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# Exploring the Role of Strategic Place-Based Risk Assessment as a Framework to Support System-Based Climate Adaptation Planning

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**Key Points:**

- Place-based evidence is vital to understand historic, current, and future climate vulnerabilities and guide effective adaptation
- Urgent near-term action and radical long-term approaches are needed to ensure adaptation is sustainable in the UK Fens
- The framework offers guidance for short- and long-term adaptation planning. Transferable to other vulnerable coastal lowlands globally

**Supporting Information:**

Supporting Information may be found in the online version of this article.

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**Abstract** Climate change adaptation requires more place-based evidence to understand the context of historic, present and future vulnerability and how this translates to local patterns of risk. This study illustrates a globally relevant framework focused on multiple and often interconnected climate risks in a major coastal lowland, the Fens region, UK. It offers a practical approach, moving beyond a sectoral assessment, to produce a strategic, place-based assessment of risk pertinent for regions facing multi-hazard multi-response challenges. The study draws on a harmonized suite of spatially explicit climate risk models and regional literature to provide accessible information on key regional risks at near-term (2030s–2050s) and long-term (2070s–2100) timescales for flooding, drought, water scarcity, heat, agriculture, biodiversity and sea-level rise (SLR). Including SLR as an additional growing existential risk continuing beyond 2100 identifies an issue that is not widely recognised and yet is fundamental to the Fens future. It indicates more radical approaches to adaptation will be necessary beyond 2100, which may influence decisions through the 21st Century. Fundamental to informing and supporting this shift in thinking is the provision of data and information that can help stakeholders to engage, understand and approach adaptation planning in different ways. The framework has potential to support risk assessments for other coastal lowlands around the UK and internationally, which face coupled climate hazards and risks alongside SLR, and where more radical approaches or changes to manage future risk will be required in the longer-term, alongside local and national socio-economic and environmental objectives.

**Plain Language Summary** Adapting to climate change means making decisions that will help communities cope with both current and future risks. To do this well, adaptation planners need clear, easy to use climate information that can be combined with local data and knowledge. This study uses the Fens, a large low-lying coastal region in eastern England, important for agricultural and national food security, as an exemplar. The area faces several serious threats, including sea-level rise (SLR), flooding, drought, water shortages, and a further loss of biodiversity. The research examines how these risks might change and interact in the near-term (2030s–2050s) long term (2070s–2100) and for SLR beyond 2100. Findings from the risk assessment suggest there is no single solution to adapting to these cross-sectoral challenges and so a wide range of adaptation choices need to be considered. The framework presented here, and applicable to other coastal lowland regions nationally and internationally, provides an example of how systemic data provision could promote more systemic understanding of risks and stimulate new and innovative thinking about the full menu of adaptation choices that could be implemented.

## 1. Introduction

Climate change is one of the greatest threats facing society and the natural environment. We are already seeing evidence of widespread changes in the Earth's climate, affecting human and natural systems (IPCC, 2023). The global community is committed to limiting warming through emission reductions to well below 2°C, preferably to 1.5°C, compared to pre-industrial levels under the Paris Agreement (UNFCCC, 2016). However, if we consider current policies and commitments they do not yet go far enough, with projections suggesting we could reach 2.7°C by 2100 (range 2.2°C–3.4°C) (Climate Action Tracker, 2023).

Adaptation, alongside mitigation, is crucial for managing risks from today's climate and the unavoidable risks from future climate change. Yet the gap between existing adaptation efforts and adaptation need is widening

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(UNEP, 2024). It can be difficult to identify comprehensive evidence of implemented adaptation action on the ground from peer-reviewed (Berrang-Ford et al., 2021) or gray literature (Jenkins, Ford et al., 2022). However, such studies highlight a focus on incremental adaptation to existing systems and infrastructure in response to climate change risks. This is opposed to recommendations for more transformational adaptation (i.e., shifts in the structure or functioning of systems to reduce vulnerability to climate change and other risks), focused on the longer-term planning horizon (O'Neill et al., 2022; Fedele et al., 2019; Glavovic et al., 2022; Kates et al., 2012).

Clear and accessible climate risk assessments are also crucial to highlight key risks and priorities for adaptation planning. Yet national level assessments can reduce the utility and applicability of climate risk evidence for specific regions that may have more heterogenous characteristics. The scale and generic level of detail is often not compatible with needs of local adaptation decision makers who require more place-based evidence to understand the vulnerability of their region and/or sector and how this translates to local risks and adaptation needs (Dessai et al., 2023; Smith et al., 2025). This mismatch in scale is a critical issue given the remit of national climate advisory bodies, present in over 40 countries worldwide, to provide expert advice to support climate change adaptation policy (Dudley et al., 2022).

To support the evidence base, the aim of this paper is to demonstrate the application of an integrated risk assessment framework, considering how multi-hazard, multi-risks will develop and interact over the near-term (defined as the 2030s–2050s), long-term (defined as the 2070s–2100) and beyond 2100 for sea-level rise (SLR), illustrated with a case study of the Fens coastal lowland region in the UK. It highlights the benefits of taking a strategic, system-wide view of risks to support the provision of evidence and inform priorities for adaptation decision-makers.

The integrated assessment draws on existing outputs from a suite of national, spatially explicit climate risk models, underpinned by consistent socio-economic, land-use, development and climate data. This framework provides harmonized information on a range of intersecting climate-related risks presented for the near- and long-term which are aligned with policy relevant global warming levels of 2 and 4°C. By evaluating climate-related risks through a regional and system lens, key interactions across sectors, trade-offs, priorities, and timeframes for decision-making are highlighted. This provides a transferable exemplar of how a regionally focused and spatially explicit integrated risk assessment can provide a foundation to support place-based systematic assessment of climate-related risks to inform system-wide adaptation planning and decision-making.

### 1.1. Managing Risks in Human-Modified Coastal Lowlands

Mid and low latitude low-lying coastal areas represent the largest concentration of people on earth (Kulp and Strauss, 2019; McGranahan et al., 2007). Sedimentary coastal lowlands are particularly important, with deltaic areas formed by river borne sediment being extensively analyzed and discussed in the literature (Anthony et al., 2024; Eslami et al., 2025; Nicholls et al., 2020). Other populated coastal lowlands have developed around estuaries and sheltered embayments such as much of the coast of the southern North Sea, including in France, Belgium, the Netherlands and Germany. Examples of coastal lowlands in the UK include the Thames Estuary, Norfolk Broads, Somerset Levels and the Fens. These systems are also widely studied but more from a natural and ecosystem perspective (Kennish et al., 2023; Wolanski et al., 2019) than the societal perspective considered here.

These low-lying coastal areas have seen extensive modification to enhance agriculture and other human activities, with dikes, canals and drainage systems being common interventions. This has widely degraded ecosystems, especially marshes. It also promotes subsidence and relative SLR, especially in peatland areas. Globally 10%–15% of peatlands have been artificially drained, with much greater modifications in populated coastal lowlands, which enhances flooding and waterlogging encouraging further dependency and investment in protective and drainage infrastructure. Hence, the history of human management often sets a fundamental backdrop when considering climate related risks in coastal lowlands.

Key stakeholders operating in coastal lowlands can face numerous challenges, as they attempt to balance flood risk management, biodiversity conservation, climate change mitigation ambition, agricultural production, urban development and population change (Den Uyl and Wassen, 2013; Mossman et al., 2015). This balance becomes ever more fragile when future climate-related risks are considered, which can threaten coastal lowland areas on multiple fronts. SLR and more frequent and extreme storm surge and rainfall events increase risk of flooding and salinization (Nicholls et al., 2018). Beyond 2100 SLR is expected to continue for centuries even under a stable climate. For low-lying coastal areas that already sit well below normal high tides, this continued rise in sea levels could pose extremely high or even existential risk to such regions (e.g., Magnan et al., 2022; Sayers, Moss et al., 2022), given the potential for land to be inundated, infrastructure destroyed, and populations permanently displaced.

Increased frequency and duration of drought events may alter the specific water and nutrient balance of terrestrial and aquatic habitats, resulting in changes in species composition (Gould et al., 2021), additional to the largely universal changes caused by shifting species climate envelopes (Warren et al., 2018). The economic dependency on agriculture of many coastal lowland communities due to the fertile peat soil renders them sensitive to subsequent changes in crop yield and suitability driven by climate change, particularly as these soils are also vulnerable to degradation by drainage, agricultural management and climatic factors (Joosten et al., 2016; Morris et al., 2010).

In the face of such acute and multi-sectoral challenges, a strategic approach to planning, informed by multi-sector risk modeling, will be necessary to support adaptation planning and decision making on the ground.

