The UK Fens Climate Change Risk Assessment: Big challenges and strategic solutions

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Executive Summary

Context of the Fens

The Fens is the UK's largest coastal lowland. These productive floodplains are strategically important to food production (containing around half of the UK's Grade 1 agricultural land), and home to a growing population and economy (linked to expanding economic centres such as Cambridge and Peterborough). A natural floodplain and wetland, the Fens have evolved over the last four centuries into an engineered landscape of drainage channels, flood and coastal defences, tidal barriers and extensive pumping. Drainage of the former wetland allowed the development of productive agriculture on the fertile peat soils, but this remains dependent on the maintenance of a complex water management regime governed by engineered solutions to drain cropland that would otherwise be waterlogged/inundated and to irrigate crops when rainfed conditions would be insufficient. Whilst agriculture in the Fens remains productive for a wide variety of crops, intensive agricultural practices have resulted in widespread oxidisation of the fertile peatland soils and progressive consolidation and subsidence (with up to 5m of elevation lost in places). The degradation of the peatlands has also released substantial quantities of carbon and led to loss of the natural inland wetland habitats. Past land conversion in the Fen's has led to losses of habitat for terrestrial biodiversity, leaving it isolated into relatively small pockets with limited connectivity. Coastal salt marshes continue to border much of the Fen's shoreline, but as sea levels rise they are being 'squeezed' between the rising tide and the hard defences that protect the Fens from coastal floods. Relevant tide gauge data from East Anglia shows a sea level rise trend of 2.8 mm/yr since 1956 but with acceleration; 0.5 mm/yr rise in the first 30 years and 4.0 mm/yr rise over the most recent 30 years.

Evidence highlights that climate change is already influencing the magnitude and frequency of extreme weather across the UK. Devasting floods in 2013 and drought in 2018 highlight the Fen's present-day vulnerability, which is being exacerbated by climate change in both the near and far future. The management of flood risk relies upon the critical protection provided by an extensive network of embankments, pumps, and barriers. In recent years, significant investment has been made in the Boston Tidal Barrier and the St Germans pumping station but maintaining the performance of the extensive network of aging embankments, pumps, and barriers presents a significant challenge. A 24 hour, 365 days a year commitment is needed to manage water levels across the 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. 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.

Looking to the future, climate change (including sea level rise and other climate related trends) alongside socio-economic drivers is set to increase these challenges. If current and future risks are to be well-managed, strategic choices need to be made today about the long-term vision of the Fens and investment secured to realise that vision. This is an urgent need, and not one that can be delayed. In the absence of an agreed vision, investment in mal-adapted infrastructure and stranded assets is a real risk. Sea levels will continue to rise for decades and centuries to come (regardless of climate mitigation efforts), and although the future is yet to be revealed, much is known, providing a window of opportunity now to set out a future vision for the Fens that responds and builds resilience to these challenges.

Why a Fens Climate Change Risk Assessment?

Globally, the Intergovernmental Panel on Climate Change (IPCC) provides the most comprehensive assessment of the latest scientific evidence on climate change, its causes, potential impacts and response options. The latest IPCC 6th Assessment Reports (AR6) concluded that human activities have unequivocally caused global warming, with a clear trend of rising greenhouse gas concentrations driving global surface temperature rise (IPCC, 2023). Global surface temperature is currently 1.3°C above the pre-industrial baseline (1850-1900), with observed changes in weather and climate extremes in every region across the globe leading to adverse impacts on people, the environment and economies (*Ibid*.). In the UK, as required by the Climate Change Act of 2008, the UK Government undertakes an assessment of risks of climate change at the UK scale every five years, underpinned by an independent assessment carried out by the Climate Change Committee (CCC). To date, there have been three UK-level Climate Change Risk Assessments (CCRAs) which help to inform England's National Adaptation Programme (NAP), setting out actions that the Government will take to adapt to the challenges of current and future climate change (with similar programmes in Northern Ireland, Scotland and Wales). However, given the national scale focus of the CCRA, limited spatial detail was provided, reducing the utility of this evidence in assessing regional risks of climate change at the geographical level of the Fens. This Fens CCRA fills this gap by providing spatial maps and analysis of a suite of climate risks. It provides future climate hazard and risk information on water resources, crops, flooding, sea level rise, terrestrial biodiversity and heat stress, including the potential interactions between risks and sectors. It then considers the strategic choices, including their trade-offs, by imagining a series of alternative storylines to illustrate the need to consider risks and adaptation in the Fens through a system-wide lens.

The timing of this report is significant. It is almost certain that sea levels will continue to rise for many decades to come. At the end of century sea levels may be 1-metre higher that those experienced in the recent past (1981-2000). Assuming that greenhouse gas emissions are not rapidly reduced and are very high, global surface temperature will likely exceed 2°C compared to the pre-industrial period between the 2030s and 2050s (with central estimates around 2040) (Carbon Brief, 2020, IPCC, 2023), 3°C between the 2050s-2070s and 4°C between the 2070s to 2100 (IPCC, 2023)). Even if current policies and action are considered, projections suggest we would reach 2.7°C by the end of the century (with a range between 2.2°C and 3.4°C (Climate Action Tracker, 2023)). The research presented here highlights the challenges that even a 2°C world, for which there is no historic experience, will pose in terms of future climate-related risks for the Fens and the critical timeframe for adaptation planning and implementation to manage present and future risks. There is a significant shift in the magnitude of risks between 2 and 4°C highlighting the need for both adaptation and strong climate change mitigation to avoid such an unmanageable future.

Key sectoral risks and challenges

Flood related risks and challenges

- **Flood protection has, and continues to, profoundly shape the landscape of the Fens:** The Fens are exposed to multiple forms of flooding (groundwater, pluvial, fluvial, and coastal). The Fens has been adapted over centuries to manage these threats and today flood protection is provided by a complex system of drainage channels, embankments, pumps, sluices, and barriers. The continued performance of this system is fundamental to life in the Fens, enabling people, agriculture, and commerce to thrive. This is however under threat.

- **Without significant investment in adaptation, flood risk is set to increase:** The Fens has experienced several devastating floods, including in 1947, 1953, and 2013. These major events, and the threat of future events, have triggered significant investments, including major upgrades of the St Germans pumping station and the new Boston tidal barrier. Further significant investment will be needed to maintain the existing defence system and further adapt this in response to climate change. The UK CCRA suggests investment in the existing defence system, through enhanced maintenance and incremental adaptations, may not be sufficient to manage risk. Present day risks in the Fens may double by the 2080s given a 4°C rise in global mean surface temperature and a high population growth projection. In the case of a low adaptation future, with no further upgrades to existing defences and limited maintenance, flood risk may increase ~16-fold over the same period (with a ~7-fold increase by the 2050s).

- **Choices today will determine the future risk:** As the climate continues to change, flood defences will be increasingly exposed and at risk of failure. As salt marshes narrow in response to sea level rise, coastal defences will experience increased and more frequent wave loading. Barriers and pumps will be called upon routinely, reducing the window for maintenance and possibly increasing operating costs and investment pressures for Internal Drainage Boards. Innovation in how flood risk is managed in the Fens over the short and long term will be needed. Extreme storm events will be more severe, but perhaps the most profound impact will be the increased severity of the more frequent events. There is an urgent need to set out a strategic vision for flood risk management in the Fens through the 21st Century and beyond. Without this strategic vision, investment may be wasted and assets may be stranded.

- **The Fens is highly sensitive to climate change, taking action to mitigate climate change is an important part of flood risk management:** Flood risk in the Fens is highly sensitive to the rate of climate change, particularly sea level rise. If climate change can be successfully limited to a rise of 2°C (current projections highlight that if emissions are not rapidly reduced, we will exceed 2°C between the 2030s and 2050s) and population growth is low, the projected increase in risk by the 2080s with limited adaptation is projected to be ~7 times the present-day risk. Although this is still significant it is much less than the ~16-fold increase projected under a 4°C future. This sensitivity to climate change is also reflected in a projected rapid increase in flood risk between the 2050s and 2080s as the 2°C and 4°C climate trajectories diverge. By limiting climate change, the costs of adaptation (including the feasibility of maintaining existing systems and the scale of defences and barriers needed) are likely to be significantly less, maintaining a window of opportunity to decide how best to respond. While inertia and feedback in the response of sea level to climate change means that sea level rise will continue over the coming century and beyond (even if emissions are successfully reduced), the continued rate and scale of the rise through to 2300 and beyond will crucially depend on mitigation efforts.

Temperature related risks and challenges

- **The Fens are getting hotter:** Whilst the Fens face lower projected extremes of temperature compared to other regions of the UK, such as London and the South East, the magnitude of temperature extremes will accrue as global mean surface temperature rises. Even at 2°C, which could occur between the 2030s and 2050s, there will be multiple repercussions of increasing temperatures and heatwaves, including on transport infrastructure, the built environment, labour productivity, livestock and human health.

- **Heat related risks to human health are projected to increase:** Heat stress can lead to human morbidity and mortality, particularly in vulnerable people such as the elderly. With global warming of 2°C by 2050, heat-related deaths are projected to increase 4-fold from the 1981-2000 baseline, with 53 additional average annual deaths. With warming of 4°C by 2080, heat-related deaths are projected to increase 12-fold to 173 additional average annual deaths. Large inter-annual variability is expected, with deaths lower or higher in individual years. In high years, this will place additional strain on health and social services, particularly in regions of the Fens with high levels of social vulnerability. The design of all new buildings should consider heat and comfort to support adaptation.

Water related risks and challenges

- **Droughts are projected to persist for longer:** Evidence highlights a trend towards wetter winters and drier summers in the UK. This trend is projected to continue, including in the Fens, with risks accruing with each additional increment of global warming. Hydrological and meteorological droughts are projected to worsen under future climate change. At 2°C, which could occur between the 2030s and 2050s, the number of months in severe drought in a 30-year period is projected to be 34.3. With 4°C of global warming, which could occur by the end of the century under higher emission scenarios, this increases to 110.1 months.
- **Investment and innovation in water resource management will be needed:** Water resource management is challenging given the need to consider and adapt to multifaceted climate risks, environmental and habitat degradation, socio-economic pressures (e.g., growing population) and competing water demands. Water companies have a long history of planning and adapting for growth and climate-related risks, including development of strategic adaptation pathways, and are actively investing in new strategic supply side options, such as reservoirs in the Fens.

Agriculture related risks and challenges

- **Significant agricultural challenges arise as temperatures increase:** At higher levels of warming (up to 4°C), many current major crops are likely to show more plateaus or decreases in yield/climatic suitability compared with the rest of the UK. Given the high proportions of total agricultural production currently supplied by the Fens, this is likely to have a significant impact on UK food security. Limiting warming to more moderate levels (up to 2°C, which could occur between the 2030s and 2050s) reduces this risk and may even result in increased yield for current crops. However, water availability is likely to become more limiting than in the present day, even under more moderate levels of warming.
- **Some agricultural opportunities may emerge:** A warming climate brings the potential to adopt new, more climatically suitable crops with which to diversify agricultural systems. However, these are strongly conditional on adequate water availability and the ability to manage agricultural systems in an optimal way, both of which may be strongly influenced by climate change. Novel agricultural systems (e.g. paludiculture, which is wetland-based agriculture) also offer ways to keep land agriculturally productive while mitigating further peat loss and carbon emissions. However, the success of novel crops and agricultural systems as a route to keeping the Fens' contribution to UK food security more climate resilient, depends on successfully transforming all levels of the food supply chain, from the agronomic knowledge of farmers, to local processing and distribution facilities, through to national markets.

