

# Managed re-alignment; a salt marsh dilemma?

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**Abstract** Managed re-alignment of sea defences is seen as the way to strengthen these by rationalising the line between land and sea and creating a buffer of inter-tidal habitat in front of them. This buffer is most commonly salt marsh which absorbs wave energy thus protecting the defences. The global area of salt marsh is in decline due to a range of issues and managed re-alignment is a way of creating or recreating this important habitat. This review examines managed re-alignment schemes in the light of salt marsh loss, rising sea levels and a changing climate. The ecosystem services and benefits provided by salt marsh can be assessed and given a monetary value. Managed re-alignment can be an important tool for salt marsh creation and coastal zone management. The number and size of schemes in the UK has increased in recent years but the area of recreated salt marsh is still insufficient to replace that lost by erosion and other processes. Background data from a proposed site, and adjacent areas likely to be affected, need to be collected prior to embarking on a scheme that may prove successful. Stakeholder interests cannot be neglected and there will also be a need for long-term monitoring. Re-created salt marshes may form an effective sea defence buffer but they remain significantly different from adjacent natural marshes for

many years both in their vegetation and functional equivalence.

**Keywords** Salt marsh · Habitat creation · Nature conservation · Coastal erosion · CZM · Sea level rise

## Introduction

Salt marshes can be defined as intertidal areas built up by the accumulation of generally fine sediments transported by water and stabilised by vegetation (Boorman 2000). The herbaceous vegetation consists of a range of plant species which are more or less tolerant of submersion by sea water. Where there is a degree of protection from wave action the low lying coastal areas are fronted by mud flats through the deposition of fine sediments brought in by tidal action. The establishment of vegetation can only occur when the area is covered by the tide for less than 50% of the time. When the level of the surface has accreted sufficiently for this to happen, plant establishment can occur, assuming that is that seeds of appropriate species are brought in by the tide. The rate of sedimentation is increased as the incoming sediment is intercepted and trapped by the developing vegetation cover. In addition, the vegetation also reduces the re-suspension of deposited material and, at the same time, organic matter is added both by the accumulation

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of litter on the sediment surface and by root growth below the surface (Boorman 2003). Together these processes lead to a steady build-up in the surface elevation of the marsh and consolidation further increases the stability of the deposited material.

The benefits of salt marshes come through the stabilizing effect of the vegetation on the sediment surface. Salt marshes have also been shown to act as natural wave breaks which reduce the extent of marine erosion (Möller et al. 2014). This facilitates new salt marsh growth which itself further increases erosion protection and the development and spread of low-lying inter-tidal areas. Thus, where there is a good steady sediment supply from the sea or from the land, there are considerable possibilities of the steady development of the coastline seawards. Marsh expansion through seawards development of salt marsh plant communities is, however, limited in part by the degree of exposure to wave action (Fagherazzi et al. 2013). In more sheltered areas the extent of salt marshes and the subsequent fresh-water marshes may in time amount to advances of tens of kilometres. The sediment supply is the key factor in this process and it appears that tidal wetland stability can be inferred from model studies of channel sediment fluxes over a limited time scale (Ganju et al. 2013).

There are, however, a number of factors which can limit salt marsh growth. Weather patterns may change and salt marsh can be eroded by exposure to increased wave action. On a longer time scale there can be changes in the relative level of land and sea and salt marshes can only accommodate small rates of sea level rise (of the order of a few millimetres per year). Salt marsh growth and survival is largely dependent on the supply of sediment and any reduction in marine or riverine sediment input can greatly affect the growth and survival of salt marshes. Often these changes are man-made; either the result of marine dredging increasing erosion or caused by changes in river management reducing its sediment load. The latter seems to be something of a Europe-wide phenomenon with the increasing use of dams to reduce flooding at times of peak flow (Wolanski et al. 2004).

Before the advent of human interference the losses of salt marshes by increased erosion tended to be balanced by a natural re-conversion of low-lying land (which had been salt marsh perhaps centuries earlier) through flooding and the regeneration of salt marsh

communities (Boorman 1999). In recent years, human development pressures have increasingly demanded a fixed coastline which has resulted in increased rates of salt marsh loss. Early responses to this problem were to increase the height and durability of the sea wall. However, while this ensured the level of flood protection was maintained the rate of loss of salt marshes continued to increase. It was gradually recognised that increasing the height of the sea wall only served to accelerate the rate of loss of intertidal habitats outside the sea wall (Goudie and Viles 2016). Attention has thus been turned to whether in fact salt marsh development can be furthered by the employment of techniques for salt marsh creation. A re-examination of salt marsh erosion also suggested that rising sea levels and falling supplies of sediment meant that the salt marshes were effectively being squeezed out against the sea wall. The sea wall needs to be re-sited landwards for there to be a sustainable natural balance between accretion and erosion. The way to compensate for higher rates of erosion with reduced sediment supplies is to give salt marshes more space to develop. Tidal wetlands will be increasingly threatened by coastal squeeze as sea level rise accelerates and land development intensifies (Goudie and Viles 2016). If the defence line of the sea wall can be moved landwards, then the natural equilibrium between accretion and erosion could be restored and the salt marshes could resume their former role in protecting erodible (soft) coastlines. This approach also facilitates the maintenance of biological diversity of coastal habitats.

As salt marsh creation schemes have become established, the individual areas involved in salt marsh creation have become much larger; the areas involved could initially be counted in tens of hectares, whereas new proposals involve tens of square kilometres. There is still a need, however, to achieve full success in terms of plant and animal communities and food chains. Recent studies have shown that caution is needed in the use of contemporary aerial photography and cartographic data (Baily and Pearson 2007; Baily and Inkpen 2013). The complexity of salt marsh processes and their sustainable reconstruction suggests that there is still a need to develop decision-making tools which can accommodate the concerted action needed to conserve intertidal mudflats and salt marshes sustainably (Foster et al. 2013).