### 1.2. Challenges for the UK Fens

The UK Fens situated in eastern England comprise the UK's largest coastal lowland covering almost 4,000 $km^2$ (Mossman et al., 2015). The region has been significantly transformed by human agency, beginning in the medieval times, and then more significantly since the 17th Century, when drainage began in earnest to reclaim the low-lying wetlands (Migoń, 2020). Consequently, the landscape seen today has been dramatically and artificially transformed through fundamental adaptation and development decisions taken over several centuries, aimed at keeping the area flood free, well drained and agriculturally productive.

This has resulted in the region being of national strategic importance for food security, comprising around half of the UK's Grade 1 agricultural land, the largest fresh produce logistics hub in the UK, and a large and sophisticated commercial food chain (NFU, 2019). However, while agriculture remains productive for a wide variety of crops, intensive agricultural practices have resulted in widespread oxidation of the fertile peat soils and progressive consolidation, lowering land levels (and raising relative sea level) by up to 5 m over the last 100–200 years.

Hence, large areas of the Fens are below mean sea level, with the lowest point 2.75 m below sea level (Migoń, 2020). The rivers are perched above the flood plains which are dependent on engineered defences and drainage. As the world's coast is committed to centuries of SLR due to historical anthropogenic emissions alone (Nicholls et al., 2018; Oppenheimer et al., 2019) this raises a growing challenge. By 2100, sea levels in the Fens may already be 1-m higher than the late 20th Century (1981–2000) with significant further rise to 2,300 (Palmer et al., 2018). Whilst land lowering in the Fens appears to have ceased (Thiéblemont et al., 2024) future relative SLR, in this century and beyond, will be dominated by climate change.

Paradoxically, the Fens is also one of the driest areas in the UK in terms of rainfall, with drought and water scarcity posing further challenges. Drought in 2018 resulted in water use restrictions and irrigation bans in parts of the Fens (NFU, 2019).

Drainage and land use change also means that less than 1% of the original fen habitat remains (Mossman et al., 2015), affecting terrestrial biodiversity that is now isolated into relatively small pockets with limited connectivity. Coastal salt marshes and tidal flats continue to border much of the Fen's shoreline, but they are potentially being "squeezed" between SLR and the fixed defences (Foster et al., 2013; Ladd, 2021).

Fluvial, pluvial, and coastal flooding have historically been an important issue for the region. Coastal flooding in 1953 was driven by a major storm surge which breached flood defences in Lincolnshire and Norfolk, causing extensive flooding and 113 deaths in local towns and villages (Hall, 2015; Ngenyam Bang and Church Burton, 2021). A similar event in December 2013 damaged coastal defense structures and breached others in Norfolk and Lincolnshire. While no deaths were reported, in part reflecting good flood warnings (Wadey et al., 2015), damage to property was estimated to be ~£28–£84 million. Much of this damage was in Boston where the tidal surge flooded the town, affecting 590 homes and 105 businesses.

The management of flood risk relies upon the critical protection provided by an extensive network of embankments, pumps, and barriers. A 24-hr, 365-day a year commitment is in place to manage water levels across the Fens landscape. The Fens, as with all engineered coastal lowlands, is an area where maintenance is critical and incremental upgrade is the norm, reflecting factors such as progressive elevation loss. In recent years, significant investment has been made in the Boston Tidal Barrier (after the 2013 flood) and the St Germans pumping station

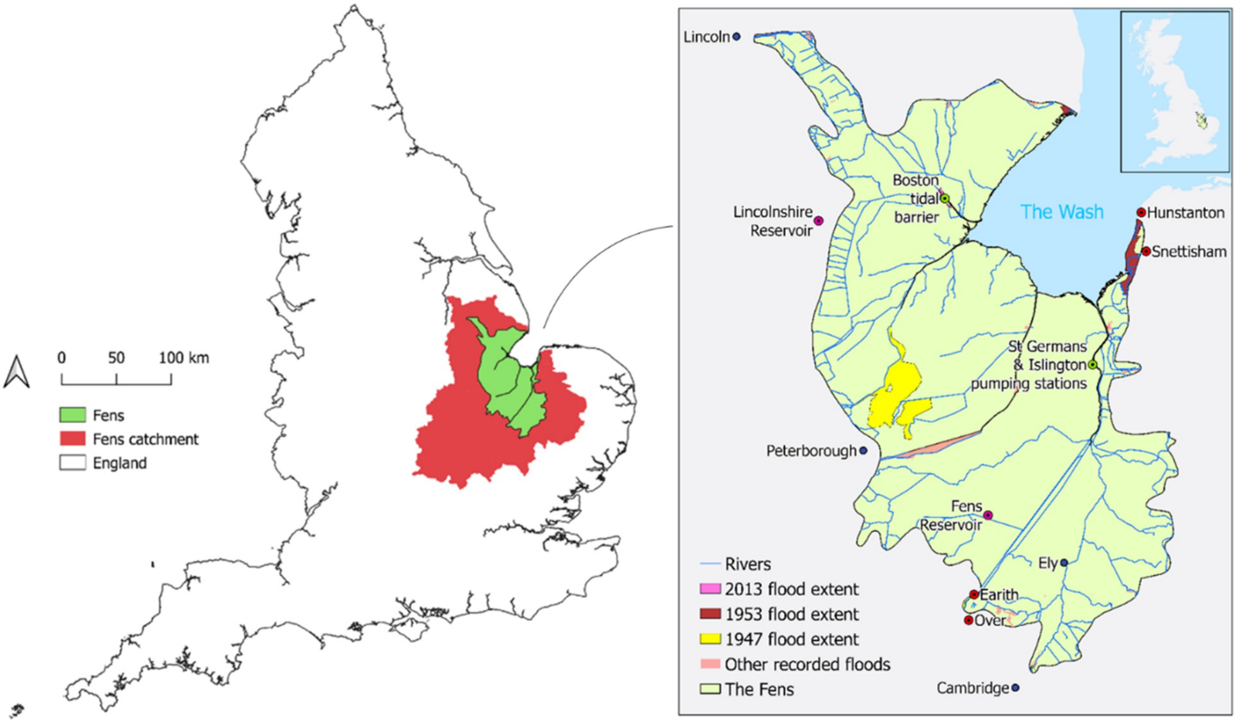


**Figure 1.** Left: The Fens and its catchment which drains much of eastern England (source: Based on Sayers et al. (2020)). Right: The Fens boundary used in this study, showing the rivers, key towns and infrastructure assets, and flood extents observed from 1947 to 2019 (source: Environment Agency (2025b)).

(Figure 1). However, maintaining the overall performance of the extensive network of aging embankments, pumps, and barriers is costly and requires ongoing investment and institutional support. It has been estimated that an additional investment of £4.5bn would be needed over the next 100 years to manage flood risk in the Fens in today's costs, before accounting for growing risks due to climate change (Environment Agency, 2023). The government has planned investment of £2.65 billion in flood and coastal erosion risk management across the whole of England from 2024 to 2026, yet there are no priority projects for the Fens region. Approximately £42 million in investment is indicated for the region in smaller scale defense and capital maintenance schemes (predominantly additional work around populated areas such as Boston) (Environment Agency, 2025a). Consequently, investment needs present a significant and ongoing challenge, thus exploring alternative solutions will be fundamental to support the future ability to live, work and farm in the Fens.

This is critical given ~686,000 people live within the boundary of the UK Fens (ONS, 2023) (Figure 1). Few locations in the Fens lie outside defined floodplain areas, meaning there are limited options for future growth and development outside the floodplain. Many parts of the region suffer from high unemployment (ONS, 2024) and high levels of social deprivation when considering income, employment, education, health, crime, barriers to housing and services and living environment (McLennan et al., 2019).

## 2. Method

Looking to the future, climate change (including SLR) alongside socio-economic drivers is set to increase current challenges in the Fens. At the regional and local level, adaptation action to reduce flooding and address other climate-related risks, or exploit opportunities, is essential to support and enhance resilience of the Fens in line with government goals (Environment Agency, 2020a). These goals extend across, inter alia., flood risk management; water supply; food security; economic growth and development; sustainable land management to support climate mitigation (Defra, 2018) and biodiversity targets (Parmesan et al., 2022). Yet, there remains a need for more place-based and integrated information on climate-related risks to be presented collectively to key local stakeholders to support such action.

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### 2.1. Integrated Assessment Framework

This study brings together a library of existing data from sectoral models that were developed as part of the Open Climate Impacts Modeling (OpenCLIM) Framework. OpenCLIM developed a coherent framework to provide spatially explicit information on climate hazards and climate-related risks for the UK at global warming levels of 2 and 4°C, embedding internal consistency in climate, socio-economic, development and land use data (Smith et al., 2025). This study draws on a subset of model outputs (Table 1) that were selected through stakeholder engagement to elicit priorities (Section 2.1.4 and SI) to develop a Fen specific assessment of key hazards and climate-related risks. As OpenCLIM does not include flood data for the Fens this was additionally extracted from results for the Third UK Climate Change Risk Assessment (See SI for further details).