Biodiversity related risks and challenges

- **Even limited global warming poses a significant threat to terrestrial biodiversity in the Fens:** Climatic refugia are defined as areas remaining climatically suitable for >75% of the species in different taxonomic groups. Even if global average temperature is kept to 2°C, which could occur between the 2030s and 2050s, almost none of the Fens is likely to remain as an area of refugia. The risk to insect pollinators, even at lower levels of warming, could have serious implications for insect-pollinated crops and wild plants. Historical conversion of natural habitats in the Fens further exacerbates this problem.
- **Careful planning to support biodiversity is needed:** Little natural land for biodiversity currently exists within the Fens (landward of the defences), although there are extensive

designated intertidal and subtidal habitats in and around the Wash. The region provides major potential for restoration of salt marsh and other coastal habitats, although any restoration would need to be supported to cope with sea level rise. Making more space for terrestrial and fenland biodiversity in the future will require consideration of climate change and careful planning and siting of restoration projects alongside stringent climate change mitigation, given the severe risks projected even at 2°C. Properly sited rewilding projects will benefit terrestrial biodiversity by allowing ‘space’ for biodiversity to attempt to adapt *in situ* as well as space for colonisation of environmental refugee species.

Insights from our integrated assessment of climate-related risks and challenges

- **The Fens is highly vulnerable to a wide range of climate hazards:** Due to the landscape and economy of the Fens it differs from many urban and rural parts of the UK where dominant risks from climate change can be identified and prioritised, such as flooding, heat stress and drought. In contrast, the Fens is highly vulnerable to a multitude of climate related risks, including sea level rise, that can compound each other (Figure ES-1). Furthermore, climate risks and adaptation have co-developed over time and are intimately linked so it is not just climate-related risks that need to be considered but also the consequences of past and future human adaptation interventions that can exacerbate or reduce risks. It is difficult to prioritise and adapt to one risk without considering and adapting to others in parallel.
- **Infrastructure underpins societal functions and is highly vulnerable:** Damage to infrastructure such as highways from flooding and drought will be exacerbated with future climate change. For example, the proportion of class C and U roads that have little or no foundations in regions such as Lincolnshire, mean they are highly vulnerable. Cascading effects can include impacts on health and social care delivery, emergency response times and education accessibility. Likewise impacts of extreme weather on interconnected power, water and telecommunications networks can propagate across the affected region and beyond.
- **A sectoral assessment lens is insufficient to capture the multiple and cascading impacts:** The lens of residential and non-residential damage (expressed through an Expected Annual Damage, EAD) provides only a partial picture of the true risk. For example, short and long term impacts of flooding on agricultural production; soil erosion and declines in soil quality; losses to terrestrial biodiversity; damage to infrastructure such as roadways and loss of electricity supply, which will have system-wide implications, that are not reflected in EAD. Understanding the ‘full’ picture of flood related risks will be an important next step to exploring investment choices.
- **A shared long term strategic vision**: Each activity in the Fens relies on choices made by the other activities which share the landscape. Developing a shared long term vision and understanding how to progress towards that shared vision will provide important guidance for future investment and development choices. This may include managing investments in the existing flood defence system or transitioning to an alternative configuration. This may include continuing to defend some areas into the long-term while accepting more flooding in other parts of the Fens. There are a wide range of detailed choices and options available that need to be considered.

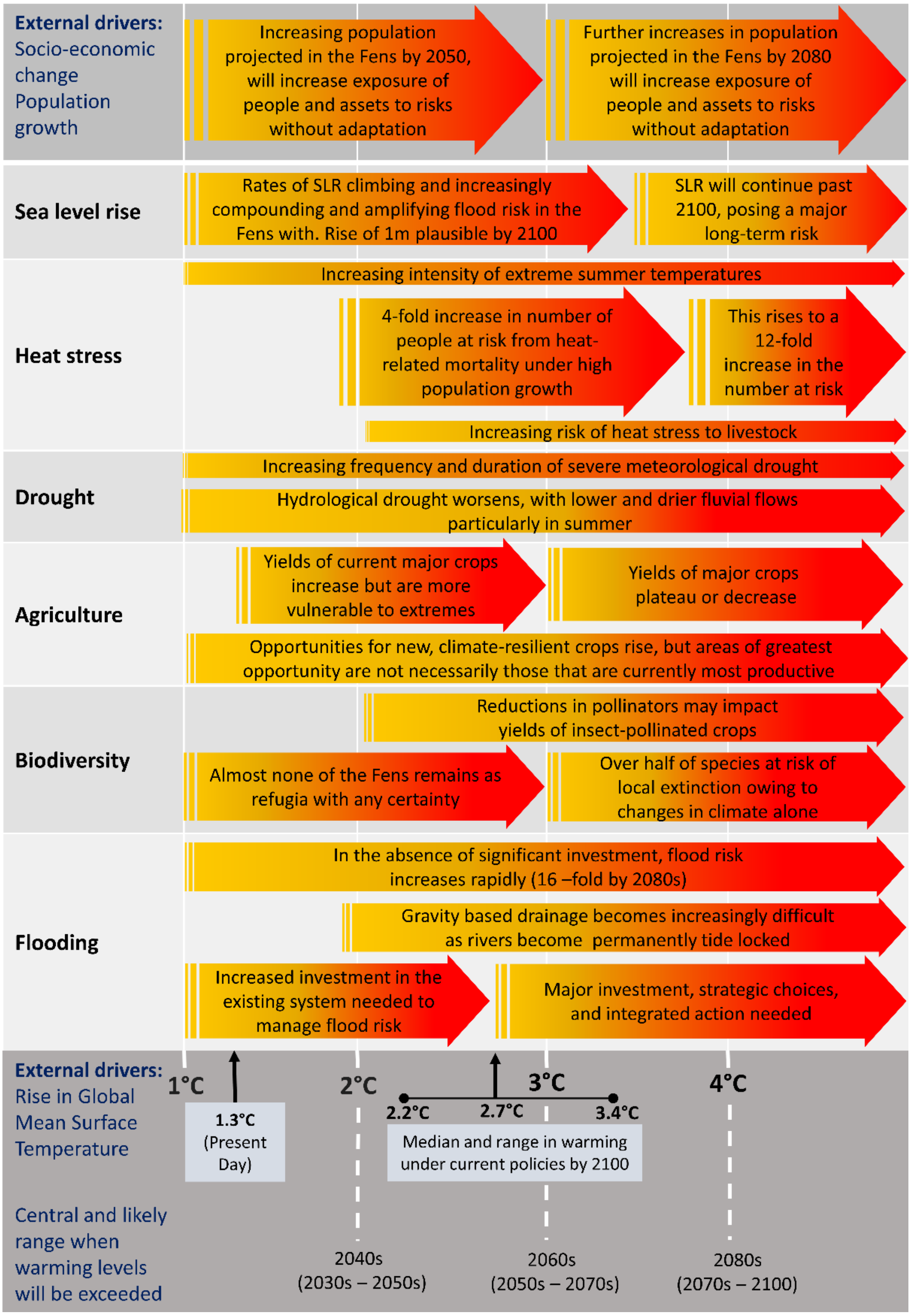


Figure ES1: The myriad of risks that could impact the Fens as global mean surface temperature increases, based on the climate risk modelling presented in this report. The arrows highlight when risks may be faced based on modelled trajectories of when warming levels of 2°C, 3°C and 4°C are reached, reported by the Carbon Brief (2020) and IPCC (2023) and assuming a high emission future (note the height of arrows are for illustrative purposes only and do not depict the significance or size of risk). Even if current levels of government action and pledges are considered, temperatures rise beyond 2°C and potentially 3°C by the end of the century, with continued increases after that date (Climate Action Tracker, 2023).

- **An integrated management strategy and investment approach is needed:** The Fens is a highly managed system where flood management investment has delivered some of the most intensely used and valuable agricultural land in the UK. While flood risk management remains fundamental to sustaining the productive use of the Fens, the form that it takes needs to be considered, since the choices do not stand alone. Flood risk management influences, and is influenced by, development goals and associated water resources, agricultural, habitat, and infrastructure choices. A tractable integrated assessment and aligned planning process will be central to the success of the Fens as a region in the long-term.
- **Exploration of future adaptation choices must be through a system-wide lens**: There are a range of possible adaptation futures for the Fens depending on societal and management decisions in the face of climate and other changes. These can be illustrated by a range of contrasting futures from major advance through to widespread retreat and intermediate cases assuming similar but enhanced investment in the existing system. However, there will be fundamental trade-offs concerning land use in the Fens, especially agriculture versus other land uses such as biodiversity restoration or conservation and development in the long-term, as the land resource is finite. Rather than stopping at the defence line, consideration of the Wash and the intertidal areas around it is needed, as the position of the defence line may well change and the intertidal areas generally enhance protection.
- **There will be multiple, competing demands for freshwater in the Fens.** Socio-economic changes such as projected population growth and urbanisation will lead to increased domestic and industrial water demand. Drought and water scarcity are projected to increase under future projections of climate change, which can lead to reduced soil health, risks to crops and livestock, loss of biodiversity and reduced water quality. Changes in water salinity can affect irrigation and crop production whilst high levels of pollutants can reduce the quantity of water available for abstraction with any restrictions on irrigation further amplifying risks to agriculture. While agricultural land may be protected from flooding by enhanced investment in flood defences, it will only remain productive if drought and water quantity and quality issues are addressed in parallel.
- **There are potential opportunities for agriculture:** The future of agriculture in the Fens needs to be considered in a systemic way, including the direct and indirect effects of climate change (e.g. changes in drought and groundwater) and other changes such as the evolving agricultural system itself, as well as human demand. There are opportunities for agriculture in the Fens to adapt to warmer and drier conditions through investment, for example, farm-level reservoirs and increased irrigation. Longer term this will become more challenging to align with national targets on environmental improvement, which will require reduced water abstraction alongside projected increases in temperature and drought magnitude. Continued intense agriculture would demand long-term and continued flood protection, but could be supported by a shift to vertical farming or low carbon glasshouse farming that would allow the relocation of agricultural food production to flood-safe land under controlled climatic conditions.
- **Agriculture and biodiversity are intrinsically linked:** Climate impacts and projected declines of insect pollinators will add to stresses facing some current crops and may limit the number of future crops that can be grown. Care needs to be taken in future plans so as not to further exacerbate biodiversity losses and to aim to reverse such losses where possible. While agricultural land may be protected from flooding by enhanced investment in flood defences, it will only remain productive if biodiversity, such as insect pollinators, is addressed in parallel. Alternatively, less intense agriculture may allow more flooding through managed rewetting and rewilding in certain areas. Alongside this, there are opportunities for agriculture in the Fens to adapt to wetter conditions through novel agricultural systems (e.g. paludiculture). This depends on successfully adapting all levels

of the food supply chain, from the agronomic knowledge of farmers to local processing, distribution facilities and national markets.

