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Regional assessment of climate change impacts on coastal and fluvial ecosystems and the scope for adaptation

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Abstract Ecosystem changes in floodplains could be a major issue during the twenty-first century as designated habitat areas are affected by climate change and floodplain management options. As part of the RegIS project, a Regional Impact Simulator has been developed to investigate these potential changes. This paper presents the methodologies and results of biodiversity metamodels used within the Regional Impact Simulator for two regions of the UK: East Anglia and North West England. Potential impacts and adaptations to future climate and socio-economic scenarios are analysed for three habitat types in floodplains (saltmarsh, coastal grazing marsh and fluvial grazing marsh) and selected species. An important finding is that management choices, which can be linked to socio-economic futures have a greater potential impact on habitat viability than climate change. The choices society makes will therefore be key to protection and conservation of biodiversity. The analyses also show that coastal grazing marsh is the most vulnerable habitat to sea-level rise, although there is a scope for substituting losses with fluvial grazing marsh. These results indicate that these methods provide a useful approach for assessing potential biodiversity changes at the regional scale, including the effect of different policies.

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1 Introduction

It is increasingly recognised that coastal wetland habitats will become more vulnerable to tidal inundation and loss under future climate change and sea-level rise, both globally (Hoozemans et al. 1993; Nicholls et al. 1999; McFadden et al. 2007), and at national and sub-national scales (Holman et al. 2005a, b; Lee 2001; Gardiner et al. 2007). Climate change is predicted to cause a general decline of valuable intertidal habitat types such as mudflats and saltmarsh (Nicholls et al. 2007); the distinct habitats of coastal and fluvial floodplain grazing marsh, which have often developed due to historic flood management may also be changed, but these systems are also sensitive to flood management (Watkinson et al. 2007). Even if these habitats persist, their constituent species may change due to rising temperatures and/or changing precipitation (Harrison et al. 2006). The aim of this paper is to demonstrate the methods and selected results of a set of coupled metamodels that describe for the first time the coupled-ecosystem-species response to climate change scenarios and socio-economic storylines, using the Regional Impact Simulator;[1] combining landscape scale changes in habitats with species scale changes. The metamodels simulate, in a simplified way, the impacts of future climate change and socio-economic changes on a range of wetland habitats; comprising saltmarsh, coastal grazing marsh and fluvial grazing marsh, as well as representative constituent species, including the effects of a range of adaptation options from do nothing to extensive re-creation up to available limits. Two contrasting regions of the UK are considered: East Anglia with its relatively dry climate, low-lying topography and intensive agriculture; and the North West with its wet climate, uplands dominated by extensive grazing and urbanised lowlands (Holman et al. 2005a, b; Fig. 1). The use of a simplified model, a metamodel, within the Regional Impact Simulator interface is aimed at reducing the time taken for the model to run whilst still returning realistic regional-scale results (Holman et al. 2005a, b).

Under current UK and European legislation (the UK 'Habitats Regulations,' EU 'Habitats Directive' [Council Directive 92/43/EEC] and the 'Birds Directive' [Council Directive 79/409/EEC]) the UK government is required to take appropriate steps to avoid the deterioration of natural habitats in Natura 2000 sites (including Special Protections Areas [SPAs] and Special Areas for Conservation [SACs]; Lee 2001). This policy will become increasingly difficult to adhere to under future climate change and future development pressures. Currently, in East Anglia losses of saltmarsh are estimated at around 60 ha a year (English Nature 2004) and these losses are mainly attributed to coastal squeeze; where coastal habitats are squeezed between a fixed landward boundary and rising sea level (Taylor et al. 2004). However, coastal squeeze is not the only explanation for the recorded coastal saltmarsh losses and it is more likely to be due to a number of both natural and human factors (Van der Wal and Pye 2004): for example, episodic losses of saltmarsh in the greater Thames Estuary may be due to changes in the wind/wave climate (Van der Wal and Pye 2004). In addition, increased saltmarsh erosion may be due to an

[1] The Regional Impact Simulator is the product of the RegIS2 project 'Development of a metamodel tool for regional integrated climate change management'. Its aim was to produce a series of coupled metamodels within a user-friendly interface for a stakeholder-led, regional Integrated Assessment (IA; Holman et al. 2008).

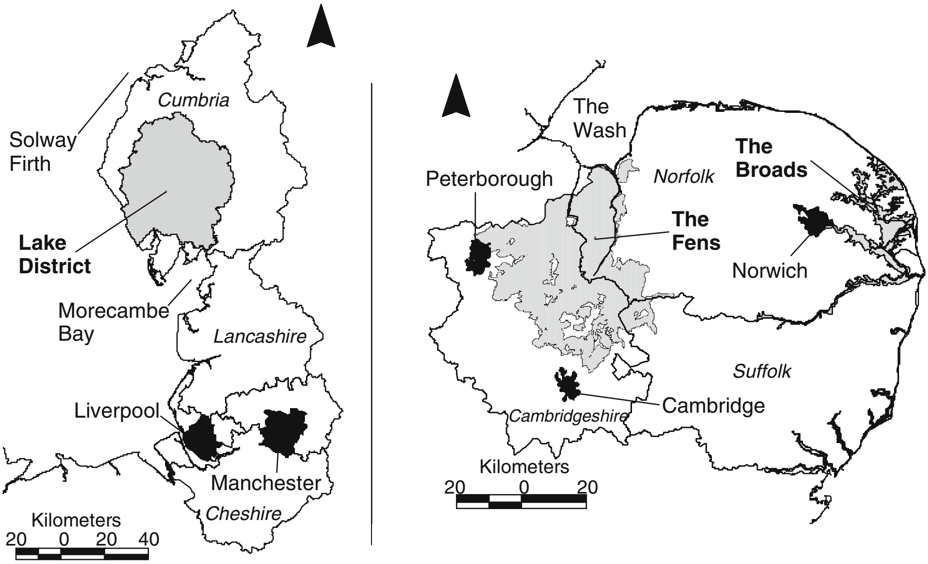


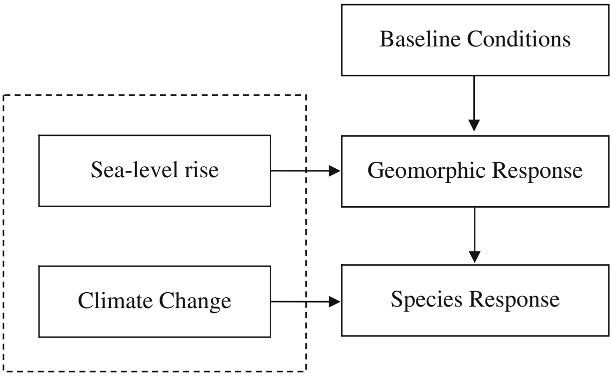
Fig. 1 The study regions: the North West of England (*left*) and East Anglia (*right*) (after Holman and de Vries 2005)

increase in the number of the infaunal polychaete *Nereis diversicolor* and hence an increase in bioturbation and herbivory (Hughes and Paramor 2004; Paramor and Hughes 2004); reduced sediment supply due to protection of coastal cliffs, and changes in the geotechnical characteristics of saltmarsh sediments (Crooks and Pye 2000).

National and regional assessments suggest that the coastal zone and its associated habitat and species could be particularly vulnerable to climate change and sea-level rise (Shackley et al. 1998). This paper explores these potential impacts in the two RegIS regions, using models of coastal impacts and species' responses.

Two modelling methodologies are used to investigate both geomorphic and species responses to climate change (Fig. 2): the flooding metamodel and the SPECIES methodology. The flooding metamodel is described in Mokrech et al. (2008), where regional sea-level rise is combined with extreme water levels (Dixon and Tawn 1997) to predict the increase in flood frequency on the coast, and changes in precipitation are applied to rivers as changes in flow and an increase in flooding frequency. These predicted flooding frequencies are used to determine impacts on habitats, and also to predict the availability of habitat re-creation areas. Other variables, such as sediment and biomass availability, flood defence standards of protection, location of urban development and agricultural land are also taken into account. The datasets used within the flood metamodel are also summarised in Mokrech et al. (2008). The SPECIES (Spatial Estimator of the Climate Impacts on the Envelope of Species) methodology (Pearson et al. 2002; Berry et al. 2003; Harrison et al. 2006) is used to simulate species' responses to the impacts of climate change (e.g. change in temperature and precipitation) within the Regional Impact Simulator. The species' responses are conditional to the existence of habitats; as a

Fig. 2 Investigated responses to climate change in modelling methodologies



habitat disappears due to a geomorphic response, so the associated species disappear as well.