## The concept of managed realignment

Managed re-alignment can be defined as any controlled change to the boundary between the sea and the land. Esteves (2014) discusses in detail the various forms that managed re-alignment may take, its different aims and the alternative terms that have been, and are being, used for managed re-alignment in its widest sense, and she also proposes a new comprehensive definition. Generally managed re-alignment has been seen to involve the creation, re-creation or restoration of inter-tidal habitats (e.g., Dixon et al. 1998; Boorman and Hazelden 1997; Boorman et al. 2002; French 2006; ABPmer 2015), although the term has also been used for the removal of sea defence lines fronting shingle banks, sand dunes and cliffs (Rupp-Armstrong and Nicholls 2007). This review is concerned with the use of managed re-alignment to restore, or create inter-tidal salt marsh, whether as a primary aim or as a secondary benefit.

In the context of this review, managed re-alignment is defined as the adoption of a new, generally landwards situated, sea defence line, usually a sea wall but which may be on rising ground or upland (e.g., Burd 1995). Where a sea defence line is in the form of a sea wall, and is to be relocated landwards, then there are two options for the old sea wall. Most commonly the wall is breached giving the sea access through one or more openings in the wall; but a more expensive option is to remove the old wall completely. Either way, this increases the inter-tidal area and facilitates new inter-tidal habitat development, most desirably salt marsh, seaward of this wall as an ecological buffer. Using salt marsh vegetation as a buffer affords the sea wall additional protection from erosion and thus saves on building and maintenance costs (e.g., Dixon et al. 1998; Boorman 2000; Garbutt and Boorman 2009). The first major managed re-alignment site in England was near Tollesbury in Essex, where the sea wall was moved inland in 1997 (Reading et al. 2008; Boorman and Hazelden 2012a) and an area of salt marsh re-established. Salt marsh had grown well covering thirteen hectares (62%) of the 21 hectare site by 2007. After a further 9 years (19 in total—2016) the salt marsh was even more extensive covering over 17 ha (80%) as shown in Figs. 1 and 2 (Boorman and Hazelden pers. comm.).

Managed re-alignment is usually conceived as a way of both creating or restoring coastal habitats and

renewing sea defences in rural areas. However, there are also possibilities in urban situations, such as the estuary of the river Thames in and near London, where landward shifts in the defence line may be made during development and redevelopment projects (Shih and Nicholls 2007). The term managed retreat has also been used to refer to the possibilities of the large-scale landward relocation of developed areas with homes and other infra-structure (Alexander et al. 2012).

Early trials on salt marsh creation or regeneration through adopting a more landward defence line showed that, with a little encouragement, salt marsh regeneration and regrowth could successfully replace salt marshes lost to marine erosion. Formerly the process of managed re-alignment was referred to as ‘set-back’ (Pethick 2002). However, the negative implications of the term ‘set-back’ resulted in it being dropped in favour of ‘managed retreat’. Again, partly because of the negative connotations, this term was replaced by ‘managed re-alignment’ (Garbutt and Boorman 2009; Esteves 2014). The latter term has the advantage of including situations where, in order to rationalise a sea defence line, some movement seawards might be included. Within mainland Europe other terms for managed re-alignment include ‘depolderisation’, ‘de-embankment’, ‘outdiking and ‘outembankment’ (Rupp-Armstrong and Nicholls 2007). Other aspects of managing soft, erodible coastlines are covered by such terms as ‘ecological restoration’ and ‘habitat creation’.

The critical parts of managed re-alignment to create an inter-tidal habitat (salt marsh) include both the relocation of the boundary between land and sea (however defined), and the interventions needed to ensure that the chosen boundary is maintained. The former can be achieved by relocation of the sea wall or other man-made or natural defence line. The latter is more complicated; frequently, the land being restored to inter-tidal habitat was salt marsh and had been embanked and converted to farmland. However, following embankment, physical and chemical changes have taken place in the sediment and soil including bulk density, carbon content, redox potential, nutrient levels and C/N ratio (e.g., Hazelden and Boorman 2001; Barkowski et al. 2009; Kadiri et al. 2011). Some of these changes are irreversible, and how they interact with the ecological functioning of a salt marsh is poorly understood (Spencer and Harvey 2012). When this land is returned to an inter-tidal environment then these changes can have a long-term

**Fig. 1** The re-created salt marshes at Tollesbury, Essex, UK, (May 2016) as seen from the former sea wall. This shows the younger marshes largely established over the past ten years. There are still some quite large areas of bare ground



**Fig. 2** The older re-created marshes up to approximately 20 years old at Tollesbury, Essex, UK, as seen from the new sea wall (May 2016). The plant cover is largely complete as plant species diversity increases



effect on the establishment and development of salt marsh vegetation. Marshes created by managed re-alignment often remain significantly different from adjacent local marshes for many years in terms of their species diversity (Barkowski et al. 2009; Mossman et al. 2012a, b). The critical factor for the success of managed re-alignment as a management tool for salt marshes lies in their resilience. Feedbacks can play a critical role in facilitating the necessary rapid ecosystem shifts associated with human impacts (Altieri et al. 2013).

Another problem with the re-creation of salt marsh following managed re-alignment is that land being returned to the inter-tidal zone is usually lower than the present inter-tidal zone. Since enclosure sediment deposition has continued seaward of the sea defences while sediment within the enclosed site has dried out and shrunk leaving a difference in the height of the

land either side of the sea defence. Thus, the land returned to the inter-tidal zone may be too low for the ready establishment of salt marsh vegetation. One way to circumvent this is to control the tidal range within the site. This can be done by the technique of Reduced Tidal Exchange (RTE) where the extent and duration of the tidal flow is limited by sluices in the sea wall (e.g. Mossman et al. 2012a). The sea defence remains in place, but a controlled inter-tidal zone is created behind the sea wall so that the boundary between land and sea is effectively moved landward.

Active steps are often needed to facilitate the re-establishment of salt marsh vegetation, such as the introduction of seeds or young plants. It is sometimes necessary to import sediment onto a managed re-alignment site in order to create conditions more favourable for the establishment and growth of salt marsh plants (Crooks and Pye 2000; French 2006).

However, careful assessment of both sediment and site is needed when importing sediment because the site itself or the imported sediment may be contaminated. Kadiri et al. (2012) examined the release of potential contaminants (heavy metals and herbicides) from both the newly flooded soils and dredged sediment that may be used in managed re-alignment sites, and they demonstrated that both metals and herbicides can be released after flooding.