- **A mosaic of different adaptation approaches could help address potential trade-offs:** The role of the Fens in national food supply and security has been key in how flooding has been managed in the region and how the government recognises this importance now and in the future. The current approach is uniform, but a more diverse and targeted adaptation approach is possible, which could be used to capitalise on different opportunities for agriculture, biodiversity, and flood risk management, alongside competing demands and needs of supporting sustainable development, economic growth, and Net Zero strategies.

Deciding the future today: Next steps

The findings from this climate change risk assessment highlight that the future of the Fens cannot be secured through local tactical actions to improve a particular barrier or embankment, but demands a long term 'whole of Fens' strategy. This is not to suggest a detailed Master Plan, setting out detailed actions in all locations, but it does demand the establishment of a coherent strategy and vision to enable a wide range of stakeholders to develop and implement reponses that align with that overall strategy. This will be imperative given the challenges that even a 2°C world will pose in terms of future climate-related risks and the short timeframe remaining to plan and implement adaptation to manage present day and future risks. There is a crucial window of opportunity for future work to build upon this risk assessment and support the next stage choices.

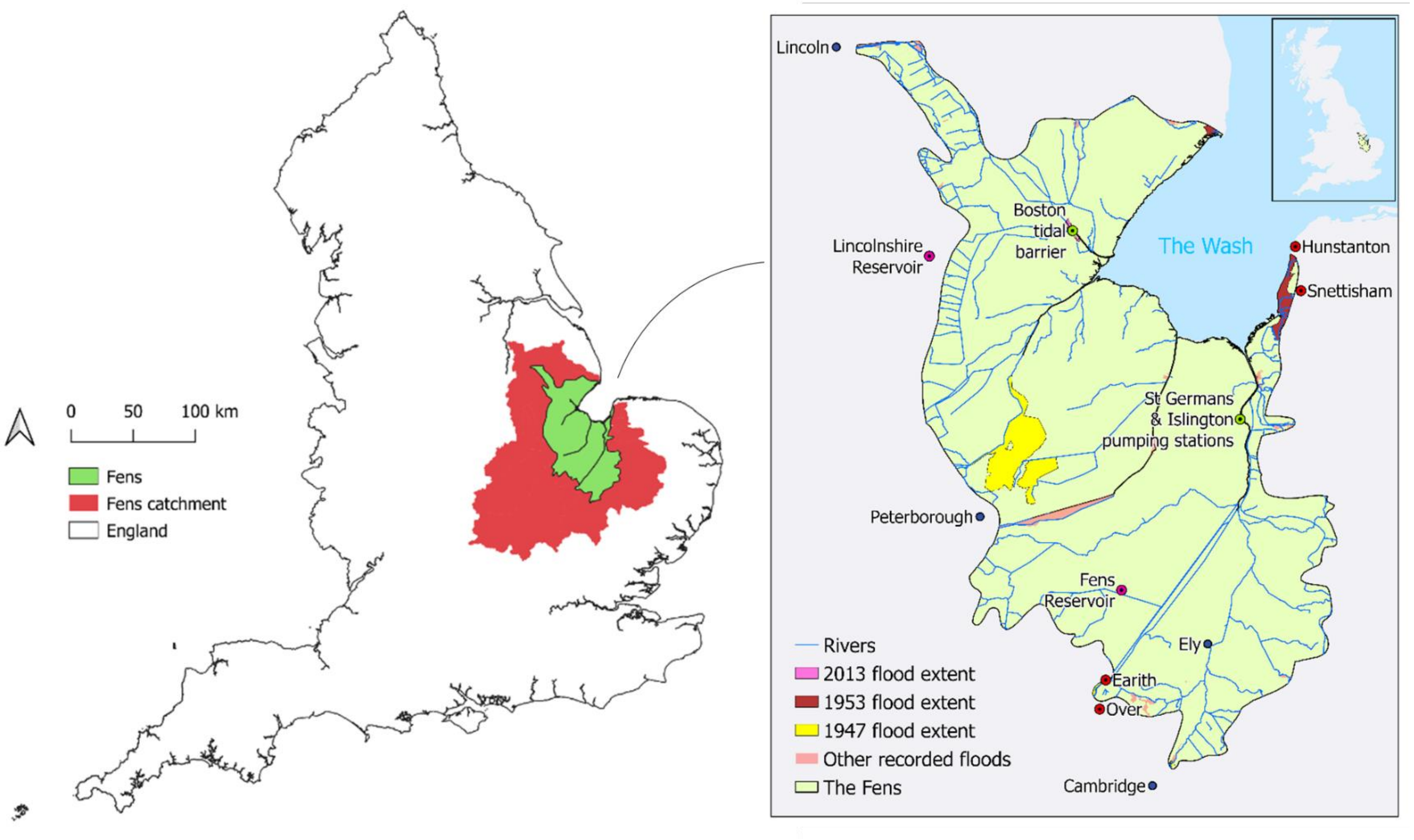
1. Introduction

Overview of the evolution of the Fens landscape

Fens are flat, low-lying, and peat-forming wetlands fed by tidal forces and by freshwater from rainfall, surface water runoff, and groundwater. Geographically, the Fens region of East England represents the nation's largest coastal lowland (Anglian Water et al., 2021), covering almost 1,500 square miles (NFU, 2019), and reaching from Lincoln in the north to Cambridge in the south, and from Peterborough in the west across to western areas of Norfolk (Figure 1). The lowest point in England is located in the Fens, 2.75m below sea level (Migoń, 2020) and large areas are below mean sea level.

The Fens developed over thousands of years of relatively stable sea levels (Brew et al., 2015). Historically, communities in the Fens were well adapted to living in the wetlands, benefiting from the abundance of natural resources the landscape provided (Boyce, 2020). However, the region has been significantly transformed, beginning in the mediaeval times, and then more significantly in the 17th Century, when drainage began in earnest to reclaim the low-lying land from the water (Migoń, 2020). The driver was primarily economic, given the taxes that could be levied on farmers who would benefit from the new expanses of highly fertile peat soils (Boyce, 2020), but also to improve navigation and reduce flood risk (Migoń, 2020). The drainage of the Fens region, which took place in stages over hundreds of years, was accomplished through a combination of digging new canals, which transformed the fluvial network, building new embankments and sluices, and creating washes to store the flood water (for historical accounts of the Fens pre and post draining also see (Darby, 2011)).

Today, it is estimated that less than 1% of original fen habitats remain. The landscape has been dramatically transformed with an extensive network of ditches and drainage channels (Mossman et al., 2015), which along with pumping, modern machinery, embankments, and broader water resource management, aim to keep the area flood free and well drained. This transformation paved the transition to an intensive agricultural landscape benefitting from the fertile peat soils (Mossman et al., 2015). The Fens are now of high strategic value, containing around half of the UK's grade 1 agricultural land. Economically, the region contributes over 7% to the UKs total agricultural production (NFU, 2019, which used a comparative boundary for the Fens region). Whilst it is often described as the 'breadbasket of Britain' due to the number of cereal crops grown, it also produces 33% of all vegetables grown in England as well as high quality salads, flowers and bulbs, (*ibid*). The Fens also provide important but somewhat degraded ecosystem services, including historically storing vast quantities of carbon and regulating water quality and quantity. Furthermore, despite the widespread modification and intensification of agricultural land use, the remnant areas of semi-natural habitat (fen, marsh, swamp, wet meadows and waterbodies) continue to provide a unique and internationally important resource for biodiversity (Mossman et al., 2012), being home to diverse and often unique species, including birds, insects, and plants.



Left: The outline of the Fens and its catchment, demonstrating how much of the east of England drains into and through the Fens. Source: Sayers -FFE. **Right:** The boundary of the Fen region used in this study, showing rivers of the Fens, historic flood extents and the location of towns and infrastructure assets highlighted in the text below. Flood extents are taken from the Environment Agency based on data from 1946-2024, with events recorded in the Fens from 1947-2019.

Figure 1: The outline of the Fens, its Catchment and its rivers

Today's challenges

Managing flooding and keeping the Fens well drained remains a significant and important challenge today. Following many centuries of subsidence (with land levels lowering by up to 5m over the last 100 to 200 years due to oxidation of the peat) substantial areas are now below mean sea level (Dawson et al., 2010). Riverbeds are elevated above their floodplains (by up to 2m in places) requiring ongoing maintenance and upgrade of embankments to prevent inundation (Migoń, 2020). This process is now slowing (Thieblemont et al., 2024) suggesting the peat has largely been lost with potentially significant negative implications for agriculture. A 24 hour, 365 days a year commitment is needed to manage water levels across the landscape to drain the Fens. 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 for the region, with competing water demands for people, agriculture and industry, and wider implications for nature and biodiversity.

Present day risks from extreme weather events are already being compounded by climate change. The Lowestoft tide gauge shows a sea level rise trend of 2.8 mm/yr since 1956 but with acceleration; 0.5 mm/yr in the first 30 years and 4.0 mm/yr over the most recent 30 years. Near coast sea-surface temperature was the warmest on record in 2023. Crucially, the world's coast is committed to centuries of sea level rise from historical anthropogenic emissions alone (Nicholls et al., 2018; Oppenheimer et al., 2019), and UK realisations of sea level rise to 2300 are available for various emission scenarios from Palmer et al (2018) and Howard et al. (2019). Hence, even if we meet the Paris Agreement targets to keep global warming levels below 2°C or ideally at 1.5°C (UNFCCC, 2016), the region will still need to adapt to this major risk. Whilst there is uncertainty over the magnitude of sea level rise to 2100 and beyond, a rise is inevitable (Le Cozannet et al., 2022).

In parallel, the UK is projected to experience warmer and wetter winters, hotter and drier summers driving more frequent and intense weather extremes including fluvial and coastal flooding, heatwaves and drought (Climate Change Committee, 2021). Without effective climate change mitigation and adaptation, these risks will contribute to increased social, economic and environmental losses and damage, with the most vulnerable populations likely to be disproportionally affected (IPCC, 2023). Even with effective climate mitigation, adaptation will be essential, most especially for sea level rise. Risks, such as those to biodiversity, may also be further compounded by ongoing and future land use and management strategies, for example that fragment habitats or drain land (Parmesan et al., 2022).