2 Socio-economic scenarios and their impacts on coastal habitats

The socio-economic scenarios were developed within the RegIS project (Shackley and Wood 2001) and updated within the current RegIS2 project using the Foresight project framework (Evans et al. 2004), adjusted to the specifics of the study regions (Holman et al. 2008). The scenarios have been further developed through discussion between the authors to establish storyline attitudes to future conservation of habitats and these have been applied through the metamodel methodology.

Sediment availability is an important factor when forecasting future habitat developments. It is complex to predict due to the variability in sources, and their spatial and temporal patterns (Stoddart et al. 1989; Orford and Pethick 2006). However, an important assumption is made within the metamodel in relation to the impacts of the scenarios and the amount of coastal protection: that a decrease in coastal protection both within and outside each region will lead to an increase in both sediment availability (Nicholls et al. 2005; Orford and Pethick 2006), and accommodation space, through realignment and abandonment. However, the specific mechanisms are not discussed further here.

The four socio-economic scenarios used are: Regional Stewardship (RS); Global Markets (GM); Regional Enterprise (RE) and Global Sustainability (GS) (Lorenzoni et al. 2000; Evans et al. 2004).

The Regional Stewardship storyline is based on a strong emphasis of conserving regional assets even if this is at the expense of regional economic growth, and local natural systems are highly valued assets (Shackley and Wood 2001). There is a limit placed on development in the floodplain and the coastal zone by increasingly strict planning controls; landscape and biodiversity resources are priorities in order to mitigate and recreate what has been lost in the past. As a result of the cost involved in protecting biodiversity there will be limited economic resources available for future capital investment in flood defences or coastal protection measures. It is therefore assumed that sediment availability will be high in the North West and in the northern part of East Anglia, as little coastal protection will inhibit erosion and therefore sediment supply (Nicholls et al. 2005). However, under the prevalent policies and attitudes, vulnerable and less resilient habitats will be recreated inland where possible.

The Global Markets future scenario is potentially the most environmentally damaging. Some biodiversity sites will be protected and maintained but these will be a minority of reserves that compete with others both outside the region and the country. For example, in the North West, the Lake District will be preserved for tourism and economic benefit, but other ecologically valuable areas will suffer from increased urbanisation due to a lack of protection. The provision of flood and coastal defences will be largely privately funded with the government providing a lower standard of protection than currently. This will result in high standards of protection and a 'hold the line' policy only in economically important areas. However, realignment of defences will be through unplanned abandonment rather than strategic management practices. Sediment availability will generally remain low as defences remain in place without strategic decisions to retreat the line of defence.

Under the Regional Enterprise socio-economic storyline the environment is likely to suffer degradation, in part resulting from increasing development in both coastal and floodplain areas. In order to protect these coastal assets that are valuable at a regional scale, a 'hold the line' shoreline management policy is expected (Nicholls and Wilson 2001). It is unlikely under this storyline that habitats will be recreated on anything other than a local scale. Coastal development will occur on cliffed coasts, necessitating the maintenance and perhaps increase of cliff protection measures, which will in turn decrease sediment supply from coastal cliffs to downdrift areas. These attitudes will result in a decrease in sediment availability along the coast, both to neighbouring beaches (Dawson et al. 2008), and fine-grained sediments to habitats such as saltmarsh (Nicholls et al. 2000).

The Global Sustainability storyline implies less socio-economic pressures on habitats and ecosystems than in the more economically focussed storylines. Significant areas of habitats will be created within both coastal and fluvial floodplains, for example by the large scale managed realignment of relatively undeveloped coastal areas and creation of freshwater wetlands in low-lying areas, such as the Fens, in East Anglia (Fig. 1). Measures like these will enhance the resilience of the natural systems, by allowing autonomous adaptation to climate change, including saltmarsh retreat as a response to sea-level rise (Nicholls and Wilson 2001). Any expansion of urban development would be controlled by strict planning regulations, and would only be allowed in areas outside hazard zones, including the coastal and fluvial floodplains, and any areas subject to erosion. In addition, these attitudes will, by the relaxation of defence measures in areas that are not considered highly vulnerable in a national context, increase sediment availability. Sediment availability will be highest in the northern area of East Anglia due to the amount of managed realignment that would be possible and the increased supply from the eroding coasts to the north.

3 Coastal wetland impact assessment

Saltmarsh losses may be caused by two different processes associated with sea-level rise: vertical accretion and lateral erosion (Wolters et al. 2005). Limited vertical accretion of saltmarsh, due to lack of sediments, may not be sufficient to raise the saltmarsh surface in pace with sea-level rise (Nicholls et al. 1999) and the lateral erosion of the seaward edge of saltmarsh may lead to a significant reduction of saltmarsh area (Van der Wal and Pye 2004). The lateral erosion of saltmarsh is a complex process which is influenced by various physical and biological processes and can be simulated only through extensive research and observations. Consequently, as the aim of this study is to develop a simplified model that provides reasonable output in a short run time at the regional scale, the lateral erosion of saltmarsh has not been considered. Moreover, the 1×1 km grid used in this model does not provide the right spatial scale to capture the highly localised process of saltmarsh erosion.

3.1 Saltmarsh habitat change

The wetland impact methodology that is applied within the metamodel is based on the premise that coastal wetland habitats are sensitive to long term sea-level change following Nicholls et al. (1999), Nicholls and Wilson (2001) and Nicholls (2004). The impact on saltmarshes is predicted based on their capacity to respond to sea-level rise by accreting vertically if sediment is available, or by migrating inland if accommodation space is available. If the rate of accretion of the saltmarsh surface is slower than the rate of sea-level rise, the wetland will gradually become submerged for longer periods of time on each high tide, as the relative elevation of the marsh to sea-level decreases. Unless the saltmarsh is able to migrate inland, losses are likely. However, this migration cannot occur if available low-lying areas are defended against coastal flooding by the presence of embankments or dykes, as is presently the norm around the UK coast. Hence, the current potential for wetlands to migrate inland is considerably reduced compared to the situation in earlier geological periods of rapid sea-level rise.

Saltmarshes in areas with a small tidal range are generally more vulnerable to sea-level rise than those in areas with a larger tidal range (as used subsequently by McFadden et al. (2007) in their conceptual model). To capture this behaviour, relative sea-level rise is scaled by tidal range as defined in Eqs. 1 and 2.

$$\mathrm{nTR} = \mathrm{TR}/\mathrm{TR}_{\mathrm{ref}} \tag{1}$$

$$\mathrm{RSLR}* = \mathrm{RSLR}/\mathrm{nTR} \tag{2}$$

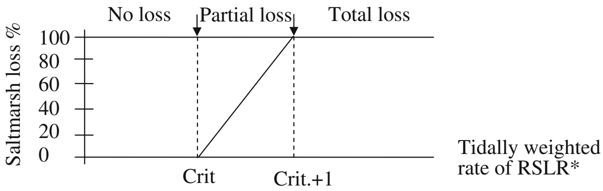
where nTR is the normalised tidal range, TR is tidal range in metres, TR_{ref} is the reference tidal range (1 m), RSLR is the rate of relative sea-level rise and RSLR* is the tidally weighted rate of relative sea-level rise.

The availability of sediment for vertical accretion is parameterised using critical values of RSLR* ($\mathrm{RSLR}^*_{\mathrm{crit}}$), which distinguishes the onset of loss of saltmarsh due to sea-level rise (Fig. 3). The saltmarsh is only lost if the rate of relative sea-level rise (RSLR*) exceeds the critical rate of the saltmarsh vertical accretion ($\mathrm{RSLR}^*_{\mathrm{crit}}$; Nicholls and Wilson 2001):

$$\mathrm{RSLR}^* > \mathrm{RSLR}^*_{\mathrm{crit}} \tag{3}$$

The threshold rate is site-specific and depends on the potential for vertical accretion. If wetland loss is predicted it is estimated as a linear function of the excess RSLR* (Fig. 3). Using this threshold approach captures the non-linear response of wetland

Fig. 3 Representation of the linear model of saltmarsh loss



systems to sea-level rise and the association of increasing tidal range with lower losses. The response of a wetland to long-term sea-level rise is not instantaneous and a 30 year time lag is applied in our calculations.

The threshold values used within the metamodel are given in Table 1. The baseline values come from Nicholls and Wilson (2001), who examined the literature and historic trends of saltmarsh loss. The thresholds associated with future socio-economic scenarios take account of human interference with the coast that is consistent with each storyline. Hence, under Global Markets and Regional Enterprise a decline in sediment availability due to coastal defence is assumed, while under Global Sustainability the opposite trend is assumed.