The approach to generating hazard and climate-related risk data is top-down (Wilby & Dessai, 2010) with scenarios of current and future exposure and vulnerability included as determinants of risk alongside hazard (Figure 2, Section 2.1.3). Whilst it can be challenging to include adaptation response as a component of risk within models (Simpson et al., 2021) for flood risk modeling a future with no adaptation is not meaningful given the current adaptation infrastructure in place, hence a representation of current defense lines is included. Where adaptation responses are not included it is argued that models still provide useful information for stakeholders in terms of understanding what a future with no adaptation would imply and using this as a starting point for discussions on adaptation choices and exploration of adaptation storylines.

Individual model results are first evaluated based on the spatial pattern of hazard or climate-related risks. Second, the consistency in model outputs provides a first step toward drawing integrated insights through a narrative discussion drawing on evidence of co-located hazards and risks that span the range of model outputs, focused on the water-nature-food nexus. The narrative discussion is further supplemented with a bottom-up approach to weave in place-based evidence on past and current adaptation strategies in the Fens and consideration of wider regional sectoral drivers, consequences and vulnerability (Section 2.1.4). Such a framework can help identify and integrate diverse data layers and information to inform a more integrated risk assessment (Kahlenborn et al. (2025)) with a mixed-method approach (qualitative, quantitative, expert and stakeholder views) supporting a more comprehensive assessment (Challinor et al., 2018; Kennedy-Asser et al., 2025). By adopting this mixed method approach the framework does not aim to propose specific adaptation actions but through the synthesis of data and information to provide a consistent basis for identifying priority risks and potential trade-offs across sectors so current and future adaptation choices can subsequently be examined in collaboration with stakeholders. Key components of Figure 2 are described in Sections 2.1.1 to 2.1.5 below.

#### 2.1.1. Climate Scenarios

Spatially explicit regional data centered on the UK Fens is extracted from a range of model results, covering risks from coastal, pluvial and fluvial flooding (Future Flood Explorer (FFE), (Sayers et al., 2020)); water scarcity and drought (HBV, Newcastle University; University of East Anglia, 2024); heat stress (Heat Adaptation Risk Model (HARM) (Jenkins, Kennedy-Asser et al., 2022)); changes in biodiversity (The Wallace Initiative (Price, Warren et al., 2024; Warren et al., 2018)); and changes in crop yield and crop suitability (CropNet and EcoCrop Model (Hayman et al., 2024; Redhead et al., 2025; Robinson et al., 2023)) (Table 1). The models primarily use climate data from the UK Met Office UK Climate Projections 2018 (UKCP18). Results are selected for the appropriate 30-year time-slices from climate model ensemble members, corresponding to 2 and 4°C of global warming relative to the pre-industrial baseline. The warming levels align with the 3rd UK CCRA which considered risks at 2°C as a minimum global warming level and 4°C as a likely upper range that cannot be excluded, and which encourages consideration of a 4°C world and adaptation implications (Betts and Brown, 2021). Assuming that greenhouse gas emissions are not rapidly reduced, global surface temperature will likely exceed 2°C compared to the pre-industrial period in the near-term between the 2030s and 2050s and could potentially reach 4°C in the long-term between the 2070s and 2100 (IPCC, 2023). Beyond 2100 we consider implications of SLR as discussed below.

#### 2.1.2. SLR Scenarios

Global mean sea levels will rise through 2100 and beyond (Fox-Kemper et al., 2021). Sea levels in the Fens region are projected to rise between 0.85 and 1.72 m by 2100 based on projections from UKCP18 and continue to rise thereafter with rates depending on future emissions and uncertainties growing with time. Subsidence and land

**Table 1**
*Overview of Models Used to Analyze Risks in the Fens*

| | Model name | Risk Indicator/s | Description | Climate data set | Socio-economic scenarios directly integrated | Model citation |
|---|---|---|---|---|---|---|
| FLOODING | **Future Flood Explorer (FFE)** | Expected Annual Damage (EAD) to residential and non-residential properties (£) | FFE provides an exploratory modeling environment that enables changes in fluvial flow, rainfall intensity, and SLR to be translated into spatially disaggregated risk taking account of the performance of the flood defense and in the influence of climate change on that performance. | All UKCP18 probabilistic projections that reach 2 and 4°C in or before 2100 (fluvial and pluvial).<br>UKCP18 Marine Projections of relative SLR projections and influence on wave overtopping (as used in UK CCRA3) (coastal) | UK-SSP2 and UK-SSP4 | Sayers et al. (2016, 2020), Sayers, Ashley et al. (2022) |
| AGRICULTURE | **CropNet** | Change in potential crop yield of wheat, oilseed rape and ryegrass (t/ha) | Potential yield of wheat, oilseed rape and grass under rainfed conditions based on key climate variables, soil properties, water availability and day length. | CHESS-SCAPE 1 km projections based on four UKCP18 12 km ensemble members. | N/A | Hayman et al. (2024) |
| | **EcoCrop model** | Crop suitability (suitability score) | Provides a suitability score based on daily temperature and precipitation using required and optimal ranges, within the known range of the growing season, for >160 annual and perennial crop species. | CHESS-SCAPE 1 km projections based on four UKCP18 12 km ensemble members. | N/A | Redhead et al. (2025); Robinson et al. (2023) |
| TERRESTRIAL BIODIVERSITY | **The Wallace Initiative** | | Underpinned by a database of the climatic range relationships of more than 135,000 species of terrestrial fungi, plants, vertebrates, and invertebrates, it provides data to quantify biodiversity loss, climate refugia for biodiversity and risks to pollination. | As global, the Wallace Initiative uses 21 alternative regional climate change projections for each warming level, derived from the CMIP5 model inter-comparison project.<br>20 km downscaled to 1 km | N/A | Price, Warren et al. (2024); Warren et al. (2023) |
| DROUGHT | **HBV Hydrological Model** | Q95 low flow | A fully distributed hydrological model, applied to assess climate and land cover changes on river flows. | UKCP18 12 member RCM (Regional Climate Model) 12 km ensemble members. | UK-SSP2 and UK-SSP4 | Newcastle University; University of East Anglia (2024) |
| HEAT STRESS | **The Heat Adaptation Risk Model (HARM)** | Heat-related mortality (heat related deaths/yr)<br>Exceedance of 28°C temperature range (days/yr) | HARM uses a threshold-based approach to calculate exceedance of temperature thresholds and a linear Exposure-Response Function to define changes in heat-related mortality. | UKCP18 12 member RCM (Regional Climate Model) 12 km ensemble members. | UK-SSP2 and UK-SSP4 | Jenkins, Kennedy-Asser et al. (2022); Kennedy-Asser et al. (2022) |

