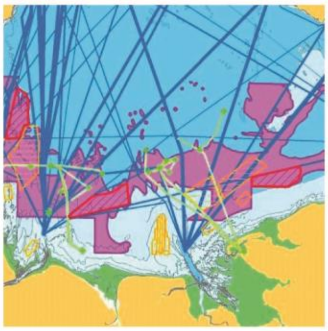
White Paper

Blue Carbon in Managed Realignments

An overview with a comparative analysis and valuation of 10 different UK sites

November 2021




Innovative Thinking - Sustainable Solutions

Page intentionally left blank

Blue Carbon in Managed Realignments

An overview with a comparative analysis and valuation of 10 different UK sites

November 2021

Summary

Background

For the last 20 years it has been increasingly recognised that coastal habitats (especially marshes, seagrass and mangroves) can play a key role in trapping and storing carbon. This recognition, and our understanding about the potential implications, have also grown progressively and substantially over the years.

The burgeoning attention directed towards this issue has been driven by encouraging results from scientific research alongside mounting concerns about the threats posed by climate change. There is still, however, uncertainty and debate about many aspects of this subject and about how it can be used to drive pro-active action for climate change mitigation and tidal wetland restoration.

To contribute to ongoing discussions in this field (and describe, particularly, the implications for habitat restoration) this ABPmer White paper summarises the situation and examines the Blue Carbon value of ten very different wetland restoration projects. It then provides some recommendations for future project delivery and research.

Current situation

We know that although saltmarshes cover a small proportion of the Earth's surface, they can outperform other marine and terrestrial habitats as carbon sinks. Thus, they can be 'hot spots' for carbon burial. This, however, presupposes they are stable in the face of climate change pressures and natural coastal processes. In many cases, UK saltmarshes are eroding (particularly the south and east coasts of England) and thus may be releasing carbon to the marine environment. This situation provides an additional motive for creating stable new coastal habitat.

The creation of saltmarshes is most effectively done through the realignment of coastal defences. Firstly, this a vital adaptation measure in response to a changing climate, changing coasts and rising seas. But it also creates carbon-sequestering habitat that can become part of Nationally Determined Contributions (NDCs) for mitigating climate change under the 2015 Paris Agreement. That is in addition to the many other benefits that the created habitats provide such as biodiversity enhancement, nutrient assimilation, fish production, improved land/seascapes and areas of recreational and health value.

The habitats created by coastal realignment are usually sheltered by old and new sea walls. They are often on low-lying land historically claimed from the sea. As such, they are naturally a bit different to more exposed and older habitats. They often exhibit a rapid build-up of sediment, depending on sediment supply. This accretion is best understood as a natural function of these environments 'bouncing back' and reversing the damage wrought by historically isolating the land from the tide (leading to sediment starvation and land compaction).

As most of the carbon in wetland habitats is in the soil, this rapid accretion can facilitate rapid and substantial carbon accumulation. Thus, realignments could be the hottest carbon burial spots of all.

This view has been expressed for years but evidence has been needed from completed restoration sites to verify it. That evidence is now emerging. The methods and results of the studies are variable however. Some studies find restored marshes are anywhere from twice to 18 times greater value for carbon than mature marshes. Others find newly restored marshes are still valuable but less so than older habitats.

Blue Carbon value of ten realignments.

To look at this further, ABPmer compared the evolution of habitats across 10 very different completed managed realignments over the first 10 years of their life. Using a simple Blue Carbon Calculator tool (that we developed a few years ago to inform our work on the design of realignment projects), we found that they can sequester double the carbon quoted for mature marshes.

We expected this finding from our past work. However, we also illustrate how the blue carbon value varies across different sites from 8 to 26 tCO_2e ha^{-1} yr^{-1} and how much greater it is in low-lying sites and sediment-rich estuaries where accretion rates are high. To put this level of sequestration into a monetary context, we find the value of these ten sites is over £11.5 million during the first ten years of their life (based on non-traded carbon prices).

To apply a sensitivity test to this analysis we used field results from the latest studies at the Steart managed realignment site in the Severn Estuary (as managed by the Environment Agency and the Wildfowl and Wetlands Trust (WWT)). These latest studies found remarkable sequestration levels of over 60 tCO_2e ha^{-1} yr^{-1}. We obtain comparable values using their survey results. This is because the core analytical principles are essentially the same for both studies.

This information can be used to help gauge the value of future 'Blue Carbon Projects' in different estuarine and coastal situations in advance of them being implemented. It shows that we are starting to collate enough information to make such comparisons between sites. It also highlights the profound importance of getting more, and better, field data urgently.

If the field readings obtained at Steart were applicable at the other realignments sites we have compared here, they would collectively have a monetary value of around £27 million during the first ten years of their life. The value for Steart alone would be £11 million over this period on this basis.

Final Recommendations

In conclusion, we provide some thoughts and recommendations for the future of this field based on our findings. The recommendations include having improved, and more targeted, monitoring (the clear value of which is demonstrated by studies cited in this paper) as well as standardised methodologies and interpretative frameworks.

It will be vital to reach a consensus and develop an accurate and viable analytical approach that can then be applied consistently across future studies. International standards already exist, and work is being actively progressed in this direction in the UK.

This review also includes a call to start planning bespoke and 'additional' Blue Carbon projects now. The information needed to do this already exists. This, of course, needs to be just one component of a much broader mix of urgent carbon mitigation and emission reduction measures.

1 Introduction

1.1 Background to blue carbon

For the last two decades, and especially over the last few years, increasing attention has been paid to the major role coastal wetlands can play in locking up carbon and contributing to climate change mitigation. Prior to this, investigations into wetland carbon sequestration were, almost exclusively, directed at expansive inland systems. Because of their size, these systems provide some of the largest biological stores of carbon on a global basis.

Historically, little credence was given to the value of marine ecosystems for sequestering 'Blue Carbon'. This was the case as recently as the 2010 UN Climate Change Conference (COP16) in Cancún, Mexico (Windham-Myers *et al*., 2018). Today, more than a decade later, and as COP26 is now taking place in Glasgow, this situation has radically changed. Substantial attention is now being directed at the carbon storing and trapping function of marine ecosystems.

It is now accepted that, while coastal habitats might be relatively small in their extent (<2% of the ocean's surface), they are hot spots for carbon burial. They are estimated to account for around 50% of all the carbon buried in ocean sediments (IUCN, 2017). As a result, coastal habitats are now understood to be important on a global scale despite their comparatively small size (Chmura *et al*., 2003; Duarte *et al*., 2005; Laffoley and Grimsditch, 2009; Chmura, 2011 and Macleod *et al*., 2011).

Saltmarsh with sea lavender and sea purslane at high water, River Hamble (Andrew Pearson, May 2021)

This greater understanding about the carbon value of coastal wetlands has been accompanied, and accelerated, by ever-growing concerns about how to deal with the climate emergency. In this context, the potential for these habitats to help mitigate greenhouse gas emissions is being increasingly recognised and viewed as an additional motive for delivering marine habitat protection and restoration.

It is now firmly recognised that stable marine habitats, and especially vegetated tidal wetlands can sequester large amounts of carbon (called 'Blue Carbon'). Therefore, one of many reasons for restoring and protecting these habitats is that they can contribute to climate change mitigation.

The increasing thought that is being directed towards this subject is evidenced by many recent collaborations, research studies and policy developments. For example, the international Blue Carbon Initiative[1] was set up to bring together governments, research institutions and other organisations to enhance understanding about coastal Blue Carbon Ecosystems (BCEs). Also, under the United Nations Framework Convention on Climate Change (UNFCCC),

[1] International Partnership for Blue Carbon, 2021. Blue Carbon Partnership.

it is now recognised that the management of coastal wetlands can contribute to a country's efforts to reduce emissions. It can count towards Nationally Determined Contributions (NDCs) under the Paris Agreement. Indeed, several countries now include measures for 'protecting and restoring blue carbon ecosystems' as well as other 'ocean-based measures' in their NDC submissions (Lopez, 2021).

The Intergovernmental Panel on Climate Change (IPCC) has also published guidance for including wetlands in national greenhouse gas (GHG) inventories (Hiraishi *et al*., 2014). Last year the Reduced Emissions from Deforestation and Degradation (REDD+) Methodology Framework was adapted to include tidal wetland conservation and restoration activities (Verified Carbon Standard (VCS), 2020). Other international voluntary carbon standards have also been produced (see IUCN (2021) for a review).

Until recently, almost all the attention was directed at three vegetated coastal habitats: saltmarshes, mangroves and seagrass beds. These are viewed as the prime BCEs because of factors such as their efficiency in transferring carbon into the sediment and their extensive below-ground biomass (Macleod *et al*., 2011 Pidgeon, 2009, Chmura *et al*. 2003).

Only these three vegetated habitats are currently being considered as part of blue carbon policy framework and within national GHG inventories (Crooks *et al*., 2020; Herr *et al*., 2018; Hiraishi *et al*., 2014). However, there are ongoing efforts to investigate other habitats, species and open-ocean carbon systems, such as coral reefs, kelp beds, phytoplankton, marine fauna, subtidal sediments and seabed habitats greater than 200 m deep (Parker *et al*., 2021; Herr *et al*., 2018).

Understandably there is a burgeoning interest in, and advocacy for, delivering coastal habitat restoration as a climate change mitigation measure. There are however many gaps in our knowledge and many efforts being made to address this and develop new standardised methods and valuation frameworks.

Despite the growing urgency and impetus surrounding this subject, as well as the improved evidence base and burgeoning advocacy of recent years, there are still gaps in our understanding about blue carbon (Parker *et al*., 2021; Macreadie *et al*., 2019; Macleod *et al*., 2011). In the UK, several individual research projects have recently been completed or are newly underway to explore this issue. This includes a new study being led by the UK Centre for Ecology & Hydrology (UKCEH), funded by a £100,000 grant from the Government's new Natural Environment Investment Readiness Fund. This project will review the value of habitat restoration measures to understand the revenue case and help evaluate and refine the Saltmarsh Carbon Code. An investment case will be developed for interested carbon buyers to help fund future projects[2].

Work in the UK also includes the NERC-funded C-SIDE project[3], an integrated study of blue carbon in UK saltmarsh habitats, undertaken by a multidisciplinary team of researchers across five organisations. It also includes the ClimateXChange initiative which is examining the blue carbon value of coastal habitat restoration in Scotland. Blue Marine has also recently set up a UK Blue Carbon forum[4] to advise on this subject.