Accommodation space available for wetlands is assessed based on coastal topography and the presence or absence of sea defences. In areas where migration is possible, wetland losses are assumed to be zero, i.e. wetland migration compensates for any losses due to inundation. In addition, gains may occur due to managed realignment or unplanned coastal abandonment (Nicholls et al. 1999, 2007). Landward migration of saltmarshes over adjacent low elevation land results in the loss of other wetlands currently situated in these locations unless these habitats are also able to migrate landwards. The impacts of this migration on coastal grazing marsh are described in Section 3.2.

3.2 Impacts on coastal grazing marsh

The response of coastal grazing marsh to climate change is dominated by the coastal management decisions predicted under the socio-economic storylines. For example, coastal grazing marsh currently located landward of sea defences would be vulnerable where defences are realigned in order to create saltmarsh, or where defences are abandoned as part of an unmanaged retreat (Watkinson et al. 2007). Under these circumstances an increase in the frequency of tidal flooding may cause unplanned losses of coastal grazing marsh due to an increase of salinity, creating a more salt-tolerant habitat and eventually if tidal flooding continues, saltmarsh. In

Table 1 Critical values of relative sea-level rise ($RSLR^*_{crit}$) for each of the socio-economic storylines, with sediment availability relative to the current baseline conditions

		Baseline	Global sustainability	Global markets	Regional stewardship	Regional enterprise
Sediment availability			Increase	Decrease	Constant	Decrease
North West		0.18	0.18	0.16	0.18	0.17
East Anglia	North	0.18	0.20	0.05	0.18	0.12
	South	0.05	0.10	0.05	0.05	0.05

this context, a flood frequency of once per year or more is assumed to lead to loss of coastal grazing marsh (Nicholls and Wilson 2001).

Concurrently, gains in coastal grazing marsh may occur if agricultural land in the coastal floodplain is subjected to a greater flood frequency, rendering it unsuitable for arable or intensive pastoral agriculture (Fig. 4). This results in potential gains of grazing marsh if the area in question is assumed to remain protected to an appropriate degree.

3.3 Impacts on fluvial grazing marsh

The effect of the changing fluvial flood flow with climate change on the standard of protection is also calculated within the flood metamodel. An increase in peak flow is translated into an increase in the risk of fluvial flooding (for more information see Mokrech et al. 2008). Increased peak river flows resulting from climate change will produce more frequent fluvial flooding, which may cause a decline in fluvial grazing marsh, although this effect will be small. In addition, urban expansion into the fluvial floodplain may contribute to grazing marsh losses. As in the case with coastal grazing marsh, if agricultural land within the floodplain is abandoned or lost through an increase in flood frequency this land may be assumed to be converted to fluvial grazing marsh.

In coastal lowlands, such as the Fens, the flood risk may potentially be exacerbated by the combined effects of sea-level rise and increased fluvial flows to create extreme impacts of climate change. This effect is considered in the flood methodology (Mokrech et al. 2008) and hence influences the results here.

3.4 Impacts of climate change on species

The impacts of climate change on the availability of suitable climate space for four saltmarsh and four coastal and floodplain grazing marsh species were simulated

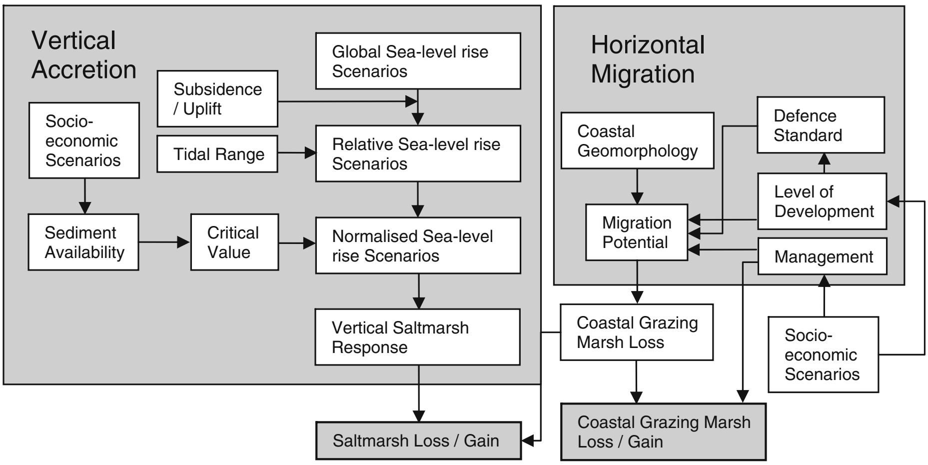


Fig. 4 Methodological framework for coastal wetland impact analysis for saltmarsh and coastal grazing marsh

Table 2 Species modelled for saltmarsh and coastal and floodplain grazing marsh habitats

Habitat and associated species	
Saltmarsh	Coastal and floodplain grazing marsh
Atriplex portulacoides (Sea purslane)	*Ranunculus baudotii* (Brackish water crowfoot)
Blysmus rufus (Flat sedge)	*Ranunculus sardous* (Hairy buttercup)
Puccinellia maritima (common saltmarsh grass)	*Trifolium fragiferum* (Strawberry clover)
Suaeda maritima (Annual seablite)	*Triturus cristatus* (Great crested newt)

(Table 2) using the SPECIES model (Pearson et al. 2002; Berry et al. 2003; Harrison et al. 2006). SPECIES is an artificial neural network model that simulates the bio-climate envelope of species based on five inputs derived from a climate-hydrological process model:

– Growing degree days > 5°C
– Absolute minimum temperature expected over a 20 year period
– Annual maximum temperature
– Accumulated annual soil water deficit; and
– Accumulated annual soil water surplus

The SPECIES model is trained on the observed European distribution of the species at a 0.5° latitude/longitude resolution in order to encompass the climate space that includes the climatic range of future scenarios for the UK. The trained and validated model is then applied at a finer 5 × 5 km spatial resolution to the two case study regions. This is in contrast to the coastal wetland impact metamodel which calculates results at the scale of a 1 × 1 km grid. The SPECIES model has been used on a variety of different species and its application is not limited to wetland species such as those listed here (e.g. Harrison et al. 2006).

The Area Under the Receiver Operating Characteristic Curve (AUC), a measure of the prediction accuracy, is used to statistically test the model performance (Fielding and Bell 1997). The AUC ranges from 0.5 for models with no discrimination ability, to 1 for models with perfect discrimination. The AUC statistics were greater than 0.9 for all species within the Regional Impact Simulator, indicating very good discrimination ability. The predictions of potential suitable climate space for species were combined with the results from the coastal wetland impact assessment by masking out areas of habitat loss and adding areas of habitat gain under future climate and socio-economic scenarios.

3.5 Application of the coastal wetland impact assessment model within the Regional Impact Simulator

The wetland methodology described above is applied within the metamodel to determine the vertical and horizontal migration response of the saltmarsh; the effects of this response in combination with the climate change and socio-economic scenarios determine the effect on the coastal grazing marsh.

The methodology applied within the metamodel is described in Fig. 4. Sea-level rise values are obtained from the UKCIP02 global sea-level rise scenarios (Hulme et al. 2002). The UKCIP02 sea-level rise scenarios propose a smaller rise in sea-level rise than the UKCIP98 scenarios used in the previous RegIS study (Hulme and Jenkins 1998; Nicholls and Wilson 2001), both in terms of the rise in the North

West Atlantic and the regional downscaling. This suggests that the impacts of sea-level rise in this study will be less dramatic than those given previously in terms of flooding and ecosystem change (Nicholls and Wilson 2001). However, the UKCIP02 scenarios incorporate more uncertainties than those presented in UKCIP98 (Hulme and Jenkins 1998). Taking account of variations in climate-related processes that control regional sea level, the possibility of a ±50% additional regional sea-level rise is included, and therefore the worst case sea-level rise under the UKCIP02 scenarios range from 4 to 54 cm by the 2050s (Hulme et al. 2002). In both the North West and East Anglia there are additional regional uplift or subsidence effects (Shennan and Horton 2002) and these are consistent spatially, showing uplift in the North West and subsidence towards the south east of England (see Mokrech et al. 2008 for details by area). The values of sea-level rise used in this study are shown in Table 3.

As described in Section 3.1, the capacity of the saltmarsh to respond to sea-level rise by accreting vertically is a function of the rate of relative sea-level rise and tidal range currently experienced by the saltmarsh. Mean spring tidal ranges in North West vary from 4 to 9 m, with an average of 8.2 m, whilst in East Anglia spring tidal range varies from 2 to 6.5 m, with an average of 3.8 m. The tidal ranges for a number of sites in both regions have been linearly interpolated across each of the regions at the 1 km scale in order to spatially attribute the tidally weighted rate of relative sea-level rise and to calculate the saltmarsh response. The critical values of relative sea-level rise (Section 3.2; Eq. 3) reflect the sediment budget in the area and are used to describe each of the socio-economic scenarios to reflect the different environmental policies (Table 1). A decrease in the critical value indicates a decrease in sediment availability.

