old Hall marshes and position of the quadrats used for botanical monitoring.

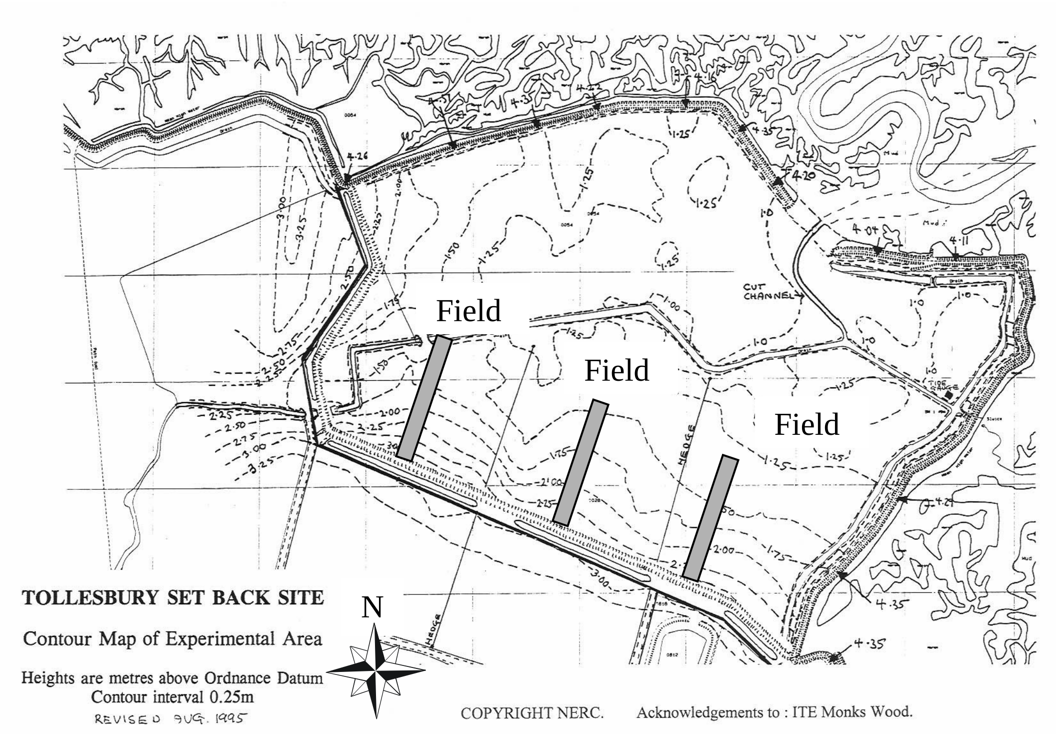


Figure 2.8 Approximate location of transects with in the Tollesbury managed realignment site (not to scale). Each transect of 20m wide and 125m long, is divided into 2500 plots of $1m^{-2}$.

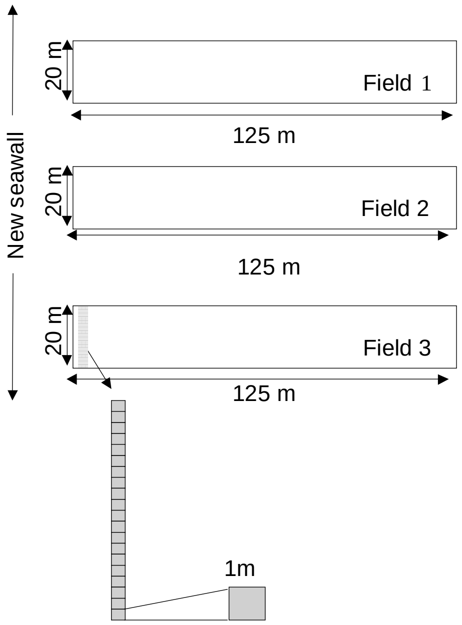


Figure 2.9 Lay-out of the three transects, each 20m wide and 125m long, extending from the foot of the seawall to the mud flat, used to monitor natural colonisation within the managed realignment site. Each transect is divided into 2500 plots of $1m^{-2}$.

Figure 2.10 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.

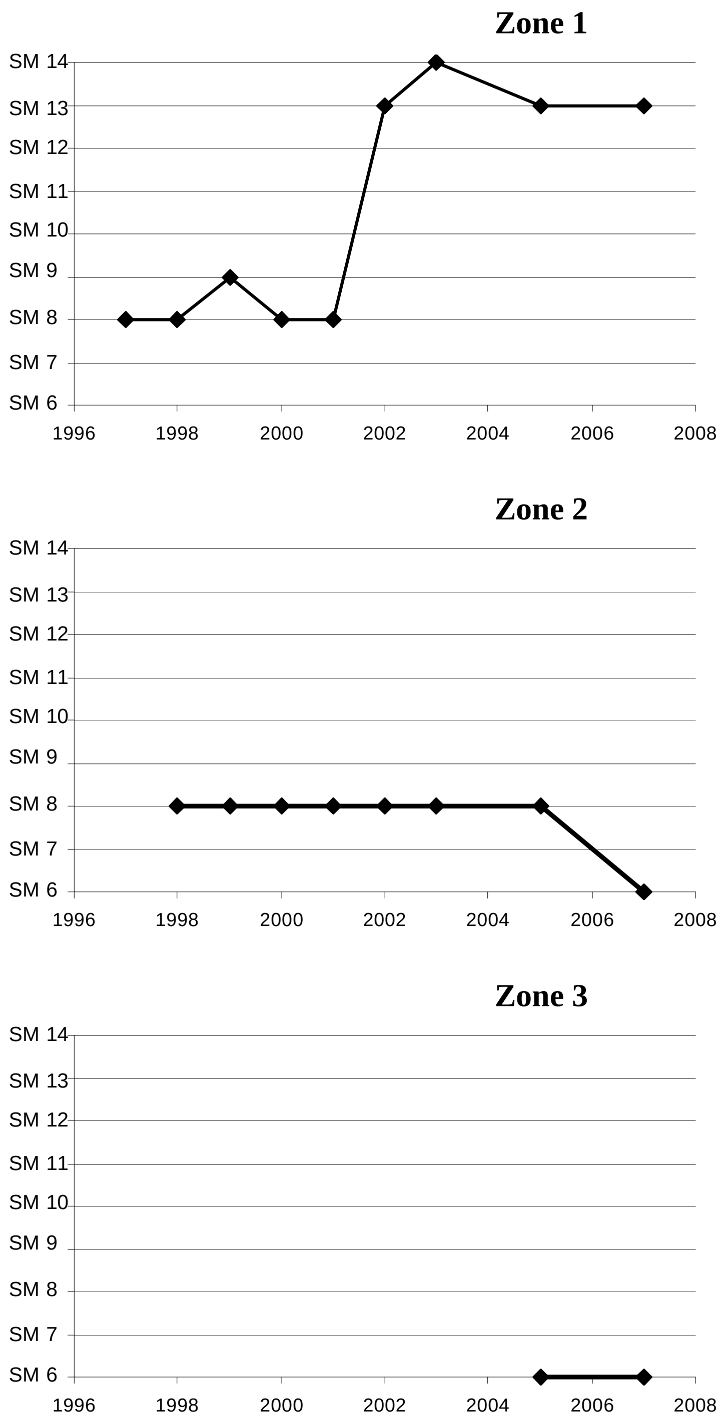


Figure 2.11 The British Plant Communities, as described by the National Vegetation Classification, recorded within the Tollesbury managed realignment site, at three elevational zones, between 1997 and 2007. The elevation for each zone was; zone 1: 1.25m +MHWN; zone 2: 0.50m +MHWN; zone 3: MHWN. See text for a description of plant communities.

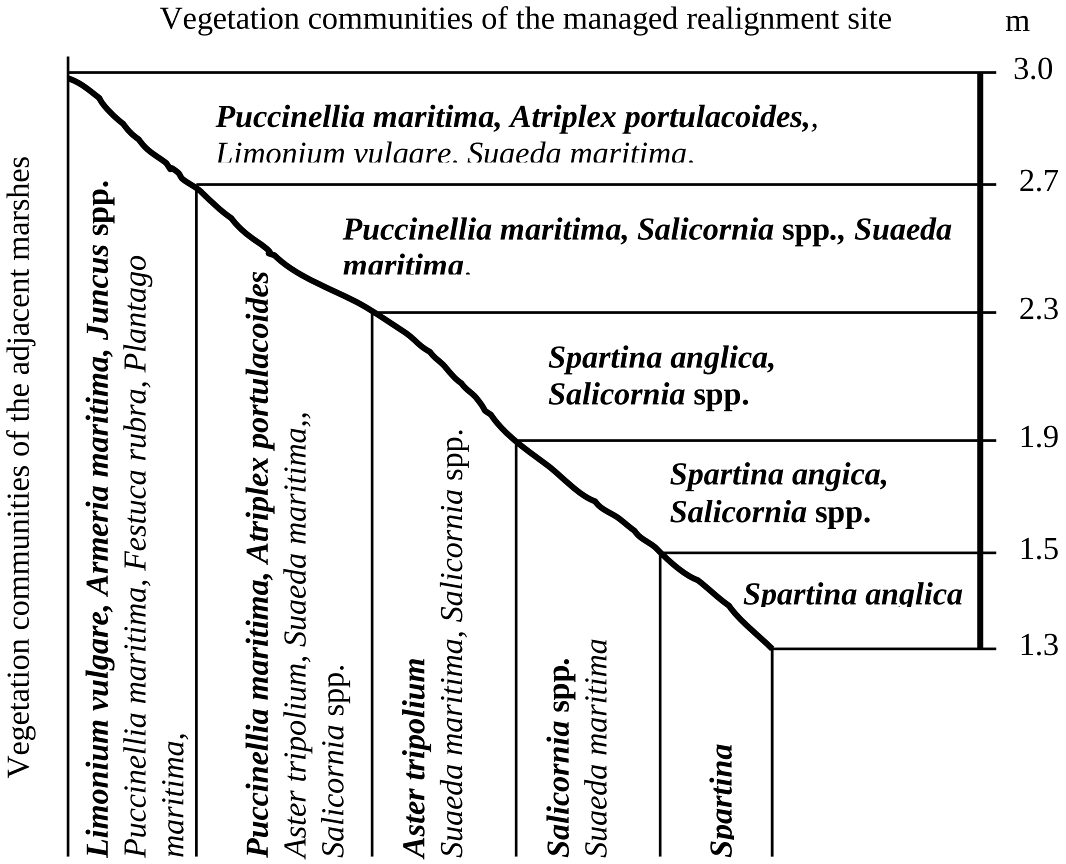


Figure 2.12 A comparison between the vegetation communities of the Tollesbury managed realignment site, recorded in 2007, and the natural salt marshes of the region (adapted from Boorman, 1992) at different ranges along an elevational gradient. Dominant species are highlighted in bold.

2.10 Appendix 2.3

Tables 2.1 – 2.7

Table 2.1 Estimated annual change in bed level, by year, within the Tollesbury managed realignment site (using the quadratic equation $y = 4.113 + 0.07561$ day - 0.000006 day2; r^2=99.3%; $p < 0.001$).

Year	Change in bed level (mm/year)
1995-1996	31.6
1996-1997	25.6
1997-1998	23.9
1998-1999	22.3
1999-2000	20.7
2000-2001	19.1
2001-2002	17.5
2002-2003	15.4
2003-2004	14.8
2004-2005	12.7
2005-2006	11.2
2006-2007	9.6

Table 2.2 Depth of marine sediment over the pre-inundation land surface at sediment transects within the managed realignment site, to2007.