Even more recently, at COP26 on 5 November 2021, the UK announced its intention to progress evidence on blue carbon habitats in the UK. This would include establishing a new cross-administration UK Blue Carbon Evidence Partnership to progress the evidence base on these habitats and fill the evidence gaps that currently hinder inclusion of saltmarsh and seagrass habitats into the UK Greenhouse Gas Emissions Inventory[5].

---

2 CEH-led UK Saltmarsh Carbon Code project
3 C-Side Carbon Storage in Intertidal Environments project
4 Blue Marine Foundation Blue Carbon: A new frontier for ocean conservation
5 COP26: Government leads on Ocean Action Day

1.2 Aim of this review

This White Paper was prepared to inform discussions about the blue carbon value of intertidal habitats and their restoration. It is hoped that it will contribute a little to the various collaborative projects and scientific reviews that are underway and are mentioned in the preceding section.

The best, and most sustainable, way to create saltmarsh is by realigning coastal defences. This is a physical adaptation to rising seas and changing coasts with the habitats created also providing multiple benefits for society (including trapping carbon).

This review specifically considers the role that managed realignment projects can play in trapping and storing blue carbon. It summarises the exciting implications from recent scientific research, as well as describes some of the issues and uncertainties that need to be resolved if we are to make a robust investment case.

Managed realignment involves the deliberate breaching, or removal, of existing seawalls, embankments or dikes in order to allow the waters of adjacent coasts, estuaries or rivers to inundate the land behind.

Such sea defence realignment schemes often include the construction of new counter walls at the back of the site where necessary (i.e. where there are still low-lying vulnerable hinterland areas). This technique represents the best way to achieve sustainable coastal protection whilst creating new coastal habitats, enhancing biodiversity and providing multiple other benefits for society. These societal benefits include nutrient assimilation, fish production, improved land/seascapes and areas of recreational and health value (as well as trapping carbon).

For many years, ABPmer has been interested in, and excited by, the potential blue carbon value of managed realignment sites. In 2014, we developed a 'Blue Carbon Calculator' tool that helps us on or project development work. We regularly use this calculator when we design, assess and value completed and proposed managed realignments (ABPmer 2014[6]). Most recently we used it to compare 774 potential managed realignment sites identified by the Environment Agency (Environment Agency/ABPmer, in prep)

Illustration of coastal managed realignment (ComCoast (2006))

For this review we have, for the first time, used our Blue Carbon Calculator to examine several completed realignment projects simultaneously. We have done this using some of the latest available data which describes how these sites are evolving. This review is designed, in particular, to compare how different types of restored habitat function, and to illustrate the importance and value of project size and location. It is hoped that this will provide a small but helpful contribution to ongoing discussions on this subject, and that this analysis (alongside all the other extant initiatives in this subject area) will provide a further, urgently needed impetus to future habitat restoration projects.

6 ABPmer's 'Blue Carbon Calculator' April 2014

2 Blue carbon in saltmarshes

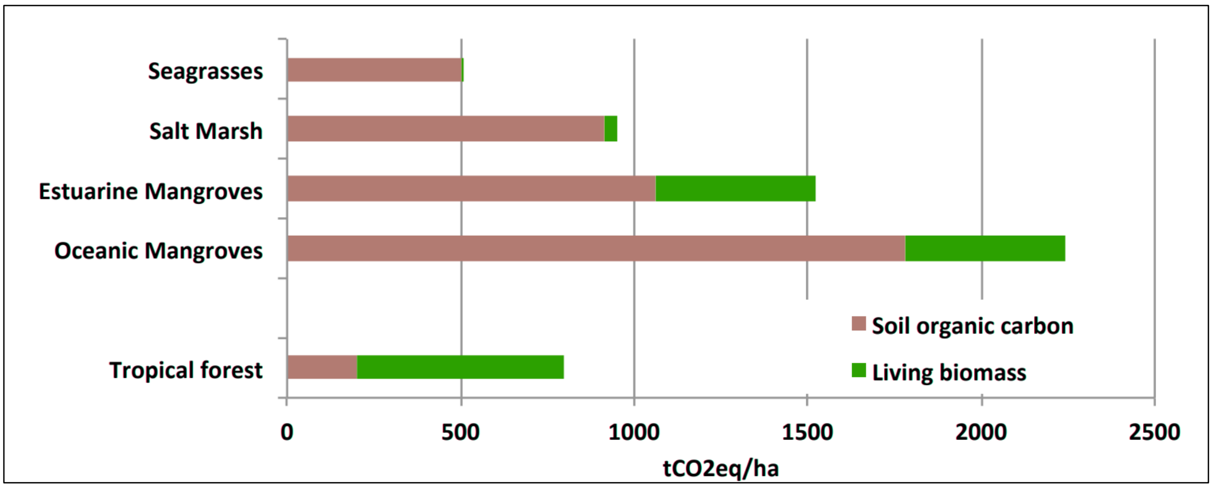
2.1 Sequestration processes

Carbon sequestration occurs in saltmarshes because the plants capture CO_2 by photosynthesis and store it in their above-ground biomass, subsurface roots and rhizomes, as well as exuding it into the surrounding soil (Murray *et al.*, 2011). In addition, the roots physically bind particles within the soil and encourage rhizome microbes to do the same, trapping organic material (Ford *et al.*, 2016) and creating an anaerobic, carbon-rich sediment (Reid and Goss, 1981; cited in Ford *et al.*, 2016). The anaerobic nature of the soils (resulting in slow decomposition) means carbon can be accumulated without the soil ever reaching saturation, potentially storing carbon over millennial timescales (Stewart and Williams, 2019).

In wetlands the carbon is mainly trapped in the soil. To understand the blue carbon value of coastal habitat it is, therefore, necessary to understand the scale of this sedimentary carbon load (stock) as well as the processes which influence it and the net changes taking place (the balance between loss or gain).

The salinity of the water column is a crucial factor in this process. It is currently understood that salinities need to be greater than 18. This is because salinities over that level suppress the production and release of methane by bacteria. Methane is 25 times more potent as a greenhouse gas than CO_2 (Forster *et al.*, 2007).

While there are many inter-dependent physical and biological factors driving the carbon sequestration process, the rate and pattern of sedimentation is a pivotal consideration. There is a broad consensus that sediment/soil organic carbon is by far the biggest carbon pool for all the BCE habitats (Murray *et al.*, 2011; Pendleton *et al.*, 2012 Macdonald *et al*, 2017). Figure 1 illustrates the average global carbon pool in the top 1 m of vegetated coastal habitats. It shows how the main carbon store in marshes is in the soil organic matter, rather than the living biomass.



Source Murray, *et al.* (2011).

Figure 1. Global average carbon pools in coastal habitats (top 1 m only)

Marshes can have several metres of carbon-rich sediment below the surface 1 m layer (Murray *et al*., 2011), although that can vary between sites. For example, saltmarshes on the west coast of the UK generally have a shallow organic-rich clay layer (<1 m) underlain by sandy substrate and are frequently grazed by livestock (May and Hansom 2003; cited in Beaumont *et al*., 2014). By contrast, the marshes of the south and east UK coasts are characterised by a deep (>10 m) organic-rich clay substrate and are most commonly ungrazed (Beaumont *et al*., 2014).

Due to the importance of this below-ground sediment component, the process of accretion, facilitated by reduced flows across the marsh surface, is a key mechanism driving progressive carbon sequestration. This means that these intertidal habitats need to be physically stable to retain the carbon store and need to be progressively accreting to continue being important carbon sinks.

Carbon sequestration rates also vary greatly between location (Parker *et al*., 2021). This is due to numerous factors such as the hydroperiod (time spent submerged), salinity levels, nutrient input (i.e. from pollution), substratum type and thickness and sediment supply (Nelleman *et al*., 2009). They will also be related to factors such as habitat condition, vegetation cover and wave exposure that will, on their own, influence the physical rate of accretion and carbon sequestration value of any given marsh system.

This also means that, where marshes are eroding and deteriorating, as they are along much of the south and east coasts of England, then they will be net emitters of carbon locally. Pendleton *et al*. (2012) estimated that 'lost sequestration' from marshes, seagrasses and mangroves was equivalent to 3–19% of those from deforestation globally, and will result in economic damages of $US 6–42 billion annually. A study of Chichester Harbour (Lockwood and Drakeford, 2020) concluded that continued marsh loss in this inlet could amount to a carbon loss value of between £1 million and £2 million between 2018 and 2030.

Habitat stability is a crucial factor. Marshes that are eroding (and many are) will be net emitters of carbon. Ones that are stable and accreting could trap sediment for centuries. This situation provides an extra impetus for creating stable new coastal habitat through the managed realignment of sea defence.

These and other research studies are providing an extra imperative for taking measures to protect existing saltmarshes from ongoing deterioration, as well as a motive for carrying out new habitat creation projects. The value of habitat creation through managed realignment though is likely to be very high and that is discussed further in the following section.

2.2 Sequestration rates

A great deal of the research and attention paid towards carbon sequestration in BCEs over the last 20 years has been focused on saltmarshes. As a result, there is now a much improved, if still incomplete, understanding about their blue carbon function. Some of these gaps are described further below, but what is evident is that saltmarshes have a generally higher carbon burial rate per unit area than other marine habitats (Stewart and Williams, 2019; Laffoley and Grimsditch, 2009).

Several studies and reviews have quantified the sequestration rates of saltmarshes and described the between-site variability. The global average identified by Chmura *et al*. (2003) is 210 g C m^{-2} yr^{-1} (grams carbon per square meter per year) and that value is commonly used in other national and international reviews (Burrows *et al*. (2014); Laffoley and Grimsditch (2009). Macleod *et al*. (2011) quoted a comparable global average value of 218 g C $m^{-2}yr^{-1}$ while Duarte *et al*. (2005) expressed a value of 151 g C m^{-2} yr^{-1}.

For UK marshes, Beaumont *et al*. (2014) described the carbon sequestration values ranging from 64 and 219 g C m^{-2} yr^{-1} and selected out more 'typical figures' within a narrower range of 120 to 150 g C m^{-1} yr^{-1}. This was based on upon research and reviews by Adams *et al*. (2012); Cannell *et al*. (1999) and Chmura *et al*. (2003).

A lot of research has been done to describe the rates of carbon sequestration in saltmarshes. The values obtained are very variable between sites and studies. They range wildly from <1 to 63 tonnes Carbon Dioxide equivalent per hectare per year (t CO_2e ha^{-1} yr^{-1}). Typical values quoted are around 3 to 8 tonnes CO_2e ha^{-1} yr^{-1}.