Under the present day conditions (baseline; Table 1), critical values for the North West are uniform and reflect a generally positive sediment budget and stable saltmarshes. In East Anglia the baseline critical values vary spatially; in Norfolk the value of 0.18 reflects the positive sediment budget, whilst in Suffolk 0.05 reflects the limited sediment supply and hence more vulnerable saltmarshes. In East Anglia the critical values are linearly interpolated along the coast at the scale of the 1 km grid.

The socio-economic storylines as well as the approach to the management of the coast determine the level of development across the regions, including within the floodplain (Shackley and Wood 2001; Shackley and Deanwood 2003). This information is used in the metamodel to determine which areas are available for managed realignment of flood defences with the aim of creating new habitat. The standard of protection of the current flood defences describes the flooding frequency of the floodplain (see Mokrech et al. 2008) and establishes the likelihood that it would be suitable for the horizontal migration of a wetland (Fig. 4).

Table 3 Sea-level rise default, credible range and extreme limit values, for each of the climate change scenarios

Climate change scenario	Default value (cm)	Credible lower limit (cm)	Credible upper limit (cm)	Extreme lower limit (cm)	Extreme upper limit (cm)
Baseline	0	No credible limit	No credible limit	0	+100
2020s low	+6	+2	+21	0	+100
2020s high	+7	+2	+21	0	+100
2050s low	+14	+4	+45	0	+100
2050s high	+18	+5	+54	0	+100

3.6 Habitat re-creation options

Four adaptive responses are applied to wetland habitats within the metamodel, according to the socio-economic storylines (Table 4). "No planned creation" is essentially a 'do nothing' option, where the effects of climate change will cause the loss of saltmarsh in front of sea defences, and no attempt is made to create habitat, but there may also be a gain of habitat in areas where unplanned retreat occurs through defence failure. "Maintain existing stocks" is the baseline option, implying a continuation of UK policies where under current legislation existing areas of designated habitats must be maintained or compensated like for like if the habitat is lost (Lee 2001). Within the metamodel, this involves systematic creation of habitats to maintain constant habitat area, and is applied to all three habitats of saltmarsh, coastal grazing marsh and fluvial grazing marsh. Under the "double existing stocks" option the aim is to have doubled the present day area of each of the three habitats by 2050s, and under "maximum creation" the maximum habitat area is to be achieved by 2050s. Hence, these options cover the full range of possible responses including rather radical options compared to present practise.

It is assumed within the metamodel that any gains of saltmarsh occurring within each 1×1 km grid only occupy 50% of the area available. The remaining 50% of the area is assumed to be converted to tidal flats or channels (after Lee 2001). The re-creation options described above are applied within the flood metamodel under the following set of rules and statements:

3.6.1 No planned creation option

1. Saltmarsh
   - Saltmarsh will migrate inland at the expense of coastal grazing marsh due to sea-level rise, through increased flooding frequency.
2. Coastal grazing marsh
   - Coastal grazing marsh will be lost where there is increased urban development in the floodplain.
   - Frequent flooding (>once per year) will result in the conversion of coastal grazing marsh into saltmarsh.
3. Fluvial grazing marsh
   - Fluvial grazing marsh will be lost where there is increased urban development in the floodplain.
   - Frequent flooding (>once per year) will result in the conversion of fluvial grazing marsh into fen and marsh habitats.

Table 4 Habitat re-creation options according to socio-economic scenario

Socio-economic storylines	Baseline	Global sustainability	Global markets	Regional stewardship	Regional enterprise
Habitat creation options	Maintain existing stocks	Double existing stocks	No planned creation	Maximum creation	No planned creation

3.6.2 Planned creation of habitat options

The planned creation options for the habitats of saltmarsh and coastal grazing marsh are controlled geographically by limiting the distance inland to which defences are relocated. Under the 'double existing habitat' option, defences are relocated within a zone up to 10 km from the coastline (defined as the open coast or estuary shoreline), and under the 'maximise the existing habitat' option a larger coastal strip is made available within a zone of up to 15 km from the coast. This is a simplification of the effects of the limit of tidal incursion. Both are, however, also limited to the extent of the tidal floodplain. Within the floodplain, saltmarsh is limited to the area seaward of the defences and coastal grazing marsh will only be created or maintained landward of the defences. The statements above relating to the no planned creation options apply in addition to the following:

1. Saltmarsh
   - If the urban area within the tidal floodplain in a specific grid cell amounts to less than or equal to 1% of the area, all the area within the tidal floodplain will be converted to saltmarsh. Any area of coastal grazing marsh within the area will be lost.
   - If the urban area within the tidal floodplain in a specific grid cell amounts to greater than 1% of the area, it is assumed to be protected and will remain in-situ.
   - Only saltmarsh that is sustainable under the future climate change scenario is considered (i.e. if the saltmarsh created is predicted to be lost within the timescale of the modelling, it is assumed not to have been created).
2. Coastal grazing marsh
   - If the urban area within the tidal floodplain in a specific grid cell amounts to less than or equal to 1% of the area, the urban area within the tidal floodplain will be converted to coastal grazing marsh if inland of defences.
   - Areas of grass or arable land within the tidal floodplain will be converted to coastal grazing marsh, if inland of defences.
3. Fluvial grazing marsh
   - Areas for the creation of fluvial grazing marsh are defined by the fluvial floodplain and where the fluvial and tidal floodplains overlap (East Anglia only).
   - If the urban area within the defined floodplains in a specific grid cell amounts to less than or equal to 1% of the area, the urban area within the floodplain will be converted to fluvial grazing marsh.
   - Areas of grass or arable land within the defined floodplain will be converted to fluvial grazing marsh.

4 Results of the habitat re-creation and species' climate space analysis

The combinations of climate change and socio-economic scenarios examined in this paper are listed in Table 5. Under the socio-economic scenarios within the interface 'Existing upgrade' is the default variable for flood defences, and this is the

Table 5 Climate change and socio-economic scenario combinations applied to the habitats

Scenario number	Climate scenario	Socio-economic storyline	Flooding variable	Additional variables (other variables interface default unless stated)
1	2050s low	Global markets	Existing upgrade	Default sea-level rise (14 cm)
2	2050s high	Global markets	Existing upgrade	Default sea-level rise (18 cm)
3	2050s high	Regional stewardship	Existing upgrade	Default sea-level rise (18 cm)
4	2050s high	Global markets	Existing upgrade	Highest sea-level rise (+54 cm)
5	2050s high	Global markets	No upgrade	Highest sea-level rise (+54 cm)
6	2050s high	Global markets	Existing upgrade	Default sea-level rise (14 cm) Highest annual temperature change (+3.5°C) Highest winter precipitation (+21%) Lowest summer precipitation (−20%)

implementation of current government policy (MAFF 1999). However, the options of 'no upgrade' and 'enhanced upgrade' can also be applied. Under the no upgrade option it is assumed that the flood defences are not upgraded from the baseline conditions and the corresponding standard of protection will decrease over time with climate change. The enhanced upgrade option is not included in the current analysis and will not be examined here, however, for more information on the defence parameters and their application within the metamodel see Mokrech et al. (2008). The regional results are presented in Tables 6, 7, 8 and 9 and Figs. 5, 6, 7, 8, 9, 10, 11 and 12.

For the purposes of this paper two contrasting socio-economic storylines are examined: Global Markets and Regional Stewardship. Under the Global Markets socio-economic storyline creation of habitats is not planned, and the default is

Table 6 Habitat stock and change results for the scenarios listed in Table 5 for East Anglia

Scenario	Saltmarsh			Coastal grazing marsh			Fluvial grazing marsh		
	Area (ha)	Change relative to baseline		Area (ha)	Change relative to baseline		Area (ha)	Change relative to baseline	
		ha	Percent		ha	Percent		ha	Percent
Baseline	4,259			15,360			13,964		
1	4,170	−89	−2	15,281	−79	−1	13,188	−776	−6
2	4,107	−152	−4	15,281	−79	−1	11,431	−2, 533	−18
3	16,121	11,862	279	48,491	33,131	216	188,607	174,643	1,251
4	3,586	−673	−16	15,162	−198	−1	11,381	−2, 583	−19
5	10,313	6,054	142	1,760	−13,600	−89	10,085	−3, 879	−27
6	4,107	−152	−4	15,281	−79	−1	10,729	−3, 235	−23

Table 7 Changes in suitable climate space and habitat under the scenarios listed in Table 5, using 5 × 5 km cells

