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A generalisable integrated natural capital methodology for targeting investment in coastal defence

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ABSTRACT

Coastal ecosystems, such as saltmarsh, produce a range of ecosystem services that underpin human well-being. In the UK, and globally, saltmarsh extent and quality is declining due to coastal squeeze, deteriorating water quality, and agricultural activities. Here, we develop a general framework to evaluate changes in coastal defence. Using this framework, we identify priority areas for saltmarsh re-alignment: re-creation of saltmarsh in areas that have been saltmarsh in the past – but that have been claimed for a variety of land uses, particularly agriculture. We base our re-alignment prioritisation on the ecosystem services provided by saltmarsh in the North Devon Biosphere Reserve: specifically carbon sequestration and recreational benefits, and the economic values of those services. We compare potential economic benefits with the economic costs of creating new saltmarsh areas – specifically lost agricultural output, property damages and direct re-alignment costs. We identify a number of priority areas for managed re-alignment that generate high recreational values in areas where properties would not be damaged. These findings provide a necessary and timely analysis for the managers of the North Devon Biosphere Reserve. Furthermore, we outline a comprehensive methodology to plan future management of coastal zones.

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Coastal planning; ecosystem services; managed re-alignment; natural capital; opportunity costs; saltmarsh

1. Introduction

Marine and coastal ecosystems provide a number of essential functions, such as primary production and climate regulation, which underpin life on Earth (MEA 2005). These essential functions deliver flows of ecosystem services that support human well-being, including food, flood protection and opportunities for recreation (Roberts et al. 2001; Rees et al. 2010; Arkema et al. 2013; Potts et al. 2014; Rees et al. 2014; Arkema et al. 2015). In recognition of the crucial interdependencies between natural and human systems, targets to sustainably manage marine and coastal ecosystems are embedded in international (CBD 1992, 2010; OSPAR Convention 2002; UN 2014) and national policy (Ostle et al. 2009; H.M. Government 2011, 2018). In the UK, managed re-alignment is a policy to recreate saltmarsh, intertidal grasslands, in areas where they have occurred historically, for example,

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in areas converted to agriculture or other land uses (Luisetti et al. 2014). Saltmarsh produces a range of ecosystem services including carbon sequestration (Beaumont et al. 2014), recreational benefits (Barbier et al. 2011) and fisheries support services. The relevant policy question is: where should re-alignment occur, to maximise the benefits that new saltmarsh provides to society, relative to the costs of removing land from its current use?

In the North Devon Biosphere Reserve (Figure 1), a programme of managed re-alignment is currently being undertaken. Understanding where managed re-alignment should be prioritised is a pressing question for the Biosphere managers. In this research, we worked closely with the Biosphere managers to identify areas where the ecosystem services generated by new saltmarsh areas in the Biosphere would generate the greatest economic benefits, relative to the economic costs. We develop a general framework to guide the assessment of projects that involve changes in coastal defence activities. As part of this framework, we describe a methodology outlining the biophysical and socio-economic analyses that are necessary to conduct a complete economic assessment of potential changes in coastal defence.

The application of this framework to the assessment of changes in saltmarsh extent, managed re-alignment, has focused on identifying priority areas for re-alignment. This approach contrasts with previous exercises that have asked a more general question – whether managed re-alignment can provide economic benefits. For example, Turner et al. (2007) and Luisetti et al. (2011) took a spatially explicit approach to the assessment of the potential costs and benefits specific to managed re-alignment. In particular, Luisetti et al. (2011) aimed to provide decision support by quantifying the costs and benefits of existing re-alignment areas. However, little work has been undertaken to identify *priority* areas for future managed re-alignment. A key innovation in our prioritisation approach has been to incorporate temporally discrete carbon sequestration rates by saltmarsh, and the lost carbon sequestration values of previous land use. Previous studies (e.g. Turner et al. 2007) have assumed a single value for carbon sequestration by saltmarsh and a single carbon price, this approach ignores differences in sequestration rates following the establishment of saltmarsh. We follow best-practice described by Bateman et al. (2014) to consider changes in marginal abatement costs over time. Finally, we conduct an initial assessment of property damage caused by managed re-alignment.

Our approach is to identify the full range of biophysical and socio-economic components that should be analysed for a complete assessment of changes in coastal flood defence, e.g. managed

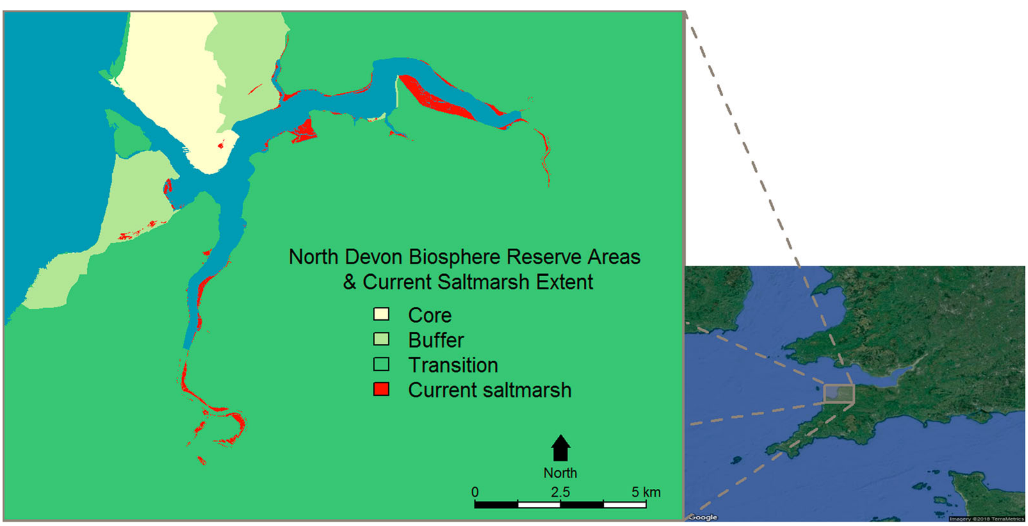

Figure 1. North Devon Biosphere Reserve (left) includes all the catchment areas draining to the north Devon coast and extends to 12 nautical miles beyond Lundy island. The different designations of the reserve: core, buffer and transition areas are indicated. South West England (right) with location of North Devon Biosphere outlined.

re-alignment. Our analysis focuses on a subset of these components for which data is available – we also identify important areas for future research to overcome existing data limitations. Specifically, we evaluate the following costs and benefits associated with managed re-alignment of saltmarsh in the North Devon Biosphere: opportunity costs to agricultural production, property damages, direct re-alignment costs, carbon sequestration benefits and recreational benefits. We use data on the tidal flood frame in the North Devon Biosphere (Figure 1) to identify potential managed re-alignment areas. The opportunity costs of lost future agricultural production, capitalised in land value, are based on the agricultural land classifications (ALC, MAFF 1988) and land-sale price data (DEFRA 2006). We use ORVAL (Day and Smith 2018b) to estimate recreational benefits, land use data from Bateman et al. (2013), and the CoolFarm Tool (Hillier et al. 2011) to estimate carbon sequestration benefits. Candidate re-alignment sites are prioritised by assessing the annualised costs and benefits of conversion to saltmarsh, adjusted to 2016 prices.