Future plans

At the regional and local level adaptation action to reduce flooding and address other climate-related risks, or exploit opportunities, will be essential to support and enhance the future resilience of the Fens, its local communities, economy and the environment in line with government goals (EA, 2020a). Consideration of how adaptation can contribute to climate change mitigation through e.g. peat restoration or more sustainable land management practices to retain topsoil is equally important (Defra, 2018). Consequently, the evolution of climate-related risks needs to be considered collectively within a single framework that acknowledges broader physical and social influences in reducing or enhancing risk to support effective and integrated adaptation and management. This aligns with a fundamental realisation in the last few decades that the implications of past and future adaptation decisions for the Fens need to be carefully considered, with a need to start more actively selecting the longer-term adaptation pathway and outcomes desired rather than thinking short-term.

An opportunity for leadership

Internationally, the UK is considered at the forefront of adaptation planning (Lesnikowski et al., 2020). Under the UK Climate Change Act (2008) there is a continuous 5-year cycle, beginning with the UK CCRA, which then informs the National Adaptation Programme (NAP) aimed at responding to key risks (Defra, 2022a). The CCRA provides evidence on the risks for the UK, England and the Devolved Administrations, but provides limited detail at more local scales. For the fourth UK CCRA there is a desire to reflect this local adaptation analysis. The Fens CCRA presents an opportunity to provide an exemplar case study to show how regional analysis of climate risks and adaptation can be explored in meaningful and robust way. It is at this regional scale that multiple risks and adaptation responses can be explored in a consistent and integrated way includes the potential interactions between different sectors and adaptation options that may emerge. This integrated approach will be central to successfully managing risk in the Fens but will not be easy. It will require the decision makers to challenge the status quo and consider transformational and potentially radical approaches to manage climate-related risk in the long-term, in a way that meets local and national socio-economic and environmental objectives.

Report aims and objectives

This report aim is to provide a climate change risk assessment that provides a more detailed regional understanding of the current and future risks facing the Fens on timescales out to 2100 and beyond. To achieve this the report:

- Draws on a set of existing, spatially explicit, models that provide climate hazard and risk information on flooding, sea level rise, heat, drought and water supply, agriculture and terrestrial biodiversity. The climate hazard and risk data are mapped and the risks for the Fens under future global warming scenarios of 2 and 4°C are assessed.

- Considers climate-related risks and consequences for the Fens for each sector/theme individually and then through a systems lens to recognise the potential for risks to interact or cascade across or between multiple sectors. This is important to help inform and support the next steps in the future direction of climate risk management for the region for the Environment Agency and to help inform the work of the Future Fens Integrated Adaptation Taskforce (FFIA) and the Fens2100+ Programme.

- Builds on the findings from the risk assessment to emphasise how future adaptation planning to 2100 and beyond will need to consider the integrated nature of risks across all sectors. Five exploratory storylines of how the Fens could look in the future under different adaptation strategies, and their implications for system level change across development, water resources, flood protection, agriculture and biodiversity, are presented to highlight the integrated nature of risks in the Fens and need to consider system wide adaptation.

2. Basis of the climate change risk assessment

This Fens CCRA builds on methods, models and data produced as part of the OpenCLIM project which developed an integrated framework for future risk assessments linking detailed climate and socio-economic scenarios with spatially explicit, state-of-the-art risk and adaptation models across multiple sectors. It provides consistent and spatially explicit results for the UK at various increments of global warming from 1.5 to 4°C, with results presented here focusing on 2 and 4°C. It embeds the best available science alongside internal consistency in the climate and socioeconomic data and assumptions on adaptation, development and land use applied across sectors.

The models used provide spatially explicit national results. In this report existing data are used to support a regional CCRA for the Fens. These spatially explicit models are:

- **Flooding.** The Future Flood Explorer[1] (FFE, e.g., Sayers *et al.,* (2016)) enables changes in fluvial flow, rainfall intensity, and sea level rise to be translated into spatially disaggregated risk. This includes providing insights into expected annual damages, the impacts on people (differentiated by social vulnerability), and the changing exposure of infrastructure, agricultural land and natural areas to fluvial/coastal and surface water flooding. The FFE is used within OpenCLIM to explore the benefits of natural flood management (linking with the HBV and SHETRAN models, Sayers *et al*, in preparation). For the purposes of the Fens CCRA, the version of the FFE applied and reviewed in support of the UK CCRA3 on fluvial and coastal flooding and National Infrastructure Assessment on surface water flooding (Sayers et al., 2020, 2022b) is used.
- **Agriculture.** The CropNET[2] and EcoCrop[3] agricultural models are used, providing changes in crop yield (for four crops), and crop suitability (a wide range of crops).
- **Terrestrial Biodiversity.** The Wallace Initiative[4] database providing data on risks to biodiversity and natural capital at 1×1 km resolution (Wallace initiative 3HR) is used, quantifying biodiversity losses; change in species richness; climate refugia for biodiversity; risks to pollination; and risks to natural capital (Price et al., 2024b; Warren et al., 2018). Intertidal habitats are not included.
- **Water Resources.** Results from the Water Resource for England and Wales[5] model are drawn upon, with simulations supported by the Environment Agency and published in Murgatroyd et al. (2022) considering different adaptation options for demand and supply side management.
- **Heat Stress.** The Heat Adaptation Risk Model (HARM) is used, which provides data on spatially explicit heat-related risks (including mortality) and the role of adaptation.

Further details on the models are available Appendix A and described in Warren et al., (2023). A glossary of terms used in the report is included in Appendix B.

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[1] http://www.sayersandpartners.co.uk/future-flood-explorer.html

[2] https://www.ukclimateresilience.org/projects/crop-net-monitoring-and-predicting-the-effects-of-climate-change-on-crop-yields/

[3] https://en.wikipedia.org/wiki/Ecocrop

[4] https://wallaceinitiative.org

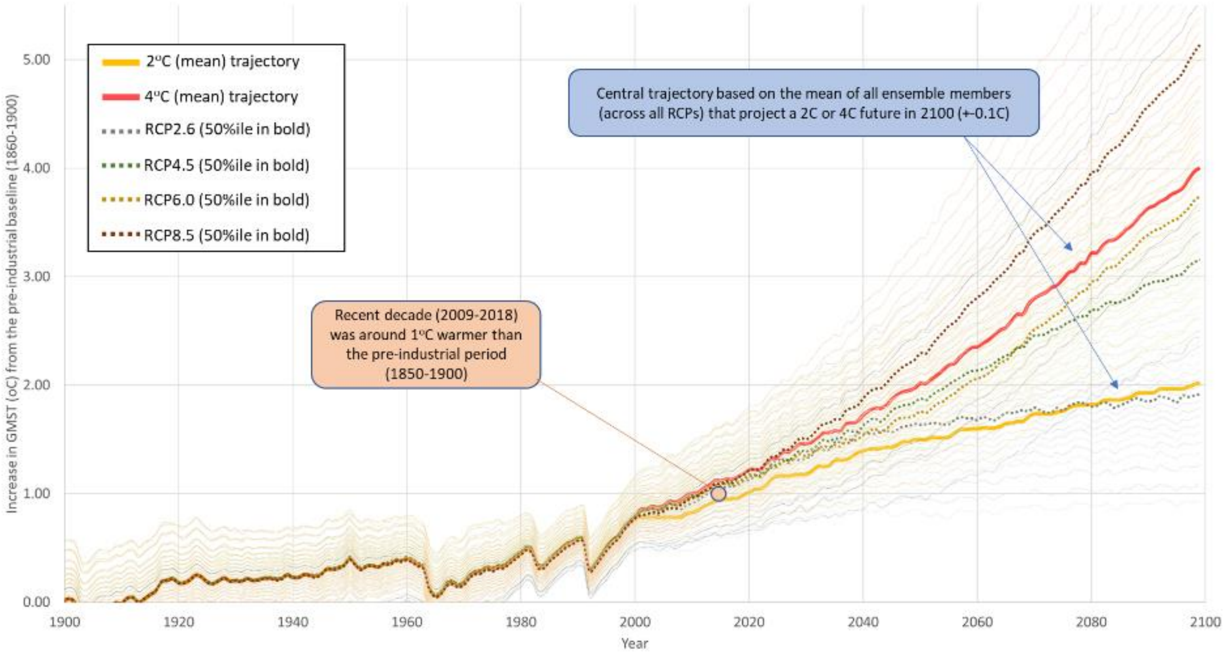
[5] https://www.gov.uk/government/publications/review-of-englands-emerging-regional-water-resources-plans/review-of-englands-emerging-regional-water-resources-plans

3. Future scenarios of external change

Climate scenarios

This report presents an assessment of different climate-related risks at global warming levels of 2°C and 4°C average above pre-industrial levels. Current average global temperatures are 1.3°C above the pre-industrial period. Importantly, 2 or 4°C does not mean that the amount of warming in the Fens is 2 or 4°C, but that when averaged over the whole world, the amount of average global warming is 2 or 4°C. Presenting results at defined warming levels allows risks to be considered in a more policy-relevant manner. 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 ruled out, and encourages thinking of what a 4°C world could look like for adaptation planning (Betts and Brown, 2021).

Figure 2 illustrates that the specific timing when humanity is projected to exceed given global warming levels, based on the climate models and greenhouse gas emission scenarios used. Carbon Brief (2020) estimated that if emissions are not rapidly reduced, the world will likely exceed 2°C between the 2030s and 2050s. If some mitigation is assumed, then it is projected that humanity exceeds 2°C between the late 2030s and 2070s. 4°C is modelled to be exceeded under higher emission scenarios towards the end of the century, between the 2070s to 2100 (IPCC, 2023).



Central trajectory based on the mean of all ensemble members (across all RCPs) that project a 2C or 4C future in 2100 (+-0.1C)

Recent decade (2009-2018) was around 1°C warmer than the pre-industrial period (1850-1900)

Figure 2: Rise in Global Mean Surface Temperature (GMST) to 2100 (from UKCP18 probabilistic projections). Source: Sayers et al., 2020

Box 3-1: A basic introduction to Representative Concentration Pathways (RCP)

RCP 8.5 - representative of increasing greenhouse gas emissions over time and high greenhouse gas concentration levels; **RCP 6.0** - represents a scenario that stabilizes shortly after 2100. UK Climate Projections 2018 (UKCP18) sea level anomalies have not been estimated for this RCP and therefore is not used here at the coast; **RCP 4.5** represents a second scenario that stabilizes shortly after 2100; **RCP 2.6** represents a "peak-and-decline" scenario that leads to low greenhouse gas concentration levels by 2100.

Based on Sayers et al., (2020)

Sea level rise – Projections of change

The Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report (AR6) notes that there is high confidence that sea level rise has accelerated since the 1960s (1971–2018: averaging 2.3 mm/yr; 2006–2018: averaging 3.7 mm/yr)(Fox-Kemper et al., 2021).

The IPCC also warn that it is virtually certain that global mean sea levels will rise through 2100 and for many centuries beyond. It is highly likely that sea level rise will exceed 1m by 2100 (above pre-industrial levels). The Environment Agency reports that sea levels can be expected to rise between 0.85-1.72m at King's Lynn by 2100 based on UKCP18 data (Environment Agency, 2020).