### The need for managed re-alignment

The need for managed re-alignment is based on the short and long term loss of salt marsh and other intertidal habitats, their conservation value and the protection that they afford the coastal defences (Rupp-Armstrong and Nicholls 2007; Möller et al. 2014). Additionally, salt marshes have a high conservation value for birds and marine fauna and so they need to be protected (Boorman 2003; Mander et al. 2013). They are important players in the cycling and exchange of nutrients in the coastal environment (e.g. Hazelden and Boorman 1999; Boorman 2000, 2003; Hyndes et al. 2014). The growth of salt marshes is dependent on the supply of nutrients and trace metals. A reduction in the total intertidal area can reduce estuarine ecosystem services including the retention of nutrients and trace metals (Jickells et al. 2016). However, salt marshes are being lost for many reasons.

Sea levels are rising, relative to the land, in many parts of the world from a variety of causes putting both coastal buildings and infrastructure at risk from both short- and long-term flooding (Nicholson-Cole and O’Riordan 2009; Goudie and Viles 2016). In 2013 the IPCC projected that by 2100 global sea levels will increase within the range of 0.26–0.82 metres, relative to 1986–2005 levels. This relative sea level rise can be due to subsidence from isostatic adjustment, or it can be the result of climatic change (melting glaciers). Also, where land has been embanked and converted to agricultural land, then clay and peat shrinkage occurs as the soils and sediments dry out and so the land surface subsides. Under natural conditions inter-tidal habitats, particularly salt marsh, would migrate inland in response to sea level rise. Where there are coastal defences and other land developments that prevent this

natural migration, the habitats are being lost from this ‘coastal squeeze’ (Pontee 2013; Doody 2013).

Salt marsh loss may also occur through other mechanisms such as over-grazing (Jeffries et al. 2006), land use changes, changes and imbalances in the sediment budget, wave attack, ship wash and poor surface drainage (e.g. Johnson 2000; Hughes and Paramor 2004; Morris et al. 2004; Fagherazzi et al. 2013; Almeida et al. 2014) although there is disagreement between authors as to the relative importance of these factors (e.g. Foster et al. 2014). In addition to sea level rise, climate change may result in enhanced wave action resulting from more storms (IPCC 2013) increasing coastal erosion. It can also cause changes to the species composition and productivity of the salt marsh vegetation (e.g., Morzaria-Luna et al. 2014). These changes alter the stability of the marsh as a whole. The various causes of loss of salt marsh have implications for managed re-alignment in both the short term and long term. These have to be considered in relation to the re-creation of stable and self-sustaining ecosystems.

Foster et al. (2013) record that, despite efforts to restore and re-create salt marsh in south and south-east England, net loss of salt marsh continues in this area. In some areas, such as ports, salt marsh is lost to development and managed re-alignment can be used as one of the ways to create compensatory salt marsh (Morris 2013). However, assessing the historic loss of salt marsh is not straightforward. Areas shown on maps and those seen on contemporaneous aerial photographs often differ considerably (Baily and Inkpen 2013).

Managed re-alignment is usually seen as a means of re-creating salt marsh or creating ‘compensatory’ inter-tidal habitat following its loss or degradation elsewhere (Morris 2012). For this purpose a much more diverse marsh is required, although marshes created by managed re-alignment often remain significantly different from adjacent local marshes for many years in terms of their species diversity and their soil and sediment characteristics including bulk density, carbon content, redox potential, nutrient levels and C/N ratio (e.g. Barkowski et al. 2009; Kadiri et al. 2011; Mossman et al. 2012a). Some authors however (e.g., Morris 2012) argue that sea defence should be the prime policy driver with habitat creation a secondary concern.

Managed re-alignment as a method for re-creating inter-tidal mud flats, to enhance the subsequent development of salt marsh, is likely to be less successful than re-creating salt marsh itself due to restrictions on sedimentation. Rapid accretion in dynamic estuaries means that re-created mud flats are relatively short-lived (Mazik et al. 2010; Morris 2013; Pontee 2014). Elevation within the tidal range rapidly increases to a point at which salt marsh begins to develop.

Managed re-alignment (managed retreat) is seen by Alexander et al. (2012) as the only option for many coastal communities facing accelerated rates of sea level rise (SLR). While hard defences and other engineered structures may be appropriate for large towns and cities, this is not the case for many smaller coastal communities.

In some sites, such as Lyminster/Keyhaven in southern England (Johnson 2000), managed re-alignment may not be practical for a variety of reasons such as nearby upland, important terrestrial or freshwater habitats and past land use. Here steps need to be taken to rehabilitate the salt marsh/inter-tidal habitat in situ to give protection to the sea defences. This has been done successfully on two of the Dutch Wadden islands by using low stone dams to protect the eroding marsh and to encourage sedimentation (Van Loon-Steensma and Vellinga 2013).

Managed realignment also provides sustainable coastal defence options with significant biogeochemical value. Adams et al. (2012) examined the rates of burial of C, N and P in both natural salt marshes and those re-created following managed re-alignment. They concluded that salt marshes, despite being net sources of CH<sub>4</sub> and N<sub>2</sub>O, can sequester C and reduce estuarine nutrient loads. However, Burden et al. (2013) found that the rate of carbon sequestration in salt marsh created following managed re-alignment is slow and they estimated that, at a site in Essex in south-east England, it would take around 100 years for the carbon stored in the managed re-alignment marsh to reach the same level as in adjacent natural salt marsh. Rogers et al. (2014) looked at the potential loss of wetlands around the Hunter River Estuary in New South Wales, Australia, under different management options and suggested that the loss of habitat might be offset by significant carbon sequestration.

Salt marshes have wide benefits to adjacent ecosystems. In addition to their importance in

exporting carbon to coastal waters and adjacent ecosystems (e.g., Hyndes et al. 2014), salt marshes cycle nutrients depending on the age and maturity of the marsh (Boorman 2000). They also act as nursery habitats for fish and marine invertebrates (Boorman 1999). A desk study of Welsh salt marshes by Boorman and Hazelden (2012b) showed that, within critical load limits, salt marshes were able to absorb aerial deposits of nitrogen without ill effects. Rochlin et al. (2012) demonstrated environmental benefits from the restoration of an urbanized marsh. These included increase in the population of native marsh vegetation, bird species and estuarine fauna.