A recent review of coastal marshes in Wales applied a value of 84 g C m^{-2} yr^{-1} (Armstrong *et al*., 2020). This was based on an annual 2 mm increase in the soil stock value (as determined for Welsh saltmarshes by Ford *et al*., 2016). While higher values are quoted in the literature (as noted above) this 'proportion of the standing stock' approach was used to ensure consistency with the methods adopted for other marine habitats that were being compared.

A recent review of the carbon stock in UK territorial waters was also undertaken earlier this year (Parker *et al*., 2021). This study reviewed the carbon stock and the rates of carbon accumulation in several different existing and restored marine habitats. It cited a value of 118.5 g C m^{-2} yr^{-1} for organic carbon accumulation in mature saltmarshes.

These rates equate to between around 3 and 8 tonnes of carbon dioxide equivalent per hectare per year (t CO_2e $ha^{-1}yr^{-1}$). The values though are very variable between sites. For example, Macleod *et al*. 2011 quoted a range of 18 to 1,713 g C $m^{-2}yr^{-1}$ with an average and standard error value of 218 ± 24 g C m^{-2} yr^{-1}. This was informed by global reviews such as Chmura *et al*. (2003) and Duarte *et al*. (2005). This equates to anywhere between <1 and 63 t CO_2e $ha^{-1}yr^{-1}$.

2.3 Consideration of mudflats

In contrast to vegetated saltmarshes, seagrass beds and mangroves (as the three principal BCEs), unvegetated intertidal mudflat habitats are afforded less attention in the blue carbon research. This is, quite simply, because they are not as proficient in sequestering carbon as vegetated habitats.

Mudflats are located lower in the tidal frame than saltmarshes and are more dynamic and changeable. The surface sediment is typically mobile (often fluctuating around a dynamic equilibrium even in the most sheltered environments and stable conditions). Invertebrate assemblages in the surface layers can also continually rework the sediment. The typical guidance is therefore that *'initiation of soil carbon accumulation is only possible with the presence of vegetation'* (Hiraishi *et al*., 2014).

This perspective, however, does not recognise the distinctive evolution of mudflats in realignment sites (see next section) and it seems highly likely that accreting sediments over restored mudflats in realignment sites may be substantial net carbon sinks. When seeking to understand the value of realignments, it is important therefore that the role of this habitat type, and the validity of its inclusion in the blue carbon valuation process, are specifically considered.

One of the key issues that needs to be firmly resolved is whether mudflats remove carbon autochthonously ('formed *in situ*') from photosynthetic processes on the surface sediment or whether they are exclusively sinks for allochthonous carbon (imported from external sources). There is definitely evidence that they can store and sequester imported carbon in both organic and inorganic (carbonate) forms if there is a supply.

For example, Sanders *et al*. (2010) found intertidal mudflats in the vicinity of mangroves were storing almost four times the global average for sequestration in mangrove forests. They suggested that the large fluxes of organic carbon produced and sequestered in mangrove forests are deposited and stored in mangrove margins and intertidal mudflats.

Cook (2002) also found that organic matter in estuarine mudflats in Tasmania did not originate within the mudflats. Instead they were predominantly terrestrial sources, such as near shore estuarine transport (driven by riverine input) as well as direct terrestrial run-off and reworking of glacial and post-glacial sediments.

More research is, therefore, needed to understand the contributions that autochthonous carbon makes to overall sequestration in accreting mudflat. However, it is likely though that sediment deposition traps the algal matter of macrophytes and microflora that grow on soil surfaces (Connor *et al*., 2001). Also, research in temperate Australian mudflats by Cook (2002) indicates that they may facilitate the storage and sequestration of organic matter from external sources.

Mudflat habitat is unvegetated and the surface sediments are more mobile and reworked (by water flow and invertebrates) than is the case in saltmarshes. Therefore, it is not considered to be a main Blue Carbon Ecosystem (BCE). However, there is evidence it can act as a sink in certain circumstances.

Studies of unvegetated hypersaline flats in Northern Australia and Brazil have also indicated that these are net sequesters of carbon, primarily because of microphytobenthos (Brown *et al*., 2021). In addition, Sullivan and Currin (2000), as cited by Chmura (2009), found that benthic microflora on the surface of marshes contributed anywhere from 8% to 140% of the primary production of vascular plants.

3 Blue carbon in realignments

3.1 Distinctiveness of habitats

When considering the 'blue carbon value' of managed realignment sites, it is important to note that emerging saltmarshes and mudflats restored by this process are often structurally different from equivalent, but older and more established, intertidal habitats.

This is because these developing intertidal habitats usually remain enclosed by old and new embankments. This creates sheltered conditions where the wave energies and tidal flows are typically lower than they are at the more exposed habitats outside the sea walls. These conditions then lead to comparatively high levels of sediment deposition when compared to exposed areas.

This high level of accretion is to be expected given the environment that is created. It is a function of the landform 'rebounding' towards historical levels following a period of land-claim. During land-claim the ground levels sink due to the years of sediment reworking, sediment compaction and the sites being starved of new sediment supply because they are cut-off from the adjacent tidal waterbody. It is this damage that is being reversed by the practice of managed realignment.

Visual illustration of accretion in Jubilee Marsh which creates and then raises mudflat habitat (ABPmer, 2020b)

This accretion is potentially a very important driver of carbon retention. This is because (as shown above) most of the carbon is locked into the sediment. It is also more generally understood that any activity which promotes accretion over intertidal habitats can be viewed as one way to mitigate climate change, reduce greenhouse gas emissions, safeguard carbon stores and, in some cases, restart sequestration (Alonso *et al.*, 2012).

Given that sedimentation is often high in realignment sites (ABPmer, 2020a), the potential for carbon sequestration can also be remarkably high.

The rate and pattern of sedimentation in managed realignment sites are, however, influenced by many factors including notably the land/bed elevation. They also vary between different realignment sites and even across different parts of individual sites. There will also be a change (reduction) in accretion rates over time as the bed level progressively rise.

Accretion is often most obvious during the months after a site is first 'rewetted'.[7] This is because, as noted above, such sites are often more low lying than fronting habitats, but also due to a good proportion of the sediment being deposited in these early stages being reworked around and within a site (particularly where breaches are undersized and erosion of these provides material). This tends to reduce over time as the site settles down, and the only source of sediment is imported from external (allochthonous) sources.

This accretion predominantly occurs over low-lying parts of the realignment sites. These are inundated by the largest volumes of water for the longest periods over time, therefore more waterborne sediment is delivered to these areas, and there is more time for sediment to settle out of suspension.

In many instances, high levels of accretion can occur immediately inside (landward of) the sea wall breach because these areas are often the lowest lying, but also because tidal energies rapidly decline and sediment in the flooding tide rapidly settles out of suspension (ABPmer, 2019).

The amount of sediment in the water column is a key factor influencing the accretion rates. A managed realignment site located in a sediment-rich estuary (such as the Humber or Severn) will accrete more

[7] Reflecting terminology used in the 2013 Wetlands Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Hiraishi, 2014).

rapidly than a realignment in a sediment-poor system. This is indicated by the Steart managed realignment (WWT, 2020) shown in Image 2 and discussed later.

As a result, there is every indication that habitats created through defence realignment may be especially valuable for trapping carbon and can be viewed as one of the 'hottest spots of all' globally. There is also a potential for long-term persistence of the process of net accretion, although the rate of accretion will progressively decline as the bed elevations rise and the amount of tidal inundation reduces.

Tidal wetlands which are newly created or restored through the landward realignment of sea walls are naturally a bit different from equivalent, more established, habitats. They accrete with sediment at greater rates. Therefore, they could be substantial 'hot spots' for carbon sequestration (in both the mudflats and the marshes).

In theory, though, what potentially makes all stable saltmarshes good carbon stocks is that they may never reach saturation, but instead grow progressively and 'volumetrically' (Crooks *et al*., 2020). That could well be true of many managed realignment sites where they can accrete at rates which keep pace with sea level rise (provided suspended sediment concentrations are high enough to sustain this accretion).

Carbon processes are complex however and any understanding about carbon and its accumulation in sediment needs to be complemented by a broader understanding about the carbon cycle. We do need a wider understanding of how such wetlands function with respect to gas emissions contributing to climate change,

3.2 Sequestration rates

Mirroring the situation for BCEs generally (as described above), there is still an incomplete understanding, and lack of quantitative clarity, about carbon sequestration rates in realignment sites. This needs to be rapidly addressed if this benefit is to underpin future project implementation.

Notwithstanding this situation, a lot of work has been done on restored coastal wetlands, and several encouraging observations have emerged. It has been found that carbon accumulation in the sediments of restored marshes begins almost immediately with the establishment of vegetation[8] (Burden at al., 2019; Craft *et al*., 2003). Also, the amount of organic matter is often consistent throughout the surface and sub-surface sedimentary layers of tidal wetland soils and realignment sites (Callaway, 2020; Wollenberg *et al*., 2018; Spencer 2008). These observations provide reassurances that organic matter is rapidly and then progressively buried in managed realignments.

Some of the details about the rate and provenance of this sediment and carbon accumulation are less clear. In part this is because little attention is usually placed on monitoring accretion notwithstanding that it is such a key functional trait of restored wetlands. There has also been an inconsistent approach to monitoring of this aspect across different sites and limited publication of results where it is monitored.

To consider this further, ABPmer recently carried out a study for Natural England which reviewed changes in bed levels across ten sites (see Figure 2) using available information including Environment Agency LiDAR data (ABPmer, 2020a). The study found that average accretion rates across the sites ranged from under 2 cm to 7 cm per year.

8 Though accretion also occurs in the managed realignment sites in the absence of vegetation, as for example evidenced by notable increases in the elevation of low-lying mudflats in many sites as described in Section 3.1

In lower lying areas however, rates of up to 9.5 cm yr^{-1} were recorded. The study also made recommendations for further work to understand accretion patterns in realignments sites and inform future judgments about the functionality of the habitats created and their value for carbon sequestration.