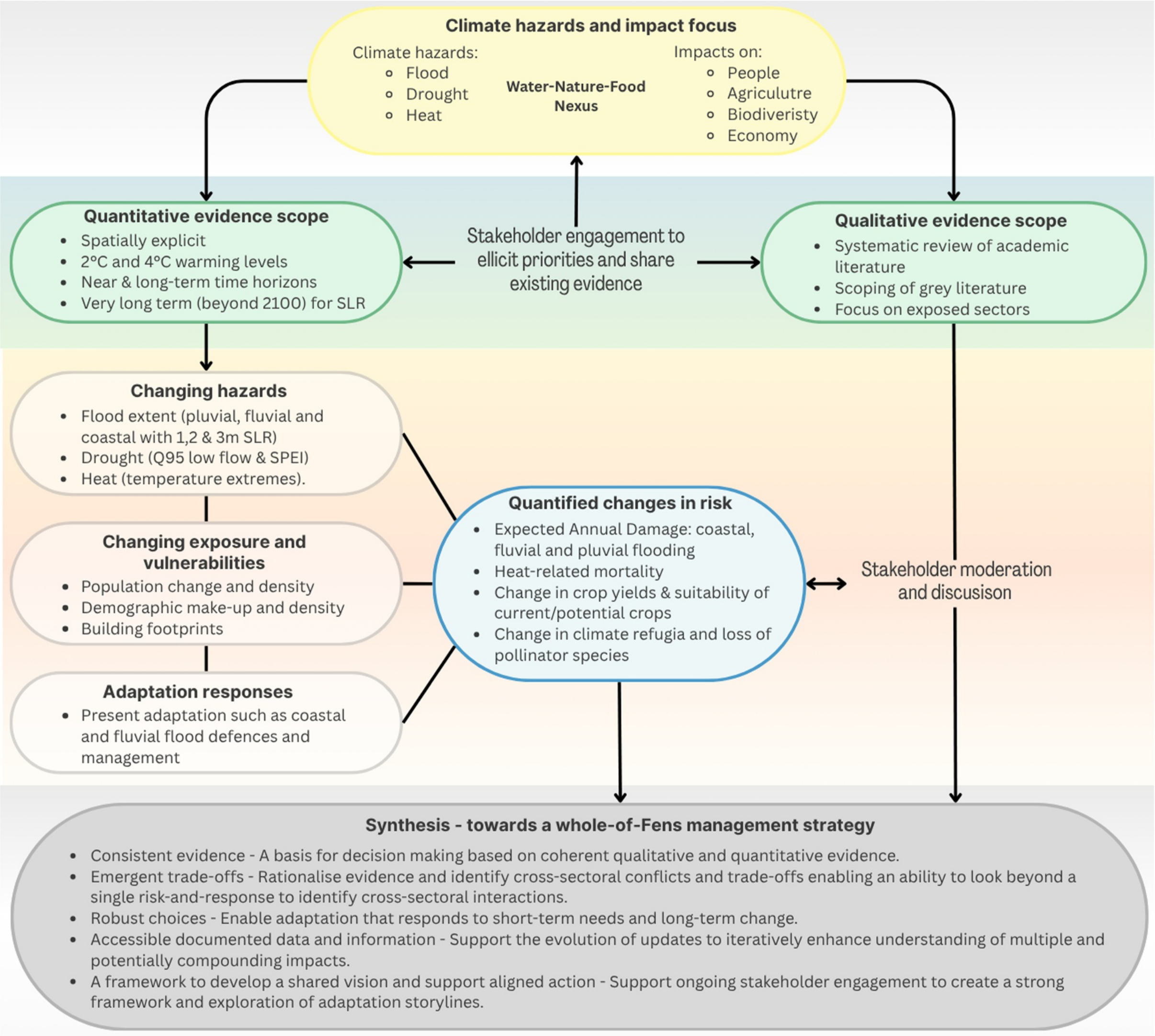


**Figure 2.** Overview of the Integrated assessment framework.

lowering within the Fens appears to have ceased (Thiéblemont et al., 2024) and does not need to be considered (Palmer et al., 2024).

This large, ongoing SLR means that any adaptation planning needs to consider risks beyond 2100 in present day planning. In this assessment two projections of relative SLR, as used in support of the UKs CCRA3, are used to assess the changing coastal flood risk aligned to the 2 and 4°C warming levels (Sayers et al., 2020). In addition, what-if scenarios are explored to assess the implications of an extreme coastal storm with a 1 in 200-year surge event given a SLR of 1, 2 or 3 m—all plausible changes over 200/300 years that can be used to explore the potential for extremely high or existential flood risk events (building upon Sayers et al., 2016). This progressive and ongoing SLR will impose major challenges for the Fens and needs to be considered in terms of adaptation responses and the potential for coastal flooding to inundate extensive coastal lowland regions beyond 2100 without significant adaptation investment.

#### 2.1.3. Socio-Economic Scenarios

Alongside data on climate-related hazards, consideration of current and future exposure and vulnerability are essential to support and align regional assessments of future risk with stakeholder needs (Bernie et al., 2024). Here, the UK shared socioeconomic pathways (UK-SSPs) (Cambridge Econometrics, University Of Edinburgh,

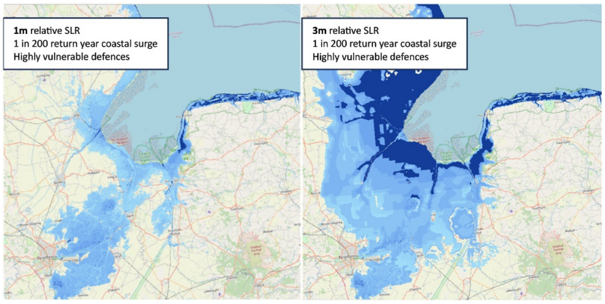


**Figure 3.** Flood inundation extent for a 1-in-200 return year coastal flood event with 1 and 3 m of sea-level rise that could occur by or beyond 2,100. The storm is assumed to breach the most vulnerable defences (defined using a critical toe level of >0.2 m below mean sea level in the model). Other defences are assumed to continue to provide protection. Light to dark blue shading reflects lower to higher depth. *Source:* Sayers et al. (2015).

University Of Exeter & Uk Centre For Ecology & Hydrology, 2021Cambridge Econometrics et al., 2021; Pedde et al., 2021), developed to be used alongside UKCP18 data, are used. The UK-SSPs align with the global SSPs used by the IPCC and explore how different socio-economic factors such as population change, economic growth and employment might change over time. In this study hazard data was linked with projected socio-economic data from the UK-SSP2 and UK-SSP4 scenarios (following the approach in OpenCLIM and other studies e.g., Warren et al., 2023; Warren et al., 2024). To align the outputs with the near- and long-term time-periods defined in Section 2.1.1 socioeconomic data is extracted from the UK-SSPs for 2050 with 2°C and 2080 with 4°C.

UK-SSP2 assumes continued economic growth, increased urbanization and increasingly dense cities. In the Fens, population is projected to increase by 13.6% by 2050 and 24.6% by 2080. UK-SSP4 is characterized by increasing inequality and an increasing divide between wealthy and poorer segments of the population and regions of the UK. There is increased urbanization in and around densely populated areas with population projected to increase by 12% by 2050 and 19.2% by 2080.

#### 2.1.4. Systematic Review of Qualitative Literature

For each of the sectoral models the assessment of present and future risks was supported by existing academic literature focused on the Fens region. Peer reviewed literature was identified through a systematic review that drew evidence from the Web of Science (see SI for further details). This was further supported by a review of gray literature, including organisational reports. Key reports were identified through online searches and through informal consultation with key stakeholder members of the Future Fens Integrated Adaptation (FFIA) Partnership, which was established in 2021 to bring together over 120 local partner organizations, across sectors, to develop a joint approach to future adaptation in the region.

#### 2.1.5. Risk Assessment Models

The models underpinning the framework can provide an array of hazard and risk-related indicators. The specific metrics that the study focused on were informed through an initial scoping process with the project funder (the UK Environment Agency) and key FFIA partners (see SI for further details). Further details on the models and indicators are summarized in Table 1.

## 3. Results: Assessment of Present and Future Risks in the Fens

### 3.1. Pluvial, Fluvial, and Coastal Flooding

Extreme wave conditions reaching the shoreline around most, if not all, of the Fens are likely to be depth limited (i.e., wave breaking is induced by bathymetric effects as waves propagate into shallow water). As a result, relative SLR has a dominant influence on coastal flooding, increasing both wave-driven overtopping, the chance of a breach and tidal overflow. To emphasize this point, the implications of an extreme coastal storm with a 1 in 200-year surge event under different SLR assumptions were explored as part of CCRA2, illustrating the connection to coastal flooding (Sayers et al., 2015). Figure 3 shows maps for the Fens with SLR scenarios of 1, 2 and 3 m. These "what-if" scenarios assume the existing coastal defense line remains in place and that the defences most exposed to the influence of increased sea level and wave attack are breached. Other defences are assumed to have been raised and are not overtopped. Significant areas of the Fens could be temporarily inundated in a future extreme storm given the low-lying nature of the region, emphasizing the significant damage and loss of confidence that could occur. Such longer-term projections inform potential adaptation pathways for the region.

The FFE model suggests that the Expected Annual Damage (EAD) in terms of direct residential and non-residential property damage from *all sources* of flooding in the Fens (after considering existing defences but excluding the recent construction of the Boston tidal barrier) is ~£16 million/yr today. In the absence of investment (i.e., with no further upgrades to existing defences and limited maintenance), this would increase