Managed re-alignment is a major tool for Coastal Zone Management (CZM). CZM forms a key part of any country's coastal defence strategy and for the United Kingdom (and many other countries) coastal flooding is second only to pandemic disease in terms of 'high consequence risks' facing the country (Penning-Rowsell 2015).

### The application of managed re-alignment

The success of any managed re-alignment project depends principally on the satisfactory completion of the necessary ground works in advance of the project. This should include determining the full range of plant and animal species and habitats, and the extent of ecological and anthropological factors affecting the salt marsh and adjoining habitats (Garbutt and Boorman 2009; Van Beijma et al. 2014). The course of salt marsh development can also be influenced by changes in relation to coastal infrastructure (Bulleri and Chapman 2010). Salt marsh creation can involve both the re-creation of new salt marshes on areas which had previously been reclaimed from the sea, as well as the regeneration of degraded existing (natural) salt marshes or mudflats. Both the operations involve the sourcing and import of large quantities of suitable sedimentary material. Detailed information is needed on geomorphic factors including tidal regimes, sediment fluxes, and patterns of currents and wave patterns. This should allow an assessment to be made of the range of possible changes that may result from the introduction of managed re-alignment (Blackwell et al. 2010; Crooks and Pye 2000). Living plant material (plants or seeds) will be needed for the creation and establishment of new salt marshes either

for there to be natural spread (Engels et al. 2011) or for planting or sowing to be used. It is vital, therefore, to consider the various options for the creation of new salt marsh with reference to local natural salt marsh resources (Dixon et al. 1998; Boorman and Hazelden 2004; Mossman et al. 2012a). This needs to be considered both in relation to the creation of the new marsh itself and also in relation to the effect the created marsh may have on the existing marsh areas adjoining the new marsh (Friess et al. 2014). The creation of new salt marsh is very likely to have effects on nearby terrestrial, inter-tidal and even subtidal plant and animal communities. Care needs to be taken when using old maps to assess past salt marsh gains and losses both in and adjoining the proposed area of operations as the reliability of this method has been shown to be variable (Baily and Inkpen 2013). New techniques are now available for salt marsh elevation and habitat mapping (Hladlik et al. 2013).

Salt marsh development is dependent on the establishment of vegetation cover of appropriate salt marsh plants over the whole, or at least the majority, of the site (Boorman et al. 2002). This requires the sediment characteristics within the area to be similar to that found in natural salt marsh in the adjoining areas. In the managed re-alignment scheme at Wallasea, Essex, the restored and natural mud flats did have similar sediment characteristics. However, the sediment characteristics in the restored salt marsh remained dissimilar to those of the natural salt marsh (Kadiri et al. 2011). The differences were observed in parameters such as moisture content, organic matter content, pH, bulk density, salinity and porosity. The interpretation was that with the created marsh the establishment and development of the pioneer vegetation preceded the development of optimal sediment characteristics.

The relict effects of the pre-managed re-alignment land use and management will be minimised if there is rapid accumulation of new sediment. This will help to overcome the problems caused by low elevation and the irreversible changes that have taken place within the soil/sediment of the reclaimed land (e.g., Hazelden and Boorman, 2001; Friess et al. 2012b). Wang and Temmerman, (2013) discussed the rapid shift that can occur from a low-lying mudflat to vegetated salt marsh when the conditions are right for plant establishment and growth. Ganju et al. (2013) highlighted the way in which channel sediment fluxes reflected the stability

of the marsh. An understanding of sediment flows to and within the site are essential pre-requisites for a successful managed re-alignment scheme (Boorman et al. 2001). Nolte et al. (2013) reviewed methods used to measure sediment concentrations in the water column, accretion or loss from the marsh surface and short- and long-term effects on marsh elevation.

There is a need to understand the way water enters and leaves at every managed re-alignment site. Friess et al. (2014) highlighted problems with tidal asymmetry. This happens when water is draining slowly from the site during the ebb, when water forms pools within the site. It can be caused by restrictions imposed from the size of the breach in the sea wall, and by water surface slopes. These issues can be addressed by adequate consideration being given to breach design and site drainage and this emphasises the need for detailed investigation and modelling (e.g., Spearman 2011) prior to re-alignment.

The tidal regimes experienced within and in the proximity of a managed re-alignment site are clearly of critical importance in relation to seedling establishment, but it is not always easy to quantify local variations in tidal regimes over trial sites which are often at considerable distances from permanent tide gauges. One solution to this problem could lie in the use of compact autonomous depth sensing data loggers (fish tags) which, when combined with high resolution GPS, can give precision data for scattered sites (Mossman et al. 2012c). It should also be noted that there are gaps to be filled at the large scale in relation to the analysis of long term sea level changes and that assumptions of exponential growth may not be well founded (Parker et al. 2013).

Reference has already been made to the value of the latest advances in remote sensing in quantifying salt marsh dynamics (Friess et al. 2012a). These studies have shown how managed re-alignment can cause a high magnitude sediment input into the local coastal system and thus significantly increasing intertidal elevations; the use of multispectral imagery can also accurately show vegetational changes within these areas.

Each site will need detailed monitoring to assess its success or otherwise following the application of managed re-alignment (e.g. Pétillon et al. 2014). Even quite small differences in surface levels can result in major changes over a wide area. Recent studies in Portugal have shown that changes in land use have

resulted in the loss and degradation of salt marsh habitats as a result of reductions in the sediment supply (Almeida et al. 2014). It is probable that the effects of such changes would be even greater during the early stages of salt marsh development for example within a managed retreat site. There is also need for considering how flooding agricultural land may change the existing salt marsh, through the potential release of contaminants (Kadiri et al. 2012).

The success of managed re-alignment critically depends on high siltation rates to raise surface levels sufficiently for plant colonisation (Morris 2013). Siltation rates within a managed re-alignment site also play a critical role in the development of new mudflat habitats, benthic in-fauna and bird usage within schemes (Mossman et al. 2012b). However, while siltation rates may sometimes be inadequate for salt marsh and related habitat development, high siltation rates may limit sustainable habitat development (Pontee 2014).