Using an integrated natural capital methodology, we identify priority areas for saltmarsh re-alignment. We identify four sites within the North Devon Biosphere Reserve that are prioritised for managed re-alignment under three assumptions about how property damages could be treated: ignoring property damages, excluding sites with properties from the analysis, and including an initial assessment of property damages into our assessment. Incorporating property damages changes our prioritisation, and reduces the annualised net present value of new re-alignment areas by 17%. In what follows we describe the current extent of saltmarsh areas in North Devon and the selection process we followed to identify potential re-alignment sites. We describe the costs of managed re-alignment estimated for each site, the ecosystem services provided by saltmarsh, and the economic values of these services. We finish by identifying priority areas for managed re-alignment in the North Devon Biosphere, and exploring the sensitivity of results to different assumptions regarding the treatment of property damages.

2. North Devon Biosphere Reserve

The North Devon Biosphere Reserve (Figure 1) is one of 669 reserves worldwide designated by UNESCO's Man and the Biosphere Programme. In total, the terrestrial extent is 233,495 ha, and the marine extent is 291,583 ha. The Biosphere contains a number of Local Nature Reserves, Sites of Special Scientific Interest and Special Areas of Conservation and the majority of the coast is designated as an Area of Outstanding Natural Beauty. Collectively, these designations make up the different zones of the reserve: core, buffer and transition zones (see Figure 1). The historical extent of saltmarsh areas in the biosphere is estimated at 968.8 ha, while the current extent is 230.7 ha.

3. Methods

We present a conceptual framework defining key areas of consideration in evaluating potential coastal defence projects (Figure 2). While applicable to the assessment of any coastal defence project, in the present analysis we focus on priority areas for saltmarsh managed-re-alignment. We further provide a complete description of how a sites' geomorphology and tidal dynamics could be assessed to understand whether a site would be suitable for managed re-alignment – although this assessment is beyond the current scope of this research. In our analysis, we address a component of the evaluation problem described in Figure 2; putting to one side the framework steps that assess climate conditions, changes in socio-economic drivers and the estuary regime. All analyses are conducted in R (R Core Team 2018) using applied spatial data analysis methods from packages "rgeos", "sp", "raster" and "rgdal" (Pebesma and Bivand 2005; Bivand, Pebesma, and Gomez-Rubio 2013; Brunsdon and Chen 2014; Hijmans 2017; Bivand and Rundel 2018; Bivand, Keitt, and Rowlingson 2018). Our approach is based on work conducted by Turner et al. (2007) and Luisetti et al. (2011) – and focuses on the costs and potential ecosystem service benefits that could be generated by returning

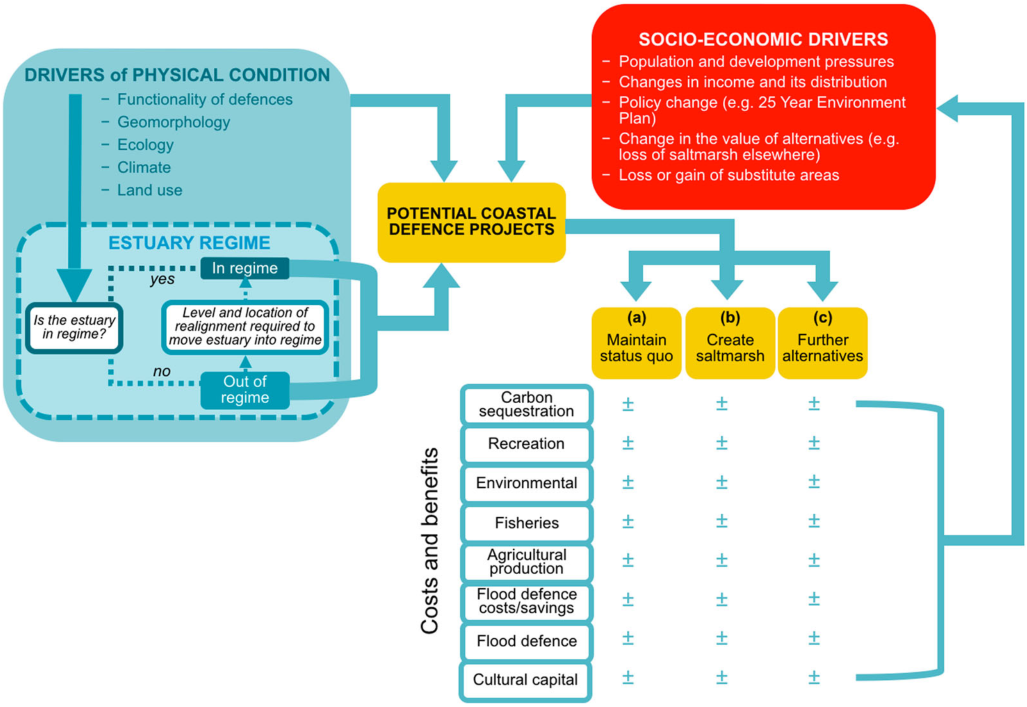

Figure 2. Conceptual framework to evaluate potential coastal defence projects, including managed re-alignment of saltmarsh.

areas in North Devon to saltmarsh. Each of these costs and benefits is discussed in more detail in the following sections.