Species	Scenario													
	Base		1		2		3		4		5		6	
	No. of cells	% change from base	No. of cells	% change from base	No. of cells	% change from base	No. of cells	% change from base	No. of cells	% change from base	No. of cells	% change from base	No. of cells	% change from base
Saltmarsh														
A. portulacoides	56		58	4	58	4	93	66	58	4	90	61	58	4
P. maritima	58		58	0	58	0	94	62	58	0	90	55	58	0
S. maritima	57		58	2	58	2	94	65	58	2	90	58	58	2
Grazing marsh														
R. baudotii	233		189	−19	227	−3	486	109	226	−3	173	−26	219	−6
R. sardous	233		183	−21	206	−12	441	89	205	−12	152	−35	219	−6
T. fragiferum	233		185	−20	227	−3	486	109	226	−3	173	−26	222	−5
T. cristatus	233		189	−19	167	−28	388	67	166	−29	116	−50	11	−95

Table 8 Habitat stock and change results for the scenarios listed in Table 5 for the North West

Scenario	Saltmarsh			Coastal grazing marsh			Fluvial grazing marsh		
	Area (ha)	Change relative to baseline		Area (ha)	Change relative to baseline		Area (ha)	Change relative to baseline	
		ha	Percent		ha	Percent		ha	Percent
Baseline	9,856			22,753			16,360		
1	10,372	516	5	21,582	−1,171	−5	15,992	−368	−2
2	10,372	516	5	21,582	−1,171	−5	15,992	−368	−2
3	19,020	9164	93	18,986	−3,767	−17	42,167	25,807	158
4	10,372	516	5	21,582	−1,171	−5	15,992	−368	−2
5	10,412	556	6	21,504	−1,249	−6	15,992	−368	−2
6	10,372	516	5	21,582	−1,171	−5	15,992	−368	−2

for flood defences to be upgraded over time using current UK government policy guidance (MAFF 1999). This is in contrast to the Regional Stewardship storyline, where the metamodel includes the attempt to maximise the area of saltmarsh and grazing marsh, including creation, over each of the regions as a whole.

4.1 East Anglia

Under scenarios 1 and 2, which compare the 2050s Low and 2050s High climate change scenarios, there is a net decrease in the area of all habitats in East Anglia (Table 6). The decrease in the area of saltmarsh occurs as the outer marshes are lost due to the increasing frequency of tidal inundation. Landward migration of saltmarsh areas also leads to a decline in coastal grazing marsh. However, the loss of coastal grazing marsh in scenario 2 does not increase, indicating that the rate of saltmarsh

Table 9 Changes in suitable climate space and habitat for the scenarios listed in Table 5 for the North West, using 5 × 5 km cells

Scenario	Species							
	No. cells	% change from base	No. cells	% change from base	No. cells	% change from base	No. cells	% change from base
Saltmarsh	*A. portulacoides*		*B. rufus*		*P. maritima*		*S. maritima*	
Base	82		34		85		85	
1	92	12	2	−94	93	9	93	9
2	93	13	1	−97	93	9	93	9
3	139	70	1	−97	139	64	139	64
4	93	13	1	−97	93	9	93	9
5	94	15	1	−97	94	11	94	11
6	93	13	0	−100	93	9	93	9
Grazing marsh	*R. baudotii*		*R. sardous*		*T. fragiferum*		*T. cristatus*	
Base	192		171		148		124	
1	189	−2	183	7	185	25	184	48
2	191	−1	184	8	186	26	154	24
3	576	200	557	226	552	273	497	301
4	191	−1	184	8	186	26	154	24
5	191	−1	184	8	186	26	154	24
6	56	−71	181	6	186	26	13	−90

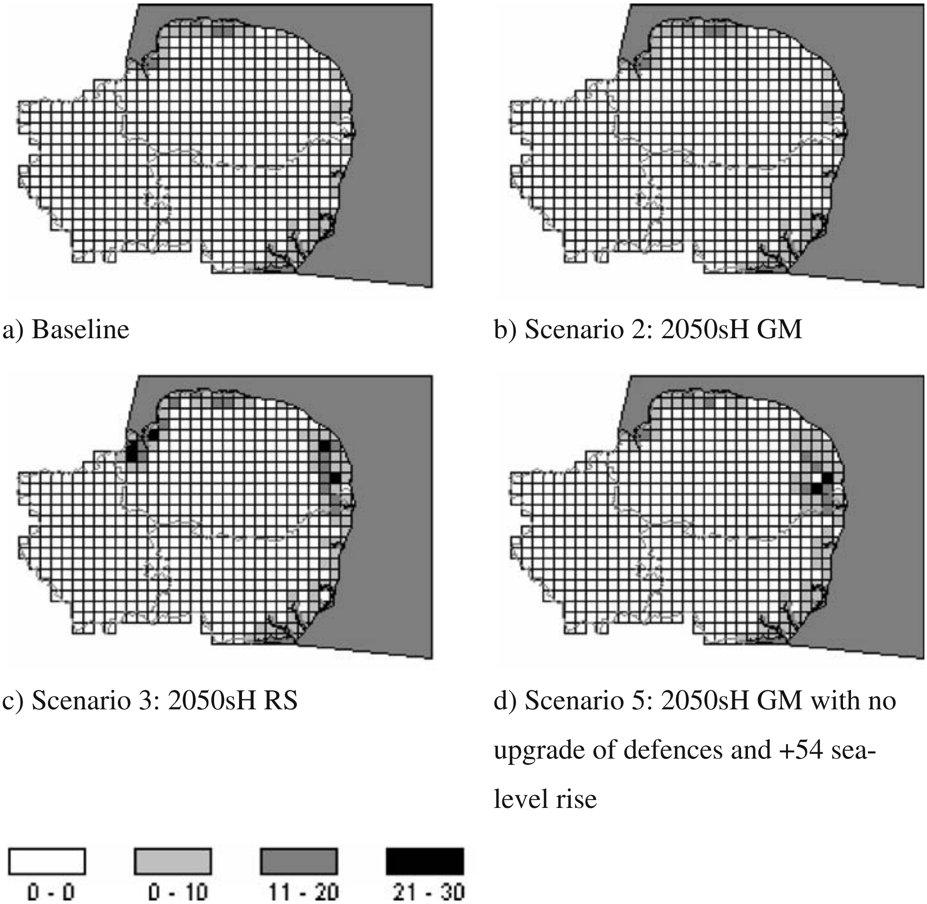
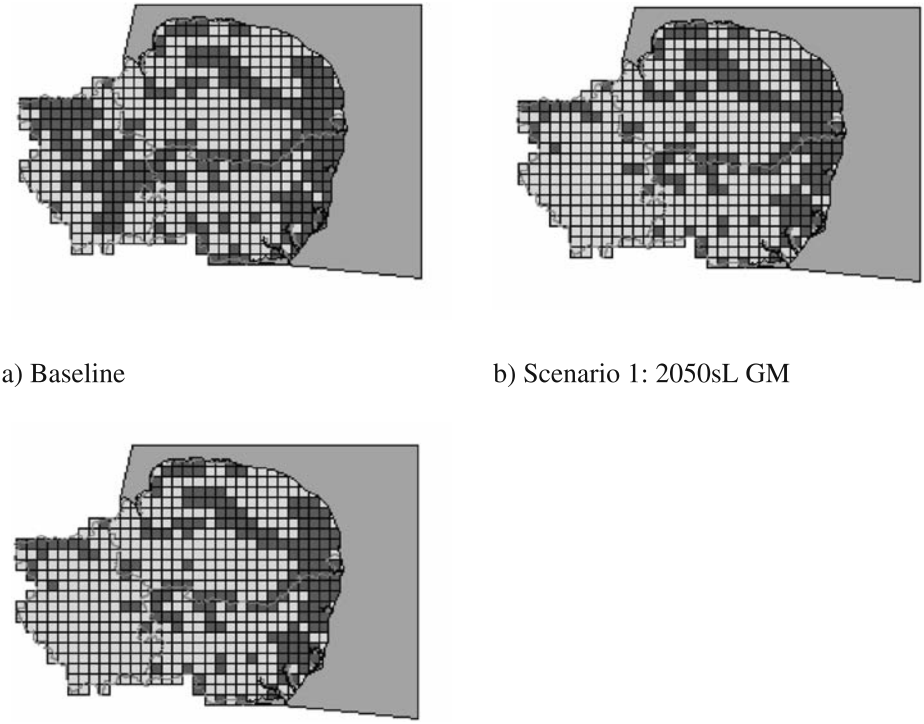


Fig. 5 Results for saltmarsh habitat for East Anglia under scenarios from Table 5. Key refers to percent of land in each grid square

loss due to sea-level rise is greater than its ability to migrate landward. The greatest loss of saltmarsh is from Suffolk (Fig. 5), which follows present trends, and is to be expected as the critical value of relative sea-level rise is lower in Suffolk than in other parts of the region (Table 3).