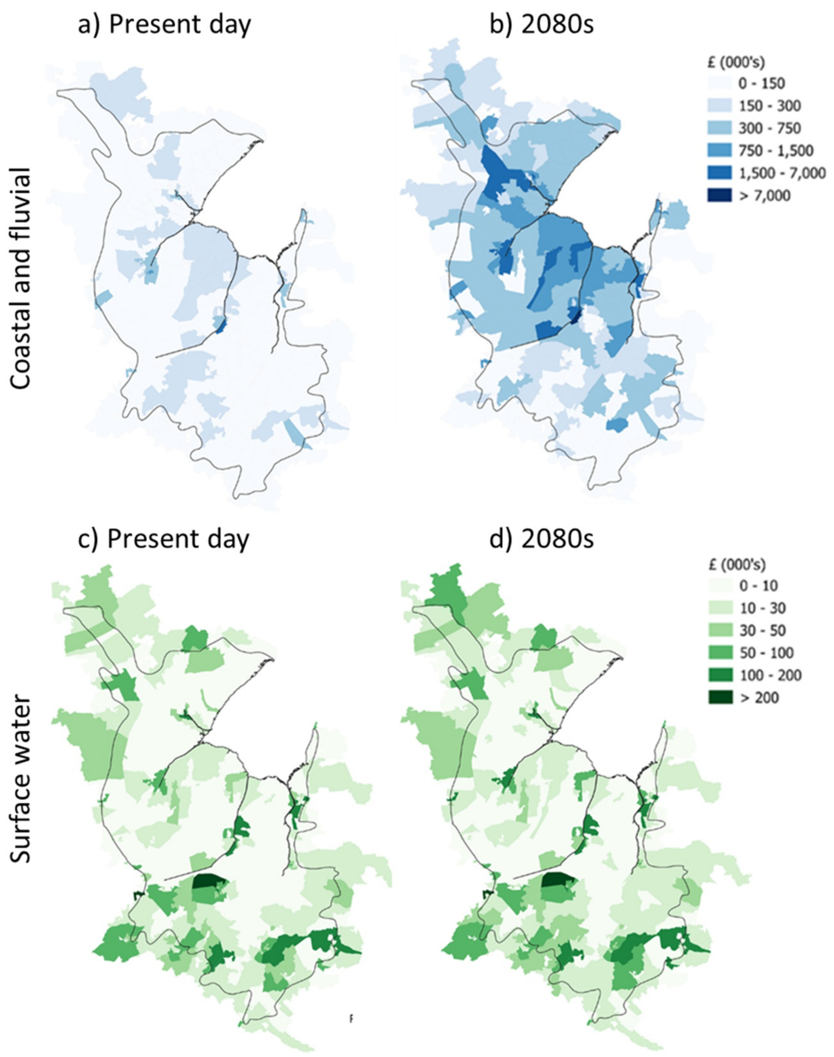


**Figure 4.** Flood risk shown as Expected Annual Damage (EAD) (direct damages) from fluvial and coastal sources for (a) the present-day and (b) the long-term aligned to SSP data from the 2080s given a 4°C rise in global mean temperature, high population growth, and limited future adaptation; and EAD (direct damages) for surface water flooding for the (c) the present day and (d) the long-term aligned to SSP data from the 2080s given a 4°C rise in global mean temperature, high population growth, and limited future adaptation.

significantly in the near-term to ~£110 million/yr (7-fold) by the 2050s assuming a 2°C rise in global mean surface temperature and high population growth, and to ~£250 million/yr (or 16-fold) by the 2080s assuming a 4°C rise and high population growth.

Investment in the existing defense system is projected to reduce EAD, although this will still double from the present day to ~£32 million/yr under the long-term (2080s) 4°C high population growth scenario. Whilst the value of investment required is not modeled it does assume that sufficient investment is made available to maintain condition and raise defences given existing rules and standards; that development controls continue to be effective; and that flood forecasting and warning continues. In reality, the levels of investment needed to address an increasing adaptation gap is likely to be a significant barrier in the Fens given the scale of the challenge faced.

EAD from coastal and fluvial flooding is projected to be largest along the east coast and propagating along major rivers/drainage channels into central and northern regions of the Fens (Figure 4), exceeding £7 million/yr in some regions. Overall, damages related to surface water flooding are lower than from coastal and fluvial flooding but are widespread across the region, with damages particularly high in the southern Fens.

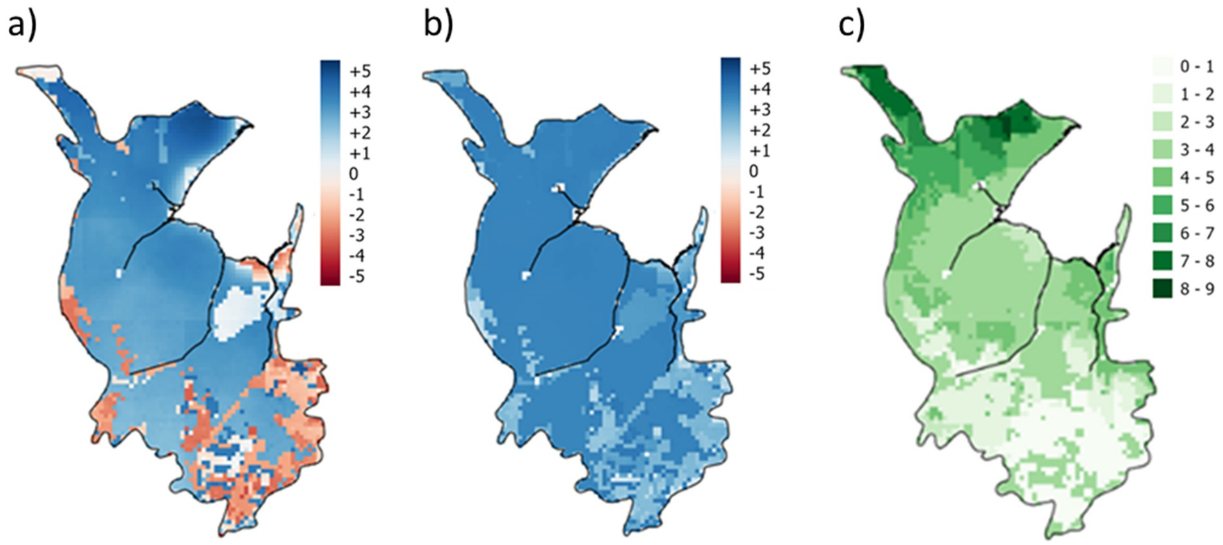


**Figure 5.** (a) Modeled change in potential wheat yield (tonnes per hectare) for the Fens under a long-term (2070–2100) 4°C warming scenario derived from CropNet models; (b) as (a) but for oilseed rape; (c) Median change in climatic suitability for over 160 food crops for the Fens under a long-term (2070s–2100) 4°C warming scenario.

Importantly, the EADs presented here reflect only a small proportion of the potential change in flood-related risk from the present day. The systematic review and qualitative evaluation highlighted many categories of impacts that cut across sectors in the Fens that are excluded. Not all flood and erosion sources, including groundwater and reservoir failure, are considered. Soils lost due to erosion are often the most productive and this is already a significant challenge (Sustainability West Midlands, 2021). Agricultural damage from flooding can be severe, especially salination from coastal flooding which can affect soil and crop growth (Gould et al., 2021), lead to waterlogging and have wider knock-on effects for food processing and food security (Ruto et al., 2021). Floods can damage roads, rail, and other infrastructure with smaller road networks in the north of the Fens highly vulnerable with indirect impacts for transporting agriculture produce (Harrison et al., 2023). Energy supply and distribution can be affected with system-wide implications. There will also be well-being, health, and social care costs, particularly acute in areas in the north of the Fens that are projected to be highly vulnerable when explored using the Neighborhood Flood Vulnerability Index (NFVI) (Sayers et al., 2018). The NFVI integrates various indicators of social vulnerability that relate specifically to challenges faced by vulnerable households in preparing for, responding to and recovering from, a flood event at a neighborhood scale, such as age, health, mobility, property tenure, income, housing characteristics, direct flood experience, social networks and service availability. Furthermore, increases in rainfall, high river flows and flooding, including increased Combined Sewer Overflow, have been shown to impact water quality and biodiversity (Harrison et al., 2008; Harrison and Whitehouse, 2012).

### 3.2. Agriculture

The agricultural sector is a fundamental part of the Fens economy, employing 80,000 people and generating ~£3 billion a year for the region in 2020 (Page et al., 2020). However, degradation of peat soils has been ongoing since the original drainage of the Fens, with the remainder of its fertile topsoil potentially being lost in just 30–60 years given current land management practices and the changing climate (Environment Agency, 2020a).

The CropNet model projects that, on average, climate change is likely to bring moderate short-term (2030s–2050s) increases in the potential yield of several current major crops (winter wheat, oilseed rape, ryegrass). Despite shorter-term opportunities, more significant challenges are projected to occur for the sector in the long-term (2070s–2100) at higher levels of warming (Figure 5). In the long-term with 4°C, wheat is likely to show plateaus or decreases in yield, which is likely to have a significant impact on the region's contribution to UK food security. These impacts are not spatially homogenous, with a trend toward decreased yields of wheat in the southern half of the Fens, whilst the more northerly areas are projected to show greater resilience to climate change given temperature and precipitation regimes and a reduced vulnerability to drying of the soils (Figure 5).

Outputs from EcoCrop highlight that several current major crops are likely to show decreases in their climate suitability in the Fens even under 2°C warming in the short-term (e.g., onions, parsnips, wheat, strawberries), whilst many other crops show moderate to strong increases in their climate suitability up to 2°C. However, in the long-term at 4°C many more current crops show decreases in their suitability, to the point where, for southern areas of the Fens, the median change in suitability across all crops approaches zero (Figure 5c). Crops showing increases in suitability include many crops currently associated with more Mediterranean climates of continental Europe (e.g., wine grapes, sunflowers, hemp, chickpeas).