3.1. Geomorphology and tidal hydrodynamics

A complete understanding of whether a site would be suitable for managed re-alignment can be achieved by evaluating its geomorphology and tidal hydrodynamics. The elevation and

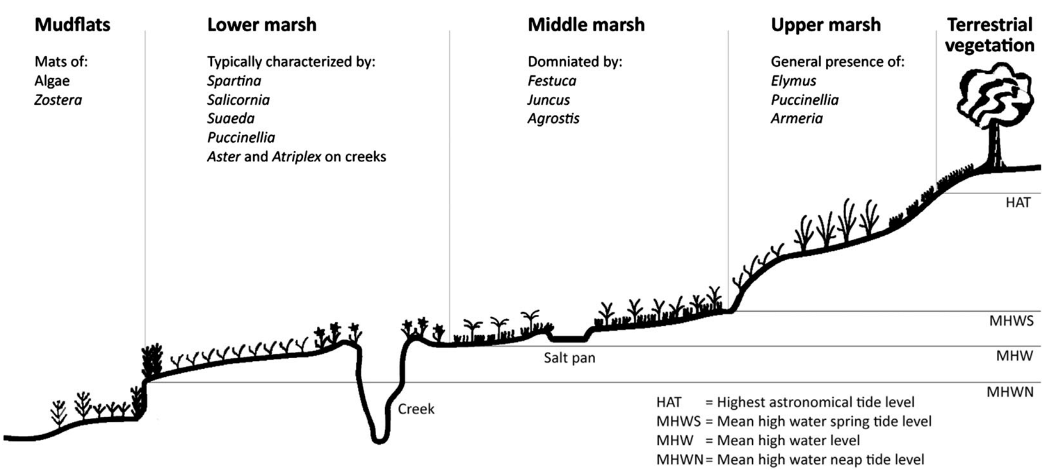

Figure 3. Indicative UK intertidal mudflat and saltmarsh profile. Adapted from Foster et al. (2013). Tides: HAT: highest astronomical tides; MHWS: mean high water springs; MHW: mean high water; MHWN: mean high water neaps.

geomorphology of a site is a crucial factor in helping establish a healthy saltmarsh. A network of creeks across the site is fundamental in providing sediment transport pathways into the saltmarsh, facilitating sediment deposition and saltmarsh aggradation. The network of channels also helps regulate tidal flows by increasing frictional drag, more conducive to depositional environments. Saltmarsh habitats are found high in the tidal frame (Figure 3) and consequently, their colonisation is closely linked to the tidal inundation of a site.

The tidal prism (i.e. volume of tidal water exchange passing a given point in an estuary) at a location determines the frequency and duration of inundation. This, in turn, impacts sedimentation, salinity, soil redox potential and propagule delivery to the site (Mossman, Davy, and Grant 2012; Mossman et al. 2012; Spencer and Harvey 2012). While consensus on the optimum inundation regime is lacking, Table 1 provides a summary of the habitat types most likely to colonise a site based on elevation within the tidal range. Depending on the site, the method of habitat creation can be tailored to maximise the optimum geomorphological and hydrodynamic conditions required. A Regulated Tidal Exchange allows control over inundation rates, to ensure – through careful management – tidal flows across the site are suitable. This technique requires close monitoring as biofouling and mechanical faults can result in poor inundation rates, limiting scheme success (Masselink et al. 2017). Where coastal defence is not a factor for the site, barrier breaches can be undertaken, providing a more natural channel to match local tide levels. Further, full bank retreats that remove the entire structure are a less controlled but more naturalistic approach. Consequently, the physical parameters of a selected area, in conjunction with the tidal hydrodynamics and the proximity of neighbouring marsh, will all need to be carefully considered for a successful re-alignment site.

3.2. Identifying candidate managed re-alignment sites

We identified candidate areas for managed re-alignment from data provided by the Environment Agency (n.d.). Using ordnance survey mapping products and Light Detection and Ranging (LIDAR) land surface information, these data identify historic saltmarsh areas that have been subsequently claimed for other land use. In particular, 'landclaim' area is identified as any location below the highest astronomical tide that is adjacent to the estuary and sitting behind an artificial flood defence. Examination of the landclaim area in the North Devon Biosphere Reserve identified 57 candidate sites for managed re-alignment that ranged from 0.3 ha to 339 ha in size, with an average of 15.32 ha.

3.3. Economic costs of managed re-alignment sites

A full assessment of managed re-alignment must count all service flows (market and non-market) coming from *current* land use as a cost. The change in ecosystem services delivered by existing land uses – relative to potential saltmarsh areas – must be captured to appropriately assess whether there will be a *net gain* in the economic value of ecosystem service provision under re-alignment. Here we focus on lost agricultural output, property damages, and the direct costs of re-alignment.

Table 1. Summary of optimum hydrodynamic conditions for intertidal habitat generation.

Habitat type	Site gradient	Annual inundation p/yr	Tidal range
Mudflats	1–3%	450–600	Between MHWN and MHWS, <2.1 m ODN
Saltmarsh (salinity > 10)	1–3%	Pioneer marsh = 300–450	~MHWN
		Lower marsh = 30–300	~MHW
		Upper marsh = <30	~MHWS
		Transitional marsh	MHWS – HAT

Note: MHWN: mean high water neaps; MHWS: mean high water springs; HAT: highest astronomical tides; ODN: Ordnance Datum Newlyn, a mean sea level datum in the UK.
Source: Environment Agency (2003), Nottage and Robertson (2005).

In all cases, there is an upfront cost associated with re-alignment. In the context of our analysis, we consider these costs as occurring in year 1, but annualise these values for comparison with the benefits of re-alignment. Our calculation of annualised net present value is derived from the equivalent annual annuity formula:

$$\frac{(NPV \times r)}{1 - (1 + r)^{-n}} \tag{1}$$

where r is the discount rate, and n is the number of periods. With an infinite time horizon, as is the case in our analysis where we assume a stream of recreational benefits that continue indefinitely, then this equation collapses to:

$$x = NPV \times r \tag{2}$$

where x is the annualised net present value.

3.3.1. Opportunity cost to agricultural production

We assume that, with a well-functioning land market, the selling price at which a landowner would be willing to trade productive agricultural land will be the net present value of the flow of future profits from that land. As such, land prices provide a guide to the value of the agricultural output emanating from that land. To calculate the land prices for each of our managed re-alignment sites, we used spatially explicit data on ALC grades (MAFF 1988) and sale price data specific to those grades (DEFRA 2006) (Figure 4)[1]. The ALC framework classifies land according to the extent to which its physical or chemical characteristics impose long-term limitations on agricultural use (MAFF 1988). The principal physical factors influencing agricultural production are climate, site and soil. These factors, together with their interactions, form the basis for classifying land into one of five ranked grades: from Grade 1 land being of excellent quality down to Grade 5 land of very poor quality (MAFF 1988).