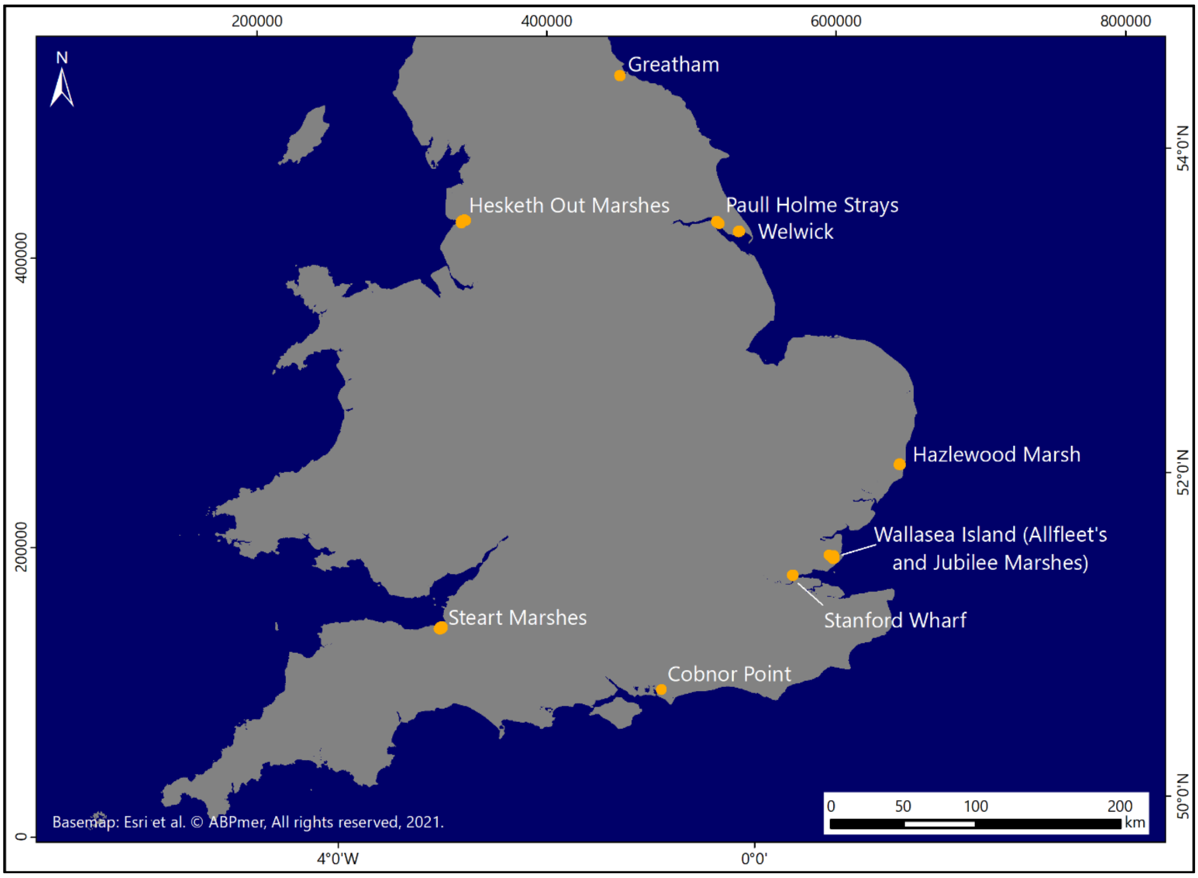


Figure 2. Location of realignment sites studied in the accretion review

Alongside gaps in understanding about accretion rates, there are uncertainties (and certainly a lack of consensus) about the processes at work and the provenance of the carbon. Questions which need to be firmly resolved are the extent to which accreting habitat traps allochthonous or autochthonous carbon (see Section 2.3) and in what relative proportions and with what relevance for climate mitigation calculations.

In realignment sites, both mudflats and saltmarshes accrete. Indeed, because accretion is typically at its largest over lower lying areas, rates tend to be highest on mudflat habitat (where this is present), as well as over the lower elevation marsh fringes and in lower-lying ponds and scrapes. It does appear likely that microalgae on sediment surface will be contributing autochthonous carbon, however further research is required to clarify the role and relevance of these sources.

Another aspect to consider is how this accretion influences carbon cycling and the balance between labile carbon (the active mobilised fraction in the oxygenated surface layers) and refractory carbon (the recalcitrant/inactive fraction in the subsurface anoxic layers). Or, indeed, to agree whether this is relevant if the net change is towards progressive burial of the subsurface inert fraction over the long term anyway.

Finally, there are questions about how existing understanding can be applied towards, and future monitoring directed at, enabling marsh restoration to be considered within the UK's GHG inventory. Aspects such as whether additionality[9] applies will need to be resolved for future projects.

3.3 Sequestration processes

The previous sections described the potential that managed realignments have to trap and store carbon. They also highlight some gaps in understanding that exist and need to be addressed. While the knowledge gaps are understood, several studies have examined carbon sequestration in managed realignment sites and compared them with external marshes to help describe the value of restored sites.

These are previous studies are reviewed and compared below. These studies often adopt different approaches. For example, some take account of the baseline (pre-restoration) habitat and other do not. Burden at al. (2013) for example carried out a detailed series of field investigations at the Tollesbury realignment site (Essex, UK). They derived a carbon sequestration rate of 92 g C m^{-2} yr^{-1}. The soil carbon pool was calculated using bulk density and percentage carbon figures. The 'per year' increase in carbon was derived by taking the difference in the soil carbon pool between agricultural land ('before') and the adjacent salt marsh and dividing by the number of years since managed realignment.

This work was followed up by Burden at al. (2019) who carried out further detailed work to describe the carbon accumulation rates in nine UK marshes that were 4 to 116 years old[10]. They found that carbon accumulation was rapid during the first 20 years (average 104 g C m^{-2} yr^{-1}) before then slowing to around 65 g C m^{-2} yr^{-1} thereafter. Drawing upon this and other studies, Parker *et al*. (2021) also concluded that sequestration in restored marshes was low when compared to the levels recorded in saltmarshes in general (see Section 2.2). This review derived a value of 96.4 g C m^{-2} yr^{-1} from their review work.

MacDonald *et al*., (2017) and Gauld (2014) also looked at completed and proposed realignment sites at Hesketh West and in Inner Firth of Forth. At Hesketh West, MacDonald *et al*., (2017) considered the above and below ground biomass, and the soil organic carbon and then compared the rate of sequestration in the baseline agricultural state and then again after the restoration. They concluded that the developing saltmarsh was sequestering around 79 g Cm^{-2} yr^{-1} (or around 3 t CO_2e ha^{-1} yr^{-1}). However, they also concluded that the land was emitting nearly this amount before the restoration. So, the net benefit was closer to 6 t CO_2e ha^{-1} yr^{-1}.

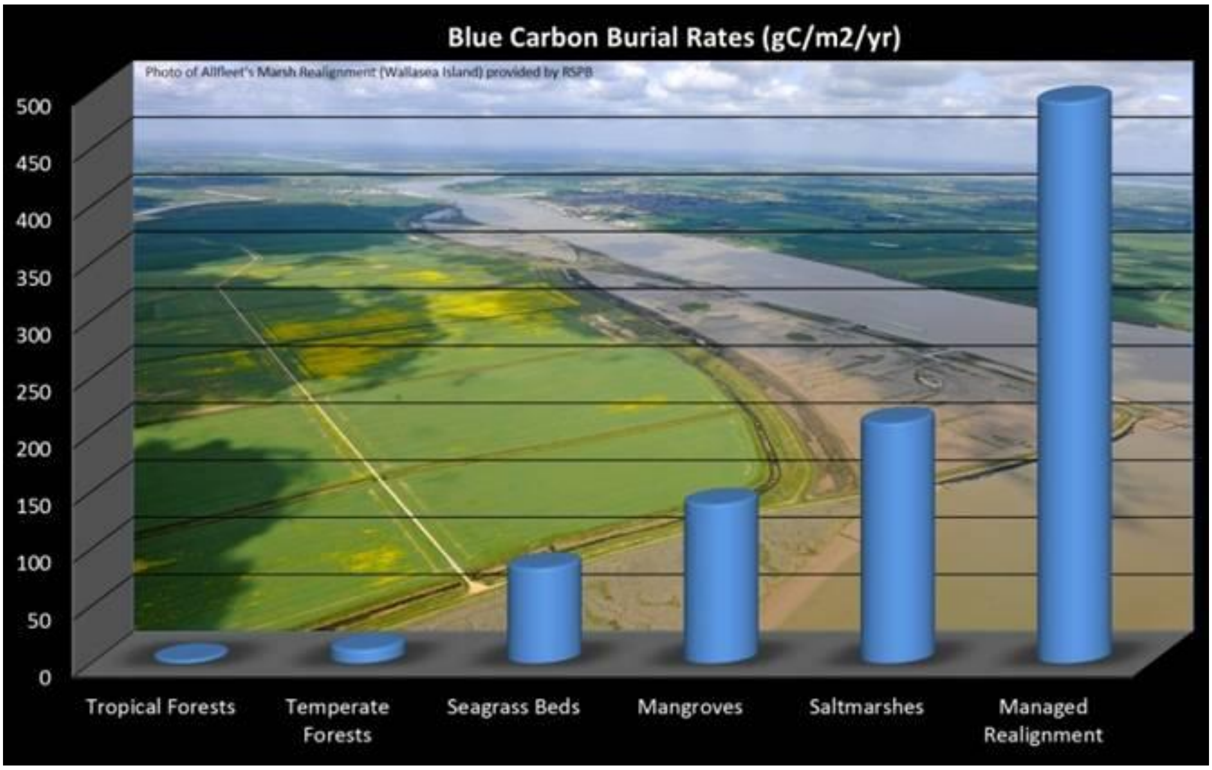
By way of contrast, much higher carbon burial rate values were found during recent work on the Aulac Dyke realignment[11] (New Brunswick, Canada). This site lies in the upper Bay of Fundy, which has an especially large tidal range with a high suspended sediment load. As a result, there is high level of accretion in the site of between 3 and 102 cm after 6 years and the sequestration rate was calculated as 1,329 g C m^{-2} yr^{-1} (Wollenberg *et al*., 2018). This was more than five times the rate reported by the same study in a nearby mature marsh.

ABPmer began to look at sequestration in 2014 during our monitoring work on the Allfleet's Marsh realignment (ABPmer, 2014). This was a low elevation site that was progressively accreting by around 5 cm per year. We examined sediment organic matter content at depth and made simple calculations based on sediment bulk density as well as drawing on evidence from field work by Burden at al. (2013). We concluded that the realignment could be sequestering twice the rate of that quoted for saltmarshes generally (see Figure 3). The uncertainties associated with carbon provenance and additionality were recognised (as noted above).

9 Reconciling the concept of additionality itself is not simple but in essence "*GHG reductions are additional if they would not have occurred in the absence of a market for offset credits*" (Broekhoff *et al*., 2019).