Paludiculture crops are associated with (or tolerant of) wetland conditions and capable of maintaining agricultural production in a re-wetted peat system (Mulholland et al., 2020). EcoCrop highlights some of these (e.g., cranberries, wild rice, club-rush, bur reed) may increase in suitability under climate change and could help to resolve the underlying issue of peatland degradation. However, expert elicitation highlighted that the success of adopting novel crops as an adaptation will depend on successfully transforming all levels of the food supply chain. The Fens grow a wide range of crops, so repurposing of agronomic knowledge, machinery and supply chains to handle new crops may be less of a barrier than in other areas of the country, albeit still challenging for many perennial crops that require specialist agronomy and longer-term investment.

As with flooding, there are wider interactions with climate-related risks not modeled that would also affect risk. CropNet's metric of "potential" yield does not account for imperfect management, pests, diseases, crop nutrient requirements, compound effects of climate on such factors, or any extreme weather events that are not well captured by the input climate data (e.g., summer storms). The model also assumes that all precipitation is available to replenish soil available water content, so accounts for neither the restrictive effects of abstraction and drainage on water availability or the potential alleviation offered by irrigation. However, the reliance of current systems on irrigation for some crops may further impact yields if water availability becomes restricted at critical times due to increased drought (Section 3.3). Furthermore, increased flood frequency and extent, as highlighted in Section 3.1 above, may render large tracts of arable land unsuitable in the long-term.

### 3.3. Drought and Water Supply

Droughts can be classified in various ways depending on meteorological or hydrological conditions or links to agricultural and socio-economic impacts. Whilst the primary driver is a decline from average rainfall levels, other factors such as high temperatures and human interventions can also exacerbate the severity of events (Van Loon et al., 2016). This is paramount for the Fens given much of the area is already classed as being in serious water stress.

Climate projections analyzed here highlight that the Fens will face wetter winters and drier summers with the probability of meteorological drought projected to increase (Price, Forstenhäusler et al., 2024). Evapotranspiration will be a main driver of drought (due to projected higher temperatures, Section 3.5). Based on the Standardised Precipitation Evapotranspiration index (SPEI12, −1.5), which is often used when looking at potential drought issues for agricultural and natural lands, the number of months that are classed as being in severe drought in a 30-year period were projected to increase to 34 with 2°C warming in the short-term (2030s–2050s) and to 110 months with 4°C warming in the long-term (2070s–2100) (Price, Forstenhäusler et al., 2024).

Results from HBV highlight that hydrological drought conditions are also projected to worsen with climate change. The indicator Q95, defined as the flow in $m^3/s$ equaled or exceeded for 95% of the flow record, is often used as the characteristic value for minimum river flow. All three catchments in the Fens show a reduction in low flow discharge with 2°C in the short-term (2030s–2050s) and with 4°C in the long-term (2070s–2100), with more significant decreases in the long-term with 4°C. The Ely Ouse catchment experiences the largest reductions, especially in the long-term with 4°C, approaching a 25% decrease. Reduction in river flow can impact water availability, ecosystems, and overall environmental health of the river systems (He et al., 2021).

The systematic review and qualitative analysis highlighted that resource management in the region needs to account for and adapt to evolving and multifaceted climate risks, socio-economic pressures (e.g., growing population) and competing water demands. Regional water resource planning includes developing a 300 km-long strategic water transfer pipeline to deliver water from the wetter north to the drier south of region by 2025 and two new reservoirs (WRE, 2023) which could have wider benefits for recreation, biodiversity and flood protection. Yet some trade-offs may also occur between abstraction from existing sources and environmental requirements to maintain healthy river systems (WRE, 2023). Availability of water for abstraction may also be inhibited by a projected reduction in groundwater recharge in the region (Holman, 2006). Furthermore, coastal aquifers are highly vulnerable to saline intrusion due to increased tidal surges and groundwater flooding, whilst risk of saltwater seepage is increased if water abstraction occurs (Moulds et al., 2023). This could result in soil salinification, further reducing the yield of most crops grown in the area as noted in Section 3.2 (Gould et al., 2021).

Additional pressures on water demand from projected housing and economic growth, including non-household growth in demand; needs of agri-food and other abstractors; and implications of Net Zero strategies and energy production on water are flagged as needing further consideration.

### 3.4. Terrestrial Biodiversity

The current impacts on biodiversity in the Fens are already large, owing to past habitat conversions (Price, Forstenhäusler et al., 2024). The biodiversity modeling highlights that in areas where the future climate is projected to exceed the modeled climatic tolerance of many species, the species currently present may not be able to persist into the future. On the other hand, there are places where the climatic tolerance of most species is not exceeded, classified as refugia (areas remaining climatically suitable for >75% of the terrestrial biodiversity in that area). These may be the best places to protect or focus restoration efforts to conserve biodiversity in the future despite climate change.

However, results highlight that even limited global warming poses a significant threat in the Fens. In the short-term (2030s–2050s) with 2°C of warming almost none of the Fens is likely to remain as an area of refugia. Spatial maps of risk show a homogenous picture of declining biodiversity refugia across the whole of the Fens.

If the focus is solely on birds or mammals then more of the Fens would be suitable refugia, at least in the short-term (2030s–2050s) with 2°C of warming, but large losses of species richness in many invertebrate groups, and some plants, is also projected meaning that food and habitat resources would be lost. Furthermore, the risk to insect pollinators, even at lower levels of warming, could have serious implications for insect-pollinated crops and wild plants. Given the agricultural importance of the area, this potentially hampers the ability to grow certain crops,and potentially impacts the yields of insect pollinated crops as discussed in Section 3.2. With increases in temperature, greater attention will also need to be placed on dealing with increases in extreme weather events such as longer, more severe droughts, or more frequent flooding as alluded to in Sections 3.1 and 3.3 above.

The qualitative review has highlighted that properly sited habitat restoration or "rewilding" projects will benefit terrestrial biodiversity by allowing "space" for biodiversity to attempt to adapt in situ as well as space for colonization of environmental refugee species (Richards et al., 2008). Yet, whilst there are extensive designated intertidal and subtidal habitats in and around the Wash (Figure 1) future trends, including possible coastal squeeze under SLR or loss of coastal grazing marsh and related freshwater habitats with reduced ecosystem coastal protection benefits, can have implications for coastal defense and their location (Holman et al., 2005; Richards et al., 2008).

Whilst significant adaptation will be required even in the short-term (2030s–2050s) with 2°C of warming, the model illustrates that in the long-term (2070s–2100) with 4°C of warming biodiversity adaptation efforts are going to be much more expensive and may require replanting with species more tolerant of the new climate regime, or other habitat engineering.

### 3.5. Heat Stress

Average and extreme temperatures are both projected to increase across the UK, including the Fens, with a shift toward hotter and drier summers and wetter and warmer winters (Climate Change Committee, 2021). For the Fens, average monthly July (summer) temperature is projected to increase from 17.1°C to 18.1°C with near-term (2030s–2050s) warming of 2°C, and to 20.5°C under a long-term (2070s–2100) future with 4°C (Price, Forstenhäusler et al., 2024). The HARM model shows that extreme heat days are projected to increase in the Fens. Days that exceed 28°C, which can impact infrastructure such as power networks, roads and railways and affect health, are projected to increase from 0 to 2 days per year across the region in the 1981–2000 baseline to 0–11 and 2–33 days per under a near-term (2030–2050s) 2°C and long-term (2070s–2100) 4°C warming scenario respectively.