Transect	Depth (mm)	Transect	Depth (mm)
1	192	11	354
2	246	12	136
3	255	13	348
4	212	14	240
5	133	15	233
6	103	16	252
7	144	17	22
8	337	18	202
9	129	19	200
10	278	20	100

Table 2.3 Means (s.e.) of percentage frequency data in 5 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, 2004 or 2006.

Species	Marsh Type	1994	1995	**Breach**	1996	1997	1998	1999	2000	2001	2003	2005	2007	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	75.5 (5.9)	5.1 (2.1)*
	Lower	-	-		-	-	-	-	-	-	-	-	-	-
Plantago maritima	Upper	14.7	13.3		14.9	13.1	12.4	13.7	16.7	15.2	12.7	13.7	13.2 (4.1)	-0.1 (1.2)
	Lower	-	-		-	-	-	-	-	-	-	-	-	-
Sarcocornia perennis	Upper	10.7	21.7		27.7	30.7	23.7	30.0	23.7	22.1	22.5	30.8	33.5 (5.8)	10.8 (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	48.4 (6.8)	4.2 (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	51.2 (7.3)	6.5 (2.9)*
	Lower	-	-		-	-	-	-	-	-	-	-	-	-
Spartina anglica	Upper	1.5	2.0		2.0	3.6	4.3	3.9	4.5	5.9	9.9	13.9	18.2 (4.4)	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	92.3 (3.7)	-1.6 (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 (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	76.0 (7.4)	-10.5 (2.9)***
	Lower	8.0	6.8		3.6	5.6	3.6	2.4	4.0	4.0	0.8	2.4	3.6 (3.2)	-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	59.6 (6.2)	13.4 (2.7)***
	Lower	59.2	58.0		56.8	54.0	47.2	53.6	54.8	56.4	50.8	50.8	52.4 (12.3)	-5.6 (2.1)*
Suaeda maritima	Upper	72.7	80.4		86.7	87.5	84.1	82.3	68.1	62.7	73.1	94.1	80.0 (5.5)	3.2 (2.9)
	Lower	52.0	50.0		54.0	60.0	44.0	36.0	16.8	20.8	22.8	46.4	57.2 (7.7)	-11.2 (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	80.3 (6.6)	18.6 (4.3)***
	Lower	96.0	96.0		98.0	96.4	94.8	92.0	90.0	88.8	90.4	96.4	89.6 (2.1)	1.4 (3.1)
Algae >10%	Upper	1.7	0.8		0.3	11.1	15.9	18.0	12.1	27.2	5.2	16.7	14.3 (6.1)	11.5 (3.6)**
	Lower	21.2	27.2		58.4	80.8	45.2	47.6	51.2	27.2	0.0	22.0	22.0 (8.6)	15.2 (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	19.3 (6.0)	15.6 (3.5)***
	Lower	73.2	91.6		93.6	98.8	96.8	97.6	100	100	100	100	100 (0)	16.1 (5.7)*

Table 2.4 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, 2004 or 2006.

Species	Marsh Type	1994	1995	**Breach**	1996	1997	1998	1999	2000	2001	2003	2005	2007	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	49.2 (5.8)	-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	35.4 (6.1)	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	79.4 (5.3)	-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	17.5 (4.4)	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	16.9 (2.6)	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	18.7 (7.1)	-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	37.4 (5.2)	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	52.5 (9.7)	-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	46.8 (4.7)	-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	11.1 (5.7)	-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	14.6 (4.1)	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	55.5 (11.9)	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	11.5 (3.7)	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	88.2 (8.1)	-3.9 (4.6)

Table 2.5 Correlation between botanical change (post – pre-breach) in 1m^{-2} quadrats in relation to marsh type; elevation; distance of quadrats to breach; distance to nearest creek of 5, 10, 20, and 50m width; and change in bathymetry; and creek cross-sectional area (CSA).
* p < 0.05; ** p < 0.01; *** p<0.001.

Species	Marsh type	Elevation	Breach distance	Distance to creek of minimum width				Bathymetric change			
				5m	10m	20m	50m	min	mean	max	CSA
Atriplex portulacoides	Upper	0.24	0.43**	0.08	0.17	0.17	0.19	0.26	0.33	-0.13	-0.07
Limonium vulgare	Upper	0.15	-0.15	-0.05	0.06	0.13	0.12	0.06	0.12	-0.24	0.19
Puccinellia maritima	Upper	0.08	-0.14	0.13	0.22	0.22	0.11	0.3	0.18	0.27	0.01
Triglochin maritima	Upper	0.13	-0.05	0.01	-0.3	0.04	0.14	0.01	0.24	-0.43**	-0.38*
Aster tripolium	Upper	0.09	0.22	0.02	0.12	-0.80	-0.90	-0.31*	-0.17	-0.05	-0.12
	Lower	0.27	-0.09	-0.20	-0.30	0.12	0.41	0.58*	0.54*	-0.54	-0.15
Salicornia europaea agg.	Upper	-0.23	-0.25	-0.22	-0.28	-0.22	-0.18	-0.15	-0.06	-0.16	-0.19
	Lower	-0.18	0.05	0.06	0.20	0.34	0.33	-0.11	0.12	-0.02	-0.35
Suaeda maritima	Upper	-0.05	0.24	0.24	0.04	0.03	0.02	0.14	0.11	-0.12	0.04
	Lower	0.33	-0.06	0.03	-0.56*	-0.30	-0.13	-0.01	0.06	-0.05	0.01
Algae	Upper	-0.31*	0.00	-0.21	-0.20	-0.36*	-0.48**	-0.58***	-0.616	0.44**	0.00
	Lower	-0.16	0.03	0.03	0.25	0.03	-0.55	-0.53	-0.58	0.02	0.10
Bare mud	Upper	-0.58***	-0.19	-0.19	-0.18	-0.30	-0.38	-0.23	-0.27	0.14	0.05
	Lower	0.43	0.12	-0.02	0.41	0.55*	0.42	0.32	0.46	0.06	0.08

Table 2.6 Correlation between botanical change (post – pre-breach) in 5m^{-2} quadrats in relation to marsh type; elevation; distance of quadrats to breach; distance to nearest creek of 5, 10, 20, and 50m width; and change in bathymetry; and creek cross-sectional area (CSA).
$*$ $p < 0.05$; $**$ $p < 0.01$; $***$ $p<0.001$.

	Marsh type	Elevation	Breach distance	Distance to creek				Bathymetry			
Species				5m	10m	20m	50m	min	mean	max	CSA
Atriplex portulacoides	Upper	0.06	-0.04	0.23	0.23	0.27	0.38*	0.26	0.34	-0.38	-0.08
Limonium vulgare	Upper	0.04	-0.35	0.03	0.02	0.16	0.39*	0.22	0.40*	-0.55**	-0.24
Puccinellia maritima	Upper	0.05	-0.24	0.06	0.14	0.24	0.28	0.31	0.28	-0.18	-0.06
Triglochin maritima	Upper	0.17	-0.21	-0.05	-0.13	-0.01	0.12	0.12	0.07	-0.18	0.09
Aster tripolium	Upper	0.09	-0.29	-0.22	-0.24	-0.22	0.02	-0.42*	-0.24	0.01	-0.25
	Lower	0.38	0.23	0.27	0.26	0.32	-0.07	0.35	0.17	-0.41	0.58
Spergularia media	Upper	-0.02	-0.54	-0.02	0.02	0.11	0.22	-0.05	-0.04	-0.19	-0.07
Plantago maritima	Upper	-0.14	-0.23	0.02	-0.10	0.10	0.30	-0.06	0.27	-0.50	-0.60
Sarcocornia perennis	Upper	0.13	0.28	-0.21	-0.25	-0.39*	-0.50	0.06	-0.30	0.50**	0.56
Salicornia europaea agg.	Upper	-0.12	-0.46	-0.07	-0.12	0.03	0.28	0.01	0.23	-0.45*	-0.32
	Lower	0.58	-0.16	-0.05	0.41	0.89***	0.71*	0.34	0.52	-0.05	-0.41
Suaeda maritima	Upper	0.04	0.15	0.09	-0.02	-0.06	-0.13	-0.09	-0.21	0.22	0.02
	Lower	-0.26	0.13	-0.26	0.35	0.16	-0.19	0.26	0.03	0.44	0.14
Algae	Upper	-0.39*	0.21	-0.25	-0.27	-0.39*	-0.56**	-0.42*	-0.48**	0.42*	0.12
	Lower	-0.28	0.27	0.13	-0.00	-0.21	-0.7*	-0.43	-0.54	-0.11	0.46
Bare mud	Upper	-0.52**	0.05	-0.36	-0.43*	-0.50**	-0.54**	-0.31	-0.31	0.21	0.07
	Lower	0.03	-0.46	0.31	0.02	-0.3	0.33	-0.17	0.09	-0.05	-0.48

Table 2.7 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; ns – not significant.

	1997	1998	1999	2000	2001	2002	2003	2005	2007	Difference 2007-2005
Salicornia europaea	15.6	57.5	66.5	63.2	58.4	58.3	55.7	66.8	68.4 (0.4)	*
Suaeda maritima	0.5	19.4	13.9	13.5	11.2	10.8	8.0	8.2	7.0 (0.2)	*
Sarcocornia perennis	0.01	0.5	0.3	1.4	1.4	1.8	3.1	2.0	5.2 (0.2)	***
Spartina anglica	0.01	0.1	0.3	1.9	5.2	18.2	35.9	57.9	65.1 (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	23.0 (0.4)	***
Atriplex portulacoides		0.3	0.9	0.8	1.3	1.3	1.3	2.7	3.3 (0.1)	**
Aster tripolium		0.3	0.9	2.5	3.8	5.7	5.5	9.7	9.6 (0.2)	ns
Atriplex littoralis		0.2	-	0.3	0.4	-	0.01	-	0.1 (0.1)	ns
Limonium vulgare			0.4	0.7	1.0	1.3	1.1	1.5	2.0 (0.1)	ns
Cochlearia anglica			0.1	-	-	0.1	0.03	-	0.01 (0.01)	ns
Spergularia media				0.5	1.3	2.8	2.8	5.7	5.3 (0.2)	ns
Elytrigia atherica					0.2	0.6	0.7	1.3	1.6 (0.1)	ns
Hordeum marinum					0.2	0.1	-	-	-	-
Atriplex prostrata					0.01	-	-	-	-	-
Beta maritima						0.01	-	0.03	0.2 (0.2)	ns
Inula crithmoides								0.03	-	

CHAPTER 3

FURTHER MONITORING OF THE STRENGTH AND STABILITY OF SEDIMENTS AND SOILS ON THE TOLLESBURY MANAGED REALIGNMENT SITE

C.W. WATTS

Cross Institute Programme for Sustainable Soil Function, Rothamsted Research, Harpenden, Herts., AL5 2JQ: chris.watts@bbsrc.ac.uk

3.1 SUMMARY

Measurements of sediment strength (using the fall-cone and cone penetrometer) and stability (critical shear stress measured using the cohesive strength meter) were performed in September 2003 and 2007 over five different vegetation zones within the managed realignments site at Tollesbury with the purpose to seek links between measures of strength and stability with the development of the saltmarsh and sediment ecosystems. Critical shear stress (above which erosion is likely to occur) and shear strength vary significantly between the different vegetation zones. In general, soils with higher shear strength in the surface layers also have higher critical shear strengths. Saltmarsh plants were found on sediments with shear strengths ranging from 5 to 70 kPa with *Salicornia* and *Spartina anglica* occurring over this entire range. Greater species diversity occurs where the sediment is stronger than 30 kPa. There were no significant plant communities where shear strength was below 5 kPa. The colonisation by *Spartina anglica* of vegetation zones *c* and *d* in 2007 was associated with a reduction in shear strength and stability of the surface sediments, but where it colonised the mud flat, strength and stability increased. Creeks and gullies began forming once sediment exceeded a critical depth 20 – 30 cm. The lower extent of *Salicornia* is extended along the faster draining and stronger (up to 18 kPa) margins of these creeks and there is some evidence that these plants may contribute slightly to higher sediment strength. In 2007 pioneer clumps of Spartina colonised the area where we had characterised the creek margins resulting in the loss of these creeks. We found no evidence of significant creek formation where *Spartina anglica* dominated. However, we observed *Salicornia* continuing to grow along creek margins at several locations; in particular in the north east of the site on deep sediment with an original elevation of 1.25 m.