10 I.e. 4 to 116 years since tidal flows were returned to these habitats.

11 https://www.omreg.net/query-database/0016-aulac/



Data from Laffoley and Grimsditch (2009). ABPmer (2014)

Figure 3 Carbon burial in different habitats and in Allfleet's Marsh realignment

There have also been more recent studies at the Steart managed realignment site (Wildfowl and Wetlands Trust (WWT), 2020; Mossman *et al*., 2021) to indicate that that the site is sequestering at even higher rates. This is attributable to factors such as the high levels of accretion at Steart but also the comparatively high sediment bulk density values recorded.

Recently, on behalf of the Environment Agency, ABPmer reviewed the Ecosystem Services that could be provided by over 3,000 potential coastal habitats restoration sites around the English coast (Environment Agency/ABPmer, in prep). This included comparing 774 potential managed realignment sites using our Blue Carbon Calculator. This review considered the blue carbon function of the existing land and then predicted the sequestration rates following tidal inundation and then estimated the net change for the next 20 years. The average value across all sites was 749 g C m^{-2} yr^{-1} but the range was very large and encompassed negative to large positive values. This large variability was a consequence of substantial variations in project size as well as differences between sites in terms of their existing (pre-restoration) habitats and land uses which influenced the nature and scale of baseline carbon emissions or sequestration rates.

3.4 Comparing ten realignments

The findings from studies summarised in the preceding section, reinforce the message that newly restored wetlands can trap large quantities of carbon. A few of these studies indicate that these quantities could be vastly in excess of the amounts sequestered in mature marshes.

There is, however, a great deal of variability between studies. This will be because of differences in the research methods and also because the conditions experienced at different survey locations will vary greatly. Furthermore, there will also be variations across individual locations because the habitat composition and the physical environment change across their full extents (especially in large sites). Between-site and within-site variations in carbon sequestration and storage are also observed, and indeed will be even greater, on mature marshes. Among other factors it will be dependent upon the size and stability of these marshes which varies greatly from site to site. Many mature marshes are also eroding rapidly, especially along the English south and east coasts, and these will be net exporters of carbon. By contrast, habitats created within managed realignment sites are typically stable and accreting so should all be trapping carbon to some degree.

Comparing the evolution of habitats across 10 very different realignments we found that they can sequester double the carbon quoted for mature marshes. We also illustrate how this varies across different sites (from 8 to 26 t CO_2e ha^{-1} yr^{-1}) and how much greater it is in low-lying sites and sediment-rich estuaries where accretion is high.

To explore this further, we examined 10 realignments using our in-house carbon calculator. As described above, the basic principle of the approach is that it takes the volume of sediment and then calculates the stock and sequestration rates based on the bulk density of the sediment and, in part, on the rate of ongoing accretion. It now also draws upon the findings from field studies carried out by Burden *et al*. (2019).

This analysis is underpinned by informed and realistic, but generic, values for sediment carbon content and bulk density. It also uses data from a managed realignment accretion review completed for Natural England (ABPmer, 2020a) (see Figure 2). This review examined the results from valuable Environment Agency LiDAR (Light Detection and Ranging) data (see Figure 4) and these results were also 'ground-truthed' with field data where available.

Once these values were derived a value for the Carbon Dioxide equivalent (t CO_2e) was made and a monetary value (£) applied. This monetary value was based on the non-traded central values starting at £70.4 tonne^{-1} CO_2e from Department for Business, Energy and Industrial Strategy (DBEIS, 2012). The value of £70.4 tonne^{-1} is the 2021 rate. We have used the increasing rates for each year of the next decade with appropriate discount factor applied annually to obtain a value for each site.

Using the information on accretion from this study, the carbon calculation (as described above) was relatively simple, and we are aware there are uncertainties associated with it (as noted above and in the conclusions section). However, the value of it is that it is informed by available data and represents a standardised approach that can be used to compare different sites in a comparable manner. The results are outlined in Table 1 and in Figure 5.

The results consistently indicate that restored habitats in realignments can sequester more than double that of stable and established marshes. The outcome is strongly influenced by accretion rate and so the BCC values are highest in the more rapidly accreting sites located in the sediment rich estuaries of the Humber and Severn. The sequestration rates are also high in lower lying sites that exhibit comparatively high rates of sediment import.

To see how our estimates, compare with the recent results from Steart, the values from Mossman *et al*., (2021) were put into the calculations. That had the effect of further magnifying the results (by a factor of 2.4). The main reason for this is mainly that the bulk density values of the sediment at Steart are much higher than the generic values usually embedded in the calculator.

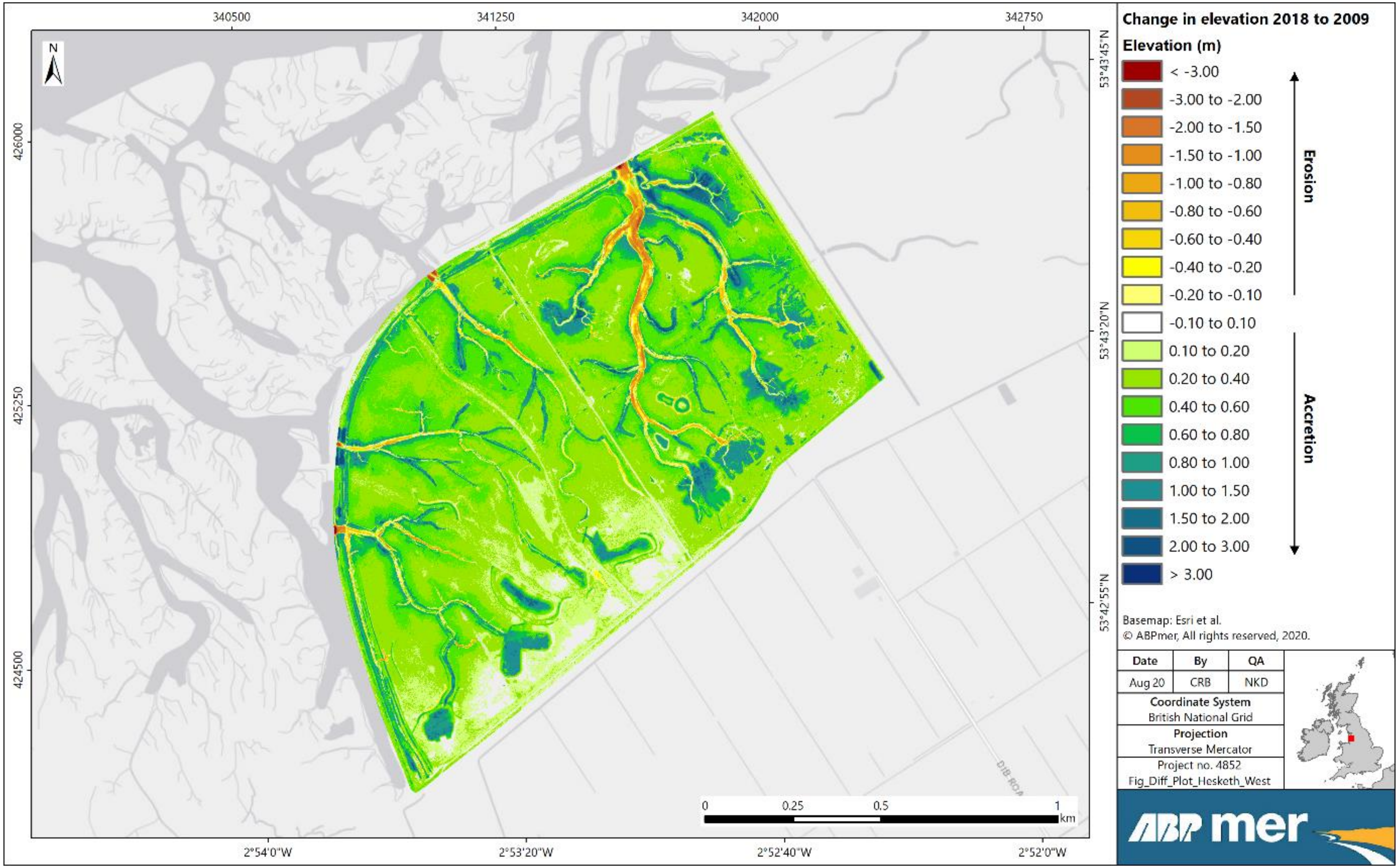


Figure 4 **Elevation changes at Hesketh West between 2009 and 2018.**

Table 1. Estimated carbon values for the ten managed realignment sites over ten years

Site Name (including links to OMReg website)	Extent Intertidal Habitat (ha)	Annual Accretion Range (cm)	Annual Sediment Volume (m^{-3} yr^{-1})	Sequestration Rates (g C m^{-2} yr^{-1})	Carbon Stock Annually (t C yr^{-1})	CO_2 Equivalent Annually (t CO_2e ha^{-1} yr^{-1})	Annual Carbon Value (£ yr^{-1})	Monetary Value Over a Decade (£)
Allfleet's Marsh	108	<1 to 5	42,730	466	503	17	£129,102	£1.1 million
Jubilee Marsh	112	1 to 6	38,200	436	489	16	£125,409	£1.2 million
Hazlewood Marshes	64	1 to 2	12,350	221	142	8	£36,340	£330,000
Paull Holme Strays	80	2 to 9	45,250	680	544	25	£139,557	£1.3 million
Welwick	40	2 to 8	24,000	699	279	26	£71,733	£670,000
Greatham North	30	2 to 5	8,000	375	113	14	£28,894	£270,000
Hesketh West	157	3 to 7	57,900	500	784	18	£201,318	£1.8 million
Cobnor	4	1 to 3	950	292	12	11	£3,001	£28,000
Steart	325	4 to 12	150,000	613	1,994	22	£511,729	£4.6 million
Stanford Wharf	27	2	5,400	224	61	8	£15,539	£140,000
Steart (using new field data)*	250 *	7.5*	178,628*	1,849	4,622	68	£1,138,840	£11 million

Notes: This table shows the annual carbon sequestration rates (estimated with the ABPmer calculator) and the value over a 10-year period. It is based on available field measurements from past and published research work. These measurements are used to derive a set of generic values for parameters such as carbon content and sediment bulk density. It does not consider baseline carbon fluxes in the pre-restoration habitats or the carbon used to implement the realignments.