Under scenarios 1 and 2, two saltmarsh species, *A. portulacoides* and *S. maritima*, show a slight expansion in range (Table 7) due to the addition of climate space in southern Suffolk. *B. rufus* is a northern saltmarsh species which is not found in East Anglia and thus has been omitted from the analysis.

Losses of fluvial floodplain grazing marsh result from increases in fluvial flows, which, despite the continuing upgrade of flood defences, result in a decrease in the standard of protection and therefore an increase in flood frequency over time. As the flood frequency increases fluvial grazing marsh is converted to fen or marsh habitat. Much higher losses are experienced under the High climate scenario (scenario 2), due to the increase in winter fluvial flows when compared to scenario 1.



a) Baseline

b) Scenario 1: 2050sL GM

c) Scenario 2: 2050sH GM

Fig. 6 Changes in suitable climate space and habitat for *Triturus cristatus* in East Anglia under scenarios from Table 5

T. cristatus loses around 28% of suitable climate space and habitat under scenario 2 (Fig. 6) reflecting changes in both the availability of suitable climate space (Table 7) and habitat (Table 6). The losses largely occur in Cambridgeshire, due to the loss of suitable climate space. The same is true for *R. sardous*, but for the other two species *R. baudotii* and *T. fragiferum*, the changes are driven by loss of habitat.

These results can be contrasted with those for a 54 cm sea-level rise under scenarios 4 and 5. Scenario 4 includes upgrade of the flood defences at the UK Government recommended allowance (MAFF 1999) of 6 mm/yr, a total allowance increase of 300 mm, whereas under scenario 5 the lack of upgrade of the defences implies that the standard of protection of defences will gradually decrease with increased sea-level rise and fluvial flows. Under scenario 4 losses of saltmarsh (Table 6; 673 ha) are experienced; there is also some inland migration of saltmarsh as for the more moderate sea-level rise scenario (scenario 1), as flood frequency increases and coastal grazing marsh is assumed to be lost to saltmarsh. However, there is some increase in the area of coastal grazing marsh further inland as higher flooding frequencies inundate agricultural land. The decrease, 13,000 ha, in area of coastal grazing marsh is much larger in scenario 5 directly related to the decrease in the standard of flood protection. Rises in sea level with concurrent reductions

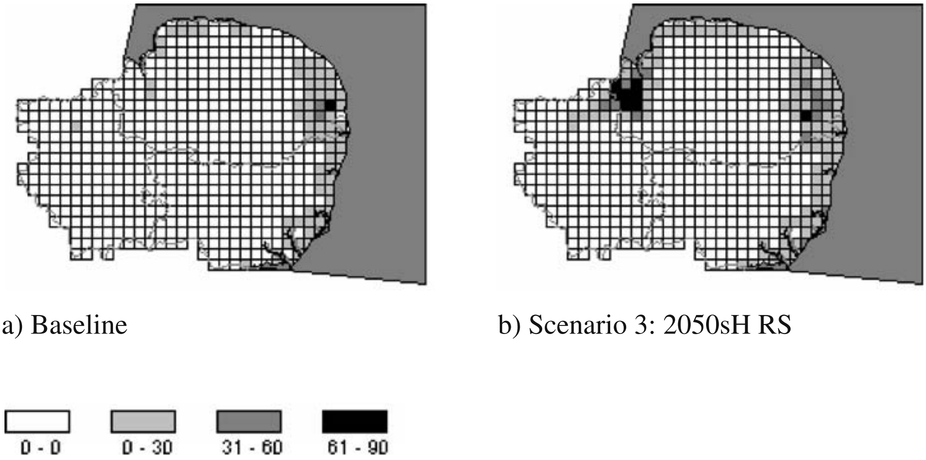


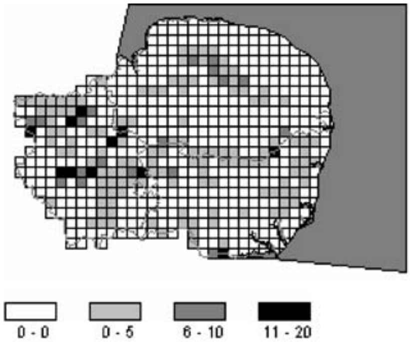
Fig. 7 Results for coastal grazing marsh habitat for East Anglia under scenarios from Table 5. Key refers to percent of land in each grid square

in the standard of protection, large areas of coastal grazing marsh will flood more frequently, and within the metamodel will be assumed to become saltmarsh and mudflats. This can clearly be seen in Fig. 5f as the amount of saltmarsh on the coast decreases but increases further inland, mainly in the Broads area of Norfolk.

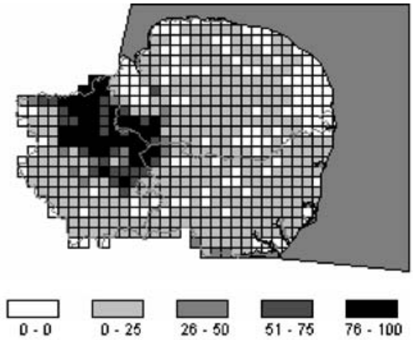
In contrast, the coastal and floodplain grazing marsh species show losses of suitable climate space under both scenarios, and significant decreases are experienced by *T. cristatus* (Fig. 6) and *R. sardous* (Table 7). Fluvial grazing marsh losses under scenario 5 (Fig. 8c) are found where tidal and fluvial floodplains overlap. Only a small amount is due to the increase in sea-level rise as tidal flood frequency increases and defences gradually fail. More fluvial grazing marsh is lost as the standard of protection of fluvial defences decreases over time, particularly where defence standards are currently low, such as parts of the Cambridgeshire Fens and in southern parts of Suffolk (Fig. 8c).

Under scenario 3, the 2050s High climate change scenario and Regional Stewardship socio-economic storyline, which includes the habitat re-creation scenario to attempt to maximise the area of habitat over the region, the area of saltmarsh is increased by the realignment of flood defences inland. In Fig. 5c it can be seen that the increases in saltmarsh stocks take place on the North Norfolk coast, in the Fens and the Broads, where large tidal floodplains exist. There is little increase in Suffolk due to the limited area in the tidal floodplain and the greater vulnerability of saltmarshes in this area to sea-level rise. There are also large increases in the area of coastal grazing marsh in both the Fens and the Broads areas, Fig. 7b, due to conversion of low density urban areas and agricultural land to grazing marsh.

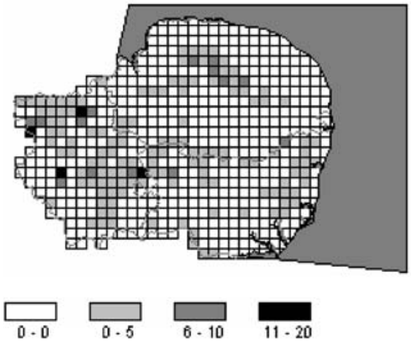
The increases in the area of fluvial grazing marsh under this scenario are very large, from almost 14,000 to over 188,000 ha and are due to the availability of much of the fluvial floodplain, through the conversion from arable and pastoral agricultural land and in areas with low urban density. Much of the area of the Fens



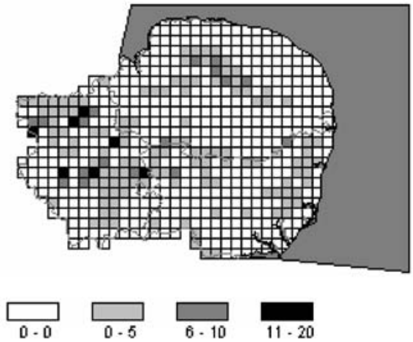
a) Baseline



b) Scenario 3: 2050sH RS



c) Scenario 5: 2050sH GM with no upgrade of defences and +54 sea-level rise

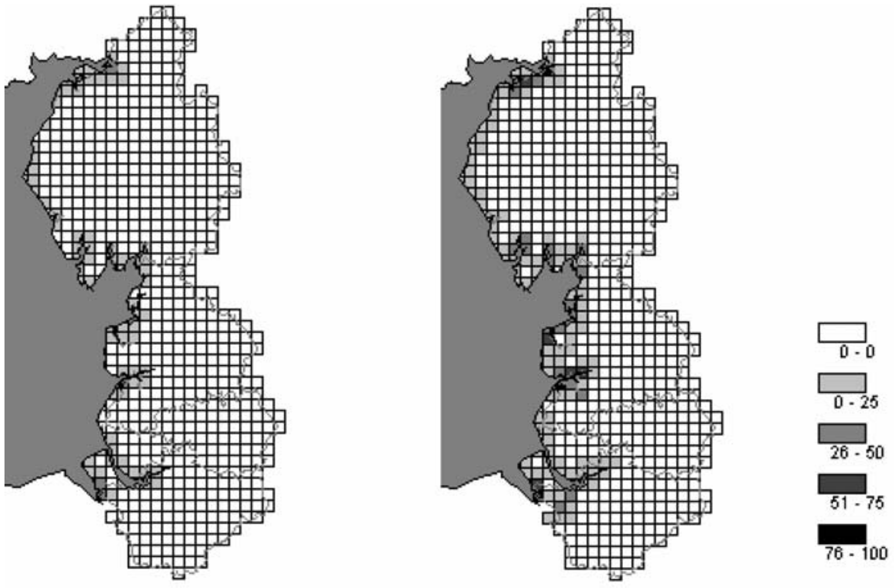


d) Scenario 6: 2050sH GM sea level rise of 54 cm with more extreme climate changes

Fig. 8 Results for fluvial grazing marsh habitat for East Anglia under scenarios from Table 5. Key refers to percent of land in each grid square

in Cambridgeshire and Norfolk is converted to fluvial grazing marsh, reflecting the extent of the fluvial floodplain, the present dominance of agricultural land in this area and the current low urban density (Fig. 8b).