Looking beyond 2100, Palmer et al. (2024) developed five storylines of sea-level rise for the UK to 2300 that draw on the IPCC AR6 and which are consistent with the UK Met Office Climate Projections 2018 (UKCP18). They suggest that even the most optimistic sea level rise outcomes for the UK will require adaptation of up to 1m of sea level rise for large sections of coastline by 2300. For the storyline that is most consistent with current international greenhouse gas emissions pledges, and a moderate sea level rise response, UK capital cities will experience between about 1 and 2m of sea level rise by 2300, with continued rise beyond 2300. The storyline based on the upper end of the IPCC AR6 likely range of sea level projections yield much larger sea level rise, with a range between about 3 and 4m by 2300. Two high-end scenarios are also presented in Palmer et al. (2024). These include accelerated sea level rise associated with ice sheet instability feedbacks, leading to sea level rise in the range of 8 m and 17m by 2300. These magnitudes of rise are unlikely but cannot be entirely dismissed. If they materialise, such a change would pose enormous challenges for UK and global coastal communities, and are likely to be beyond the limits of adaptation for some locations.

For this assessment, two projections of relative sea level rise, as used in support of the UKs CCRA3, are considered (Sayers et al., 2020). The first assumes a 2°C rise in global mean surface temperature by the end of the century from a pre-industrial baseline and the second a 4°C rise.

Fluvial flows – Projections of change

Climate change influences fluvial flood risk through changes in rainfall extremes that in turn change in-river flow and levels (and hence standard of protection).

The assessment used here reflects the analysis undertaken as part of the UK CCRA3 (Sayers et al., 2020). This analysis used all of the UK Met Office UKCP18 probabilistic projections that reach a 2°C or 4°C rise in global mean temperature in or before 2100 (from a pre-industrial baseline) to assess the change in fluvial flows. The selected combinations of ensemble members and time-periods are used to derive changes in peak flows (as described in Environment Agency (2023a)). The analysis undertaken for the UK CCRA3 highlights that the change in return period of peak flood flows will vary across the Fens region. Under a 4°C rise in global mean average surface temperature by 2100 based on RCP8.5, (which represents increasing greenhouse gas emissions and high greenhouse gas concentrations), extreme flows increase in most locations, changing by up to 35%, particularly in the north of the Fens. In some locations, particularly in the central Fens, extreme flood flows may reduce by as much as 15%, highlighting the spatial variation.

Intense rainfall – Projections of change

Recent developments in kilometre-scale climate modelling used in surface water analysis for the National Infrastructure Commission (Sayers et al., 2022b) provide projections of changes in sub-daily rainfall given a 2°C and 4°C rise in global mean surface temperature. Chan et al, (2021) provides an analysis of the percentage change in short duration rainfall intensity from the 1981-2000 baseline for England for a 1-in-30 year return period (a relatively frequent event) and 1-in-100 year return period under a 4°C future. Short duration rainfall is projected to increase across England. Although the percentage increase projected in the Fens is not as severe as for parts of Western England, it is projected to see a 20-24% increase with warming of 2°C, which could occur between the 2030s to 2050s, and a 24-28% increase with warming of 4°C respectively, which could occur by the end of the century.

Current and future socio-economic trends in the Fens

Population growth and employment

The Fens covers an area of almost 1,500 square miles (NFU, 2019). Fifteen Local Authority Districts intersect the Fens boundary used here (referred to as ‘Total Fens’), however, only four Local Authorities have over half of their area within it: South Holland, Boston, Fenland and East Cambridgeshire (referred to as ‘Central Fens’). Despite the population rising throughout the total Fens region in the last 40 years, growth rates have declined over the last decade, although this varies geographically (Figure 3). Boston and South Holland are experiencing a rising share of 0–15-year-olds, and East Cambridgeshire is showing signs of an aging population (ONS, 2023b).

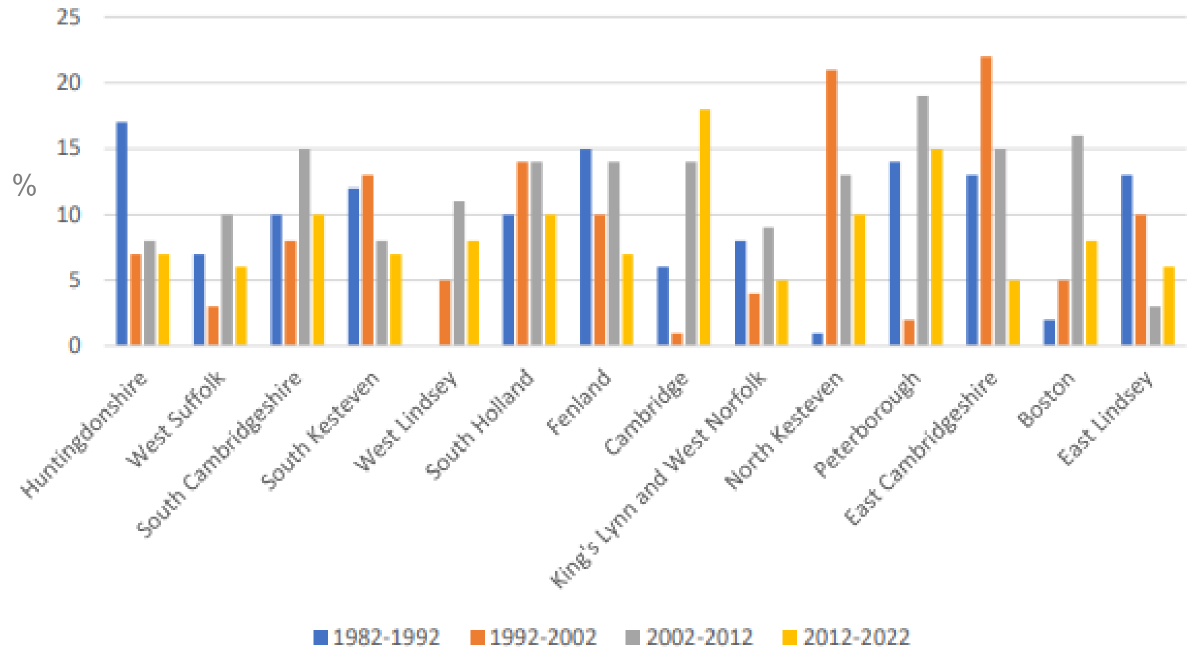


Figure 3: Population growth rate per decade (%) between the first and last year of each decade for Fens Local Authority Districts that intersect the Fens boundary, demonstrating the range of population growth in the region. Source: ONS (2023b)

Many parts of the region, including those mentioned above, suffer from high unemployment (ONS, 2024) and a low wage economy. Boston and South Holland have the largest share of people with no qualifications, and the Central Fens generally have a higher-than-average share of elementary level workers and a smaller proportion of professionals in comparison to England (ONS, 2023a). These districts showed particularly high unemployment following the 2008 financial crisis, which had an acute impact on elementary occupations while professionals and managerial roles were better protected (The UK Commission for Employment and Skills, 2014).

The UK's Business Register and Employment Survey from 2019 (Cambridge Econometrics et al., 2021) highlights that wholesale and retail trade and repair of motor vehicles is the dominant sector in terms of number of employees in the total Fens. Employment in manufacturing and construction has grown throughout the central Fens since 2014, but steeply declined in 2023. This aligns with a jump in unemployment from ~2.5% in 2022 to almost 4% in 2023 throughout the Fens. It could be related to the impact of Brexit tariffs and border checks on manufacturing (Bailey et al., 2023), whose workforce appears to have shrunken the most of all sectors in the central Fen districts.

The agriculture and fisheries sector has also seen a declining share of the workforce (ONS, 2023a) since 2013. In Fenland, the total farmed area has increased 8% between 2013-2021, but the number of labourers has declined 35% and the number of holdings has decreased 7% (Defra, 2022b). A similar trend is apparent in South Holland, suggesting a possible concentration of land ownership which is benefitting fewer workers. Given its agricultural nature, the Fens has the largest fresh produce logistics hub in the UK and a large and sophisticated commercial food chain (NFU, 2019). Economic activity in the region contributed £40.4 billion to the UK economy, with agriculture contributing £2.9 billion a year in 2018 (Cambridge Econometrics et al., 2021), making up 7.4% of the regions Gross Value Added.

Socioeconomic pressures

Current and future risks from climate change pose large risks to society, particularly for communities with higher vulnerabilities. Identifying areas with high vulnerabilities and considering how they may change over time provides another layer of detail when evaluating climate-related risks. Approximately 4% of the 372 small areas (Lower Super Output Areas) in the Fens are ranked in the most deprived category for regions in England, according to the 2019 English Index of Multiple deprivation (McLennan et al., 2019) (Figure 4). This index accounts for income, employment, education, health, crime, barriers to housing and services and living environment, with areas in East Lindsey (Northeast), Kings Lynn and West Norfolk (East) and Fenland (central) particularly vulnerable.

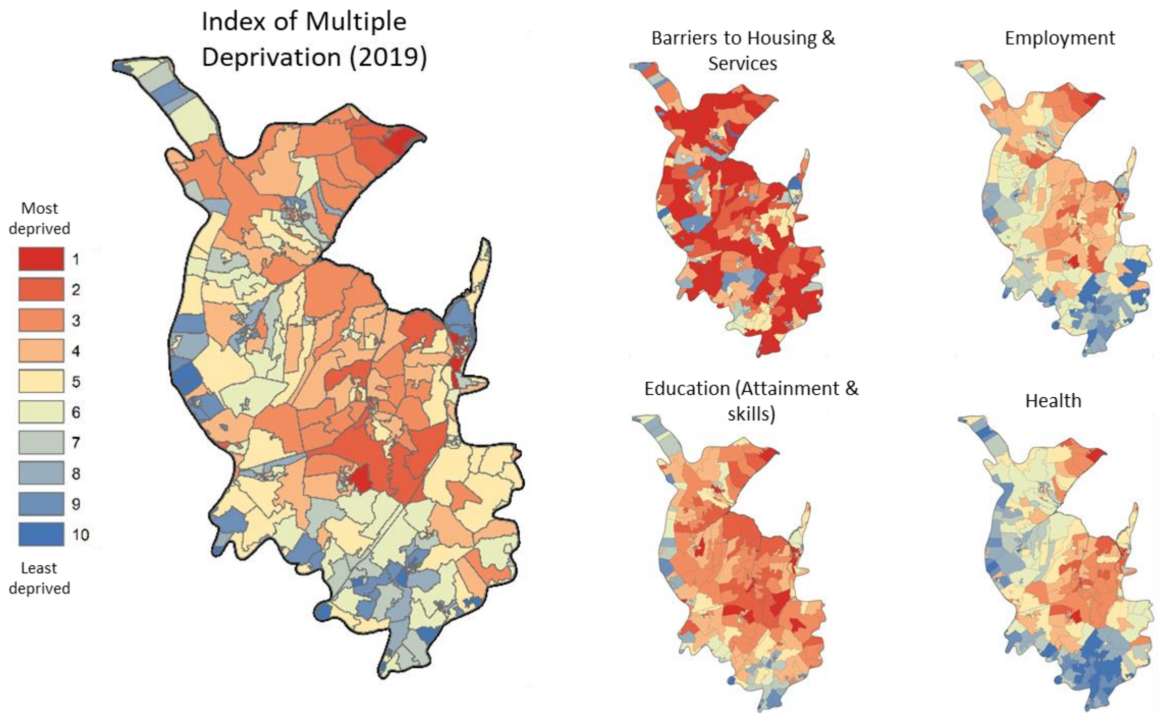


Figure 4: Index of Multiple Deprivation for each Lower Super Output Area intersecting with the Fens (left), and a sub-set of the domains of deprivation that are included in the index (right). Areas with compounding socioeconomic pressures may suffer higher vulnerability to climate change. Source: Data extracted from Ministry of Housing, Communities & Local Government (2019).