3.2 INTRODUCTION

The success of managed realignment depends on the ability of the soils and sediments within the site to resist the eroding action of waves and tides, and to allow the accretion of sediment, at least at the rate of the effective sea level rise. Sediment stability is a key factor in determining the success of a managed realignment scheme because of the role it plays in the erosion, deposition, transport and consolidation cycle (EDTC). Previous monitoring work on the managed realignment site at Tollesbury has shown that the development of saltmarsh is a dynamic process (Reading *et al*., 2003). Sediment is still accreting and the area of saltmarsh continues to expand. As the older sediments begin to consolidate and a complex system of creeks had started to develop, draining and helping to further stabilise the marsh (Watts *et al*., 2003). Monitoring of the physical status of the marsh so far has shown that: (i) the stronger sediments are to be found at the higher elevations, (ii) that the faster the sediment accretes the weaker it is, (iii) that the strength and stability of the new creek walls is substantially greater than the surrounding sediments and (iv) sediment shear strength provides a good indication of its ability to resist erosion.

3.3 OBJECTIVES

During this phase of the study we aim to link measures of strength and stability with the development of the saltmarsh and sediment ecosystems. Firstly, we will investigate whether more stable sediments encourage the establishment of salt marsh plants and find out the level of additional sediment stability that we can expect from saltmarsh plants of different species, maturity and density as the site evolves. In addition, we aim to investigate to what extent the ability of the sediment to drain quickly as a result of creek formation is a factor in the conversion of a system dominated by benthic invertebrates to one dominated by salt marsh plants. Finally we aim to better understand to what extent creek formation speeds the development of stronger sediments and the desirable switch to saltmarsh vegetation.

Monitoring strength and stability within the realignment site at Tollesbury will be conducted at the same locations and times as the vegetation survey (done by CEH). This will provides information on the processes that determine the development of saltmarsh communities on former agricultural soils after managed realignment. Here we describe measurements of sediment strength and stability performed during the first week September 2003 and again during the first week of September 2007, 8 and 12 years respectively after the old sea wall was breached. Strength and stability measurements were made on the sediment surface and additional measurements using a cone penetrometer provide an indication of soil strength down to 0.5 m.

3.4 METHODS

3.4.1 Site

The experimental managed realignment site just north of the river Blackwater, Essex, in south-east England was established in part to try and improve the understanding of the processes involved and the practical techniques required for successful managed realignment in a typical UK situation. The site consists of 21 ha of low-lying land between the 1.0 and 2.8 m contours (all elevations in this report are measured with respect to ordinance datum) and is approximately 1 km north of the Tollesbury (51^o 46.5’N 0^o 51.0’E). The site was originally drained and set to grassland more than 150 years ago and part of it was converted for arable use 25 – 30 years ago.

Prior to inundation, the site was divided into four fields. Along the seaward edge to the north, and immediately behind the old sea-wall, was a field of rough grazing. This was separated from the three remaining arable fields by an open ditch, which linked up to the old sea-wall borrow-dyke. Drainage from these ditches occurred at low tide through the old sea-wall via a culvert fitted with a one-way valve. The three arable fields (identified in this report as 1, 2 and 3 and numbered from west to east) rise slowly towards their southern boundary, which coincides with the position of the new sea-wall (Figure 3.1). Construction of the new earth-bank sea-wall, forming a boundary to the south and west of the site was completed by July 1995 and a 40 m breach was made in the old sea-wall on 4th August 1995.

Following breaching, the sea has been free to enter the site, twice a day with the high tides. Mean high water neap tide (MHWN) is at approx. 1.60 m elevation flooding 15 of the 21 ha. Mean high water spring tide (MHWS) is at 3.0 m covering virtually the entire site. The mean tidal range at Tollesbury is around 4.5 m. Mean tidal immersion times within the site range from around 45 % immersion time at the 1.0 m elevation, with inundation twice a day to around 10 % immersion time at 2.8 m elevation, which is not reached by the sea during neap tides.

The underlying soil within the site was characterised as clayey marine alluvium (Claydon & Hollis, 1984), belonging to the Wallasea series (Hazelden & Boorman, 2001) and some key physical characteristics (strength and stability) are reported by Watts *et al*. (2003).

3.4.2 Sampling zones

Five sampling zones (*a* to *e*) were used for both soil and vegetation measurements. These were located on each of three transects (T1 to T3) running from a fixed datum at the foot of the new sea wall, down to what was in 2003 an un-vegetated mud flat (Figure 3.1). These transects, which run approximately from south to north in each of the former arable fields were also used by CEH to monitor the natural colonisation of vegetation (Table 3.1, RA.Garbutt, personal communication). Four stations were selected to represent a different vegetation zone in 2003 (zone *a* to *d*) and the fifth represented the mudflat (zone *e*). Similar measurements were made at these same locations in September 2007 although significant changes occurred in the vegetation during the intervening period (see Table 3.1).

Watts *et al*. (2003) reported that a series of creeks and gullies had begun forming for the first time during 2001 and 2002 and that these drain the newly accreted sediment on the low lying (northern) end of the former arable fields. These creeks drained into the central drainage ditch. Other creeks also formed in the deeper sediment on the south east and west edges of Field 4.

3.4.2.1 Measurements along creek boundaries

Measurements of soil strength and stability were made across a series of short transects set at right angles to the direction of creeks in the northern end of Field 2. These measurements were made on both in vegetated and on bare sediment in September 2003 (Figure 3.1 x, y and z). Similar measurements were made in the vicinity in 2007 although the vegetation had changed and these particular creeks had disappeared.

3.4.3 Strength and stability measurements

Currently it is not possible to predict the stability of fine-grained intertidal sediments, such as those at Tollesbury, from one or more easily measurable components such as grain size or water content (Paterson & Black, 1999). Nor can samples be removed to the laboratory, because disturbance invariably influences the stability of the surface sediments in an unpredictable fashion.

Table 3.1 Elevation and corresponding vegetation zones of sample stations.

Sample zone	Elevation (m) above OD	Vegetation zones 2003 and (2007) Angus Garbutt personal communication.	Distance (m) along transect from datum T1	T2	T3
a	2.70-2.80	Diverse zone with 13 plant species present in 2003. (Some loss of diversity dominated by *Puccinellia maritima* or *Elytrigia atherica*, 2007).	3	1	1
b	2.45-2.55	Zone dominated by *Salicornia*, *Puccinellia maritima*, *Suaeda* & *Aster tripolium in* 2003 (Large increase in *Spartina anglica* and *Puccinellia maritima* at the expense of *Suaeda maritima* and *Aster tripolium* in 2007)	17	8	6
c	2.35-2.45	*Salicornia europaea* dominated with *Aster* and *Puccinellia* in 2003. (*Spartina anglica* appears to displace *Salicornia europaea* and *Aster tripolium* in 2007)	23	22	10
d	2.00-2.10	*Salicornia europaea* zone 2003. (Dominated by *Spartina anglica* 2007)	45	53	30
e	1.70-1.80	Mud flat 2003. (*Spartina anglica* colonised the mud flats in 2007)	97	71	59

3.4.3.1 Relative critical shear strength measurements

In 2003 and 2007 the cohesive shear stress meter, CSM (Tolhurst, 1999) was used to provide *in-situ* estimates of the critical stress above which sediment is eroded. These measurements provide an index of the behaviour of the sediments when subjected to stresses from turbulent flowing water such as waves and tides. The CSM utilises a vertical jet of water to erode the sediment surface within a water-filled chamber. A series of three measurements were made with the CSM from each sampling zone and transect in both years. Erosion was deemed to have occurred at the jet pressure that caused sediment suspension, leading to >10% reduction in light transmission across the measuring cell. Inconsistencies in the original published CSM calibration procedure required a completely new calibration method (Vardy *et al*., 2007). This calibrates the CSM jet pressure to an equivalent pressure on the surface sediment, known as the stagnation pressure. The stagnation pressure occurring when erosion is detected is now assumed to be a relative (but not an absolute) measure of the erosion threshold. To facilitate comparison between results obtained in the different years, data collected in 2003 (and reported in that year) was reworked and subjected to the new calibration.

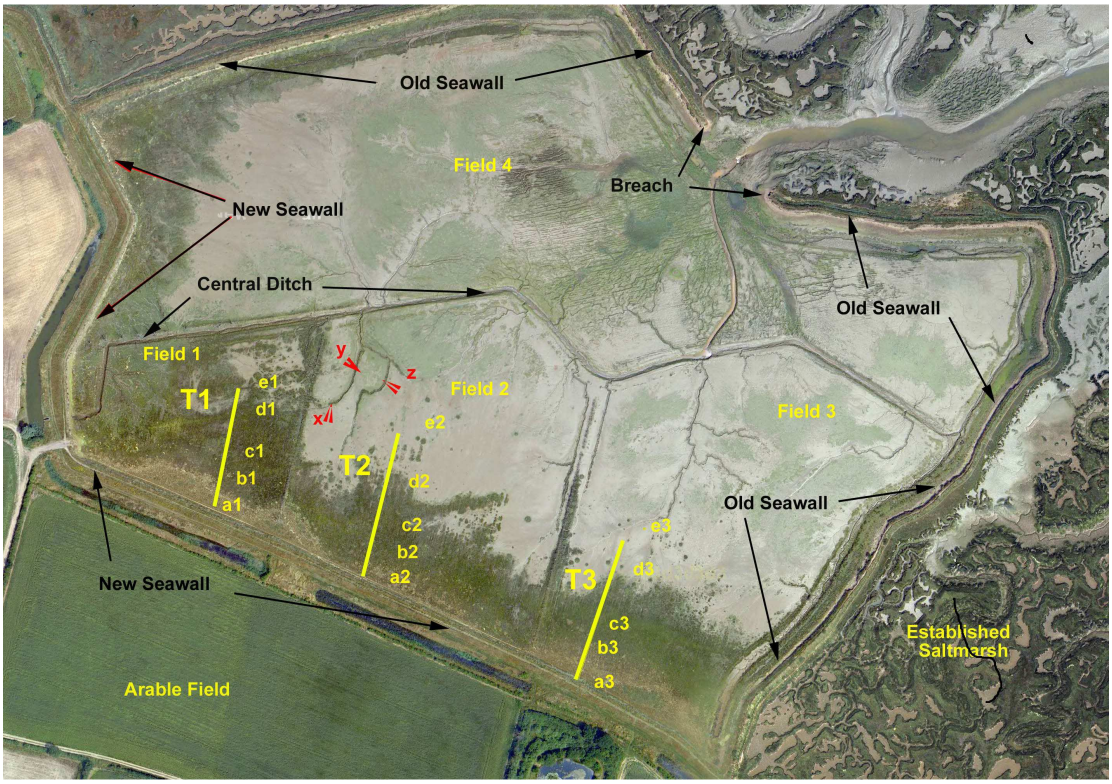


Figure 3.1 An aerial view of the Tollesbury managed realignment site (David Welsh, Environment Agency). T1, T2 and T3 represent the approximate location of the three sampling transects. Points prefixed with letters *a* to *e* represent the approximate location of the different vegetation zones (see Table 3.1). Points *x*, *y* and *z* show the approximate position where the creek boundaries were measured.