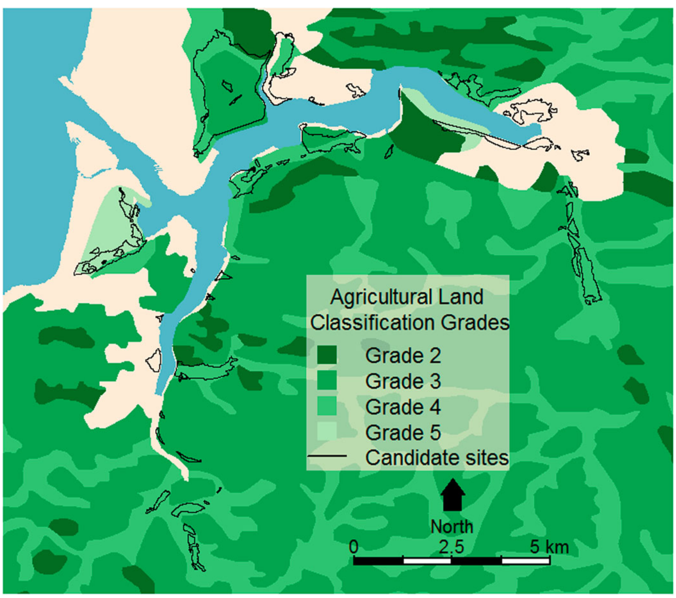

Figure 4. Spatial distribution of ranked agricultural land classifications (MAFF 1988) in the North Devon Biosphere Reserve. Grade 1 land is classified as excellent quality while Grade 5 land is classified as very poor quality. Overlap with candidate saltmarsh re-alignment areas is indicated.

We identified the spatial extent of each ALC grade in each of our 57 sites. Following Turner et al. (2007), we calculated opportunity costs by identifying the proportion of each site in each ALC grade, then multiplying this proportion by the sale price specific to the land grade and summing all areas. All values were converted to 2016 prices using the GDP deflators published by H.M. treasury (H.M. Treasury 2018). We then calculated the annualised stream of costs for comparison with other economic costs (e.g. expected property damages and direct costs) and benefits (e.g. recreational and carbon sequestration) as per Equation (2). We use a private discount rate, set at 2.5% in line with the 2016 Bank of England interest rate (Bank of England 2018).

3.3.2. Implications for flood risk and property losses

A major consideration in projects assessing changes in coastal defences are potential changes in the risk of flooding to which properties are exposed. To fully understand the economic costs (or benefits) of this change, we would ideally have a high-resolution digital terrain model with property location data – interacting with a flood inundation model to calculate the probabilities of flooding. We would then apply those probabilities to published data on flood damage costings (Penning-Rowsell et al. 2013). In the absence of such information, we take a simplified approach in this case study, which examines the direct property loss that arises when sites are flooded to re-create saltmarsh. Understanding how changes to coastal defence changes flood risk (either increased or decreased) in properties neighbouring candidate re-alignment sites is identified as an important area for further research.

In our approach, we draw on high-resolution data on property locations (Ordnance Survey 2017b) and potential saltmarsh extent. By interpreting this information, we can make assumptions about the economic impacts of managed re-alignment on properties. This implies that there can be no simple, single answer to the prioritisation of saltmarsh re-creation, rather we show that there are different ways of assessing changes to coastal defence that yield different results. We examine three scenarios with different treatment of direct property damage.

Scenario 1: Ignoring property damage – equivalent to assuming that these damages will be zero. This is an extreme approach where we ignore property impacts. We note that, despite the outcomes of this assessment, where managed re-alignment would flood private properties, it is unlikely that these sites would be realistic candidates for future re-alignment.

Scenario 2: Excluding all candidate managed re-alignment sites with properties within their bounds. This gives us a new prioritisation – a second extreme where any property impacts are considered unacceptable.

Scenario 3: Incorporating property losses. In this scenario, we take a simplified approach to estimating property losses incurred if sites with properties were flooded (converted to saltmarsh). First, for every site, we identify the number of properties within the site. Then, we take an average property value (H.M. Land Registry 2018) for each sites' postcode(s) (Ordnance Survey 2017a) and set the damage costs for each site equal to the number of properties in the site multiplied by the average property value for the postcode(s). Once we convert this figure to an annualised stream (see Equation 1), we obtain a cost value of property losses if sites were converted to saltmarsh that we can compare with other economic costs and benefits. This allows us to perform another prioritisation exercise with an initial estimate of the economic costs of property losses due to managed re-alignment.

Note that a further approach, beyond the scope of the current exercise, could consider stress related to flooding (Tapsell et al. 2002) – as experienced by property owners. This approach is relevant in cases where (a) managed retreat increases the probability of flooding or (b) managed retreat requires the compulsory purchase of properties that are then abandoned or cleared to allow flooding (Penning-Rowsell et al. 2013). This approach would move the prioritisation back towards Scenario 2.

3.3.3. Direct costs

Published estimates of the direct costs of saltmarsh re-alignment vary greatly across different regions and re-alignment projects. For example, Economics for the Environment Consultancy Ltd, eftec

(2015b) refers to costs as high as £50,000 per hectare for 'intertidal habitat creation' in the UK. Following published guidelines by Hudson et al. (2015), we assume a direct cost for re-alignment 'without major new defence construction' of £15,000 per ha. This estimate was consistent with the experience of the Biosphere managers regarding previous re-alignment projects.

3.4. Economic benefits of managed re-alignment sites

In this analysis, we focus on two economic benefits of managed re-alignment: recreational and carbon sequestration benefits. We calculate an annual stream of recreational benefits that are assumed to continue indefinitely. These benefits are annualised following Equation (2). For carbon, we calculate an annual stream of benefits across a 20-year period. This benefit stream is then annualised following Equation (2).

3.4.1. Recreational benefits

To estimate spatially explicit recreational values, we utilise ORVal (the Outdoor Recreational Valuation tool) (Day and Smith 2018b). ORVal estimates visitation to existing or newly created green spaces across the whole of England and Wales and derives monetary estimates of the value households attach to the recreational opportunities provided by those green spaces. ORVal has recently been incorporated into the UK Treasury's Green Book – the government's guidance for project appraisal and evaluation (H.M. Treasury 2018) and features in the government's 25-Year Environment Plan (H.M. Government 2018).