Population growth and development – Projections of change

The UK-scale shared socioeconomic pathways (UK-SSPs) (Cambridge Econometrics et al., 2021; Pedde et al., 2021) are a set of five scenarios developed to explore how different socio-economic factors such as population change, economic growth, employment, Gross Value Added, inequality, income or levels of social deprivation might change over time. They were developed to be combined with climate hazard data to help explore future climate related impacts and vulnerability and to help assess future adaptation planning. The UK-SSPs include five distinct scenarios (which align with the global SSPs used by the IPCC) covering sustainability: focused on sustainable development and environmental protection (SSP1); middle of the road: a continuation of current trends without significant change (SSP2); regional rivalry: emphasising a future with more regional competition and fragmentation (SSP3); inequality: a future with increased social and economic inequalities (SSP4); and fossil-fuelled development: centred on economic growth underpinned by burning fossil fuels (SSP5). In this study, we link the climate data with projections of socio-economic data from the UK-SSP2 and SSP4 scenarios, for 2050 and 2080 at 2°C and for 2080 at 4°C.

UK-SSP2 is characterised as a middle of the road scenario where social, economic and technological trends do not change markedly from the past. The scenario assumes continued economic growth, increased urbanisation and increasingly dense cities, and growing population. The UK population reaches 76.6 million by 2050 and 83.2 million by 2080 (this is higher than the 2020-based Office of National Statistics (ONS) principal population projection which reaches 71.4 million by 2050 and 71.6 million by 2080).

UK-SSP4 is characterised by increasing inequality across the UK in terms of investment and economic opportunity, with an increasing divide between wealthy and poorer segments of the population as well as regions of the UK. There is increased urbanisation in and around densely populated urban areas. The UK population reaches 71 million by 2050, declining to 68.8 million by 2080 (this is similar to the 2020-based ONS principal population projection until 2060, but becomes lower from 2060 onwards).

The Census 2021 suggests around 686,033 people live within neighbourhoods (Lower Super Output Areas) that are within or intersect the Fens-CCRA boundary. Under SSP4, population is projected to increase by 12% by 2050 and by 19.2% through to 2080. Under SSP2 (the higher growth scenario) the population of the Fens is projected to increase by 13.6% by 2050 and by 24.6% through to 2080.

There are few places within the Fens that lie outside of the areas defined as floodplain. If projections for continued population growth and development are realised, then there are limited options for future developments of buildings outside of this floodplain. If it is assumed that future development choices continue as in the recent past, then the need for increased growth could translate into an increase in flood exposure (and by extension) risk.

Evidence used in support of the Future-Flood-Explorer underpinning the CCRA3 (Sayers et al., 2020) suggests that ~200,000 people live in ground floor or basement properties within the fluvial and coastal floodplain (as of 2018). Under the high population projection, the number of flood exposed residential properties increases by ~25% (to ~250,000) by the 2080s. Assuming a low population projection results in little change in flood exposure from today.

4. Flooding – Assessment of present and future risk in the Fens

Flood management has been fundamental in shaping the Fens landscape

During the 1630s, landowners, headed by the Earl of Bedford, set out to drain the east coast fens of England so that the peat soils could be used for summer cultivation and to prevent serious winter flooding. As a result, the 'Great Fen' in England's Cambridgeshire and Norfolk region was drained and protected by dykes (improving and extending many schemes initiated many centuries before by the Romans). The construction of this vast network of major and minor drains carried many of the major rivers of England through East Anglia and exposed large areas of fertile agricultural land. Management of modification of the system in response to flooding has always been an issue for the region, with incremental heightening of embankments to account for the oxidisation and decline in elevation of drained peatland reported as early as the 17th Century (Boyce, 2020).

Adaptation of the flood defence system continues today. Recent examples include the additional capacity provided by St Germans pumping station (the largest in Britain that became operational in 2010). Likewise, a recently opened pumping station at Islington, near Kings Lynn, replaced aging diesel pumps that had been in operation since the 1950s (EA, 2020b). The construction of the Boston tidal barrier across the River Witham, completed in 2020 in response to the 2013 floods, provides an important enhancement to the existing flood defence system (EA, 2020c; Pollard et al., 2021).

Beyond these projects, maintaining the standard of service provided is a major undertaking. The Future Fens Flood Risk Management project, for example, highlighted that maintaining the current standard of service over the next 100 years for the Great Ouse Fens, stretching from Kings Lynn in the North across to Peterborough in the West and down to Cambridge in the South, would cost £1.8 billion (EA, 2021).

These historic decisions have shaped the management of the Fens for centuries and continue to do so today - *but what does the 21st century flood risk management look like in the Fens?*

An adaptation deficit exists today and in the absence of significant investment is set to increase in the future

Without flood defences, frequent and regular flooding would occur across much of the Fens. The existing flood defence system does not however eliminate all risk and several major flood events have been experienced in living memory (Box 4-1). Consequently, an adaptation deficit, defined as an adaptation gap between the current state of a system and the state it needs to be in to minimise the impacts of climate change to an acceptable risk threshold, exists today.

Today, the Expected Annual Damage in terms of direct residential and non-residential property damage from flooding (after taking account of existing defences) is estimated to be around ~£16m[6] (Sayers et al., 2020). In the absence of investment (i.e., with no further upgrades to existing defences and limited maintenance) this adaptation deficit would increase significantly in the future, increasing 16-fold by the 2080s assuming a 4°C rise in global mean surface temperature and high population growth (Figure 5, 'Low-adapt').

Investment in the existing defence system (including to maintain or improve assets, e.g. through raising, as well as investment in the operation of the assets and pumping stations by Internal Drainage Boards) moderates this increase, but risks are still projected to double to an Expected Annual Damage of £32m by the 2080s given the same 4°C future scenario (Figure

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[6] This excludes the protection provided by the recently completed Boston Barrier.

5, see the 'Enhanced Investment in the Existing System' (EIES) bar in the bottom chart[7]). This assumes sufficient investment is made available in the existing defence system to maintain condition and to raise defences where justified given existing rules; that development control continues to be as effective as in the recent past; and that forecasting and warning continue to be in place.

Box 4-1 Flood events in the Fens

The cause of recent flood events in the Fens area have been varied. The major events include:

1947 - Fluvial flooding: In March 1947 (Ngenyam Bang and Church Burton, 2021; RMS, 2007). The flooding followed a combination of heavy frontal rainfall, trigged by a succession of south-westerly depressions compounded by heavy snowmelt that was occurring in parallel. The snow thaw began on March 9, after a severe winter dominated by freezing temperatures and heavy snowfall. As the ground was still frozen the combined rainfall and snow melt drained directly into rivers, leading to significant fluvial flooding across England (RMS, 2007). In East Anglia the strong south-westerly winds caused waves that breached the barrier bank between Over and Earith before further breaches occurred leading to extensive flooding across the Fens (RMS, 2007). While flood protection was less advanced than today, the consequences of the 1947 fluvial floods prompted renewed focus on river and flood management strategies (Marsh et al., 2016).

1953 – Coastal flooding: The UK east coast has experienced several coastal flood events through the last century (Haigh et al., 2016; Wadey et al., 2015). The North Sea flood of January 31st to February 1st, 1953, was caused by a strong north-westerly gale which generated a large storm surge driven by the low air pressure, high winds which drove the water towards the shore, and shallower southern North Sea waters. The surge coincided with a high astronomical tide, resulting in a combination not considered in the design of the defences (Lumbroso and Vinet, 2011). The storm tracked down the east coast of England breaching coastal defences in 1,200 places over a period of eight hours during the night with little warning to those at risk (RMS, 2003). In England, the flooding resulted in more than 300 deaths; 30,000 people being displaced from their homes (Hall, 2015); 24,000 houses damaged; estimated economic damages of £1bn (2003 values); 160,000 acres of agricultural land flooded (RMS, 2003); as well as 46,000 livestock killed (Lumbroso and Vinet, 2011). Locally in and around the Fens, the storm breached flood defences in Lincolnshire and Norfolk, causing extensive flooding and 40 deaths in the coastal towns Mablethorpe and Sutton-on-Sea, 15 deaths in Kings Lynn and 31 and 25 deaths in the town and village of Hunstanton and Snettisham respectively (Hall, 2015; Ngenyam Bang and Church Burton, 2021). Sea defences and riverbanks were damaged and breached by direct wave action or overtopped and eroded by the surge, with the tragedy reflecting the limited maintenance of existing sea defences, which in some places had not been re-established since the war (Baxter, 2005). Consequently, the 1953 floods were a catalyst for increased defences, and the development of forecasting, warning systems and evacuation plans, including the construction of the Thames Barrier to protect the floodplain of Greater London from high tides and storm surges (Wadey et al., 2015).

2013 - Coastal flooding: On the 5th of December 2013 the highest tidal surge seen since 1953 affected the region (Huntingford et al., 2014; Sibley et al., 2015). Whilst many coastal defence structures suffered some damage, large scale coastal flooding was prevented. In North Norfolk coastal barriers were breached or overtopped causing property damage of ~ £28–£84 million (Wadey et al., 2015). At Boston the tidal surge flooded the town, affecting 590 homes and 105 businesses (Penning-Rowsell, 2021), requiring 200 people to be evacuated (Sibley et al., 2015). This lead to an £100 million investment in a new Boston tidal barrier across the River Witham to enhance protection to the town (EA, 2020c). The scheme protects Boston against tidal flooding with a 1 in 300 year return period and includes an allowance for climate change (Pollard et al., 2021).