2.4.3.2 Measurement of in situ geotechnical shear strength (τ_f)

Sediment geotechnical shear strength is defined as the maximum resistance to a vertical shearing stress and was measured using a modified Geonor fall-cone penetrometer (Watts *et al.*, 2003). It is a macroscopic measure of the undrained sediment shear strength integrated over the upper 1-2 cm of the sediment, in contrast to the measurements provided by the CSM which relate to erosion within the surface few mm. The fall-cone penetrometer operates by allowing a metal cone, the tip of which is initially in contact with the sediment surface, to fall under its own weight into the sediment. The depth of penetration of the cone is then measured (±0.1 mm). The shear strength of sediment is then calculated using the relationship derived by Hansbo (1957):

$$\tau_f = \frac{KQ}{h^2}, \qquad (1)$$

where τ_f, is shear strength (kPa), K is a constant which depends on the angle of the cone used, Q is the mass of the cone (g) and h is the depth of penetration (mm). The device used in this work was adapted from the laboratory apparatus used to measure the liquid limit of soil (British Standard BS 1377, 1975) so that it could be used *in-situ* on the sediment surface. A 200 mm diameter flat plate and a spike replaced the rigid base. The spike is pushed into the sediment until the plate is in contact with the surface. A small adjustment is then made with the aid of a bubble gauge until the apparatus is vertical. The original 80 g fall-cone and stem were replaced by one of four different cone and stem arrangements, so that a wide range of surface shear strengths (2 to 20 mm penetration) could be measured (Table 3.2). Ten replicate measurements were made on each plot.

Table 3.2 Fall-cone characteristics

Cone No.	Weight, g	Stem Weight, g	Total Weight, **(*Q*)** g	Cone Angle, °	**(*K*)**	**Shear** Max (***h***=4mm) KPa	**Strength, τ** Min. (***h***=20mm) kPa
1	8.6	16.7	25.3	60	2.46	4.0	0.6
2	59.2	16.7	75.9	60	2.42	11.5	1.7
3	98.6	16.7	115.3	30	9.91	71.4	5.4

3.4.3.3 Cone penetrometer

A Bush recording cone penetrometer fitted with a 30°, 20.3 mm diameter cone was used to measure the variation in shear strength in 3.8 cm increments down to a depth of >50 cm. This allows us to compare strength changes in the sediment and underlying previously agricultural soil with depth and also to compare the strength profiles of the managed realignment site with the adjacent, established saltmarsh.

3.5 RESULTS AND DISCUSSION

As described above, the results reported here represent strength and stability measurements made at Tollesbury in both early September 2003 and early September 2007. In general terms during this period plant populations taken at the highest point (zone *a*) in each of the three fields has remained relatively stable, dominated by *Puccinellia* or *Elytrigia* that also dominates the new sea wall. Further down the slope the big change between 2003 and 2007 has been a change between a dominance of *Salicornia* to a dominance of the much larger *Spartina*. *Spartina* has also colonised all three of the lowest elevations (zones *e*) of each transect previously mudflat in 2003.

3.5.1 Critical shear stress

Figure 3.2 shows the stagnation pressures occurring at the critical shear stress (when erosion is just starting) obtained using the CSM in both 2003 and 2007. Measurements were made in each vegetation zone (*a* to *e*) and along each transect (T1 to T3). From this it can be seen that critical shear stress is highly variable (large standard errors) but that in 2003 it was consistently greatest in zone *b*, with zone *a* having greater value than zone *c*. Mean stagnation pressure values in these three zones range from 1000 to 3500 $N\ m^{-2}$ and these can be considered relatively resistant to erosion. Previous measurements on the neighbouring established saltmarsh show typical stagnation pressures at critical shear stress of around 650 N m $^{-2}$. During 2003, at zones *d* and *e* (*Salicornia* zone and mudflat respectively) critical shear stress values ranged from 500 down to 50 N m $^{-2}$ implying that erosion could occur at relatively low flow velocities. In fact these values must have been exceeded where the surface flow is concentrated into shallow depressions, resulting in a stream flow which in turn cuts out the new creeks in the sediment.

The measurements made in 2007 show a similar trend to those obtained in 2003. The values in zone *a* had very similar values in both years. There was however a significant reductions in zone *b*, in transects T1 and T2 with zones *a* and *b* now having similar values; mostly in the 2000 to 3000 N m $^{-2}$ range. From zone *c* to *e*, stagnation pressures at critical shear stress were significantly lower than the upper zones. However, the values in the lower three zones were all generally similar, in the 800 to 300 N m $^{-2}$ range. Zone *e*, bare mud in 2003 and now colonised by *Spartina* showed a consistent significant increase in stability compared with 2003.

3.5.2 Shear strength of surface layers

Figure 3.3 represents shear strength values of the surface sediment obtained using the fall-cone apparatus. These values reflect the pattern of critical shear stress values obtained using the CSM. We reported previously (Watts *et al*., 2003) that surface shear strength may also provide a good indication of critical shear stress although the two mechanisms of sediment failure are rather different. In general terms higher strength soils have a higher critical shear stress threshold which must be exceeded before erosion can occur.

During 2003, mean shear strength values ranged from 20 to 70 kPa in vegetation zones *a* to *c.* Zones *d* and *e* had shear strengths less than 5 kPa. In fact, sediment in zone *e* had a shear strength below that used as a measure of the soil liquid limit (British Standard BS1377. 1975). The sediment in this zone thus behaves rather like a viscous liquid. During 2007, the shear strength values in vegetation zones *a* and *b* remained broadly similar to those measured in 2003, all be it with some reduction in extreme values. There was a significant reduction in the sediment shear strength in zone *c*, from 25 kPa in 2003 to 9 kPa in 2007. In vegetation zone *d*, shear strength values remained broadly similar in both years. However, following the colonisation of zone *e* by *Spartina anglica* in 2007 there was a fourfold increase in shear strength from 0.6 kPa to 2.5 kPa; although this sediment still remains very weak.

3.5.3 Penetrometer resistance

Figure 3.4 shows the change in strength of the sediment and underlying soil with depth for each of the vegetation zones measured in both 2003 and 2007. Penetrometer measurements are also shown for the established adjacent saltmarsh (Figure 3.5).

In vegetation zone *a*, adjacent to the new seawall there is a hard pan between about 15 and 30 cm; this is particularly noticeable in transects T1 and T3. This compact layer may result from construction traffic during building of the new sea wall.

In general, on the managed realignment site there is a progressive increase in strength with depth to around between 1 and 1.5 MPa, which then remain fairly constant with increasing depth. For each vegetation zone, the depth at which this constant value is reached varies: zones *a* and *b*, 10 – 15 cm, zones *c* and *d*, 20 to 30 cm and zone *e* 30-35 cm. These upper horizons represent the depth of the much weaker surface layer, which is accounted for by the accreted sediment. The lower horizon, which has a constant strength, represents the original underlying soil.

In contrast to the managed realignment site, the neighbouring and established saltmarsh has a constant but much lower strength of between 200 and 300 kPa over the entire measured depth (Figure 3.5). Between the original reclamation some 150 years ago and 1995, the underlying soils within the managed realignment sight will have changed both physically and chemically; they have ripened (dried out irreversibly) (Dent, *et al*., 1976), their density and strength have increased and their porosity decreased (Hazelden & Boorman, 2001). Soluble salts have been leached from these soils, and fertilisers may have been added. Since the breaching of the old seawall in 1995, there has been only a very slight reversal of these processes. The soils have once again become saturated with sea-water; there has been an increase in both salinity and sodium content, combined with changes in strength and stability (Reading *et al*., 2003). The underlying soil of the realignment site remains very different to that of the established saltmarsh. Much of the stability of the established saltmarsh is reliant on the binding of its upper layer by a dense and diverse root mat.

An analysis of variance was used to compare penetrometer measurements made in 2003 with those made in 2007 and at each of the vegetation zones. The mean penetrometer resistance in the upper 15 cm for both years and in each vegetation zone is shown in Figure 3.6. For each year there was a significant reduction in strength between each vegetation zone with the exception of zones *d* and *e* in 2007, which were not significantly different from each other. Both these zones were dominated by *Spartina* in 2007. There was rather surprisingly a significant reduction in strength in zones *b*, *c* and *d* in 2007, possibly due to continuing rapid sediment accretion increasing the depth of the upper and weaker sediment and the expansion of the *Spartina* dominated area.

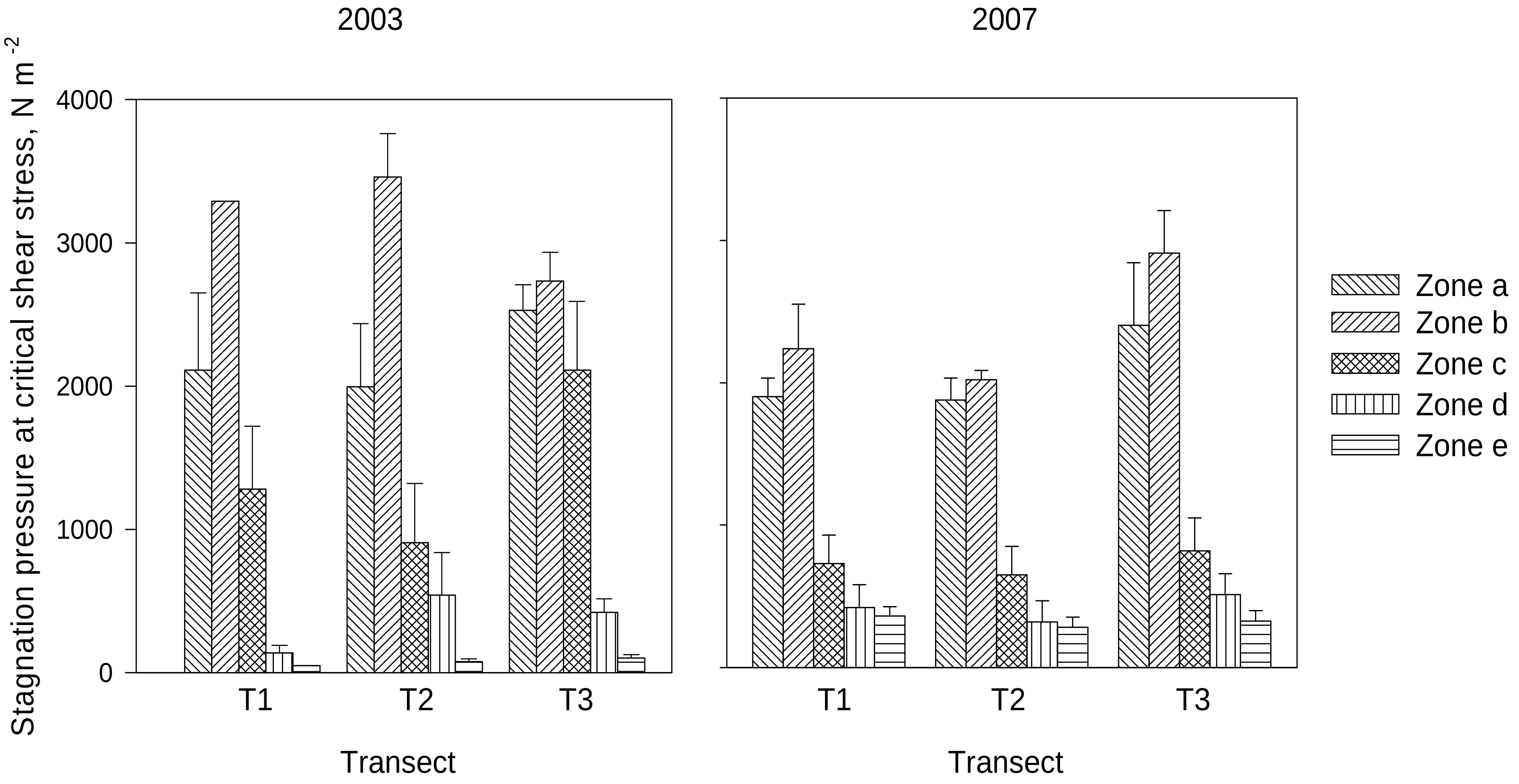


Figure 3.2 Stagnation pressure values at critical shear stress measured using the cohesive strength meter (CSM). Measurements were made in September 2003 and 2007 on three transects. Zones *a* to *e* represent different vegetation zones (see Table 3.1).