The recreation demand model that underpins ORVal is a Random Utility Model (RUM) using a cross-nested multinomial logit specification estimated on data drawn from the Monitor of Engagement with the Natural Environment (MENE) survey (Natural England 2017). The ORVal recreation demand model allows for three different dimensions of choice: (i) whether to take an outdoor recreation trip on a particular day, (ii) whether to walk or drive to a recreation site when taking a trip and (iii) which particular site to visit (for full details of the ORVal modelling, see Day and Smith 2017, 2018a). The fundamental assumption of the ORVal model is that the choices observed in the MENE data are welfare-maximising. So, when an individual is observed to have taken a trip to enjoy greenspace, it is assumed that the welfare of taking a trip at that time exceeds the welfare of doing something entirely different. Likewise, when an individual is observed to have chosen a visit to one particular recreational site, it is assumed that the welfare derived from that visit exceeds the welfare that would be enjoyed from visiting an alternative site.

Ultimately, ORVal makes probabilistic predictions about how likely it is that people with particular characteristics in particular locations visit a particular greenspace given the characteristics of the greenspaces available and the cost of travelling to them. For estimating the recreation value of new sites, the model adds that new site to each individual's set of potential choices and calculates how much welfare each gains from that additional possible trip location. The total welfare value of that new site is calculated by summing up those welfare gains for each adult across England and Wales over the course of a year.

The online ORVal tool (version 2.0) available at http://leep.exeter.ac.uk/orval (accessed on 12 May 2018) was used to calculate the value that might be realised if each of the 57 potential re-alignment sites was opened up to recreation. The details of the re-alignment sites were inputted into the ORVal tool, the centroid was used as the location and the sites were defined as 'path' features with the length of the path approximated based on the size of the site and the potential length of new high tide boundary. Finally, the sites were assigned land covers of 50% saltmarsh and 50% agriculture with an estuary water margin equal to the path length. The ORVal tool allows the travel cost calculations to be either 'crude' (straight line distances), 'good' (road networks) or 'exact' (road and path networks). In this analysis, the 'exact' method was used to allow for accurate costs to be calculated for both walking and driving recreation visits. All recreational values are outputted from ORVal in 2016 prices.

3.4.2. Carbon sequestration

We compared annual carbon sequestration rates for each potential managed re-alignment site under current land use versus saltmarsh. To estimate the annual carbon sequestration rates of existing land use we first identified existing land use from a data set (Bateman et al. 2013) describing the percentage of area at a resolution of 2 km grid squares (400 ha) attributed to the following land use categories: temporary grassland, permanent grassland, rough grazing, root crops, cereals and 'other'. Carbon emissions from these different land use categories were then estimated using the 'CoolFarm Tool' (Hillier et al. 2011). The CoolFarm Tool incorporates data on soil types and climate to estimate carbon emissions under different land uses. We calculated the annual carbon emissions in each site under current land use. Where sites were located outside of the 2 km grid, we assumed that the emissions would match emission from the 'nearest neighbour' grid cell. We further calculated the carbon stock in each site under existing land use based on previous UK estimates (Ostle et al. 2009). We assumed that this entire stock of carbon would be released upon conversion to saltmarsh – a conservative assessment.

The carbon sequestration benefits of new saltmarsh areas for sites less than 15 years old (4 $tCO_2\ yr^{-1}$) and established sites (2 $tCO_2\ yr^{-1}$) were estimated using the method followed by (Economics for the Environment Consultancy Ltd, eftec 2017). We based our valuation of carbon sequestration benefits on work by Bateman et al. (2014) and calculated the costs of carbon emissions using an estimate of marginal abatement costs (untraded). In addition, we estimated the time it would take saltmarsh to reach 'equilibrium', e.g. to have stabilised carbon and no longer be sequestering this from the atmosphere, at 20 years and this became the project time horizon. It is worth noting that where landward migration is not prevented by the presence of sea walls, saltmarsh could continue to accrete as sea level rises. This would imply that saltmarsh could continue to secrete carbon indefinitely. Our approach, therefore, represents a lower-bound estimate of the carbon sequestration benefits of managed re-alignment. We discounted all benefits and costs across this time horizon to calculate the net present value. We then annualised net present value as per Equation (2).

4. Results

We identify priority sites for saltmarsh managed re-alignment in the North Devon Biosphere Reserve, based on an assessment of lost agricultural output, potential property damages, direct re-alignment costs, changes in carbon sequestration benefits and the generation of recreational benefits. In Figure 5, we present priority sites for re-alignment under three scenarios regarding willingness to accept property damages: (1) ignoring property damages; (2) excluding potential sites where properties were located; and (3) accounting for a basic assessment of property damages. The top site prioritised for re-alignment in Scenario 1 is site 41 with an annualised net present value of £185,217. In Scenarios 2 and 3, the optimal site for managed re-alignment is site 49, with an annualised net present value of £152,408. It is worth noting that potential annualised property damages in site 41 – the site with the highest annualised net present value when property damages are ignored – is £382,666: implying that the annualised cost of ignoring property damages when prioritising managed re-alignment would be £230,259. In Scenarios 1 and 2, recreational values are a primary driver of the prioritisation (Figure 6). In Scenario 1, prioritisation is also given to sites with low opportunity costs to agriculture. In Scenario 3, prioritisation is highly influenced by recreational values (Figure 6), but also by property damage costs.

The distribution of annualised costs (Table 2) indicates that a few sites with large costs reduce the mean, such that the absolute value of the mean is an order of magnitude greater than the median, and approximately double the value of the third quartile. This skew is particularly apparent for property damage costs, where mean property damages are −£225 k, but the median and third quartile values are −£33 k and −£101 k, respectively. This skew is also present in the annualised benefits but to a lesser degree. Here means and medians are of the same magnitude. Across all costs and benefits,