Under scenario 6, which includes extreme changes to temperature and precipitation, there are no additional losses of saltmarsh or coastal grazing marsh. There are however, greater losses of fluvial grazing marsh (Fig. 8d). This is attributed to the increased winter precipitation causing a rise in Q_{med} (Henriques et al. 2008), and consequently an increase in fluvial flooding frequency (Mokrech et al. 2008). The fluvial grazing marsh will be lost to fen or lowland bog. There are small losses in three of its associated species, but *T. cristatus* suffers very high losses as a result of decreases in combined suitable climate space and habitat (Fig. 6d).



a) Baseline b) Scenario 3: 2050sH RS

Fig. 9 Results for saltmarsh habitat for the North West under scenarios from Table 5. Key refers to percent of land in each grid square

4.2 North West

In the North West region, saltmarsh achieves a net gain (516 ha; Table 8) for both scenarios 1 and 2, at the expense of coastal grazing marsh. The gains are explained within the model by the assumed higher sediment availability on the coast of the North West and the high tidal range which reduces the impacts of sea-level rise. However, at the species level *B. rufus*, a northern saltmarsh species, loses almost all climate space by the 2050s (Table 9). As there is no planned creation of habitats under the Global Markets scenario, the loss of coastal grazing marsh is attributed to an increase in flooding frequency in some relatively undeveloped areas in Cumbria and Lancashire, mostly at the heads of estuaries, where some of the area of loss becomes saltmarsh (Fig. 10b).

The available area results for both scenarios 1 and 2 are the same for all habitats (Table 8). For the saltmarsh and coastal grazing marsh this is because the critical value of relative sea-level rise leading to wetland loss is not exceeded in either case. The losses of coastal grazing marsh are only in areas where the defences are of a very low standard in the baseline conditions or where no defence is deemed necessary from the land use classification (MAFF 1999; Mokrech et al. 2008). However, the coastal and floodplain grazing marsh species show an increase in suitable area (Figs. 11b and 12b), despite the losses in habitat areas (Fig. 10b), reflecting a gain in climate space. The same gains are seen for scenarios 4 and 5.

These results can be compared with results for an extreme sea-level rise of 54 cm by the 2050s, under scenarios 4 and 5. Increased losses of coastal grazing marsh

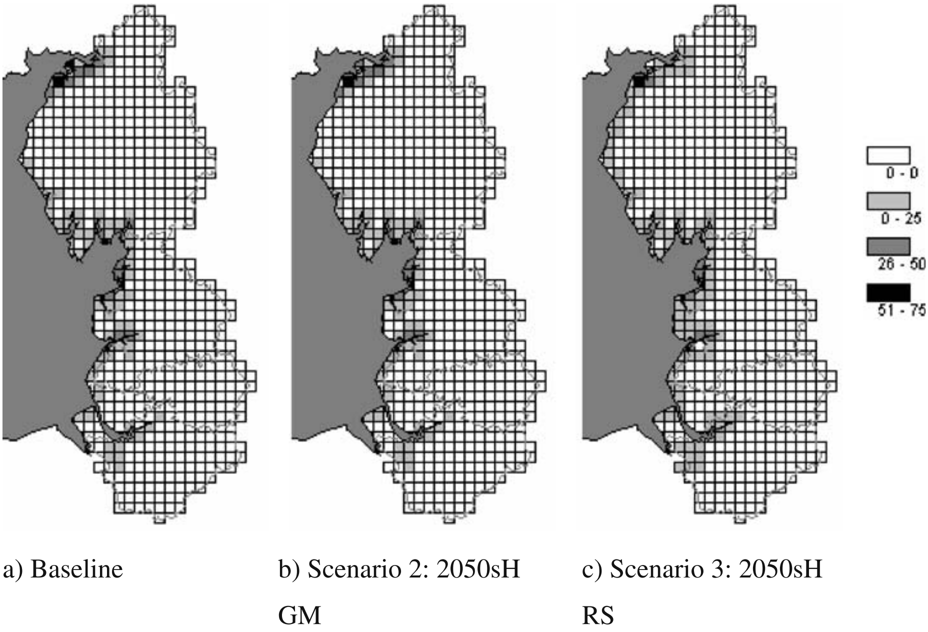


Fig. 10 Results for coastal grazing marsh habitat for the North West under scenarios from Table 5. Key refers to percent of land in each grid square

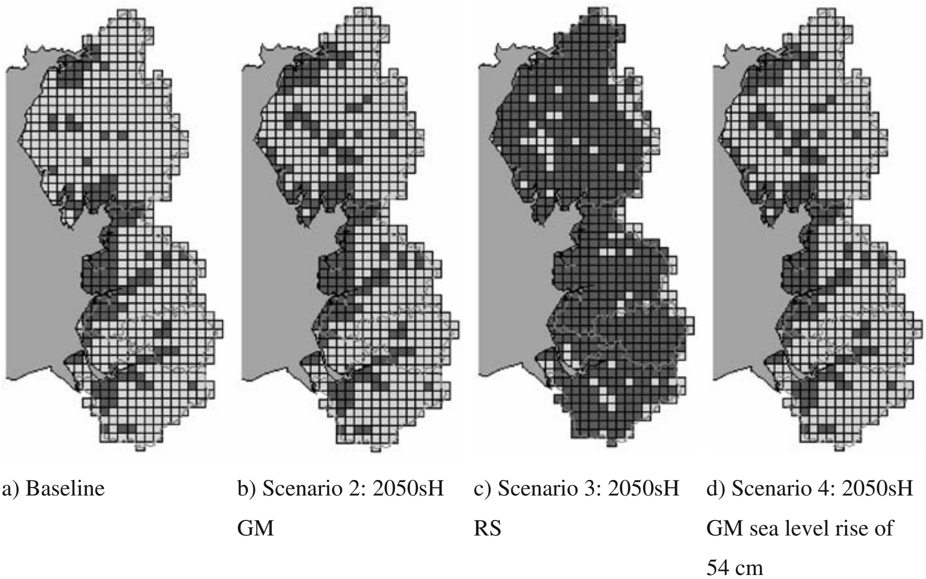
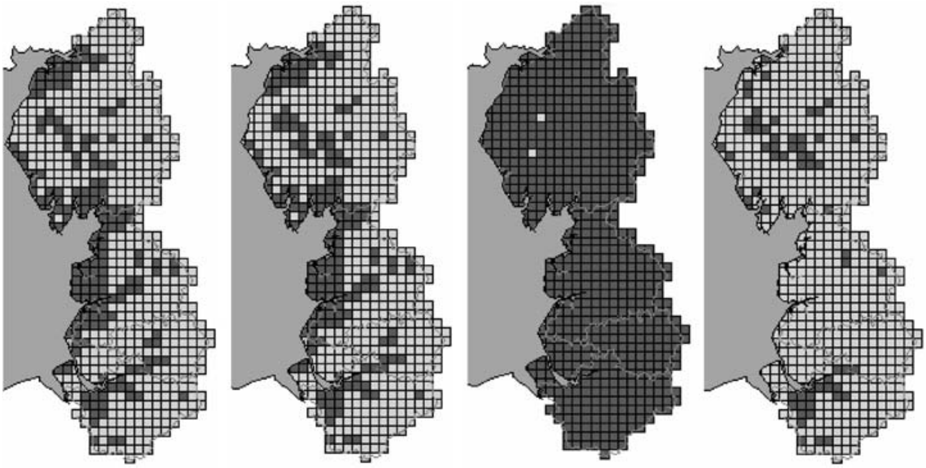


Fig. 11 Changes in suitable climate space and habitat for *Trifolium fragiferum* in the North West under scenarios from Table 5



a) Baseline b) Scenario 2: 2050sH GM c) Scenario 3: 2050sH RS d) Scenario 6: 2050sH GM sea level rise of 54 cm with more extreme climate changes

Fig. 12 Changes in suitable climate space and habitat for *Ranunculus baudotii* in the North West under scenarios from Table 5

result only when flood defences are not upgraded (scenario 5), indicating that as the standard of protection of defences decreases over time flooding of the coastal grazing marsh allows gradual conversion to saltmarsh. It can be seen from the results (Table 8) that the loss of coastal grazing marsh is approximately double the gain in saltmarsh, and this is due to the metamodel assumption that only 50% of the area becomes saltmarsh, with the rest being mudflat and tidal channels.