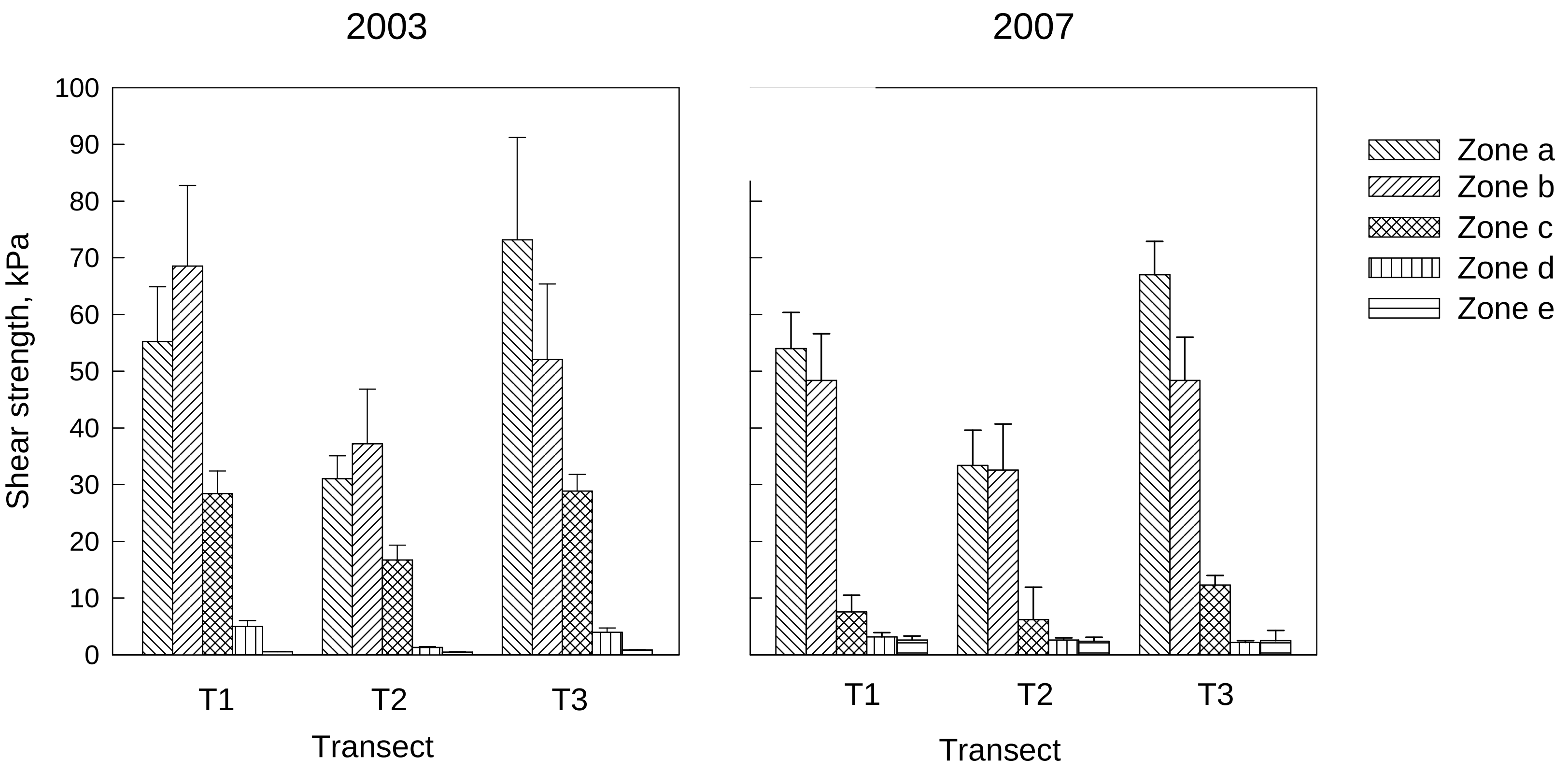


Figure 3.3 A comparison of the shear strength (kPa) of surface sediments measured using the fall-cone apparatus. Measurements were made on five vegetation zones (*a* to e) in each of three transects (T1 to T3) during September 2003 and 2007.

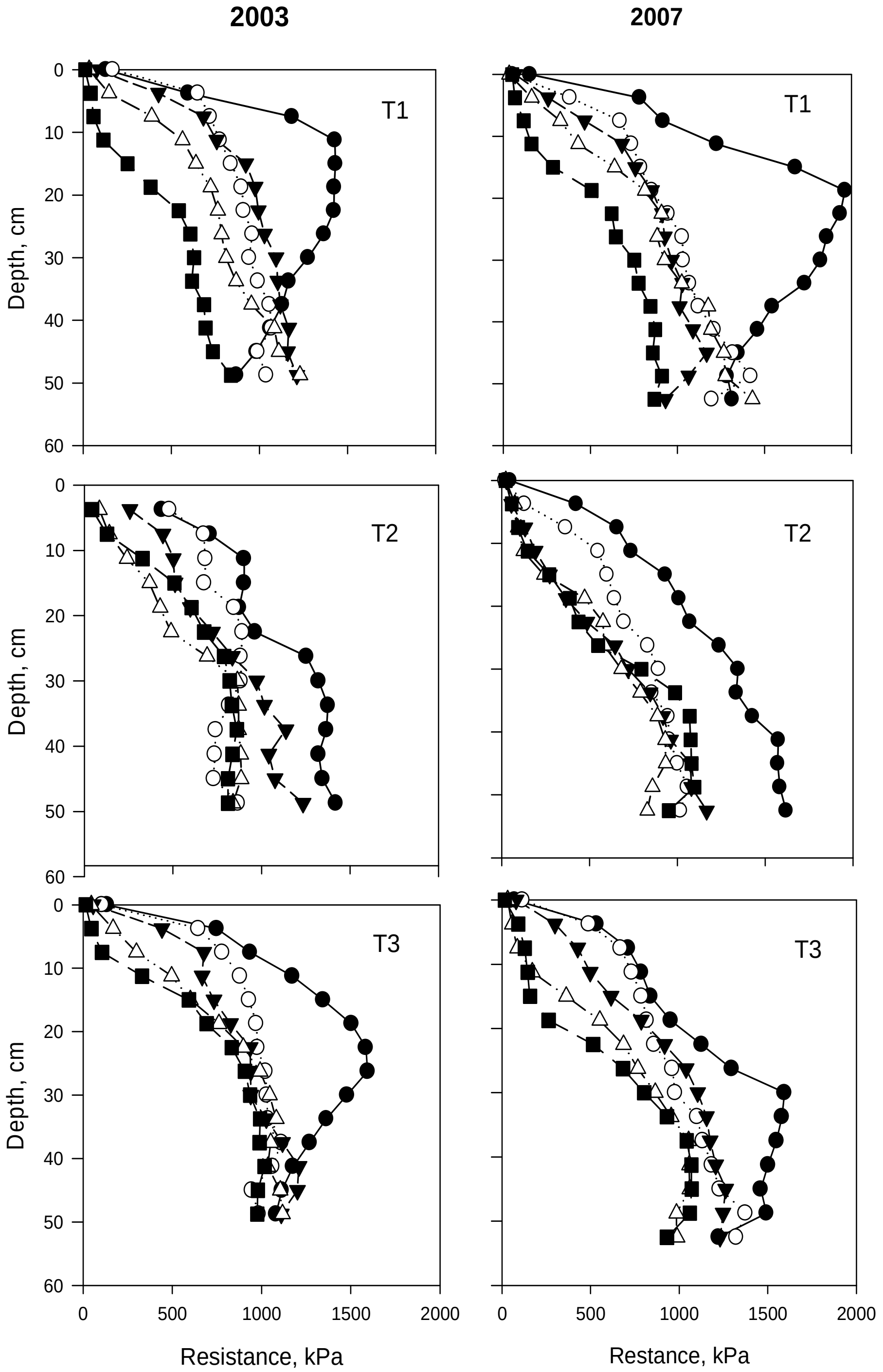


Figure 3.4 Penetrometer resistance (kPa) against depth measured in 2003 and 2007 along each of the three transects, T1, T2 and T3 (Figure 3.1). The different symbols on each graph represent the different vegetation zones in 2003 (Table 3.1); zone *a*, ●; zone *b*, ○; zone *c*, ▼; zone *d*, Δ; zone *e*, ■.

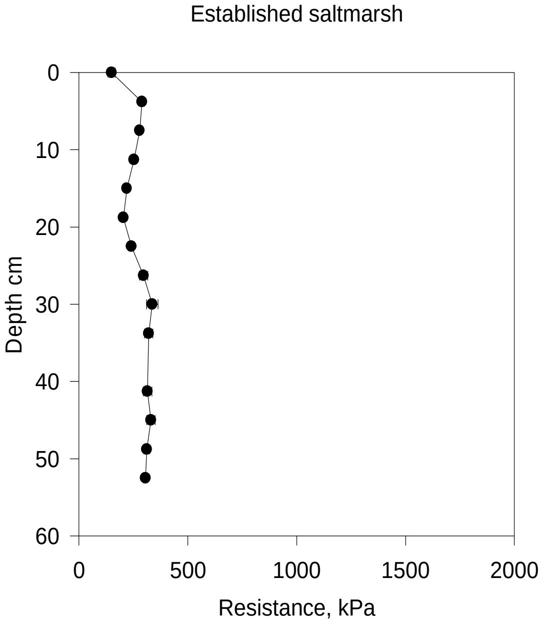


Figure 3.5 Cone penetrometer resistance (kPa) measured on the established saltmarsh

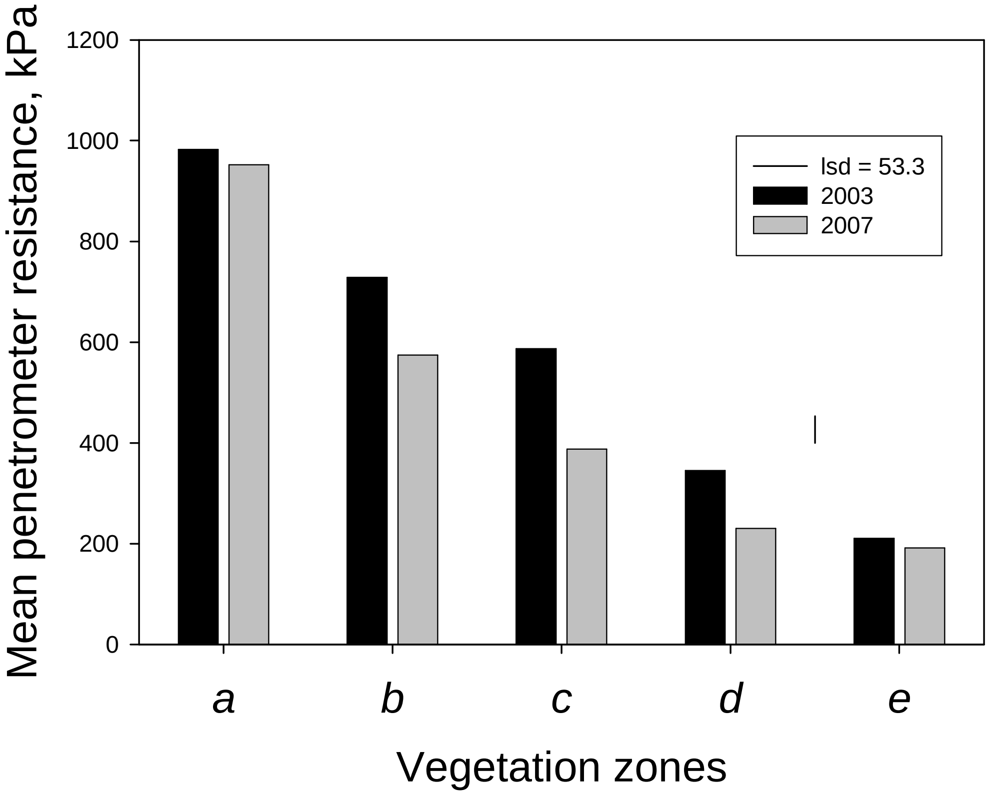


Figure 3.6 Mean penetrometer resistance (kPa) in the upper 15 cm for 2003 and 2007. Letters *a* to *e* represent different vegetation zones (see Table 3.1).