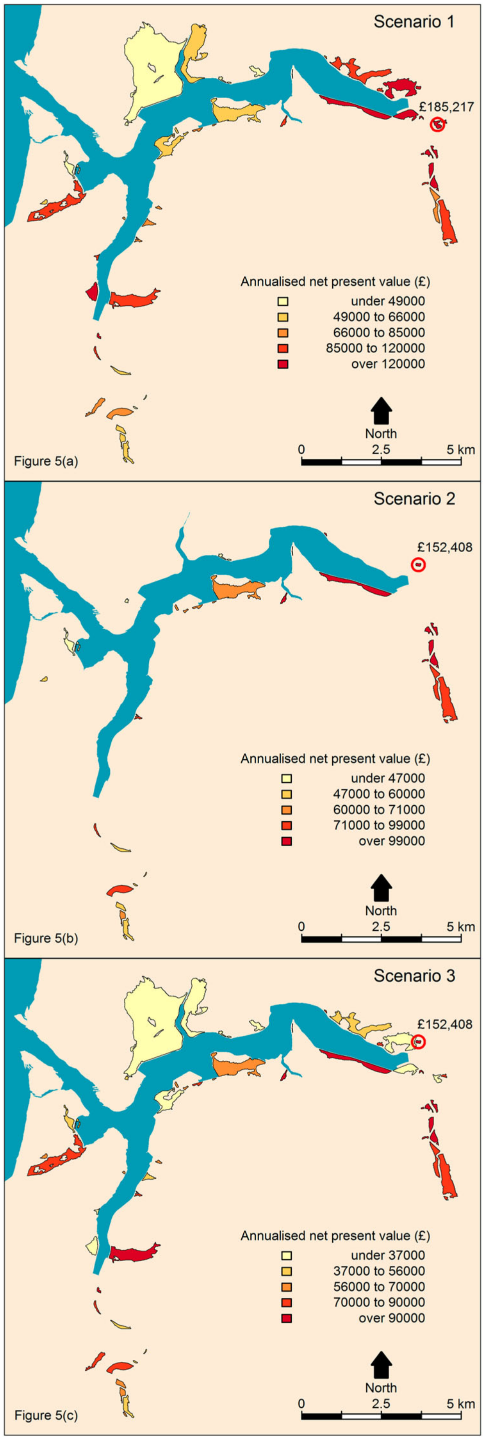

Figure 5. Prioritisation of sites for managed re-alignment of saltmarsh across three scenarios varying in their treatment of property damage: (1) ignoring damages, (2) excluding sites with properties from the analysis, and (3) incorporating a basic assessment of property damages. Prioritisation is based on an assessment of candidate sites' costs: opportunity costs to agriculture, property damages and direct costs (Scenario 3), and benefits: recreational and carbon sequestration. The site with the highest annualised net present value is circled in red and annualised net present value reported.

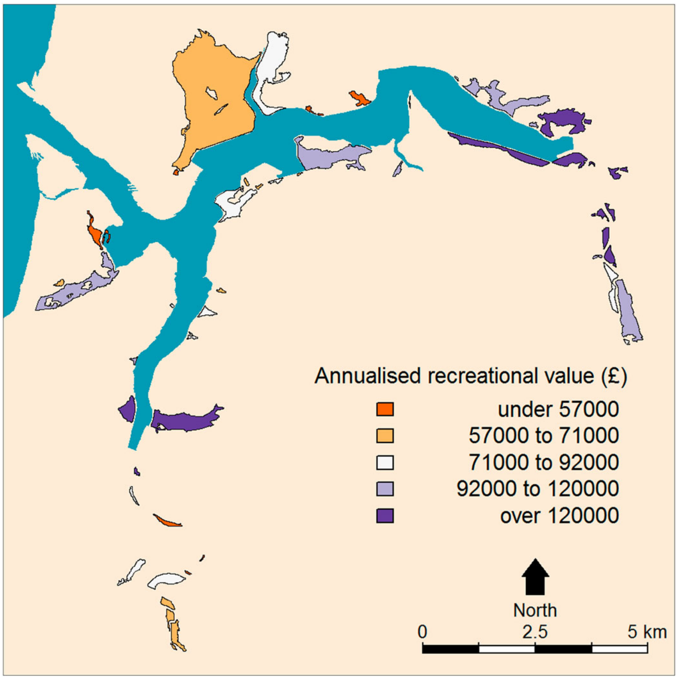

Figure 6. Annualised recreational benefits (£2016) from saltmarsh in candidate managed re-alignment sites in the North Devon Biosphere Reserve.

Table 2. Summary of annualised costs and benefits generated by the creation of new saltmarsh areas in the North Devon Biosphere, and annualised net present value across all property damage scenarios.

	Annualised costs (£)			Annualised benefits (£)		Annualised net present value (£)		
	Opportunity costs to agriculture	Property damages	Direct	Carbon sequestration	Recreational	Scenario 1	Scenario 2	Scenario 3
Min.	0	−5,513	−150	13	10,933	−124,283	15,112	−2,069,841
1st Qu.	−46	−11,025	−384	45	60,393	54,483	48,296	39,158
Median	−138	−33,075	−909	130	77,553	71,819	64,214	63,020
3rd Qu.	−752	−101,320	−4,015	534	120,672	117,592	87,761	84,517
Max.	−52,396	−2,232,207	−152,419	11,165	186,610	185,217	152,408	152,408
Mean	−1,847	−225,030	−6,896	773	89,045	81,075	71,942	−1,831

when assessed at the mean, the value of property damages dominate. However, closer inspection reveals that this result arises from a small number of sites with high property damages. Considering the overall distributions, it is notable that in absolute terms when assessed at the median, it is recreational benefits that deliver the highest values. The mean annualised net present value for Scenarios 1 and 2 is positive, but becomes negative under Scenario 3. This effect is once again due to a small number of sites with large property damage values that skew the mean downwards, as reflected in the positive median value for Scenario 3.

Across the three scenarios, there is some agreement regarding the top 10 sites that should be prioritised for re-alignment (Figure 7). Four sites are consistently prioritised across all scenarios: sites 26, 34, 47, and 49. The annualised net present value flows from these sites are all within the top quartile across the three scenarios. There are no properties in any of these sites. Conversion of site 49 to saltmarsh would not impose any opportunity costs on agricultural production, however there are small opportunity costs to agriculture (within the second quartile of annualised costs, see Table 2) in sites 26, 34 and 47. Not surprisingly, Scenarios 2 and 3 have a high degree of overlap: seven sites are in the top 10 for both scenarios.