* This is a sensitivity test using field results from recent field research at Steart (by Mossman *et al.*, 2021). This includes measurements describing carbon content, bulk density and volume of sediment accreted which was entered into the ABPmer calculator. This produces similar results (see also Figure 5) to the values from Mossman *et al.*, (2021) which were 1,940 g C m^{-2} yr^{-1} or 4,850 t C yr^{-1} over 4 years.

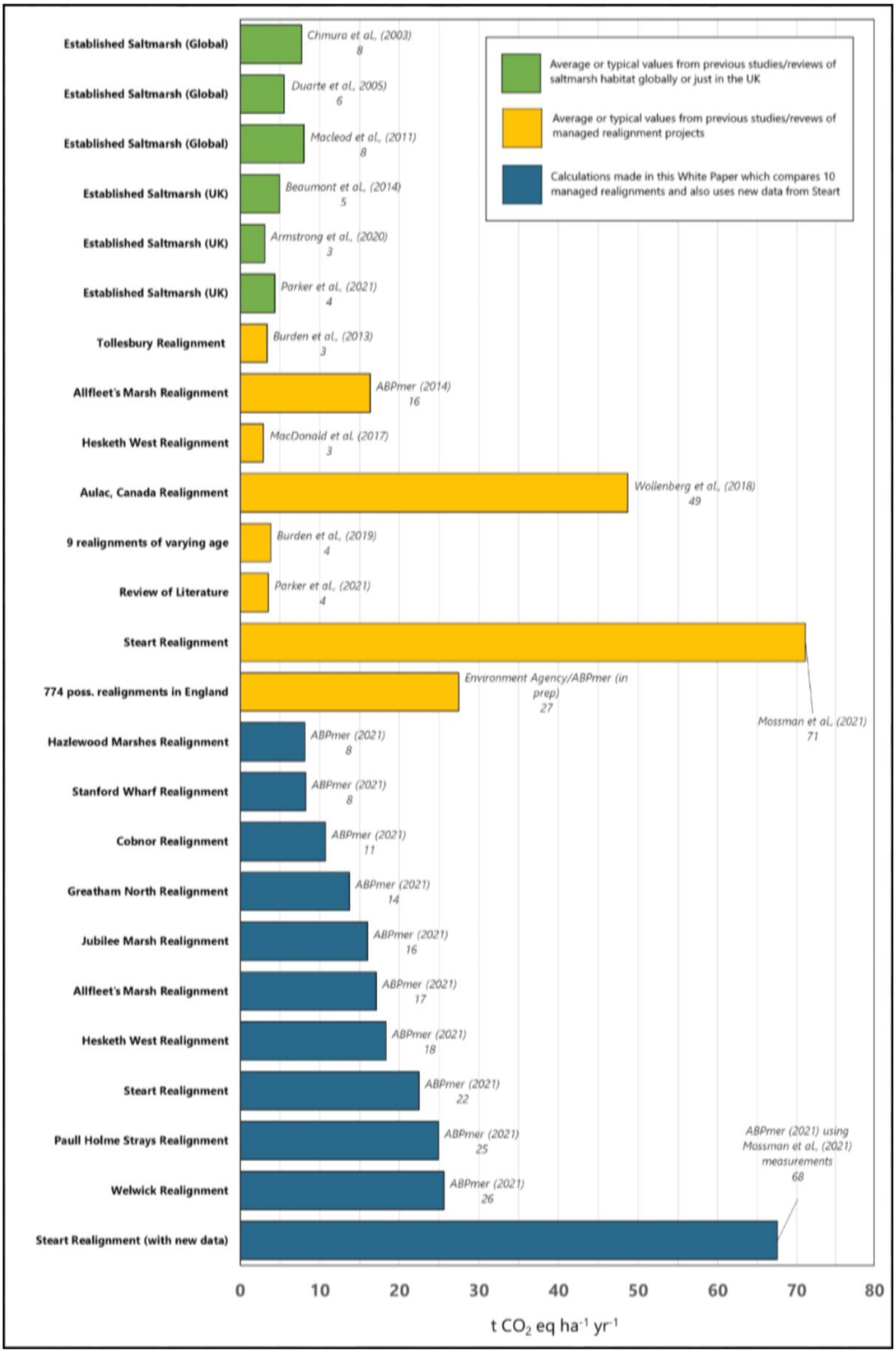


Figure 5 Comparison of average/typical sequestration rates from different sites and studies

What is clear from these studies is there is a need to keep examining this subject and to develop agreed, focused and consistent field methods and analytical approaches. This future work will almost certainly need to pay close attention to carbon levels at depth in the sediment, as well as considering the broad site-specific physical and ecological functionality of these sites.

This paper compares the Blue Carbon value of different realignment sites in different situations. It illustrates their variability and highlights the importance of getting more, and better, field data. It also shows how vital it is to reach a consensus and develop agreed analytical approaches that can then be applied consistently to inform future studies.

There are still gaps in understanding, and there is more field work, technical analysis to be done to verify the processes at work and facilitate green financing investment. However, as is discussed further in the conclusion section, our understanding is quite advanced, and we should have the confidence to start planning blue carbon projects now.

4 Conclusions

This White Paper was prepared to inform discussions about the blue carbon value of restored marshes. It summarises the findings from several published and unpublished sources including studies undertaken by ABPmer. It also involved the use of a carbon calculator (that ABPmer developed to inform the design and valuation of the managed realignment projects we support) to compare the value of 10 different restoration sites.

This comparative analysis is relatively simple and is presented to inform debate. It is recognised that processes which drive carbon sequestration in managed realignments are complex. However, we hope this analysis helps to clarify certain aspects and especially helps identify gaps in knowledge.

Also, this White Paper indicates that we really do have the information needed now to identify and pursue bespoke blue carbon projects even if there are gaps in understanding. It is hoped, therefore, that this review can help drive restoration action. Some further summary thoughts, findings and recommendation are presented below.

The results from previous studies are valuable but also remarkably variable (see Figure 5). This variability is found across different types of mature saltmarshes, as well as across different restored saltmarshes. This will be due to large variability of ecological and physical conditions at different sites but also because of differences in analytical and interpretative approaches for each study.

This variability leads to confused messaging. It means that some parties view restored marshes as having a lower value than mature habitats while others conclude restored marshes have a greater value (or even substantially greater value) by comparison. Either way, the case to pursue new blue carbon restoration projects is still there. This simply highlights the urgent need to agree the analytical principles and approaches quickly to get to a consensus.

This situation (i.e. the confused messaging and need for consensus) is understandable in view of the complexity of the relevant processes. But there are encouraging characteristics of managed realignment projects, which should be helpful for deriving consensus values and making the blue carbon market case. In particular, the structural and functional distinctiveness of these sites (when compared with mature marshes), needs to be recognised, embraced and used as the basis to drive more managed realignment projects.

It is evident that the distinctively high accretion rates in realignment sites (as described in this review) will be helping to lock away large amounts of carbon in the soil or in the below-ground biomass as well as achieving other benefits such as greater flood protection. The ecological and physical conditions within these restored marshes are also more stable, predictable and measurable than is the case for many mature marshes. This should make it easier for monitoring and developing bespoke standards to assess past projects and predict the performance of new managed realignment projects in the future.

The predictability of their evolution is especially important. This study has shown how different sites evolve in different locations but also how predictable that evolution now is using available evidence. The UK is especially well placed to use information from past projects to predict the behaviour of future initiatives because we now have a lot of real-world evidence. We have delivered around 80 such projects over the last 30 years (see Figure 6).

The stability of realignments (encircled as they often are by old and new sea walls) should also help with making the case for permanence. This is important because there is a need to ensure that blue carbon habitats will last for at least 100 years. That will be the case for managed realignment sites. The need for permanence also means that these sites should be left to evolve without intervention.

Also, there are positives regarding the clarity of ownership of these restored marshes. When a realignment is implemented the ownership of a site is generally unambiguous and often unified under a single body. This should provide transparency and security regarding who has the ownership of, responsibility for, and right to the carbon credits.

It should now be possible to develop viable mechanisms for calculating the blue carbon value of past managed realignments and predicting the performance of future projects. Such a mechanism will need to account for uncertainties and inform studies to fill gaps in knowledge. Mainly, we need to be clear about how much of the carbon being trapped by the newly restored marshes is additional.

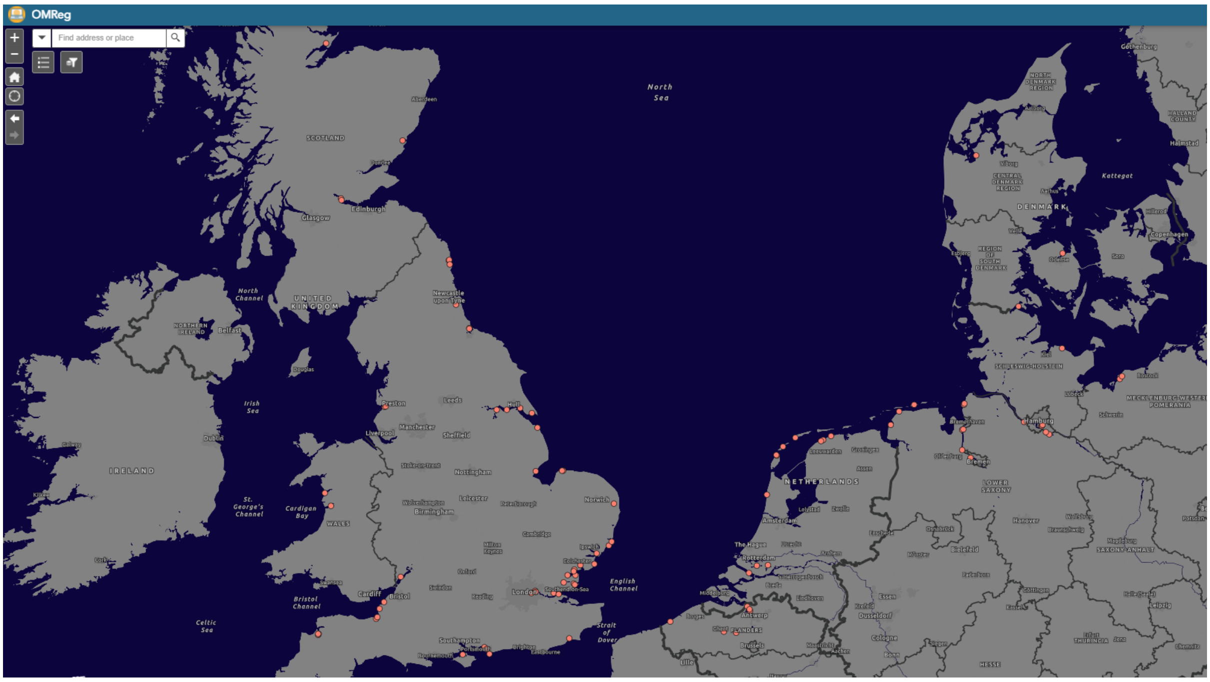
There are though uncertainties that remain and issues to resolve to progress towards a consensus and develop a standardised/ quantifiable approach for valuing blue carbon in realignment sites. These include the need to be clear about additionality (i.e. can it be confirmed that this project would not have gone ahead otherwise or even that the trapped carbon would not have been sequestered by another means). We need to firmly determine whether new projects, and the GHG reductions arising from them, would not have occurred in the absence of a market for offset credit.