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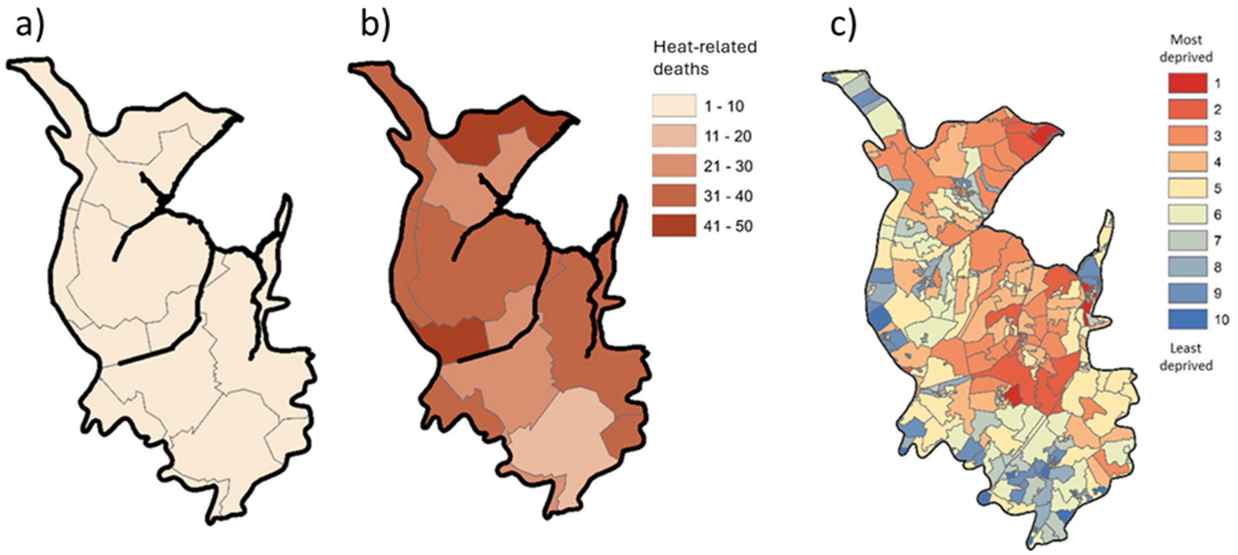


**Figure 6.** (a) Average annual heat related deaths in the Fens in the 1981–2000 baseline. Results are shown aggregated to the Local Authority District level; (b) Additional heat related deaths above the baseline in the long-term with a warming scenario of 4°C and population and demographic data from 2080; (c) Present day index of deprivation for the Fens, with geographical boundaries at the Lower Super Output Area level.

High temperatures can cause heat stress and affect human morbidity and mortality. Vulnerable populations such as the elderly are at highest risk, although there are limits to the amount of heat stress even healthy and acclimatized individuals can tolerate (Jenkins, Kennedy-Asser et al., 2022). With global warming of 2°C in the near-term and a UK-SSP2 increase in population of 13% by 2050, average annual heat related deaths are projected to increase to 68 deaths per year (compared to 14 deaths in the 1981–2000 baseline). In the long-term with warming of 4°C and considering the UK-SSP2 population in 2080, additional average annual heat related deaths increase to 173 deaths per year with an increase in population of 25%. Inter-annual variability is expected, with deaths lower or higher in individual years.

Whilst climate change is a driver of increasing mortality in the region, exposure and vulnerability change, represented by population growth and a larger elderly population in the region, is also a key driver of heat risk, particularly in the long-term with warming of 4°C and UK-SSP data from 2080. Spatially, the heat related deaths are projected to increase at a greater magnitude in the north and eastern areas of the Fens (Figure 6). In high years, this will place additional strain on health and social services, particularly in regions of the Fens with high levels of deprivation.

The qualitative analysis highlighted that the implications of increasing temperatures, heatwaves and related heat stress can also interact across risks and sectors not modeled here. This includes inter alia. Potential effects on labor productivity; infrastructure; and livestock welfare, productivity and fertility (Polsky and von Keyserlingk, 2017). Whilst the region is predominantly arable, the risks to livestock would include indirect impacts such as the subsequent economic losses of changes in productivity of livestock to farmers and additional demands for clean and plentiful water during heat events, for example.

## 4. Discussion: Supporting Decision-Making Through an Integrated Climate Change Risk Assessment

The results highlight that whilst a sectoral risk assessment can provide useful information on near-term (2030s–2050s) and long-term (2080s–2100) risk under future warming levels of 2 and 4°C respectively, if viewed in isolation this information will be insufficient to capture multiple and potentially compounding impacts. This is particularly pertinent for regions facing multi-hazard multi-response challenges, such as the Fens. In addition, the challenge of ongoing SLR beyond 2100 with the potential for catastrophic floods and permanent inundation cannot be ignored, given it is a dominant, possibly existential, risk driver in the region. Hence, it must be considered as part of longer term thinking when exploring adaptation options and pathways today.

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Figure 7 synthesizes the study results to demonstrate how different assessed risks will change as global mean surface temperature increases across time. Six critical insights are drawn. First, it is imperative to view coastal lowland environments like the UK Fens through a systems lens, made up of different but interconnected sectors, communities, stakeholders and environments intrinsically linked by climate change, SLR and other relevant change factors. This study provides a first exploratory framework to do so for the UK Fens. This is essential to support future thinking on adaptation in a multi-hazard context (Maani, 2013). e.g., risks to agriculture could be viewed in isolation and areas could be identified where potential crop yields would benefit (e.g., Figure 5). Yet the same areas may be threatened by declines in insect pollinators, increasing drought, water supply restrictions, and/or growing flood risk. Hence all these issues need to be considered in tandem. This framing illustrates to stakeholders not only the current and future risks that they may face in their sector, but can be a catalyst to understanding why any subsequent adaptation actions should be developed through a system-wide and integrated lens. Pasquier et al. (2020) reflects on this, highlighting the wider scope of information provision needed to underpin adaptation decision making and actions, particularly in low-lying coastal regions which face multiple and complex risks and competing interests. The method presented here, integrating knowledge from multiple disciplines and sources, and overlaying sectoral maps, is essential to begin to help tackle the complexity of the problem and identify outcomes that may not be evident from sectoral model outputs alone (Simpson et al., 2021). It is envisaged that this framing will form the basis for future work, that will further explore interactions and compounding elements that have begun to be explored through the mixed-method evaluation and results presented here. While the analysis incorporates a representation of current coastal adaptation, the integration of further context specific adaptation responses is a limitation of this study that would also benefit from future exploration and testing to support system-wide adaptation decision making.

The framework would be equally useful for assessing risks and supporting knowledge provision in other coastal lowlands around the UK (e.g., the Humber, Lancashire Lowlands, Somerset levels), Europe (e.g., the southern North Sea coast including coastal lowlands in France, Belgium, the Netherlands and Germany) and globally (e.g., Jelgersma et al., 1993) including areas with extensive populated lowlands like China (Liu et al., 2015). As sea levels continue to rise, all coastal lowlands worldwide will face similar threats to the Fens, including coupled climate hazards and the need for an integrated assessment framework to support adaptation. Region specific dimensions of risk, including context specific characteristics of vulnerability, could be identified and integrated in the analysis.

Second, the present Fens landscape exists due to critical flood risk and water level management assets that are required 24 hr a day and 365 days a year, and the continued investment to maintain and enhance this adaptation. However, there are many choices in how and where that flood management investment could occur. The assessment suggests that given identified risks, continuing to follow the present approach to maintain flood management infrastructure along the current defense lines, including along the main rivers, should be reviewed. When the rivers are considered, there is a long defense line to maintain and upgrade as flood risk and SLR increase with time. Continuing protection will also need higher and higher defences and the system-wide consequences of failure given the perched nature of rivers in the region, even if unlikely, will become progressively more severe. Failure of this infrastructure and the subsequent large-scale inundation of land could pose extremely high or even existential risks to the region, particularly when considering the longer-term projections of SLR beyond 2100.

Third, integrated risk assessment can support the exploration of a range of possible adaptation storylines created to reflect different societal and management decisions for the region in the face of climate and other changes. For example, van Alphen et al. (2022) explored a diverse set of storylines for adapting the Dutch delta to beyond 2100/high-end SLR, based on scientific evidence of SLR and impacts on current water management structures, and narratives of what this would imply for land use, society and key sectors. Similar adaptation storylines can be envisioned for the UK Fens, through consideration of a range of contrasting futures from major investment in flood protection and enhanced development of land, through to widespread retreat and restoration of nature, and intermediate cases requiring enhanced investment to maintain a system similar to today. Whilst not presented here, the co-production of such adaptation storylines will form an important part of future stakeholder engagement and research, to stimulate thinking on the adaptation choices that are faced in the Fens and to help explore and visualize what different approaches would mean for society, development, water resources, flood management, agriculture, and biodiversity. Importantly, the key elements considered in adaptation storylines would benefit from the scientific evidence stemming from the integrated risk assessment to ensure a coherent narrative.