Managed re-alignment is dependent not only on an adequate supply of sediment, the properties of the sediment are also important. It might be assumed that the standard properties of sediment (particularly particle size range) would be an adequate indication of suitability for the colonisation and establishment of salt marsh vegetation. It has, however, recently been pointed out that the cohesive properties of the sediment supply and thus its erodibility can crucially affect plant colonisation (Grabowski et al. 2011). In many salt marshes the underlying sediments contain significant levels of heavy metals and agricultural chemicals (Emerson et al. 2001; Boorman et al. 2002) and such contaminants can also be released from agricultural soils and from imported dredged sediments (Kadiri et al. 2012). The latter authors concluded that, although the effects are likely to be short term following inundation, surveys of all soils and sediments should be made during the planning stage of managed re-alignment schemes to assess the potential release of herbicides and heavy metals.

It is usually inferred that, because colonisation of mud flat areas by pioneer salt marsh plant species is part of the natural sequence of events, colonisation will also take place whenever areas of mudflats are formed at suitable levels in relation to the tidal regime (Boorman et al. 2002). However it has recently been suggested that in the future this process may also be affected by changes in climate (Green et al. 2009).

When it was first implemented managed re-alignment was seen as a low-cost way to provide adequate flood defence (Dixon et al. 1998). It is now possible to consider the relative costs of a much larger number of managed re-alignment schemes (ABPmer 2015). These data show that managed re-alignment and associated approaches to salt marsh creation can be costly and complex. The UK Environment Agency generally works to a guideline figure of £10,000 per hectare (2006 prices). However the costs can run to over twice this figure, particularly when significant engineering is required. The ABPmer also points out that some lower cost schemes are being implemented, particularly in less developed (more natural) estuaries. The lowest recorded costs were Lantern Marsh, Suffolk, at just under £800 per hectare.

### Broader perspectives

Large-scale environmental changes such as those involved in managed re-alignment will have wide implications for the public. Thus, public and stakeholders' interests in both the short and long term developments must be fully considered (e.g., Alexander et al. 2012; Roca and Villares 2012). Previous land history and management affects the way salt marsh plants establish following managed realignment. Blackwell et al. (2004) examined the short-term effects of managed realignment on soil and its hydrology and later they (Blackwell et al. 2010) recorded differences in denitrification rates and nitrous oxide production between a natural salt marsh and a marsh created following managed realignment. Old agricultural land is often high in plant nutrients and so the natural re-establishment of intertidal flora proceeds only slowly as nutrient levels decline. Barkowski et al. (2009) reported that colonisation was initially by nitrophytic plants due to the high nutrient content of the former agricultural soil. These were gradually replaced by *Atriplex* in the lower marsh and *Elymus* in the higher marsh as nutrient levels fell. The re-established marsh had much lower species diversity than that found in the natural marsh. The constraints on salt marsh development following managed realignment can also be affected by both dispersal limitations of salt marsh plant species and by the environmental tolerance of those species (Mossman et al. 2012a).



While managed realignment is mainly concerned with re-establishing salt marshes on land claimed from the sea many years previously it can also include the re-opening of old high level salt marshes to increased flooding by the opening of the ‘summer polders’ around formerly embanked salt marshes (Barkowski et al. 2009). Initially this caused the former high marsh species to die out. They were replaced by plant species associated with lower salt marsh zones. However, over a period of 3–4 years the nitrogen reserves became depleted and the number of plant species increased (Barkowski et al. 2009).

Studies on the impact of environmental factors on existing salt marshes and the ways in which the marshes can recover from their effects can provide vital guidelines for encouraging and managing the establishment of marshes through managed realignment. More than a half of the natural salt marshes in the Algarve in south Portugal have been lost since 1800 through the building of dykes and the use of the land for agriculture (Almeida et al. 2014). After the 1960s, however, considerable areas of the reclaimed marsh areas were abandoned and allowed to revert to their former state. Floristically diverse marshes were formed in the areas with only partial or restricted tidal flooding resulting in a mosaic of fresh, brackish and saline marshes including a number of invasive species. Restored marshes were formed with a vegetation structure similar to that of natural salt marshes in surrounding areas where the dyke breaching was complete.

However, restored salt marshes often develop slowly and show persistent differences in vegetation from natural marshes (Mossman et al. 2012a). Five years after realignment plant communities of the site remained similar to those of the youngest natural reference marshes, but there were extensive areas with very limited vegetation cover. The authors concluded that the main factor limiting plant establishment and growth were low sediment redox potentials. This was largely attributed to poor drainage.

It cannot be assumed that the area will have biological characteristics equivalent to nearby natural reference sites even when a more or less natural covering of salt marsh vegetation has been achieved across a site. Mossman et al. (2012c) compared 18 managed realignment sites and 17 accidentally opened sites with 34 natural reference sites in the United Kingdom and found significant differences persisted

between the created marshes and the natural reference marshes. Early-successional plant species remained dominant in all the realignment sites even after many years of development. Characteristic high marsh species such as *Limonium*, *Triglochin*, *Plantago* and *Armeria* remained relatively rare. In the early years after managed realignment at Langeoog Island in the East Frisians the pioneer salt marsh species remained dominant and this was attributed to high soil nitrogen levels. The nitrogen content eventually decreased and other species became more competitive (Barkowski et al. 2009). Nevertheless the plant species diversity remained lower than in nearby natural marshes.

There are many different and complex interactions between the components of salt marsh ecosystems, and the interactions between two crab species might not seem to be particularly relevant to the re-establishment of marsh vegetation. It has, however, been shown to determine the course of vegetation establishment on salt marsh at Cape Cod (USA) where overfishing depleted salt marsh predators (Altieri et al. 2013; Bertness and Coverdale 2013). The invasion of the herbivorous crabs (*Sesarma reticulatum*) caused losses of large areas of *Spartina*. However, the collapse of peat banks left denuded by *Sesarma* gave rise to a muddier substrate with fewer herbivores which allowed the *Spartina* to recover. This result illustrates the need to consider the whole range of species involved in the salt marsh ecosystem.