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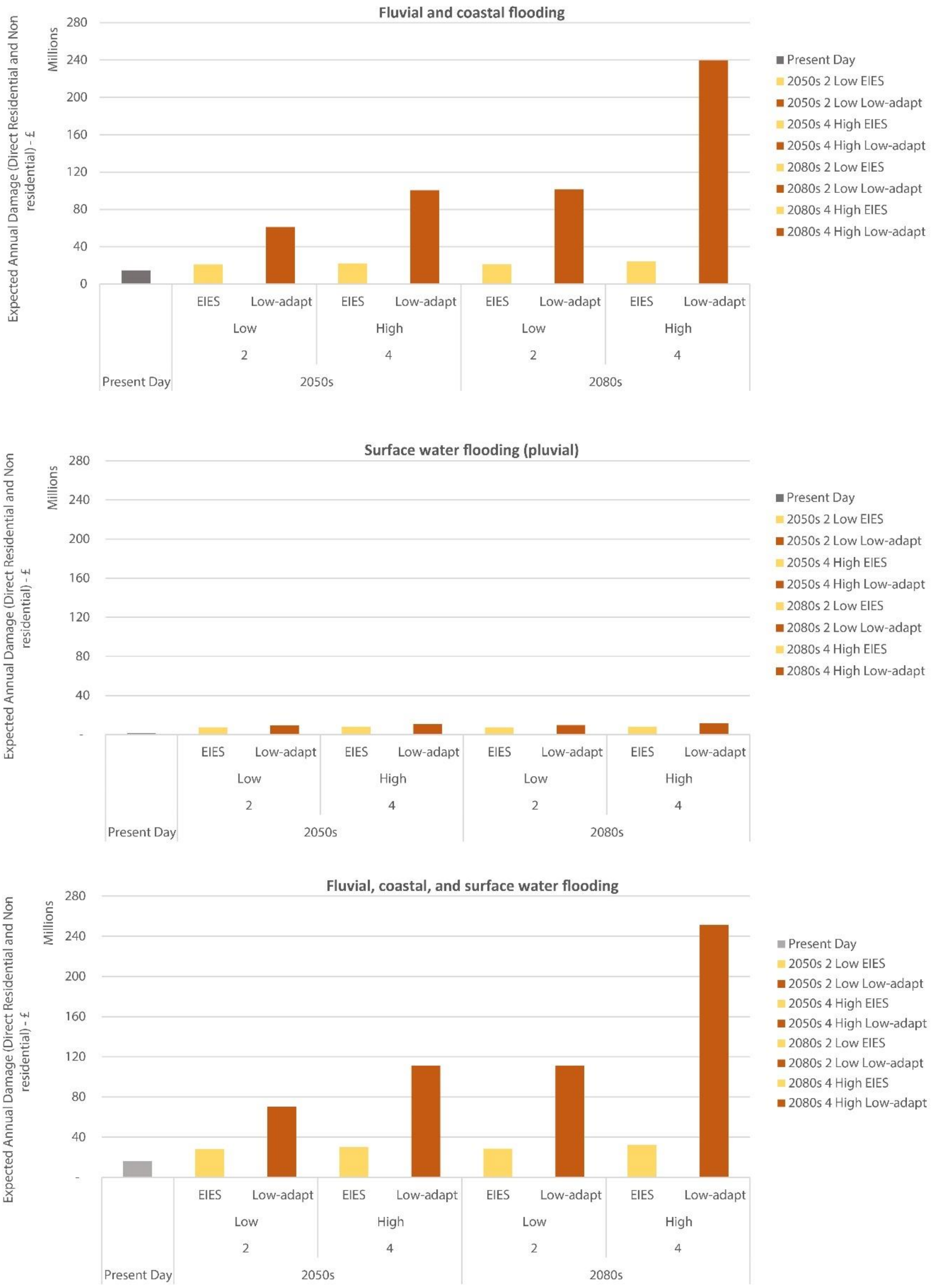
[7] The Enhanced Investment in the Existing System (EIES) adaptation assumption used here reflects the CLA assumption set out in CCRA3 (Sayers et al, 2020). It is renamed here to reflect the general understanding that maintaining the performance of existing system into today and into the future is likely to required significant investment. The quantification of this investment is not however explored here.



Top: Coastal and fluvial flood risks; **Middle:** Surface water (pluvial) flood risks; **Bottom**: All sources

Risk units used: Expected Annual Damages (£ million) – Direct residential and non-residential damages. *X-axis divisions:* **PD** - Present day, **EIES** - Enhanced investment in the existing system, **Low-adapt** – limited adaptation in raising or maintaining existing system. **Low** and **High** refer to the population projection. **2** and **4** refer to the to the increase in global mean surface temperature by the 2080s above pre-industrial times in degrees Celsius. Present day (2018), 2050s, and 2080s are epochs the projected risk refers to. Source: Future Flood Explorer

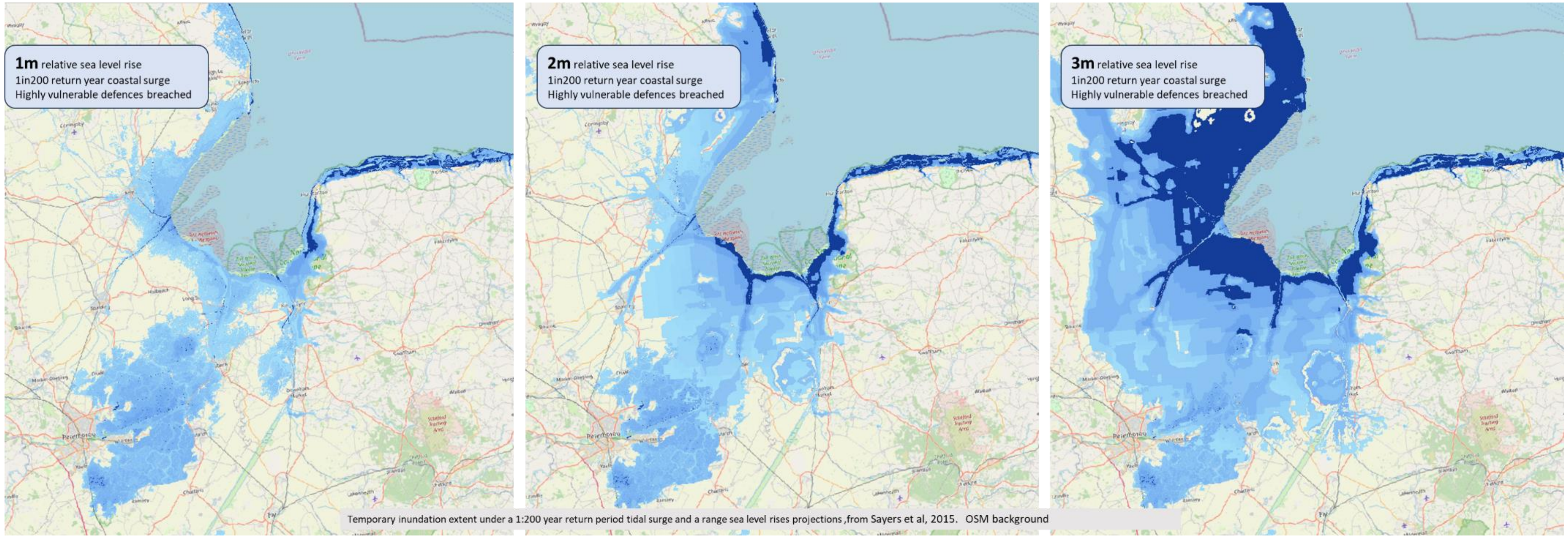
Figure 5: Coastal, fluvial and surface water flood risk within the Fens – Present and future

Sea level rise significantly affects the standard of coastal defences

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 opposed to wave breaking in deep water, usually attributed to exceeding a critical wave steepness). As a result, relative sea level rise has a dominant influence on coastal flooding (increasing both wave-driven overtopping, the chance of a breach and tidal overflow). To understand the impact of relative sea level rise on the standard of protection provided by a flood defence, the UK CCRA3 considered the offshore wave climate, wave propagation to the shoreline, and the typical structure type along each frontage (Sayers *et al.,* 2020 reflecting the methods set out in Gouldby *et al.,* 2017). The results enabled an assessment of the relative sea level rise driven change in the standard of protection that would occur in the absence of any further adaptation. The results of the analysis for the UK CCRA3 highlighted the high sensitivity of coastal defence standards to sea level rise, highlighting the rapid decline in the effective standard of coastal defences as sea levels start to rise.

As part of the UK CCRA2, the implications of an extreme coastal storm under different assumptions of sea level rise were explored to help illustrate the connection between sea level rise and coastal flooding (Sayers et al., 2015a). Figure 6 shows the resulting maps for assumed sea level rise of a 1m, 2m and 3m. These 'what-if' scenarios explore the consequences of a 1-in-200 year coastal storm surge event assuming the existing coastal defence 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. In this analysis for CCRA2 the influence of tidal barriers (such as the new Boston Barrier) are excluded.

The results emphasise the significant area that could be temporarily inundated in a future extreme storm given the low-lying nature of the region, and by inference, the significant damage that would result.



Temporary inundation extent under a 1:200 year return period tidal surge and a range sea level rises projections ,from Sayers et al, 2015. OSM background

The maps are based on those developed for, and available online, in the UK CCRA2 and are zoomed in to show the projected areas of temporary inundation for the Fens region, assuming the *existing* coastal defences remain in place, but the most vulnerable defences breach along this existing line during a 1-in200 return year storm. The storm is assumed to last three tides and the breaches occur on the central of those three tides. Other defences are assumed not to be overtopped. The influence of the tidal barriers (such as the new Boston Barrier) is excluded from the modelling. The shading represents the inundation depth with light to dark blue reflecting lower to higher depth.

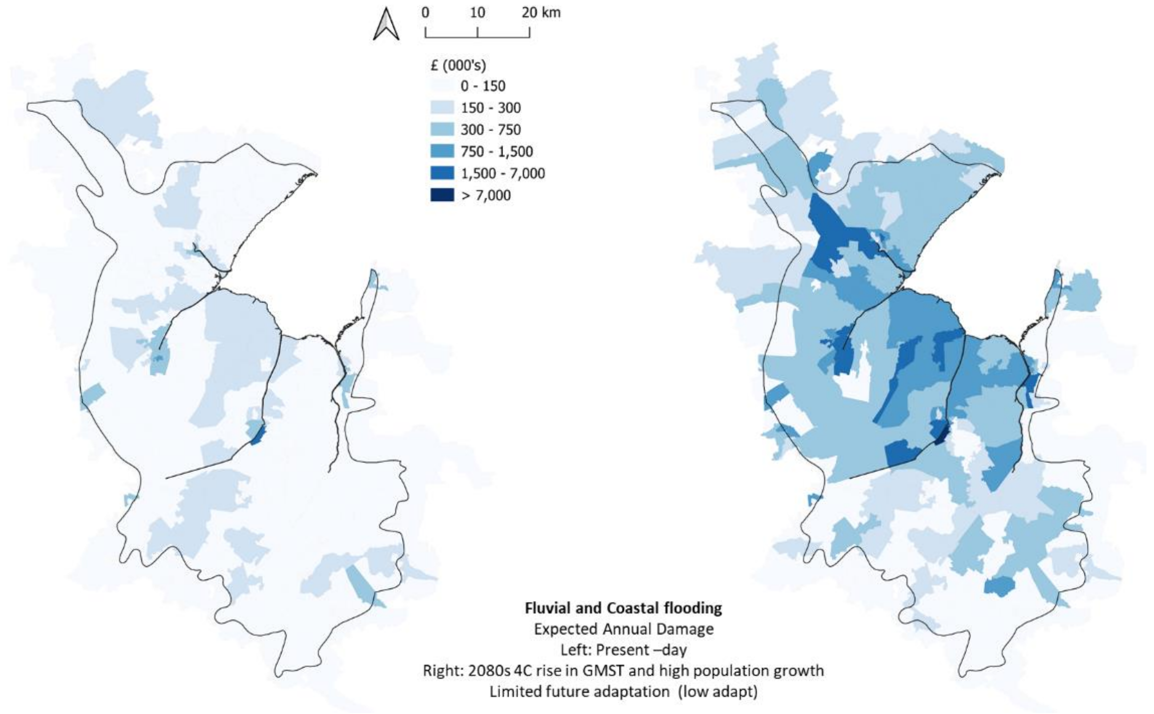
Source: Sayers et al., 2015a UK Climate Change Risk Assessment 2

Figure 6: A 1-in-200 return year coastal surge event reimagined in a future of 1m, 2m and 3m of sea level rise.