The loss of fluvial grazing marsh (368 ha) under the Global Markets scenarios is due to increased fluvial flows and the consequent increase in flood frequency. This affects areas with low standard of protection flood defences or some rural areas with no defences at all. Again, the habitat losses are found in parts of Cumbria and Lancashire that are rural or semi-rural and hence do not require extensive flood defence systems. No additional losses are found under scenarios of increased sea-level rise as, in the North West region, the Indicative Floodplain Map used does not include any areas of overlap between fluvial and tidal floodplain and it must be assumed that under scenario 5, the lack of any upgrade of flood defences has minimal effect.

Under scenario 3, the High climate change scenario and Regional Stewardship socio-economic storyline, the aim is to maximise habitat areas. As can be seen from Table 8 and Figs. 9b and 10c there is a large increase in saltmarsh (9,164 ha), but a decrease in coastal grazing marsh (3,767 ha). The increase in saltmarsh is along much of the North West coast (Fig. 9b), where it is possible to realign defences allowing marsh to migrate inland. There is a smaller increase than in East Anglia due to the smaller extent of the tidal floodplain. The decrease in coastal grazing marsh is mainly through conversion to saltmarsh as the tidal flood frequency increases, defences are realigned landward and a lack of space for re-creation within the narrow tidal floodplain. The large increase in saltmarsh area does not result in proportionately large increases in suitable areas for species at the 5 km scale, as there are comparatively few 5 km cells from which the species are absent. This is in contrast to the coastal and floodplain grazing marsh species, where the suitable area increases between 200% and 300%, mostly in the fluvial floodplain, where it is taking the place of agricultural land and areas of low urban density (Figs. 11c and 12c).

Although, in scenario 6, using extreme values of precipitation and temperature change does not alter the results for any of the habitats, there is a variable species' response, based on changes in suitable climate space. This leads to *R. baudotii* and *T. cristatus* experiencing losses, especially in the western part of the region (Fig. 12d). Changes are not expected for the intertidal habitats, but the lack of any change in area of fluvial grazing marsh would suggests either the Q_{med} does not change sufficiently to increase the flooding frequency, and/or the standard of protection is adequate to protect the habitat from increased flooding.

5 Discussion and conclusions

It is apparent from the results that management choices can have more effect on habitats and their re-creation than future changes in climate. Currently, there are insufficient areas for the re-creation of habitats that are predicted to be lost under future sea-level rise, however, this could be mitigated by the provision of more suitable areas. Specific examples include subjecting agricultural land and low density urban areas to increased flooding frequencies through removal or abandonment of defences, or relocation of properties. The conversion of both these areas to coastal and fluvial grazing marsh through an increase in flooding frequency is subject to the adaptation choice that these areas will not be protected to the same degree as densely urbanised areas. For example, under the Global Markets scenario it is assumed that arable land would not be protected, as in the global context the retention and protection of these areas would be uneconomic.

There is intense competition between saltmarsh and coastal grazing marsh for space in the intertidal zone, where coastal squeeze is causing a decline of saltmarsh, and coastal grazing marsh is restricted to protected land within the coastal floodplain which is also suitable for saltmarsh re-creation. Although the development and re-creation of intertidal habitats are too complex processes because of relevant physical and biological processes (Pontee 2003), two simple assumptions are made within the flooding metamodel: the increases in flooding frequency of coastal grazing marsh will lead to a transition to saltmarsh; and 50% of the land made available through managed realignment or abandonment will become saltmarsh. The assumption in the metamodel that a once per year flood frequency or more will lead to loss of coastal grazing marsh may be accurate over the long term, but it is unlikely that areas affected will automatically become saltmarsh at this flooding frequency, however, it is a recognised limitation of the model that without the use of elevation data this cannot be determined accurately. This may result in overestimation of the area of saltmarsh that can be created. At the regional scale of the Simulator the results provide a good indication of which might be created, which needs to be followed up with more detailed analysis (e.g. Gardiner et al. 2007).

A comparison of the results for the two regions demonstrates the difference that the critical value of relative sea-level rise has on the viability of coastal habitats under future sea-level rise. The North West generally has higher sediment availability and larger tides than East Anglia, reflected in the current condition of less threatened habitats, and lower predictions of future losses. Hence, the pressure for a policy of managed realignment is lower in the North West than East Anglia, where saltmarsh decline is a lesser problem. Within East Anglia, Suffolk is experiencing higher losses of saltmarsh in comparison to Norfolk, due to assumed lower sediment availability.

Competition for space ultimately leads to the loss of grazing marsh over the 2050s timescale due to the difficulties of maintaining coastal grazing marsh in-situ. The adaptation response represented in the Simulator is the creation of fluvial floodplain grazing marsh as a replacement for coastal grazing marsh. The creation of both coastal and fluvial grazing marsh assumes that management will be undertaken to preserve these habitats, through the provision of some defences or protection and active grazing management. These aspects are not included in the metamodel and under which socio-economic scenarios this kind of management is most likely has not been investigated.

The assumption that the floodplain will not expand with sea-level rise or increased fluvial flows is a limitation of the current methodology and data, as it is not possible to predict the future extent of the hazard zone within the Regional Impact Simulator run-times and the habitats must therefore be limited to the present floodplain. However, this is a reasonable assumption at regional scale. It is more of an issue in East Anglia where the topography is generally flatter and there is more potential for an increase in the extent of the floodplain.

The results for the species' suitable climate space not surprisingly largely mirror the changes in their habitat, with saltmarsh species in both regions showing a similar, although often small, positive response to climate change, due to the increase in habitat area through the migration of saltmarsh inland. This suggests that, in these two regions as a whole, saltmarsh is not a subject of conservation concern but losses could occur locally, where hard defences prevent inland migration. The coastal and floodplain grazing marsh species, however, show a more variable response, with differing degrees of loss under the 2050s Global Market scenarios in East Anglia, while the North West experiences mostly gains. In both areas the amount of change is primarily dependent on the degree and location of habitat change. This suggests that the habitat is more sensitive to the modelled changes.

Climate does, however, play a role in affecting the changes in available suitable area, with *T. cristatus* and *R. sardous* appearing particularly sensitive to changes in climate space in both regions and the potential loss of *B. rufus* in the North West is driven by climate change. For the remainder of the species, changes in habitat availability appear more important and this suggests that adaptation, through habitat re-creation, as demonstrated in this paper, is an important measure for facilitating species' adjustment to climate change.

The aim of this metamodel analysis was to examine potential impacts and adaptations of three habitat types and associated species to future climate and socio-economic change. An important finding is that the different socio-economic futures appear to have a greater potential influence on the habitats than the climate change scenarios, especially in East Anglia. It is apparent that it may be possible to maintain saltmarsh if appropriate management and adaptation options are adopted. However, a key habitat that is vulnerable to both socio-economic and climate changes is coastal grazing marsh and these findings agree with the results from the RegIS study (Nicholls and Wilson 2001; Lee 2001). To preserve large areas of this habitat in-situ may not be possible over the 2050s timescale and future effort may have to concentrate on creating fluvial grazing marsh as a comparable habitat (as argued by Gardiner et al. 2007 for cell 5). The creation of grazing marsh and the simultaneous restriction of development in the fluvial floodplain (as demonstrated by the Regional Stewardship socio-economic storyline) would be appropriate in light of current pressures on flood defences and increasing flood risk.

The Regional Impact Simulator allows the incorporation of both planned and reactive adaptation; planned adaptation in the form of allowances for sea-level rise in flood defences under current UK Government policy (MAFF 1999) and also the enhancement of defences; and habitat creation as reactive adaptation in response to losses through climate change associated with both increased fluvial flows and sea-level rise. At the regional scale the use of the metamodels and the Regional Impact Simulator affords a realistic assessment of the opportunities for creation of habitats, but the metamodel is limited by the data currently available and the data that can be considered within the methodology.

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