Additionality can be viewed in terms of whether the project would have gone ahead or whether the benefits from that project would not have been accrued otherwise. In terms of project delivery, we can be confident of this. We now know (after 30 years' of implementing managed realignment projects in the UK) the rate at which we create habitat using this approach. It is around 80-110 ha^{-1} yr^{-1} [12]. So, anything above this can be viewed as additional.

We also know that project implementation so far has mainly been as compensation for losses elsewhere. Such compensation measures are not strictly additional (they are replacing lost habitat). However, if restored marshes do sequester much more carbon than the mature habitats they are replacing (as seems very likely) an additionality case could be made for this extra benefit in compensation sites. But,

[12] The 80 managed realignment projects completed in the UK over the last three decades have created around 3,300 ha of habitat in total. Of this around 2,500 ha is intertidal and that is mostly saltmarsh. See ABPmer habitat creation website www.omreg.net (also Figure 6).

certainly, where new projects are implemented in the future that are not compensatory then a very good case can be made that these are additional



(ABPmer OMReg website http://www.omreg.net)

Figure 6 **Map showing many of the completed managed realignments in Northern Europe**

Additionality also relates to the carbon itself. We need a better understanding about how much of the carbon being trapped by the newly restored marshes is additional. So, we urgently need to find out how much is internally generated (autochthonous) or imported (allochthonous) and the implications of that for valuations. Also, there is a need to agree whether carbon might have accumulated elsewhere. In most estuaries, and especially those with an abundant sediment supply, this seems unlikely, but it may be the case in some systems.

Linked to preceding points we need to agree the functionally and carbon sources of the 'uniquely-stable-and-accreting-mudflat' that are created in restored marshes. There is some good evidence now to suggest that they generate a lot autochthonous carbon (from microphytobenthos) but that really does need to be clarified. There are also issues to clarify regarding the baseline emissions from land before restoration and the broader financial mechanisms (monetary value and investment process).

Notwithstanding these uncertainties there is really nothing to stop us planning Blue Carbon projects now. We know that restored marshes are valuable carbon stores irrespective of any final agreed quantifications. Also, many of the uncertainties listed above could be resolved through expert judgements and targeted short-term studies rather than prolonged programmes. There are many experts working collaboratively on this already (see Section 1.1) and we should not need to wait too much longer for a consensus. We can also get on with planning projects while we do wait given that it takes years to deliver them.

There is, though, an urgent need for more empirical data. The recent Steart study (Mossman *et al.*, 2021) provides valuable new field survey data to contribute to discussions. It reaches exciting and inspiring conclusions as a result. Having used their findings, and their bulk density values especially, equivalent carbon sequestration values were obtained using the simple ABPmer calculator. This is to be expected because the analytical principles and processes are similar in both studies. However, this confirms the value of getting more, and better, empirical evidence but also that simple tools can be valuable (even if the processes are complex) as long as there is a consensus about their design and use.

We hope that this review is useful to all those working in coastal habitat restoration and especially for those seeking for embed wetland restoration into the UK's NDCs.

5 References

ABPmer (2020a). Accretion and Breach Development in Managed Realignments., A comparative review of sedimentation and breach development in a selection of English restored coastal wetlands. ABPmer Report No. R.3369. A report produced by ABPmer for Natural England, October 2020.

ABPmer (2020b). Wallasea Island Wild Coast Project: Jubilee Marsh Monitoring During 2019, Review of surveys undertaken four years after completion of the Jubilee Marsh Realignment with recommendations for future monitoring. ABPmer Report No. R.3348. A report produced by ABPmer for Crouch Harbour Authority , November 2020.

ABPmer (2019). Wallasea Island Wild Coast Project: Phase 1 Monitoring During 2018, Surveys undertaken three years after completion of the Jubilee Marsh Realignment. ABPmer Report No. R.3045. A report produced by ABPmer for RSPB, August 2019.

ABPmer (2014). ABPmer's 'Blue Carbon Calculator'. Online (blog) content available at: https://www.abpmer.co.uk/blog/abpmers-blue-carbon-calculator/ [last accessed June 2021]

Adams, C. A., Andrews, J.E. and Jickells, T. (2012). Nitrous oxide and methane fluxes vs. carbon, nitrogen and phosphorous burial in new intertidal and saltmarsh sediments. Science of the Total Environment. 434. 240-251.

Alonso, I., Weston, K., Gregg, R. and Morecroft, M. (2012). Carbon storage by habitat - Review of the evidence of the impacts of management decisions and condition on carbon stores and sources. Natural England Research Reports, Number NERR043

Armstrong, S., Hull, S., Pearson, Z., Wilson, R. and Kay, S. (2020). Estimating the Carbon Sink Potential of the Welsh Marine Environment. NRW, Cardiff, 77p. Available at: https://cdn.naturalresources.wales/media/692035/nrw-evidence-report-428_blue-carbon_v11-002.pdf [last accessed June 2021]

Beaumont, N.J., Jones, L., Garbutt, A., Hansom, J.D. and Toberman, M. (2014). The value of carbon sequestration and storage in coastal habitats. Estuarine, Coastal and Shelf Science, 137, 32-40.

Broekhoff, D., Gillenwater, M., Colbert-Sangree, T., and Cage, P. (2019). Securing Climate Benefit: A Guide to Using Carbon Offsets. Stockholm Environment Institute Greenhouse Gas Management Institute. 60p. Available at: https://www.offsetguide.org/wp-content/uploads/2020/03/Carbon-Offset-Guide_3122020.pdf [last accessed June 2021]

Brown, D. R., Marotta, H., Peixoto, R. B., Enrich-Prast, A., Barroso, G. C., Soares, M. L. G., Machado, W., Pérez, A., Smoak, J. M., Sanders, L. M., Conrad, S., Sippo, J. Z., Santos, I. R., Maher, D. T., and Sanders, C. J. (2021). Hypersaline tidal flats as important "blue carbon" systems: a case study from three ecosystems, Biogeosciences, 18, 2527–2538; https://doi.org/10.5194/bg-18-2527-2021, 2021

Burden, A., Garbutt, A., Evans C.D. (2019). Effect of restoration on saltmarsh carbon accumulation in Eastern England. Biol. Lett. 15: 20180773. http://dx.doi.org/10.1098/rsbl.2018.0773

Burden A., Garbutt R.A., Evans C.D., Jones D.L. and Cooper D.M. (2013). Carbon sequestration and biogeochemical cycling in saltmarsh subject to coastal managed realignment. Estuarine, Coastal and Shelf Science 120, 12-20.

Burrows M.T., Kamenos N.A., Hughes D.J., Stahl H., Howe J.A. and Tett P. (2014). Assessment of carbon budgets and potential blue carbon stores in Scotland's coastal and marine environment. Scottish Natural Heritage Commissioned Report No. 761.

Callaway J.C. (2020). Accretion measurement and interpretation of wetland sediment Chapter 7 in Windham-Myers, L., Crooks, S., Troxler, T.G. (Eds.). (2020). Blue Carbon Primer

Cannell, M.G., Milne, R., Hargreaves, K.J., Brown, T.A., Cruickshank, M.M., Bradley, R.I., Spencer, T., Hope, D., Billett, M.F., Adger, W.N., Subak, S. (1999). National inventories of terrestrial carbon sources and sinks: the UK Experience. Climate Change 42 (3), 505e530.

Chmura G. L., Anisfield S.C., Cahoon. D. R. and Lynch J.C. (2003). Global carbon sequestration in tidal, saline wetland soils. Global Biogeochemical Cycles Vol 17 No. 4 1111.

Chmura (2009). Tidal Salt Marshes. Chapter in Laffoley, D.d'A. and Grimsditch, G. (eds). (2009). The management of natural coastal carbon sinks. IUCN, Gland, Switzerland. 53p.

Chmura, G.L. (2011). What do we need to assess the sustainability of the tidal saltmarsh carbon sink? Ocean and Coastal Management, 83, 25-31.

Connor, R., Chmura, G.L., and Beecher, C.B. (2001). Carbon accumulation in Bay of Fundy salt marshes: implications for restoration of reclaimed marshes. Global Biochemical Cycles, 15, 943-954.

Cook, P.L.M. (2002), 'Carbon and nitrogen cycling on intertidal mudflats in a temperate Australian estuary', PhD thesis, University of Tasmania. Available at: https://eprints.utas.edu.au/19166/ [last accessed June 2021]

Craft, C., Megonigal, P., Broome, S., Stevenson, R., Freese, R.K., Cornell, J.,K., Zheng, L.K and Sacco, J. (2003). The Pace of Ecosystem Development of Constructed Spartina alterniflora Marshes. Ecological Applications - ECOL APPL. 13. 1417-1432. 10.1890/02-5086.

ComCoast (2006) COMbined Functions in COASTal Defence Zones Interreg IIIb North Sea Programme http://archive.northsearegion.eu/iiib/projectpresentation/details/&tid=25&theme=2

Crooks, S., Windham-Myers, L., and Troxler, T.G. (2020). Defining Blue Carbon The emergence of a climate context for coastal carbon dynamics. Chapter 1 in Windham-Myers, L., Crooks, S., Troxler, T.G. (Eds.). (2018). Blue Carbon Primer

Department for Business, Energy and Industrial Strategy (DBEIS) (2012). Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal.

Duarte, C.M., Middelburg, J., and Caraco, N. (2005). Major role of marine vegetation on the oceanic carbon cycle. Biogeosciences 2: 1–8.

Environment Agency/ABPmer (in prep). Refinement and Prioritisation of Potential Habitat Restoration Maps, Comparative review of the Ecosystem Services provided by potential saltmarsh, seagrass and oyster restoration sites, ABPmer Report No. R.3571.