3.5.4 Estimation of the depth of accreted sediment

We have seen above that the underlying previously agricultural soil remains substantially stronger than the accreted sediment. During sampling in 2007 we measured the depth of sediment at six locations and found that these depths coincided with penetrometer readings in the range 600 to 800 kPa. Based on this premise we provide an approximate estimate of the depth of sediment at each station and very approximate estimate of the depth of sediment accreted over the four year period, *Δ* cm (see Table 3.3).

	Transect T1			Transect T2			Transect T3		
Vegetation zone	2007 cm	2003 cm	*Δ* cm	2007 cm	2003 cm	*Δ* cm	2007 cm	2003 cm	*Δ* cm
a	3.5	3.5	0	11.3	7.5	3.8	7.5	3.8	3.7
b	7.5	3.8	3.7	26.3	15.0	11.3	7.5	7.5	0
c	11.3	7.5	3.8	30.0	22.5	7.5	17.0	15.0	2.0
d	15.9	18.8	-2.9	33.8	26.3	7.5	26.3	18.8	7.5
e	30.0	20.0	10.0	30.0	22.5	7.5	30.0	22.0	8.0

Table 3.3 Estimation of the depth of sediment based on the transition between accreted sediment and underlying agricultural soil occurring at a penetrometer resistance of 700 kPa. *Δ* represents depth of additional sediment accretion between 2003 and 2007.

3.5.5 Measurements along creek boundaries

Watts *et al.*, (2003) observed that these creeks appeared to form only in accreted soft sediment that exceeded a certain critical depth (between 20 and 30 cm). During September 2001 there was no vegetation along these banks but by September 2003, we observed that many of the creek boundaries had a ribbons of *Salicornia europaea* extending well beyond their current seaward extent (Figures 3.7 & 3.8).

Stagnation pressures at critical shear stress measured in 2003 on the banks of the new creeks (*x, y* and *z;* see Figure 3.1) show values of around 1200 N m $^{-2}$ but these higher values are confined to the strip close to the gulley edge and dropped rapidly to values of 100 N m $^{-2}$ in a distance of less than 1m.

Shear strength measurements were also made in 2003 on transects at right angles to the new creek and these values are shown in Figure 3.9. A series of transects were made both in areas where *Salicornia* had colonised and areas of the creek margin which were free of any saltmarsh plants. In both cases there is a rapid drop in shear strength to between 0.3 and 0.4 kPa at distance of 1 m from the creek centre line. However, within this strip strength values varied considerably (high standard errors) but in the presence of *Salicornia* mean values were 18 kPa compared with 10 kPa where the banks were bare. We believe that the large increase in strength and stability in the creek margins is due to the rapid drainage and rapid consolidation of these margins.

Figure 3.7 A 2003 view from vegetation zones *c* and *d* looking out toward zone *e*, the mud flat. The new creeks cut through the accreted sediment. The more rapid drainage along the creek margins results in stronger more stable sediment allowing *Salicornia* to establish well beyond its normal lower limit and into zone *e*.

Figure 3.8 A close-up of a new creek margin showing both drier more stable sediment along its margins and newly established *Salicornia*.

Certainly the sediment has both a smaller water content and higher bulk density (Watts *et al.*, 2003). The strength of sediment in the creek margins is similar to that in zones *c* and *d*. In 2003 there was evidence of stream flow in shallow depressions forming tributaries to these new creeks which that may have in turn, encouraged rapid drainage along their margins allowing the further colonisation of saltmarsh plants thus extending the extent of zones *c* and *d*.

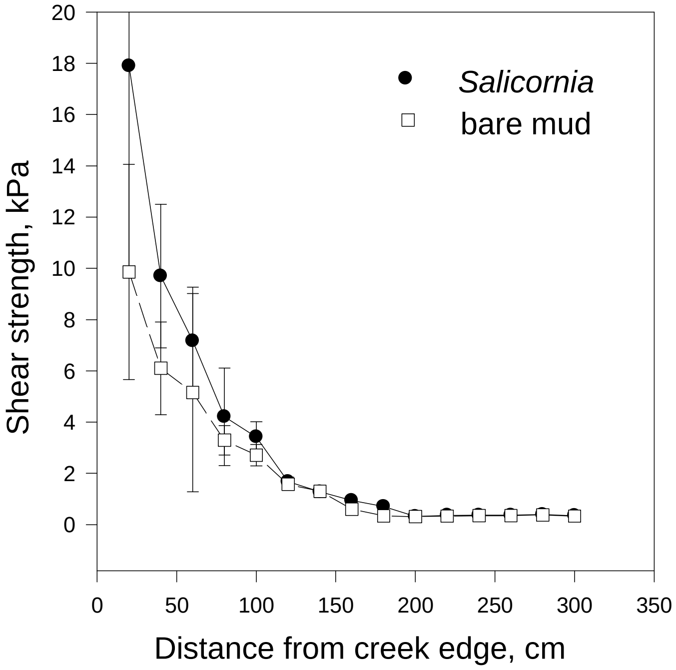


Figure 3.9 Shear strength of the surface sediment measured in 2003 along a series of transects of new creeks formed in the accreted sediment. Transects were established at right angles to the creeks with measurements taken from the centre of the creek. Comparisons between bare creek margins and margins where *Salicrnia* was growing are shown.

We remain uncertain as to whether it was the rapid drainage reducing emersion times or the sediment characteristics which are encouraging colonisation by *Salicornia* well beyond its current lower limit. In 2007 we observed *Salicornia* growing along creek margins at several locations within the site; in particular in the north east corner of the site where the original elevation was around 1.25 m (Figure 3.10). Here the surrounding accreted sediment is substantially deeper than 30 cm making it difficult to approach. *Salicornia* has an extreme lower limit of 1.50m but occurs on this site mainly between 1.80m and 2.70m (Reading *et al.*, 2003).

When we returned to re measure the creek margins (Figure 3.1; *x*, *y* an *z*) in 2007 we found this area had been colonised by pioneer clumps of *Spartina* and there was then no sign of the creeks. These *Spartina* clumps appeared to have extended along the path of the creek and in doing so removed all traces of them (Figure 3.11). With the retreating tide, water remained in pools on the sediment surface both around these clumps and in their hollow centres. Around the stems of these plants sediment appeared to be a few mm above both the surrounding mud flat and the sediment in the centre of the clump. A small number of measurements of sediment stability and strength were made adjacent to these *Spartina* clumps using the CSM and fall cone apparatus. Stagnation pressure at critical shear stress was typically around 200 kPa while shear stress was around 2 kPa – similar to values recorded for the mud flat in 2003.

3.6 SUMMARY AND PRINCIPAL FINDINGS

In-situ measurements of sediment strength (using the fall-cone and cone penetrometer) and stability (critical shear stress measured using the cohesive strength meter) were performed on the surface sediments and underlying soil during September 2003 and September 2007. These measurements were made over a range of different vegetation zones within the managed realignments site at Tollesbury.

Critical shear stress (above which erosion is likely to occur) and shear strength vary significantly between the different vegetation zones. In general soils with higher shear strength in the surface layers also have higher critical shear strengths. Saltmarsh plants were found on sediments with shear strengths ranging from 5 to 70 kPa with *Salicornia* and *Spartina anglica* occurring over this entire range.

Greater species diversity occurs where the sediment is stronger than 30 kPa. There were no significant plant communities where shear strength was below 5 kPa. The colonisation by *Spartina anglica* of vegetation zones *c* and *d* in 2007 was associated with a reduction in shear strength and stability of the surface sediments but where it colonised the mud flat strength and stability increased.

The physical characteristics of the underlying soil within the realignment site remain very different and in particular stronger than the neighbouring, established saltmarsh.

3.6.1 Zone *a*. A zone with diverse vegetation at between 2.7 and 2.8 m elevation, with 13 plant species present in 2003. There was some loss of diversity in this zone by 2007 which is now dominated by *Puccinellia maritima* or *Elytrigia atherica*. There was no significant change in shear strength (30-70 kPa) or stability (stagnation pressure at critical shear stress typically 2000 N m^{-2}) over the period. Estimated sediment depth; 3.5 to 11 cm.

3.6.2 Zone *b*. This zone with an elevation between 2.4 and 2.6 m was dominated by *Salicornia, Puccinellia maritima, Suaeda* & *Aster tripolium in* 2003. There was a large increase in *Spartina anglica* and *Puccinellia maritima* at the expense of *Suaeda maritima* and *Aster tripolium* in 2007. This zone had the highest shear strength and stability values in 2003. However, there has been some reduction in strength and stability and now values generally similar to those in zone *a*. Estimated sediment depth 8 to 26 cm.

Figure 3.10 *Salicornia* growing along creek margins at several locations within the site during 2007. This is the north east corner of the site where the original elevation was around 1.25 m

Figure 3.11 Photograph taken in September 2007 showing pioneer clumps of *Spartina anglica* colonising what was a creek in 2003 (shown by dotted line).

3.6.3 Zone *c*. This zone with an elevation of 2.3 to 2.5 m was dominated by *Salicornia europaea* with *Aster tripolium* and *Puccinellia* in 2003. In 2007 *Spartina anglica* appeared to have displaced *Salicornia europaea* and *Aster tripolium*. With the arrival of *Spartina anglica* there has been a marked reduction in shear strength from between 15 and 30 kPa to less than 10 kPa. Similarly stability has been reduced from between 1000 and 2000 N m $^{-2}$ to around 700 N m $^{-2}$.Sediment depths in this zone range from 10 to 30 cm.

3.6.4 Zone *d*. This zone with an elevation of between 2.0 and 2.1 m was dominated by *Salicornia europaea* in 2003. By 2007 *Spartina anglica* had take over dominance from *Salicornia europaea.* This zone was considered to have relatively low shear strength and stability in 2003. In general terms these values remain the same in 2007 Sediment depth estimates range from 15 to 34 cm.

3.6.5 Zone *e*. This zone with an elevation of 1.7 to 1.8 m was a mud flat in 2003 but has subsequently been colonised by *Spartina anglica. Between 2003 and 2007 there was a significant increase in shear strength (from 0.6 kPa to 2.5 kPa) and stability (stagnation pressure increase from less than 100* N m $^{-2}$ *to 400* N m $^{-2}$). The sediment in this zone remained very weak with an estimated depth range of 20 to 30 cm.

3.6.6 Creeks and creek margins. Creeks and gullies had begun forming once sediment depth exceeded a critical depth 20 – 30 cm. They appeared for the first time during 2001 and 2002 draining the newly accreted sediment. The lower extent of *Salicornia* was extended along the faster draining and stronger (up to 18 kPa) margins of newly formed creeks. There is some evidence that these plants may contribute slightly to higher sediment strength.