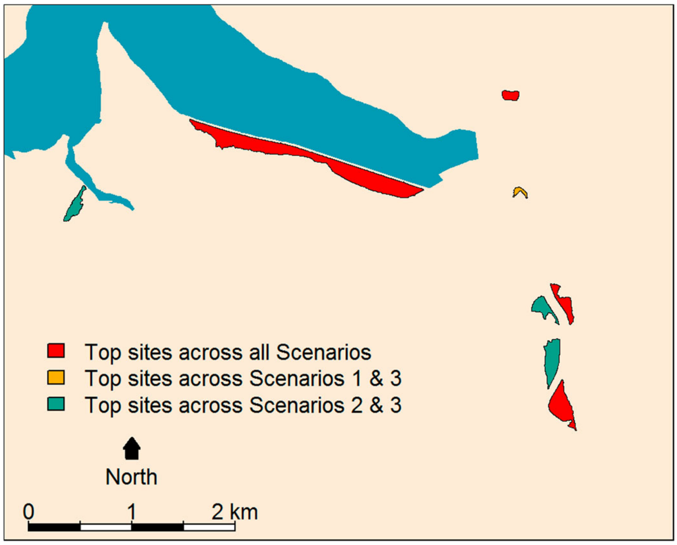

Figure 7. Sites in the North Devon Biosphere Reserve that rank among the top 10 sites prioritised for saltmarsh managed re-alignment across all (red) or two (amber and green) scenarios of property damage: (1) ignoring damages, (2) excluding sites with properties from the analysis, and (3) incorporating a basic assessment of property damages.

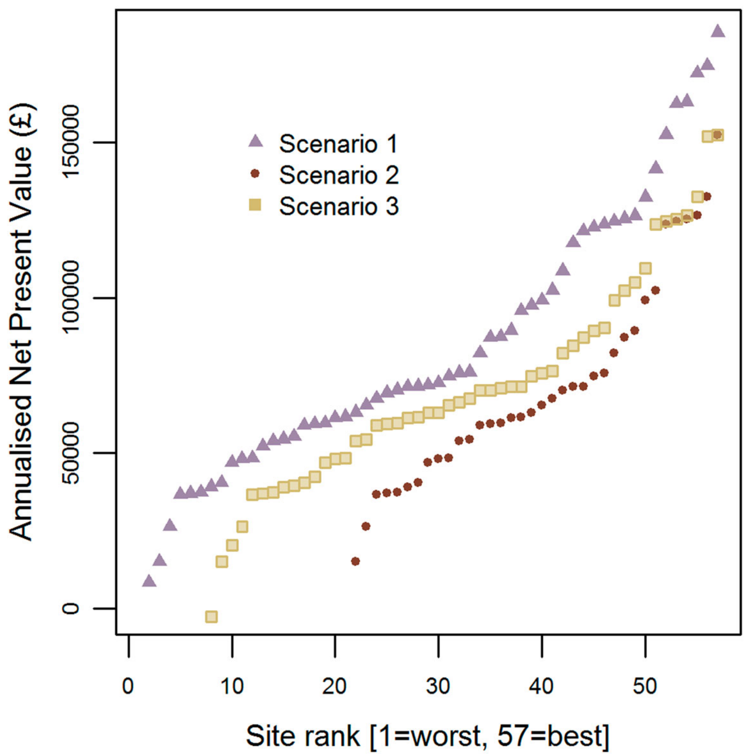

Figure 8. Annualised net present value relative to site ranking. Note that in Scenarios 1 and 3, sites are ranked 1–57. In Scenario 2, there are 36 sites, ranked here from 21 to 57 for comparison with other scenarios. Property damage scenarios are: (1) ignoring property damages, (2) excluding sites with properties from the analysis, and (3) incorporating a basic assessment of property damages. Sites with negative annualised net present value have been excluded for display purposes.

Further analysis of the sites prioritised for re-alignment in Scenario 1 shows that there is a steep improvement in annualised net present value among the highest ranked sites (Figure 8). In Scenarios 2 and 3, there is a clear difference in annualised net present value separating the top one (and two in Scenario 3's case) site and the next ranked sites. This indicates that if there are limited resources for managed re-alignment, substantial gains can be made from prioritisation.

We can also analyse sites with the greatest annualised net present values per m^2 (Figure 9). This analysis provides us with a heat map of priority areas for re-alignment – independent of the sites' size. Across all scenarios, the top site prioritised for re-alignment is different when evaluated from a site (Figure 5) versus m^2 (Figure 9) perspective. Similar to the site-based analysis, small areas continue to be prioritised for re-alignment. It should be noted that areas where partial re-alignment of a site was being considered, planners would also need to consider the sites' geomorphology, tidal hydrodynamics (see Section 3.1), and whether additional 'hard' infrastructure would be required.

5. Discussion

We identify priority sites for managed re-alignment of saltmarsh in the North Devon Biosphere Reserve. The study was developed in close consultation with the managers of the North Devon Biosphere Reserve and was designed to provide decision support for the prioritisation of new saltmarsh areas. Saltmarsh is rapidly degrading and decreasing in the UK and globally (Barbier et al. 2011), making managed re-alignment an environmental policy priority. At the same time, public funding for environmental programmes is limited. Therefore, new saltmarsh sites should be located in areas where they will provide the greatest benefits, relative to the costs. Here, we have focused on benefit (and cost) flows that arise as ecosystem services. Sites that were high priorities for re-alignment were sites with high recreational values, as well as low opportunity costs to agriculture (Scenario 1), and low property damage costs (Scenario 3).

In general, our findings suggest that targeted re-alignment in the North Devon Biosphere can result in positive net present values. This result is in line with the analysis of natural capital investment opportunities in the UK undertaken by Economics for the Environment Consultancy Ltd, eftec (2015a), which found that the net present value of investment in saltmarsh regeneration across the UK was £730 million (2014 prices) over the next 50 years. In our case, we find a positive change in the net present value generated by the following ecosystem services: carbon sequestration and recreational benefits, relative to re-alignment costs: including lost agricultural production, property damages and the direct costs of re-alignment. Only one site would generate negative annualised net present values if converted to saltmarsh under the assumptions of Scenario 1, and seven sites (~12% of total sites) would generate negative values under Scenario 3. There was substantial heterogeneity in the annualised net present value of sites when converted to saltmarsh: across Scenarios 1 and 3 this value differed by several orders of magnitude. This suggests that prioritising managed re-alignment will offer substantial gains for planners, and result in a more efficient use of resources.

Irrespective of the scenario, we identify four sites that are high priorities for managed re-alignment. The annualised net present value generated by re-alignment at these sites is within the top quartile across all scenarios and there are no properties located in any of these sites. These qualities may make re-alignment in these sites more popular with local communities. Three of the four high-priority sites are located in agricultural areas. If these sites were converted to saltmarsh, some of the principal ecosystem service benefits: namely recreational and carbon benefits, would be widespread, with knock-on health and well-being effects. However, the costs of lost agricultural production would be incurred by a comparatively small number of landowners. This implies that one section of society would disproportionately incur the costs of new saltmarsh areas relative to the benefits. In this case, an equitable decision-making approach would need to be considered, which balanced economic trade-offs with a consideration for the bearers of the cost burden, for example property owners.