The pioneer plant species growing on a managed realignment site will affect the final outcome. Bouma et al. (2009) examined the relationships between plant shoot stiffness and size under different conditions. Flexible shoots resulted in less scouring, and are likely to be better at establishing vegetation in exposed hydrodynamic conditions. Bouma et al. (2010) discussed the engineering efficiency of different species. They compared *Spartina anglica* and *Puccinellia maritima* and concluded that *Spartina* had the higher ecosystem engineering efficiency due to its lower planting costs rather than a higher engineering effect. Experiments measuring flow deviations caused by different plant species at different velocities demonstrated that the effects on flow, and hence sedimentation, are species specific (Bouma et al. 2013). Balke et al. (2012) examined the effects of the shape of *Spartina* tussocks and sediment grain size on the long-term development of pioneer marsh. They showed that the dome-shaped tussocks which accumulate sediment

only occur under certain abiotic conditions. Further understanding of the ecological engineering properties of different species under different conditions is clearly important for the success of managed realignment in re-creating salt marsh, although seed availability may be the key to the success of early plant colonisers (Erfanzadeh et al. 2009).

The choice of plants for any given part of the re-created marsh is restricted by the conditions necessary for that species to survive and thrive. Davy et al. (2011) working on the north Norfolk coast in eastern England, showed that, although both elevation and redox potential generally increased together, their effects were distinguishable from each other in many plant species. *Salicornia europaea* was found mainly on the lower marsh, but was not influenced by redox potential. *Suaeda maritima* was absent from areas with low redox potential, but these areas were favourable to *Puccinellia maritima*. Both species occurred on a wide range of elevation. *Atriplex portulacoides* was apparently more averse to low redox potential than to low elevations and *Elytrigia aetherica* was restricted to areas with both high redox potential and high elevations.

The structure of the vegetation on the marsh influences the community structure of the fauna within the marsh. In a study of *Scirpus mariqueter* in China, Xingzhong et al. (2005) reported that shoot height and below-ground biomass best explained the community structure of the macrofauna. Habitat heterogeneity within the marsh is related to the diversity of the macrofauna.

### Managed realignment and salt marsh management

Regular monitoring of both species diversity and marsh function are key requisites in the preservation of the structural and functional integrity of the salt marsh. The long term success is dependent on an adequate understanding of the many different processes involved from the deposition of sediment on intertidal sand and mud flats through the geomorphological evolution of the site right through to the effective management of the many complex plant communities of the high marsh.

Managed realignment initiates subtle local changes in the morphodynamics of the sediment system. These changes have been combined into a predictive

mathematical model (Spearman 2011). Longer term simulations can show how the evolution of the setback area reacts to the growth of the salt marsh and how this might be affected by sea level rise. The model was based using standard survey and LiDAR data and has been used to predict the long term development of the area over periods of up to 80 years. When the model was used to consider the situation of the early managed realignment site at Tollesbury, Essex, it indicated that, under the influence of predicted sea level rise, the extent of salt marsh habitat created would not be extensive in the longer term. However, a recent visit to the area by the authors has shown that this has not happened and that there was extensive marsh growth over 75% of the site after 20 years (see Figs. 1, 2).

An important feature of all salt marshes is the spread and development of an efficient creek drainage system. Not only are the salt marsh creeks important for the water transport of the marsh-building sediment inputs, they also play an important role during the period of the emersion of the marsh in draining the marsh surface and reducing the water-logging of the marsh sediments, critical for the full development of the marsh vegetation (Boorman et al. 2001). A model has been developed of the long term stability of a tidal wetland based on channel sediment fluxes (Ganju et al. 2013). The authors suggest that sediment flux measurements are good indicators of long-term marsh stability.

In general terms sediment accretion can compensate adequately for current rates of increase in sea level rise, but isostatic adjustment can give much higher actual rates of sea level rise in relation to the land (Boorman et al. 2002). It may well be that there are other factors yet to be identified contributing to salt marsh loss; thus there is a need to develop ways in which timely decisions and more effective further action can be taken to conserve and sustainably use mudflats and salt marshes (Foster et al. 2013). However recent studies in the United States have shown that, in the lower marshes, increases in sea level will lead to reduced root growth and a decrease in the rate of elevation gain (Kirwan and Guntenspergen 2012).

A major decision in any marsh creation project is whether natural processes of vegetation regeneration will be sufficient, or whether supplementary planting or sowing is needed (Green et al. 2009). The problems

referred to in the previous paragraph about increases in sea level rise affecting plant growth and thus accretion rates, may well make the decision even more complex. Reference has already been made to the need to consider the accessibility of managed realignment sites in terms of the import of seeds or other propagules of key salt marsh species (Boorman et al. 2002). It was also noted that this process may also be affected by changes in climate (Green et al. 2009) as well as changes in the rates of sea level rise (Parker et al. 2013). It is suggested that a combination of techniques incorporating the planting of species likely to have slow establishment rates and the encouragement of natural colonisers and taken with surveys of seed sources will provide guidance as to the necessity of further steps. Long-term monitoring of the vegetation changes will also help to understand the responses of species to different environmental conditions (Green et al. 2009; Foster et al. 2013; Bellafiore et al. 2014).

Many areas of salt marsh which have a wide range of plant communities are grazed by herbivores. This has long been recognised as an important mechanism leading to the development of spatial pattern and the stability of various plant communities (Boorman et al. 2002). Grazing by different animal species is likely to have different outcomes and these need to be assessed when planning a managed realignment site (Nolte et al. 2015). Grazing reduces the plant height and decreases the efficiency of the plants in trapping sediment. Sediment is compacted by grazing animals (e.g. Elschot et al. 2013); making it less liable to subsequent erosion, but reduces the height of the marsh surface relative to the sea. However, such a reduction in level may encourage increased sedimentation. Nolte et al. (2013), in a study of marshes on the German Wadden Sea islands, concluded that, although grazing did cause compaction of the marsh surface, it did not significantly affect either accretion or rates of sediment deposition. Other biotic and abiotic factors, such as the creek or drainage pattern in the marsh and distance from the marsh edge, affected whether grazing had any influence on these processes. Sheep, cattle horses and wildfowl can be found grazing the marshes in different salt marsh areas across Europe. Generally sheep grazing or mixed grazing with sheep and cattle were more likely to increase and maintain small scale vegetation patterns (Boorman et al. 2002; Nolte et al. 2014). The effects of grazing on salt

marshes are not restricted to the effects on plant species diversity. It has also been shown that grazing can affect salt marsh accretion rates (Nolte et al. 2014).