In 2007 pioneer clumps of Spartina colonised the area where we had characterised the creek margins and there was no longer any evidence of the creeks. In addition, we found no evidence of significant creek formation within *Spartina anglica* dominated areas. In 2007 we observed *Salicornia* growing along creek margins at several locations within the site; in particular in the north east of the site on deep sediment where the original elevation was around 1.25 m

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CHAPTER 4

MANAGED REALIGNMENT – AN OVERVIEW OF THE TOLLESBURY PROJECT

R.A. GARBUTT

Centre for Ecology and Hydrology, CEH Bangor, Environment Centre Wales, Deiniol
Road, Bangor, Gwynedd, LL57 2UW, UK. ag@ceh.ac.uk

4.1 INTRODUCTION

This chapter reviews some generic issues raised by the Tollesbury monitoring work. In addition to summarising the key lessons learned from Tollesbury, it attempts to draw some wider conclusions about the environmental aspects of managed realignment.

Rising sea levels, coupled with the high cost of maintaining sea defences, have led coastal managers to look for more cost effective and sustainable methods of coastal protection. Managed realignment has, over the past decade, been increasingly used to fulfil these requirements. Although the technique is now practised widely throughout north-west Europe (Wolters et al 2005a), the potential scale, and the design and siting of particular schemes remain fairly contentious issues, with some stakeholder disputes unresolved and disagreement about the wider impacts remaining (Scott, 2007; Townend & Pethick, 2002). Despite this, there remains a strong case for its use as a strategic tool for sustainable estuarine management, on both economic and nature conservation grounds.

When the Tollesbury project was conceived in the early 1990’s, the only previous experience of managed realignment in the UK was the Northey Island scheme, further up the Blackwater estuary. Here, a short length of sea defence was removed, and 0.8 ha of grassland was re-exposed to tidal inundation (Dagely, 1995). Although the Northey Island site accumulated sediment and, over time, salt marsh plants colonised the area, uncertainties remained over the implementation and viability of larger schemes on low lying agricultural land. The Tollesbury site, along with the Orplands managed realignment site, was the first ‘large-scale’ managed realignment scheme in the UK (see E.A., 1999, for results from the Orplands project).

The main objective of the CEH-led research and monitoring programme, begun at Tollesbury in 1994, was to remove some of the uncertainties about returning agricultural land to intertidal habitat, and specifically to address the following questions (MAFF 1996):

- Will natural re-colonisation recreate saltmarsh within the managed realignment site and, if so, over what time scale?
- Is it possible to aid the processes of natural colonisation directly or indirectly?
- Will there be any deleterious effects to the existing saltmarsh?
- Will the hydraulic effects on the estuary/coastline be as predicted by modelling? And
- Will the form and sequence of sea wall removal minimise the possibility of any adverse effects on the adjacent estuary?

Here we deal mainly with the first three questions which relate to the ecological studies (see Reading et al 2002. for other results).

4.2 THE DEVELOPMENT OF SALT MARSH AND CHANGES IN PLANT COMPOSITION

Although the reliability of managed realignment as an appropriate technique for saltmarsh restoration has been under debate (Hughes & Paramor 2004; Morris *et al*. 2004; Wolters *et al*. 2005b), experience so far has shown that, where the elevation has been suitable, vegetation has colonised. The Tollesbury project has shown that, with fairly minimal pre-treatment and management, allowing tidal ingress through a simple, relatively small breach onto low-lying agricultural land will quickly produce intertidal mudflats which are colonised by saltmarsh plants.

After the sea defences were breached in 1995, the existing terrestrial vegetation within the realignment site was quickly killed with the reintroduction of tidal inundation. As part of the initial research programme, saltmarsh plants, seeds and turfs of saltmarsh vegetation were planted or sown on the site to assess whether a rapid cover of vegetation could be established, prior to natural colonisation (Garbutt et al. 2006; Reading et al. 2002). Establishment of the introduced plants and seeds was poor, and it was recommended that managed realignment sites in low energy environments, located near natural marshes should be left to regenerate naturally. Prior to tidal inundation, four treatments, replicating possible land use scenario’s, were trailed. The treatments were; stubble left from a wheat crop; ploughed land; cultivated land (level, bare earth); and abandoned agricultural land with rye grass and ruderale species. Plant colonisation on the four different land use types was measured, with results showing shoot densities of *Salicornia* spp. were about 40% higher in the vegetated plots than plots left unvegetated. The remnants of the terrestrial vegetation, even when killed off by saltwater inundation, provided the best surface for initially trapping propagules and subsequently retaining seedlings. Future projects should consider leaving existing vegetation on the site prior to inundation, either uncut or a high cut, if mown. Experience has shown that areas of managed realignment sites compacted by construction traffic take longer to be colonised by saltmarsh plants in the early stages of site development. It is recommended that these areas are lightly cultivated prior to inundation.

The regeneration of saltmarsh vegetation after managed realignment relies on regular tidal inundation as the key agent for the dispersal of seeds and plant fragments into a site. Saltmarsh seeds can float in sea water for varying amounts of time, from a few hours to several months. Most seeds retain their viability in salt water and germinate when exposed to freshwater conditions. Experience from UK sites to date has shown that, after realignment, relatively rapid colonisation of pioneer and low marsh species occurs, provided they are present in a nearby source area and the elevation is suitable. Although several nationally scarce plant species were recorded within the Tollesbury site by 2007, colonisation of ‘high marsh’ species (e.g. *Armeria maritima*, *Plantago maritima*, *Juncus gerardii* and *J. maritimus*) was restricted, even though the elevation of the site was within these species’ range. This was thought to be a combination of the species’ relative scarcity in the local species pool, and subsequent low number of seeds available to colonise (Wolters et al. 2005c). In addition, a dense cover of *Puccinellia maritima* restricted the ‘gaps’ within the vegetation into which plants could colonise. The distribution of plant species on salt marshes is a balance between tolerance and competition and it appears that, within the realignment site, this has not yet been achieved.

The lack of less common, ‘high marsh’ species is not restricted to the Tollesbury site. Several studies have examined salt marshes that have regenerated on reclaimed land following breaches in embankments due to storm events as analogues for managed realignment. These reports show that, in some cases, it can take decades for plant communities to reach equilibrium with natural reference conditions, and the regenerated plant communities can lack certain species (Burd 1992; Onaindia *et al*. 2001). Garbutt & Wolters (2008) surveyed the plant communities of regenerated salt marshes within managed realignment sites, and sites of abandoned reclamations up to 107 years old, in Essex. In common with Tollesbury, plant diversity within the regenerated marshes was lower than in adjacent natural marshes, and was correlated with a greater abundance of *Spartina anglica*. The plant communities were, in general, representative of less diverse communities or those typical of lower elevations. It is perhaps surprising that given the low levels of plant species diversity found in the salt marsh flora, differences were detectable over such long timescales. This suggests that the vegetation communities may be relatively static or that severe disturbances are rare. Seedling recruitment in salt marsh communities is generally precluded in dense vegetation by competition from adults, as the Tollesbury experience shows. If the vegetation within the de-embankment sites is relatively static there may be little opportunities for new species to colonise.

The sparsely vegetated mudflats that typify the early phases of saltmarsh development within realignment sites provide ideal conditions for the establishment of *Spartina anglica*. Whilst *Spartina* is now currently accepted as an integral part of the flora of European salt marshes (Lacambra et al. 2004), its presence in the early stages of saltmarsh regeneration may be less desirable. The dominance of *Spartina* in the Tollesbury site, questions the ability of the regenerated marshes to ‘function’ in a way that reflects natural marsh processes. Restoration theory attempts to set criteria from which success can be measured, such as composition, sustainability, biotic interactions and nutrient retention relative to a ‘natural’ base line (Zedler, 2001). The establishment of *Spartina* early in the development of saltmarsh within managed realignment sites gives the regenerate marshes a very different starting point to that of natural marshes, and may affect the eventual outcome of habitat creation efforts. The results presented here should not be interpreted as the inevitable failure of saltmarsh creation schemes in matching reference conditions, but as a cautionary note that in fact, restoration efforts may never fully replace natural wetland functions. They will, however, almost certainly fulfil their intended purpose of providing coastal protection through the dissipation of wave energy and the provision of bird feeding areas. Whether managed realignment sites are any less valuable for nature conservation, or in the services they provide, requires further attention.

4.2.1 Effects on existing marshes

Whilst there were changes in the frequency of saltmarsh plant species growing on the Tollesbury marshes adjacent to the site, there was no evidence to suggest that the creation of the managed realignment site was the cause. Pre- and post-breach differences appear to be part of longer-term trends. The changes in frequency may be part of a natural cycle in response to population dynamics or may be a response to changes in the natural environment. The changes in plant frequency are occurring against a background of large-scale loss of saltmarsh in the region. It is estimated that the total saltmarsh loss, in Essex, between 1973 and 1998 exceeds 1,000 hectares (Cooper et al. 2001). There were increases in *Spartina* *anglica* and declines in *Atriplex portulacoides* between 1994 and 2007, on the marshes adjacent to the site. Although these changes were not linked to the creation of the managed realignment site, the results raise issues about the long-term stability of the saltmarsh communities of the region and their ecology. The balance between sediment accretion and erosion, in relation to elevation, primarily determines the stability of saltmarsh communities. Whether the increasing frequency of *Spartina* into the system alters this balance, and the natural dynamics of the plant communities, remains uncertain.

4.3 SEDIMENTS

The rate of sediment deposition within managed realignment sites can be extremely rapid in the early phases of implementation, with up to 50mm per month being recorded at Paull Holmes, the Humber estuary, UK (Boyes & Mazik 2004). These rates are short lived however, with low lying areas predicted to build up sediment to find equilibrium profiles, around that of relative sea level rise (Temmerman *et al*. 2004). The Tollesbury managed realignment site appears to be responding in this way where the amount of sediment being deposited is reducing over time, from 31mm a year in 1995-96 to 9 mm a year by 2006-07. In time, the surface of the site would be expected to build up to a level equivalent to that of the adjacent natural marshes. This can be observed at the many ‘accidental’ breach sites in Essex, where sea walls have been breached by storm events in the past (e.g. the storms of 1953). The present level of the marshes regenerated within these sites is comparable to that of the adjacent natural marshes.

The build up of sediment within the site allowed a greater area of mud flat to be colonised by saltmarsh vegetation, presumably in response to an increase in elevation. Sediment infilling will have a long-term impact on the future of the site, both for the conservation interest and flood defence. The reduction in the area of mud flat will impact on feeding areas and roost sites used by birds within the site. By 2007, there was transition from mud flat through pioneer to low and mid marsh vegetation communities within the site (albeit dominated by *Spartina anglica*). This is uncommon in the Essex region where most saltmarshes are cliffed on their seaward edge leading to a scarcity of pioneer communities. If deposition continues, as expected, there will be a gradual infilling of the site up to the level of the surrounding marshes, with the consequent loss of the pioneer/low marsh communities. This process is probably inevitable, given a constant supply of sediment, but should be considered when mitigating for losses of pioneer communities elsewhere.

The natural salt marshes, adjacent to the Tollesbury managed realignment site, appear to be able to maintain their position in the tidal frame, despite projected eustatic changes. A constant rate of vertical accretion was recorded throughout the 14 year monitoring programme at around 3mm-4mm a year, similar to rates predicted by sea level rise for the region. There was no evidence that the creation of the managed realignment site had any effect on sediment deposition on the marshes adjacent to the site.

4.4 COLONISATION BY INVERTEBRATES

Whilst the creation of saltmarsh must be of primary concern when realigning seawalls for coastal defence objectives, the creation of intertidal mudflats is none the less valuable. Intertidal mud- and sand flats are important feeding areas for shorebirds, and some wildfowl, during the low water period when they are exposed, and for diving ducks and fish when they are submerged.