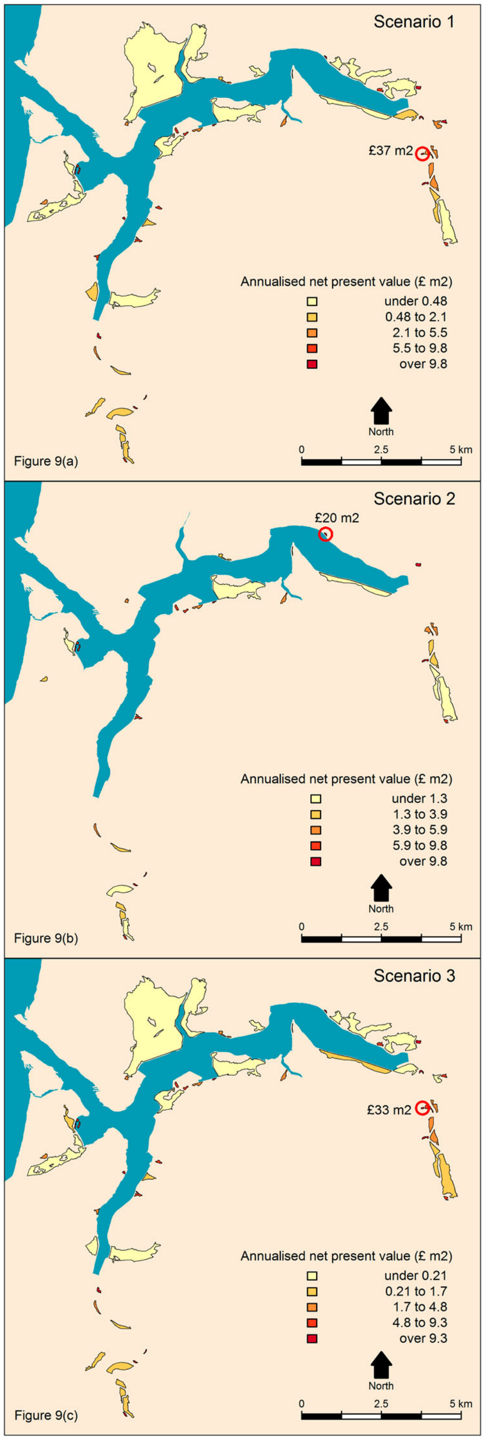

Figure 9. Prioritisation of sites for managed re-alignment of saltmarsh across three scenarios varying in their treatment of property damage: (1) ignoring damages, (2) excluding sites with properties from the analysis, and (3) incorporating a basic assessment of property damages. Prioritisation is based on an assessment of candidate sites' costs: opportunity costs to agriculture, property damages and direct costs (Scenario 3), and benefits: recreational and carbon sequestration, per m^2. The site with the highest annualised net present value per m^2 is circled in red and annualised net present value reported.

This study is confined to the prioritisation of sites by purely economic assessment. However, we emphasise that re-alignment should also be determined by the geomorphology and tidal dynamics of the estuary. Re-alignment in the wrong place can lead to erosion of important areas elsewhere in the system, resulting in no net gain or even loss of upper intertidal habitats such as saltmarsh. Future research should include a geomorphological model as part of the decision support tool. Planners must also be aware that the land where re-alignment is planned may currently be providing valuable freshwater flood storage that will need to be replaced to sustain existing flood defence for communities around the estuary. Other potentially significant non-monetised benefits (or costs) of re-alignment should also be considered. For example, impacts on biodiversity, the productivity of fisheries, and water quality. Re-alignment may also have important implications for landscape-scale processes like habitat connectivity, for example, saltmarsh is thought to be a key habitat for migratory birds (Iwamura et al. 2013; Murray et al. 2014).

An important area for future research is to identify how the condition of saltmarsh (e.g. JNCC 2010) will impact provision of ecosystem services generated by saltmarsh. According to the 2000 Natura assessment (JNCC 2010), 57% of saltmarsh in the UK is in unfavourable condition, with 43% in favourable condition. Natural England, as the UK statutory conservation advisor to Government, has a duty to report on the condition of saltmarsh features within conservation designations every six years. Condition is divided into favourable or unfavourable based on an assessment of habitat extent; physical structure (creeks and pans); vegetation structure (zonation and sward structure), vegetation composition (characteristic species, indicators of a negative trend) and; other negative indicators. The identification of quality indicators (notable species or important, distinctive species) is not mandatory within this process. Further evidence is required as to how the condition of the saltmarsh interacts with the provision of ecosystem services e.g. carbon sequestration. In addition, saltmarsh are particularly sensitive to pressures linked to sea level rise, storm events and human use (including agriculture). Assessments of how condition supports the resilience of saltmarsh and the levels of ecosystem services flows will serve to improve our understanding of how and where to prioritise managed re-alignment.

In conclusion, we outline a comprehensive methodology for identifying priority areas for managed re-alignment of coastal defences based upon consequent costs and benefits. We illustrate this methodology through an application to the North Devon Biosphere Reserve. This, in turn, allows us to demonstrate the flexibility of the approach when faced with a multi-functional environment, such as saltmarsh. Results show that our framework could be used to prioritise managed re-alignment projects and predict the impact on ecosystem service provision of different scenarios of change: including climate change, agricultural policy (e.g. under Brexit) and water quality scenarios. As research is increasingly identifying the importance of saltmarsh for flood defence and the provision of other ecosystem services, our methodology provides the necessary basis for future management of coastal zones. Developing a decision support tool capable of incorporating the flexibility of this methodology would be particularly timely given ongoing and rapid policy change both in response to Brexit and in line with the UK Government's recent commitments to a 25-year plan to improve the environment (H.M. Government 2018).

Note

1. Over long timescales (e.g. >50 years) it is expected that climate change will result in the flooding of some coastal areas. Arguably, this should be incorporated in a social cost benefit analysis of managed re-alignment, for example, by reducing the future value of land. However, when undertaking policy action in the present, the responsible agency has to purchase land at current market prices. Impacts such as the effects of climate change on coastal land will be reflected in market prices only to the extent that those prices incorporate future changes.

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Underlying research materials

The underlying research materials for this article are available upon request from the corresponding author.

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