### **Risks associated with managed realignment**

With a relatively new marsh management strategy such as managed realignment, it is inevitable that from time-to-time some unexpected changes will occur, even after careful preparatory planning. Even then many of them may only require minor adjustments to vegetation management, or some other aspect of the system. It has been shown that vegetation plays a vital role in determining patterns of accretion of salt marsh sediments (Boorman et al. 2001). When a project involves large scale geomorphological changes, such as when large quantities of sediment are brought into raise the level of the surface, then there are particular risks with extensive areas of bare sediment exposed to the action of winds, waves and tides during the period before and during plant establishment. To some extent these risks can be reduced by timing marsh creation activities, including the import of sediment, to match the natural spread of pioneer salt marsh plant species. It is likely that some form of protection from erosion may be needed before and during plant species establishment particularly with larger sites. This will be especially true in areas where salt marshes are already in retreat. An effective way to reduce erosion has been to use low stone dams around the edge of the developing marsh (Van Loon-Steensma and Slim 2013). The authors showed that the erosion protection provided by these dams could give a strong reduction in the retreat of the salt marsh edge, with typical pioneer salt marsh plant communities developing between the stone dams and the former marsh edge.

### **Long-term monitoring and assessment**

So far we have been considering the day-to-day progress at specific sites and their particular problems. While there can be no question of the importance of this (short term) approach there is much more to be learnt from comparative observations over longer periods (monitoring tends to have been concentrated on the early years of progress) and of as wide a range

of comparable sites as possible. Most of the published information relates to studies at individual sites, rather than considering the information now available over wider areas. There are exciting new possibilities now available through the efforts of Associated British Ports (ABPmer 2015) which maintains an on-going website (<http://www.omreg.net>) covering most British and many mainland European sites where salt marsh creation and management has been or is being undertaken. The data base currently covers 82 sites in the United Kingdom where there is some form of salt marsh creation or management; and 41 of these sites involve managed realignment. The data base also covers activities at a further 57 sites in mainland Europe.

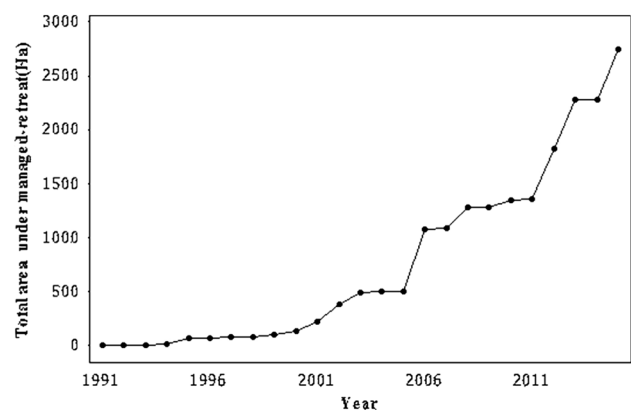
The data collected by ABP enable comparisons to be made of various parameters at each site. The average size of each of the 41 UK managed realignment sites is 48 ha, although individual sites range from less than 1 ha to over 450 ha. The majority of the managed realignment sites (73%) were established in the last 15 years. Figure 3 shows how the total area involved has grown over the past fifteen years. It is important, however, to note that although the quoted area of a managed realignment site generally represents the maximum possible area of vegetated salt marsh that could be created few if any of the sites will ever become 100% salt marsh and even an estimate of 50% would probably be on the optimistic side. The total area of managed realignment sites would represent a maximum mean annual increase in the area of salt marsh created by managed realignment over the past 25 years of  $78 \text{ ha year}^{-1}$  and if the initial ten years are excluded the figure increases to  $122 \text{ ha year}^{-1}$ . However, it might be more realistic,

in planning terms, to reduce these figures to 40 and 60 respectively. The vegetation cover in salt marshes can often be little more than 50%. The estimated potential loss of UK salt marshes from natural causes and over the period 1990–2050 was 40% or  $300 \text{ ha year}^{-1}$  (Boorman, 1992).

The highest potential annual rate of marsh creation by managed realignment achieved so far was in 2006 when seven sites involved nearly 600 ha. The next highest was in 2013 when a single managed realignment site of 450 ha was created at Medmerry (Sussex). In both these years the proposals included a wide range of coastal habitats as well as salt marsh. The average area of managed realignment sites over the past 10 years was  $184 \text{ ha year}^{-1}$  or about 90 ha of salt marsh. Thus, even if marsh loss from urbanisation or industrial developments could be avoided, we would still need to achieve at least a three-fold increase to maintain our existing area of salt marsh. It is noteworthy that the number of starts using sediment recharge has fallen markedly from one new site per year 1990–2000 to only a single start during 2011–2014. This might well reflect the high costs involved in moving very large quantities of sediment. This also seems to be reflected in the much smaller size of the sites involved (average managed recharge site is 6.8 ha) compared with managed realignment sites (average 48 ha). In marked contrast to the sites with sediment recharge after a similar slow start during 1991–1995 the number of sites under managed realignment has, between the years 1996–2014, increased at an average rate of nearly two sites each year.

The ABP website lists a total of 88 managed retreat sites for Europe, with 41 these in the UK. The majority

**Fig. 3** Yearly increases in area of managed realignment sites in the UK over the period 1991–2015. Data provided by ABPmer (2015)



of the mainland European sites are in Germany (26 sites) The Netherlands (9), or Belgium (6), although it is possible that it is only the larger sites which have been recorded. Within the broad set of sites documented by ABP, there is the real potential for answering more effectively many key questions that could facilitate the effective management of both existing and future salt marsh creation sites. This potential can only be realised if the necessary data on salt marsh development and the associated environmental parameters are made available (in many cases it would appear that is not even being collected). The large number of British managed realignment sites already has the potential to yield important information for the future creation and management of salt marshes. This information is necessary for the integration of coastal protection with all the attributes of plant and animal species and habitat conservation and associated services. In most cases monitoring was limited to the early period of plant establishment and this only gave a broad indication of the likely final degree of success at that site.