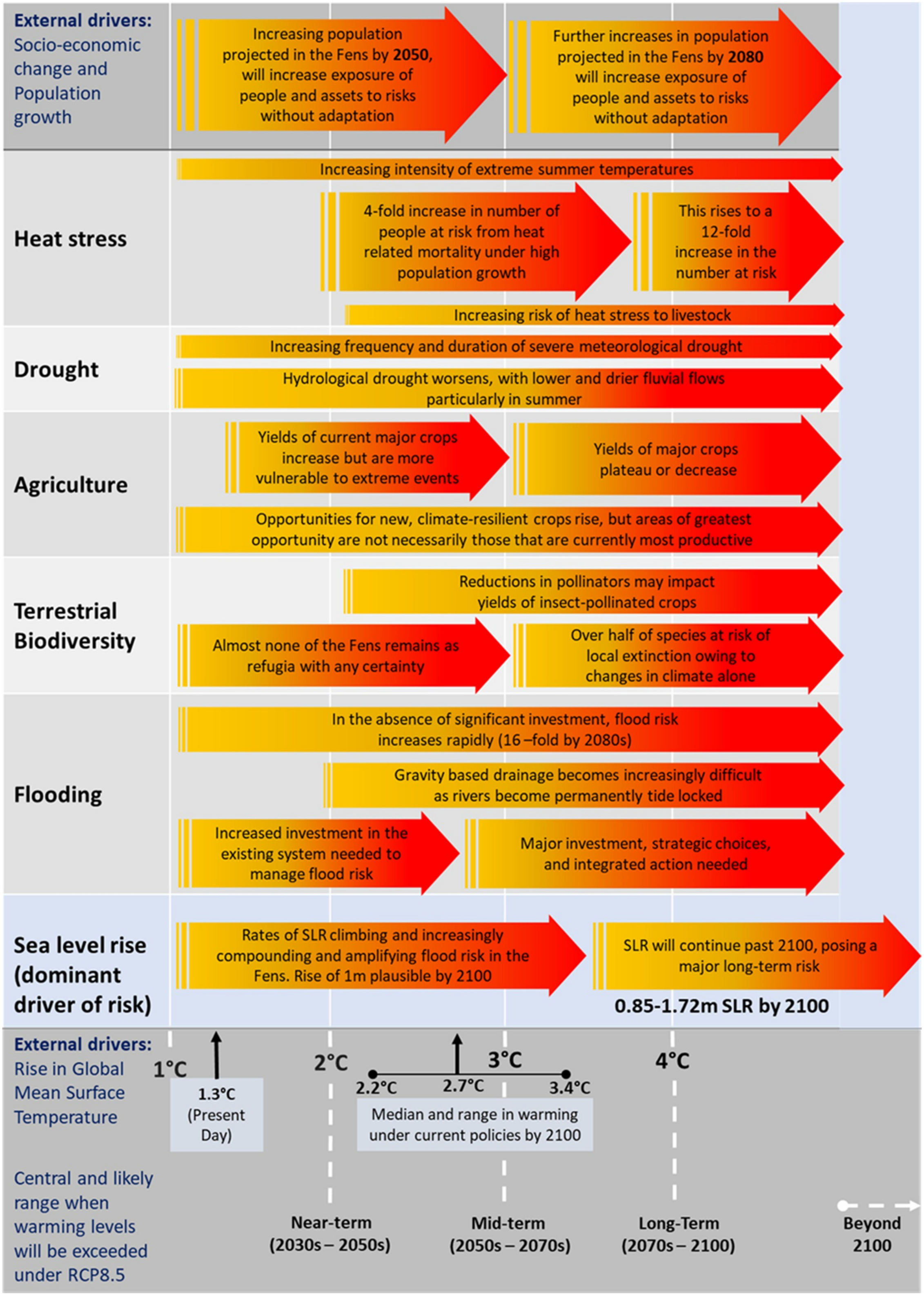


**Figure 7.** Synthesis of the modeled risks captured through this integrated assessment that could impact the Fens as global mean surface temperature increases. The arrows highlight when risks modeled by this study may be faced based on warming levels spanning 1°C–4°C. Risks are linked to time-periods assuming a high emission future (*Source:* Carbon Brief (2020) and Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2023). Data on the median and range in projected warming given current mitigation polices are highlighted (*Source:* Climate Action Tracker (2023)).

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Fourth, considering risk through a systems lens highlights the issues of focusing on individual sectors and adaptation strategies. Stakeholder feedback on multi-model results for a study of a coastal lowland in the UK Broads, situated in Eastern England, highlighted an improved understanding of the need to develop adaptation strategies that contained a mix of responses and measures (Pasquier et al., 2020). The strategic role of the Fens in national food supply and security has been key in how flooding has been managed uniformly across the region, but more diverse and targeted adaptation approaches could be developed based on local prioritization of agriculture, biodiversity, flood risk management, development needs, economic growth, and Net Zero strategies. Given that the risks are not spatially uniform, and that this variation can be mapped, it is proposed that stakeholders could build on this information to create local strategies that would allow a more varied landscape and set of activities to evolve that would enhance resilience. This would naturally build on the proposed creation of adaptation storylines. For example, a future strategy may include more diverse approaches such as continuing to defend some areas into the long-term while accepting more flooding in other parts of the Fens.

Fifth, the findings from this assessment highlight there is a crucial window in which to respond in the near-term given our current emission trajectory could see the 2°C threshold exceeded as early as the 2030s, and to begin planning and responding to higher levels of warming that may be faced in the long-term (2070s–2100). The time frame for this, and whether we see warming of 2.5, 3 or 4°C depends on the action we also take to mitigate climate change. While inertia and feedback in the response of sea level to climate change means that SLR will continue for centuries, even if emissions are successfully reduced, for other climate-related risks if we can successfully limited global warming to a rise of 2°C then the costs of adaptation (including the feasibility of maintaining existing systems) are likely to be significantly less, maintaining a longer window of opportunity to decide how best to respond.

Sixth, achieving a fundamental system-wide change, away from the present approach to flood management, to address multiple near- and long-term risks in an urgent manner will require more transformational adaptation. This will require higher ambition and engagement of multiple stakeholders and institutions in developing a longer-term and spatially diverse vision for the Fens. Fundamental to informing and supporting this shift in thinking is the provision of data and information that can help stakeholders to engage, understand and approach issues in different ways, including by identifying and evaluating potential opportunities and trade-offs, such as agriculture versus other land uses. The framework presented here is a first step in contributing to this space for the UK Fens. It supports evidence generation and knowledge provision from key adaptation decision-makers that promotes the consideration of risk through a systems-lens, focused on near, long-term and beyond 2100 timescales. The mixed-method approach allows for context-specific information on vulnerability to be integrated into thinking and provides outputs that can provide a foundation for creating adaptation storylines to help explore and visualize what a transformational adaptation future could look like.

## 5. Conclusion

The UK Fens, like many drained coastal lowlands, has a long history of adaptation but is now threatened by a wide range of enhanced climate hazards. Due to the landscape and economy of the Fens it differs from many urban and rural areas of the UK where dominant climate change risks can be identified and prioritized. In contrast, the Fens region is highly vulnerable to multiple climate-related risks, including SLR, that can compound each other. This reflects the historic decisions that have been made on adaptation, requiring a 24 hr, 365 days a year commitment to manage water levels across the Fens landscape. Thus, the ability to live, work and farm in the Fens is fundamentally enabled by a series of historic, progressively larger, adaptation interventions that have transformed the Fens over several centuries. This means it is difficult to separate climate risks and adaptation in the Fens as they are intimately linked and have co-developed over time: as risks have risen, so adaptation has followed and been enhanced to maintain human activity, especially agriculture.

Responding to the big future challenges facing the Fens, and other similar coastal lowlands, will require difficult decisions, trade-offs, substantial investment and innovation, as well as a willingness to work together to capitalize on potential opportunities. It also requires methods to develop shared evidence, of which this study provides both a start and framework for further development. This study demonstrates how a regional analysis of hazard and climate-related risks can be explored in a meaningful and robust way, including the spatial patterns of risk. At this regional scale, it is argued a wide range of adaptation choices can then become apparent, including more radical approaches to manage climate-related risk in the long term (2080s–2100) and beyond 2100, allowing storylines to be developed and options to be explored in a consistent way.

Ultimately, the assessment highlights that the future of the UK Fens cannot be secured through business-as-usual approaches to progressively improve a particular barrier or embankment. Rather it demands establishment of a longer-term coherent strategy and vision to enable a wide range of stakeholders to collectively develop and implement responses. This will be imperative given the current risks faced and the short timeframe remaining to plan and implement adaptation to manage future risks.

More broadly, the integrated approach presented is useful in other coastal lowlands around the UK and internationally, which face coupled climate hazards and risks alongside SLR, and where more radical approaches or changes to manage future risk will be required in the longer-term, alongside local and national socio-economic and environmental objectives. The principles of the integrated framework approach could be applied with similar data, models and literature to other coastal lowland regions nationally and internationally.

## Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

## Availability Statement

The data that underpin this study are cited in the references. In addition, the hydrological model outputs are published. The simulated discharge timeseries of all the catchments modelled are available in Newcastle University; University of East Anglia (2024) and summary metric data sets available in Newcastle University (2024). The HARM model code and input data is available in Jenkins (2023). National and sub-national regional scale outputs from the FFE are published in Sayers et al. (2020). Climate data are available for the UKCP18 Regional Projections for 1980–2080 in Met Office Hadley Centre (2018) and socioeconomic data in Cambridge Econometrics, University Of Edinburgh, University Of Exeter & UK Centre For Ecology & Hydrology (2021).

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