Initial colonisation of the Tollesbury managed realignment site by intertidal invertebrates was rapid. Fourteen species were recorded within the site, two months after the breach and 18 to 19 species a year there after until 2007. In 2007, 21 species were recorded in the site, with *Littorina littorea* (edible periwinkle) and *Palaemonetes varians* (a crustacean) recorded for the first time. In total, 31 species of invertebrate were recorded between 1995 and 2007. Species consistently recorded included, *Cerastoderma edule* (cockle), *Macoma balthica* (baltic telin), *Scrobicularia plana* (peppery furrow shell), *Eteone longa* (a bristle worm) *Nephtys hombergii* (cat worm), *Nereis diversicolor* (rag worm) and the common shore crab, *Carcinus maenas*.

The rate of establishment of intertidal invertebrates can be related to their mobility, both as adults and as juveniles, where many have planktonic larval stages. Colonisation of a newly created site also appears to be related to the availability of suitable sediments. At Tollesbury it was observed that invertebrate colonisation only occurred in the newly accreted sediments within the site, and were absent from the original, consolidated agricultural substrate. Mazik et al. (2007) recorded a species poor invertebrate assemblage, one year after the creation of the Paull Holme managed realignment site, composed predominantly of early colonising species of Oligochaeta and Nematoda (small worms), although a total of 20 species of invertebrate were recorded. More sedentary species, such as bivalves, rely on planktonic larval stages to colonise new sites and it may be several years before a stable population of these relatively long-lived species becomes established.

Atkinson et al. (2004) found that birds were quick to colonise the Tollesbury realignment site, either for roosting or to feed. In the first few years after realignment, waterbird assemblages were generally variable and large changes were observed adjusting to the biological and physical evolution of the site. Numbers of wading birds were low in the first year after creation but increased thereafter, reflecting the development of the invertebrate community within the mudflats of the site. Species such as knot and dunlin, which foraged on small polychaetes (worms), colonised the area before species, such as oyster-catcher and black-tailed godwit, which feed on larger bivalves. The subsequent development and establishment of stable bird communities will be determined by the evolution of the site and the availability of suitable prey species, or safe areas to roost. As sediment infilling continues, and saltmarsh plants continue to expand their range within the site, invertebrate diversity and abundance will adjust accordingly, and will be reflected in the species of birds that use the site.

4.5 SOIL STRENGTH AND STABILITY

Experience from the Tollesbury monitoring programme has shown that the key difference between saltmarsh creation through managed realignment and natural saltmarsh development lies in the former being based on soils which, although marine in origin, have over many years become terrestrial in their chemical and physical characteristics. The changes that occur during this process of desalination are many and varied, but the non-reversible changes are critical. These changes include the consolidation of the soil through irreversible drying and the loss of organic matter through oxidation. Although prolonged flooding will increase the moisture content, the soil may never return to its original state. Following the first six years of monitoring at the Tollesbury site, the underlying agricultural sediments were both very strong and highly resistant to erosion (Watts et al. 2003). It is thought that this ‘over consolidation’ forms a soil horizon with low hydraulic conductivity that restricts sub-surface drainage within the developing marsh sediments. As a result, the overlying, newly deposited marine sediments have a high water content and low critical shear stress (above which erosion is likely to occur). Within the Tollesbury site, saltmarsh plants were found on sediments with shear strengths ranging from 5 to 70 kPa. *Salicornia* spp. and *Spartina anglica* occurred over this entire range. Greater species diversity occurred where the sediment was stronger than 30 kPa, at the highest elevations.

The low strength and high water content of the sediment in the low lying areas of the site was thought to be a constraint to plant colonisation (Garbutt, 2006). Following an increase in the abundance of *Spartina* between 2003 and 2007, there was a fourfold increase in shear strength of the sediments from 0.6 kPa to 2.5 kPa; however, this sediment still remains very weak. Whether dewatering, or plant colonisation, led to the increase in soil strength is not clear. At the lowest elevations of the site, the sediment behaves rather like a viscous liquid. If the geography of the site changes, possibly as a result of secondary breaching in the original sea wall, there could be movement of sediment over the stable former agricultural soils. In 2007, there were several parts of the old sea wall that were less than 1 m wide, eroded by internally generated waves, and one area where the wall was around 0.75 m lower than the its original height.

Creeks are an important and integral part of saltmarshes, distributing sediments to the interior of the marsh, allowing aquatic organisms’ access to habitat, and providing drainage following tidal inundation. Because of the potential for sediments within managed realignment sites to have high water content, the development of a creek network appears fundamental to the establishment of saltmarsh vegetation. Creeks only appeared to form within the Tollesbury site in the newly deposited marine sediments and only when the sediment exceeded a critical depth (between 20 and 30 cm). This was probably due to the low velocity and sheet flow of the water in the first few years after the creation of the site. By 2003, the newly formed creeks had ribbons of *Salicornia europaea* growing on their banks, extending the lower limit of *Salicornia* below its main range in the rest of the site. This corresponded with a rapid drop in shear strength, 1 m from the creek centre line. In the presence of *Salicornia*, mean shear strength values were 18 kPa compared with 10 kPa where the banks were bare. The large increase in strength and stability in the creek margins was thought to be due to rapid drainage and consolidation of these margins. Here water content and bulk density were similar to soils, 0.5 – 1.0 m higher in elevation.

4.6 KEY FINDINGS

- With minimal pre-treatment and management, allowing tidal ingress through a simple, relatively small breach onto low-lying agricultural land will quickly produce intertidal mudflats which are colonised by saltmarsh plants.

- Managed realignment sites in low energy environments, located near natural marshes, should be left to regenerate naturally.

- Future projects should consider leaving existing vegetation on the site prior to inundation, either uncut or a high cut, if mown.

- Soils that are compacted during construction of managed realignment sites should be lightly cultivated prior to inundation, as compacted soils restrict plant colonisation.

- At Tollesbury, and other local managed realignment sites, plant diversity was lower than in adjacent, natural saltmarshes. The saltmarshes were, in general, representative of less diverse communities than natural marshes, or those typical of lower elevations.

- The establishment of *Spartina* early in the development of saltmarsh gives regenerate marshes a very different starting point to that of natural marshes, and may affect the eventual outcome of habitat creation efforts.

- There was no evidence to suggest that the creation of the managed realignment site was the cause of pre- and post-breach differences in plant species frequency.

- Sediment deposition rates within the realignment site appeared to follow expected patterns, where after initial high deposition, there was evidence of a slow down towards equilibrium profiles.

- There were no differences in pre- and post-breach sediment deposition rates on the natural marshes, adjacent to the site.

- Colonisation of intertidal invertebrates was rapid and after 2-3 years species richness had stabilised, although abundance changed through time. Invertebrates did not colonise the former agricultural soils.

- The underlying agricultural sediments of the Tollesbury site were very strong, highly resistant to erosion and probably form a barrier to sub-surface drainage, leading to water logging of newly accreted marine sediments.

- The development of a creek network appears fundamental to the establishment of saltmarsh vegetation.

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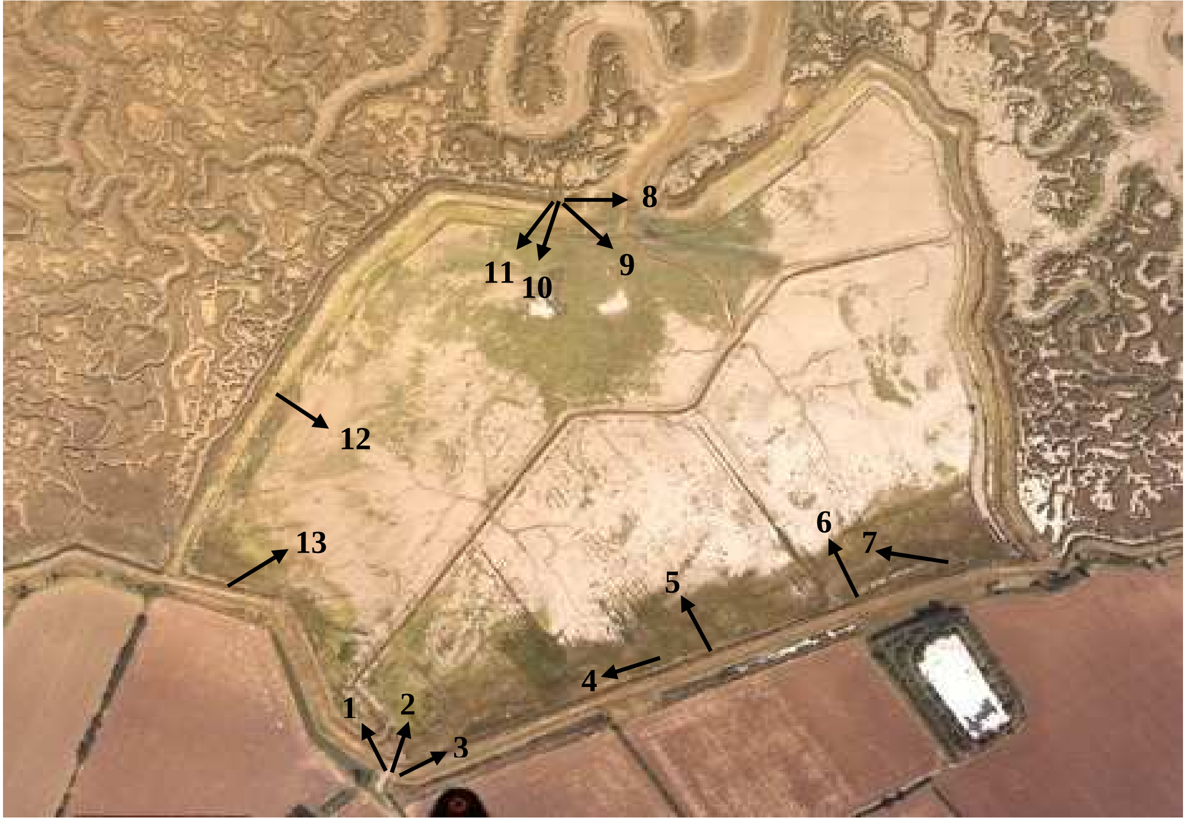
5 PHOTO ALBUM – October 2007

2001 Aerial photograph of the Tollesbury Managed Re-alignment site, supplied by the Environment Agency, showing the location and view direction of site photographs in 2007.



1: Poplar tree killed by salt water when the site was flooded.

Photograph by G. Jofré

2: Looking across the site to the breach in the sea wall.

3: The two dominant vegetation communities of the MR site; *Puccinellia* salt marsh (from the foot of the sea wall), and *Spartina*/*Salicornia* salt marsh extending down the slope.

4: *Puccinellia* dominated salt marsh on the highest area of the site with dead oak tree in the centre.

5: *Salicornia dolichostachya* and *Spartina anglica* colonising the mud flats.

6: Transition from *Puccinellia* to *Spartina*/*Salicornia* to mudflat with *Spartina*, from the foot of the new sea wall towards the breach.

Photograph by G. Jofré

7: *Salicornia dolichostachya* and *Spartina anglica* colonising the mud flats.

Photograph by G. Jofré

8: View from one side of the breach to the other.

9: Eroded area of mudflat at the entrance to the site, viewed from the breach.

10: *Salicornia dolichostachya* and *Spartina anglica* colonising the lowest parts of the site.

10


Photograph by G. Jofré

11: Channel draining the ‘borrow ditch’ along the inside of old sea wall.

11


Photograph by G. Jofré

12: View, facing south, showing the extent of the mudflats at ‘invertebrate sampling site 3’.

13: Looking east, towards the breach, from the new sea wall..

Ergon House
Horseferry Road
London SW1P 2AL

www.defra.gov.uk

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