Ford, H., Garbutt, A., Ladd, C., Malarkey, J. and Skov, M.W. (2016). Soil stabilization linked to plant diversity and environmental context in coastal wetlands. Journal of Vegetation Science, 27(2), 259-268. https://onlinelibrary.wiley.com/doi/full/10.1111/jvs.12367

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., Van Dorland, R., 2007. Changes in atmospheric constituents and in radiative forcing. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: the Physical Science Basis. Cambridge University Press, Cambridge and New York Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

Gauld, J.G., (2014). Evaluating the Impact of Saltmarsh Restoration upon Carbon Sequestration in Coastal Ecosystems. MSc Thesis. University of Edinburgh.

Herr, D., Chagas, T., Krämer, N., Conway, D. and Streck, C. (2018). Coastal blue carbon and Article 6 Implications and opportunities. IUCN Global Marine and Polar Programme Working Paper. 26p. Available at: https://climatefocus.com/sites/default/files/20181203_Article%206%20and%20Coastal%20Blue%20Carbon.pdf [last accessed June 2021]

Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). (2014). 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands Published: IPCC, Switzerland

IUCN (2021). Manual for the creation of Blue Carbon projects in Europe and the Mediterranean. Otero, M. (Ed)., 144 pages.
https://www.iucn.org/sites/dev/files/content/documents/2021/manualbluecarbon_eng_lr.pdf

Laffoley, D.d'A. and Grimsditch, G. (eds). (2009). The management of natural coastal carbon sinks. IUCN, Gland, Switzerland. 53p.

Lockwood, B. and Drakeford, B., (2020). The value of carbon sequestration by saltmarsh in Chichester Harbour, United Kingdom', Journal of Environmental Economics and Policy, 1–15.

Lopez, O. (2021) Ocean-Based Climate Solutions in Nationally Determined Contributions January 2021 Update develop bespoke national standards. Ocean Conservancy Report
https://oceanconservancy.org/wp-content/uploads/2021/01/NDC_tracker_January-2021-update.pdf

MacDonald, M.A., de Ruyck, C., Field, R.H., Bedford, A. & Bradbury, R.B. (2017) Benefits of coastal managed realignment for society: Evidence from ecosystem service assessments in two UK regions. Estuarine, Coastal and Shelf Science. https://doi.org/10.1016/j.ecss.2017.09.007

Macleod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarerte, C. M., *et al*. (2011). A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. Front. Ecol. Environ. 9, 552–560.

Macreadie, P, Andrea A., Raven, J.A, Beaumont, N., Connolly, R.M., Friess D.A., Kelleway, J., Kennedy, H., Kuwae, T., Lavery, P., Lovelock, C., Smale, D.A., Apostolaki, E., Atwood T., Baldock, J., Bianchi, T., Chmura, G., Eyre, B., Fourqurean, J., Duarte, C. (2019). The future of Blue Carbon science. Nature Communications. 10. 3998. 10.1038/s41467-019-11693-w.

May, V.J., and Hansom, J.D. (2003). Coastal Geomorphology of Great Britain, Geological Conservation Review Series No. 28. Joint Nature Conservation Committee, Peterborough, 739p.

Mossman, H., Pontee, N., Katie B., Lawrence P & Rae S., Scott, J., & Serato., B Sparkes, R., Sullivan, M., and Dunk, R. (2021). Rapid carbon accumulation at a saltmarsh restored by managed realignment far exceeds carbon emitted in site construction. 10.1101/2021.10.12.464124.

Murray B.C., Pendleton L., Jenkins W.A., Sifleet S. (2011). Green Payments for Blue Carbon Economic Incentives for Protecting Threatened Coastal Habitats Nicholas Institute for Environmental Policy Solutions, Report. NI R 11-04 March 2011. Available at: https://nicholasinstitute.duke.edu/sites/default/files/publications/blue-carbon-report-paper.pdf [last accessed June 2021]

Nellemann, C. and Corcoran, E. eds., (2009). Blue carbon: the role of healthy oceans in binding carbon: a rapid response assessment. UNEP/Earthprint.

Parker, R., Benson, L., Graves, C., Kröger, S., Vieira, R. (2021). Carbon stocks and accumulation analysis for Secretary of State (SoS) region: (2020). Cefas Project Report for Defra, 40p. http://randd.defra.gov.uk/Default.aspx?Menu=MenuModule=MoreLocation=NoneProjectID=20754 [last accessed June 2021]

Pendleton, L., Donato, D.C., Murray, B.C., Crooks, S., Jenkins, W.A., Sifleet, S. (2012). Estimating Global “Blue Carbon” Emissions from Conversion and Degradation of Vegetated Coastal Ecosystems. PLoS ONE 7(9), e43542. https://doi.org/10.1371/journal.pone.0043542

Pidgeon, (2009) Carbon Sequestration by Coastal Marine Habitats: Important Missing Sinks. Chapter in Laffoley, D.d’A. and Grimsditch, G. (eds). (2009). The management of natural coastal carbon sinks. IUCN, Gland, Switzerland. 53p.

Reid, J.B. and Goss, M.J. (1981). Effect of living roots of different plant species on the aggregate stability of two arable soils. Journal of Soil Science, 32(4), 521-541.

Sanders, C.J., Smoak, J.M., Naidu, A.S., Sanders, L.M. and Patchineelam, S.R., (2010). Organic carbon burial in a mangrove forest, margin and intertidal mud flat. Estuarine, Coastal and Shelf Science, 90(3), pp. 168-172.

Sullivan, M.J. and Currin, C.A. 2000. Community structure and functional dynamics of benthic microalgae in salt marshes. Pp 81-106 In Weinstein, M.P. and Kreeger, D.A. (eds) Concepts and Controversies in Tidal Marsh Ecology. Kluwer Academic Publishers, London, 875 pages.

Spencer, K.L. Cundy, A.B. Davies-Hearn, S. Hughes, R. Turner, S. MacLeod, C.L. (2008). Physicochemical changes in sediments at Orplands Farm, Essex, UK following 8 years of managed realignment, Estuarine, Coastal and Shelf Science, Volume 76, Issue 3, 2008, 608-619, ISSN 0272-7714, https://doi.org/10.1016/j.ecss.2007.07.029.

Stewart, C. and Williams, E. (2019). Blue Carbon Research Briefing. National Assembly for Wales, Senedd Research, December 2019.

Verified Carbon Standard, (2020) VM0007 REDD+ Methodology Framework (REDD+ MF) Version 1.6 08 September 2020 https://verra.org/methodology/vm0007-redd-methodology-framework-redd-mf-v1-6/

Windham-Myers, L., Crooks, S., Troxler, T.G. (Eds.). (2018). A Blue Carbon Primer: The State of Coastal Wetland Carbon Science, Practice, and Policy (1st ed.). CERC Press. https://doi.org/10.1201/9780429435362

Wollenberg J.T., Ollerhead J., Chmura G.L. (2018). Rapid carbon accumulation following managed realignment on the Bay of Fundy. PLoS ONE 13(3). https://doi.org/10.1371/journal.pone.0193930

Wildfowl and Wetlands Trust (WWT) (2020). A blue recovery. Four blue infrastructure projects for the UK's recovery/. Website content available at: https://www.wwt.org.uk/our-work/projects/blue-recovery/# [last accessed June 2021]

Websites

ABPmer's 'Blue Carbon Calculator' April 2014 https://www.abpmer.co.uk/blog/abpmers-blue-carbon-calculator/

ABPmer OMReg managed realignment and habitat restoration database http://www.omreg.net/

Allfleet's Marsh Managed Realignment https://www.omreg.net/query-database/33-allfleets-marsh-wallasea/

Aulac Dyke Manged Realignment https://www.omreg.net/query-database/0016-aulac/

Blue Marine Foundation Blue Carbon: A new frontier for ocean conservation https://www.bluemarinefoundation.com/2021/09/13/18172/

CEH-led UK Saltmarsh Carbon Code project https://www.ceh.ac.uk/news-and-media/news/unlocking-billion-pound-investment-restoration-saltmarshes

Cobnor Managed Realignment https://www.omreg.net/query-database/107-cobnor-point/

COP26: Government leads on Ocean Action Day https://www.gov.uk/government/news/cop26-government-leads-on-ocean-action-day

C-Side Carbon Storage in Intertidal Environments project https://www.c-side.org/

Greatham North Managed Realignment https://www.omreg.net/query-database/157-greatham/

Hazlewood Marshes Managed Realignment https://www.omreg.net/query-database/149-hazlewood-marshes/

Hesketh West Managed Realignment https://www.omreg.net/query-database/93-hesketh-out-marsh-west/

International Partnership for Blue Carbon, 2021. Blue Carbon Partnership: https://bluecarbonpartnership.org/

Jubilee Marsh Managed Realignment https://www.omreg.net/query-database/205-jubilee-marsh-wallasea/

Paull Holme Strays Managed Realignment https://www.omreg.net/query-database/22-paull-holme-strays/

Stanford Wharf Managed Realignment https://www.omreg.net/query-database/101-stanford-wharf/

Steart Managed Realignment https://www.omreg.net/query-database/154-steart-marsh/

Welwick Managed Realignment https://www.omreg.net/query-database/35-welwick/

6 Abbreviations/Acronyms

BCE	Blue Carbon Ecosystems
CEH	Centre for Ecology & Hydrology
CO_2	Carbon Dioxide
CO_2e	carbon dioxide equivalent
COP	Conference of the Parties (United Nations Climate Change Conference)
C-SIDE	Carbon Storage in Intertidal Environments
DBEIS	Department for Business, Energy and Industrial Strategy
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
LiDAR	Light Detection and Ranging
MF	Methodology Framework
NDC	National Determined Contributions
NERC	Natural Environment Research Council
OMReg	Online Marine Registry (ABPmer)
REDD	Reduction of Emissions from Deforestation and forest Degradation
RSPB	Royal Society for the Protection of Birds
tCO_2e	Total Carbon Dioxide Equivalent
UK	United Kingdom
UKCEH	UK Centre for Ecology & Hydrology
UN	United Nations
UNFCCC	United Nation Framework Convention on Climate Change
US	United States (America)
WWT	Wildfowl and Wetlands Trust
VCS	Verified Carbon Standard

Cardinal points/directions are used unless otherwise stated.

SI units are used unless otherwise stated.

Contact Us

ABPmer

Quayside Suite,
Medina Chambers
Town Quay, Southampton
SO14 2AQ

T +44 (0) 23 8071 1840
F +44 (0) 23 8071 1841
E enquiries@abpmer.co.uk

www.abpmer.co.uk