### Future prospects for managed re-alignment

This section looks at the future needs and considers the ways in which improvements in the science and technology may help to make the outcome of managed realignment more predictable. It also considers how managed realignment may be made more acceptable to stakeholders.

There is a need for more accurate models and predictions of sea level rise (Parker et al. 2013). They report that the results from models used to predict sea level rise by some local governments in Australia are not in agreement with many measurements made by tide gauges. The models used predict an exponential rise, whereas the measured rise, at present, appears much less. Signs of an increase in the melting rates of polar ice suggest that, by the end of the 21st century, the rates of sea level rise will be greater than previously predicted (Goudie and Viles 2016). This has consequences for future planning and may well lead to unnecessary expenditure.

At present most managed retreat and managed realignment sites have been located where there has been little or no infrastructure. In future, however, it is likely that more difficult decisions will be needed

where important infrastructure including houses, factories, power stations, roads and railways are sited within a potential realignment site. In the long term it may be deemed necessary to move this infrastructure inland or to higher ground if and when it becomes uneconomic to defend it from coastal flooding. Alexander et al. (2012) considered that there will be areas where managed realignment is the only option. They tested the Australian public's response to managed retreat and found, encouragingly, that people generally considered their response from multiple perspectives rather than simply from what they might lose.

Roca and Villares (2012) document conflicts over managed realignment in the Ebro delta in Spain caused by a lack of understanding of the process and a general distrust of public authorities. Managed realignment was regarded as being mainly a conservation issue and not providing as satisfactory a sea defence as traditional hard engineering. Involving stakeholders more in the whole process was seen as a way to build trust which Roca and Villares predict is the necessary way forward. Probably the best way to achieve this trust is through the demonstrable success of a few flagship schemes and the subsequent publicity, although in some instances the stakeholders' interests and concerns will remain paramount.

Managed realignment is needed to re-create and restore salt marshes and to provide an answer to rising sea levels and increased coastal inundation by the sea. Salt marshes world-wide are being lost and need to be restored or re-created for the reasons stated earlier. Baily and Pearson (2007) mapped the decline in salt marsh area in central southern England over the previous 30 years using aerial images. The reasons for this decline are very complex and need to be better understood (Goudie and Viles 2016). They include sea level rise and coastal squeeze but also other factors such as the dieback of *Spartina anglica* weakening its ability to trap and hold sediment, and nearby dredging for docks and channels increasing the speed of tidal flows. Although research has yet to identify unequivocally the cause of salt marsh decline (Foster et al. 2013), these and other factors discussed previously, which may differ from place to place, must be taken into account in any future managed realignment scheme. Foster et al. (2014) also record that, despite schemes to regenerate salt marshes and mudflats, there is still a net decline of these habitats. If successful

managed realignment is to be achieved, then the causes of this decline needs to be addressed.

Erosion of sediment from a salt marsh is influenced by many factors, not just plant cover, sediment particle size, water velocity and the different ecological engineering properties of different plant species. Most sediments show some degree of cohesion between particles. Clay mineralogy, pH of the sediment, metals present and organic matter content all affect this. The fauna and flora within the sediment also have an effect on its cohesion (Grabowski et al. 2011). The influence of these factors will vary from site to site, but all need to be better understood if managed realignment sites are to generate sustainable areas of salt marsh.

Sufficient sediment supply is also important; reservoirs, dams and flood defence measures in river valleys reduce the amount of sediment passing downstream and into the sea. This deprives salt marshes of an important source of sediment (Esteves 2014) and thus renders the marsh more liable to erosion and decline.

It is necessary to be able to map accurately salt marsh vegetation and topography in order to establish where and for what reasons salt marsh loss is occurring or has occurred. Assessing the historic loss of saltmarsh is not straightforward. Areas shown on maps and those seen on contemporaneous aerial photographs often differ considerably (Baily and Inkpen 2013). Mapping of salt marsh vegetation is a time-consuming business. Van Beijma et al. (2014) discuss the remote mapping of salt marsh vegetation using combinations of S-band and X-band quad-polarimetric airborne SAR, elevation data and optical remotely sensed imagery. They concluded that models that combined variables from multiple sources were more accurate than those based on either SAR or optical RS variables alone. The results also showed that X-band SAR data provided the best information for mapping vegetation extent and analysis showed that S-band SAR data was better at differentiating between vegetation habitats.

Managed realignment creates inter-tidal habitat, usually salt marshes and it is these with which this review is concerned. Salt marsh provides ecosystem services and benefits which have been discussed earlier, the monetary values of which can be quantified. Luisetti et al. (2011), however, concluded that, for the Humber and Blackwater estuaries in eastern England, although managed realignment was economically

viable, it was only so in some carefully selected places. In addition, it takes a long time (more than 15 years) for a restored salt marsh to be equivalent to a natural marsh in terms of its chemical and biological functions (Burden et al. 2013) and so any ecological benefits may well be seen only in the long term. The vegetation of marshes created by managed realignment remains significantly different from adjacent natural marshes for a long time. Soil and sediment characteristics including bulk density, pH and nutrient levels are generally higher on managed realignment marshes than in adjacent natural marshes. The redox potential, organic matter content and C/N ratio tend to be lower in managed realignment sites (and in accidentally realigned sites) compared to those in adjacent marshes (e.g., Kadiri et al. 2011; Mossman et al. 2012b). Indeed Mossman et al. (2012b) concluded that the differences were such that most marshes created by realignment were not good enough to satisfy the requirements of the EU Habitats Directive.

The success of managed realignment has to be assessed after the event to learn any lessons that could help to make future managed realignment schemes a success. It can be evaluated by comparing the conditions in marsh created by managed realignment with those in equivalent natural marshes. The functional and conservation equivalency must be assessed separately (Pétillon et al. 2014). The conservation equivalency was achieved quickly in their experiments, but the functional equivalency of marine enrichment and fish nursery lagged behind. It would be helpful to find ways to achieve functional equivalence more rapidly following managed realignment. It is possible that there are beneficial effects of salt marshes that are not yet fully appreciated or understood. These effects may be crucial in judging the cost effectiveness of future managed realignment schemes.

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