Expected Annual Damages – Fluvial and coastal flood risk

Spatial maps of Expected Annual Damage (direct damages - £) across the Fens area associated with fluvial and coastal sources are shown in Figure 7 for the present day (2018) and the 2080s given a 4°C rise in global mean temperature, high population growth, and limited future adaptation. This limited future adaptation scenario aligns to that modelled in Figure 5, where there is an absence of investment (i.e., with no further upgrades to existing defences and limited maintenance).

The values shown in Figure 7 reflect the annual 'average' direct residential and non-residential property damage in economic terms, determined using an integration of the probability of flooding (taking account of defences and other management measures) and the associated damages. A significant increase across the Fens emerges from the present day to the 2080s with 4°C warming. Damages are particularly high in Local Authority Districts in central and northern regions of the Fens, with EAD exceeding £7 million in some areas. It should also be noted that the EADs presented here will underestimate total costs as they exclude broader impacts beyond damage to residential and non-residential properties, that are likely to be significant in local and national terms. Further details of impacts not included in this analysis are discussed below.



Expected Annual Damage (£) – Residential and non-residential damage.

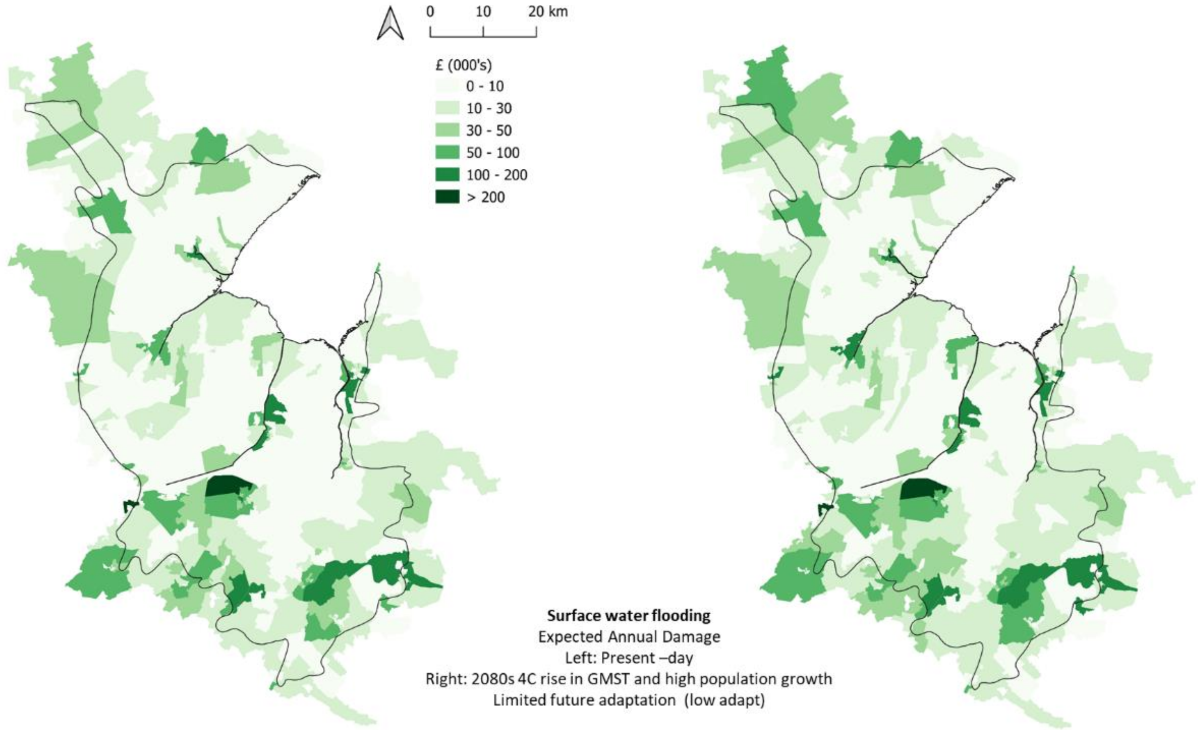
Source: Based on Sayers et al, 2020

Figure 7: Expected Annual Damage to residential and non-residential properties in the Fens from fluvial and coastal flooding. The assumption is limited future adaptation. Left map represents present day. Right map shows 4C Global Mean Surface Temperature.

Expected Annual Damages – Surface water flooding

Spatial maps of Expected Annual Damage (direct damages - £) across the Fens area associated with surface water flooding are shown in Figure 8 for the present day (2018) and the 2080s given a 4°C rise in global mean temperature, high population growth, and limited future adaptation. This limited future adaptation scenario aligns to that modelled in Figure 5, where there is an absence of investment (i.e., with no further upgrades to existing defences and limited maintenance).

Expected Annual Damage across the Fens today is projected to be ~£1.5m (annual 'average' direct residential and non-residential property damage) rising to ~£11.5m by the 2080s given a 4°C rise in global mean surface temperature. While overall damages related to surface water flooding are lower than from coastal and fluvial flooding, Figure 8 illustrates the widespread spatial distribution and nature of surface water flood risks which reach over £200,000 in some areas.



Expected Annual Damage (£) – Residential and non-residential damage.

Source: Based on Sayers et al, 2020

Figure 8: Expected Annual Damage to residential and non-residential properties in the Fens from surface water flooding. The assumption is limited future adaptation. Left map represents present day. Right map shows 4C Global Mean Surface Temperature.

Flood impacts not included in this assessment of Expected Annual Damage

The analysis of Expected Annual Damages to residential and non-residential properties presented here excludes several important categories of impacts, and consequently is likely to be an underestimate of the 'true' risk. Although not possible to include here (although could be in a further analysis) some of these additional impacts include:

Groundwater, erosion and reservoir failure – Not all flood and erosion sources are included. The importance of each aspect at the scale of the Fens is difficult to determine at a local scale.

Agricultural impacts – Agricultural impacts of a flooding event can be severe, especially salinisation due to coastal flooding, which inhibits the uptake of plant nutrients and can cause structural degradation of soil (Gould et al., 2021), as well as land being too wet to cultivate.

Agriculture is important both within the Fens but also from a national food security perspective (Ruto et al., 2021). Impacts can cascade further than direct farm losses, into the food processing sector, and potentially in national security and economy.

In addition to acute and chronic risks in the agricultural sector, acute risk from a single extreme event can be significant. Sea level rise, and the associated saline intrusion into agricultural soils and aquifers poise a creeping, chronic risk (Moulds et al., 2023). Valuing the short and long term impacts of these influences is difficult and linked with cropping choices (higher value crops such as potatoes and vegetables are more vulnerable to saline intrusion than sugar beet, wheat and barley for example (*ibid*)). Nonetheless, it is clear that incorporating these aspects into future analysis will be an important consideration.

Soil erosion – Increases in rainfall intensity and subsequent run-off increases the potential for soil erosion. The soils lost are often the most productive and this process is already a significant challenge. In 2021, Sustainable West Midlands estimated that 2.9 million tonnes of soil are being lost per year in England, equivalent to £40 million in productivity losses, rising to £150 million when total costs from decreased water and soil quality are considered (Sustainability West Midlands, 2021).

Infrastructure damage – Floods and drought damage roads, rail, and other infrastructure. Changing patterns of soil shrink-swell and compression, as well as changing demands placed upon infrastructure such as heavier transport loads, increasingly place a focus on the need for resilient infrastructure supported by appropriate investment. Harrison et al., (2023) report that the high proportion of class C and U roads in the Lincolnshire area, which usually have little or no foundations, and the dependence on road networks for transporting fresh produce, makes Lincolnshire acutely vulnerable to damage to road networks.

Well-being and health and social care delivery – Flood events are traumatic for those impacted. Recovery is difficult when health and social care assets are flooded at the same time and critical social support is lost (Sayers et al., 2017). Even small flood events can hinder ambulance response times (Sustainability West Midlands, 2021). Understanding these event scale vulnerabilities will be an important lens to underpin progress towards a resilient Fens.

Energy demand, supply and distribution: With the progress of electrification and the greater reliance on new infrastructure assets such as electric vehicle chargers at the national scale, the risk of cascading impacts increases, as faults within a 'network of networks' has system-wide implications (*ibid*).

Biodiversity impacts: Increases in rainfall, high river flows and flooding, impact biodiversity on several levels. On the one hand, increased river flows could negatively impact waterlogging-sensitive species (Harrison et al. 2008), while on the other hand increased flooding could benefit some fenland species, although salt-tolerance would be necessary downstream (Holman et al., 2005). Flooding may already be contributing to the changes in the avian community at Cow Lane Nature Reserve on the River Great Ouse, with several common breeding bird species affected by winter flood levels (Harrison and Whitehouse, 2012). Additionally, increases in Combined Sewer Overflow could have severe impacts on water quality, and by extension, biodiversity (Harrison et al. 2008). On a habitat level, analysis for East Anglia has highlighted sea level rise could lead to the conversion of entire habitats, such as from coastal grazing marsh to saltmarsh, although this is largely dependent on whether landward sea defences allow this, as coastal squeeze may cause some areas of saltmarsh to be lost entirely (Richards et al., 2008).

Insights – Beyond the numbers

Projected increases in future risks accelerate with increased global warming

Addressing the existing adaptation deficit is likely to require significant and sustained investment. This investment is likely to be a fraction of the investment that would be needed to adapt to 2°C or 4°C of climate change.

The scale of the future risk and investment needed is highly sensitive to the level of climate change and particularly the rate and magnitude of sea level rise. If climate change is limited to a rise of 2°C and population growth is low, the projected increase in risk in the absence of significant investment (i.e., 'low-adapt' with no further upgrades to existing defences and limited maintenance as shown in Figures 5, 7 and 8 above), is projected to be ~7 times the present-day risk. This is much less than the 16-fold increase projected under a 4°C future and reported above (see Figure 5 – bottom chart).

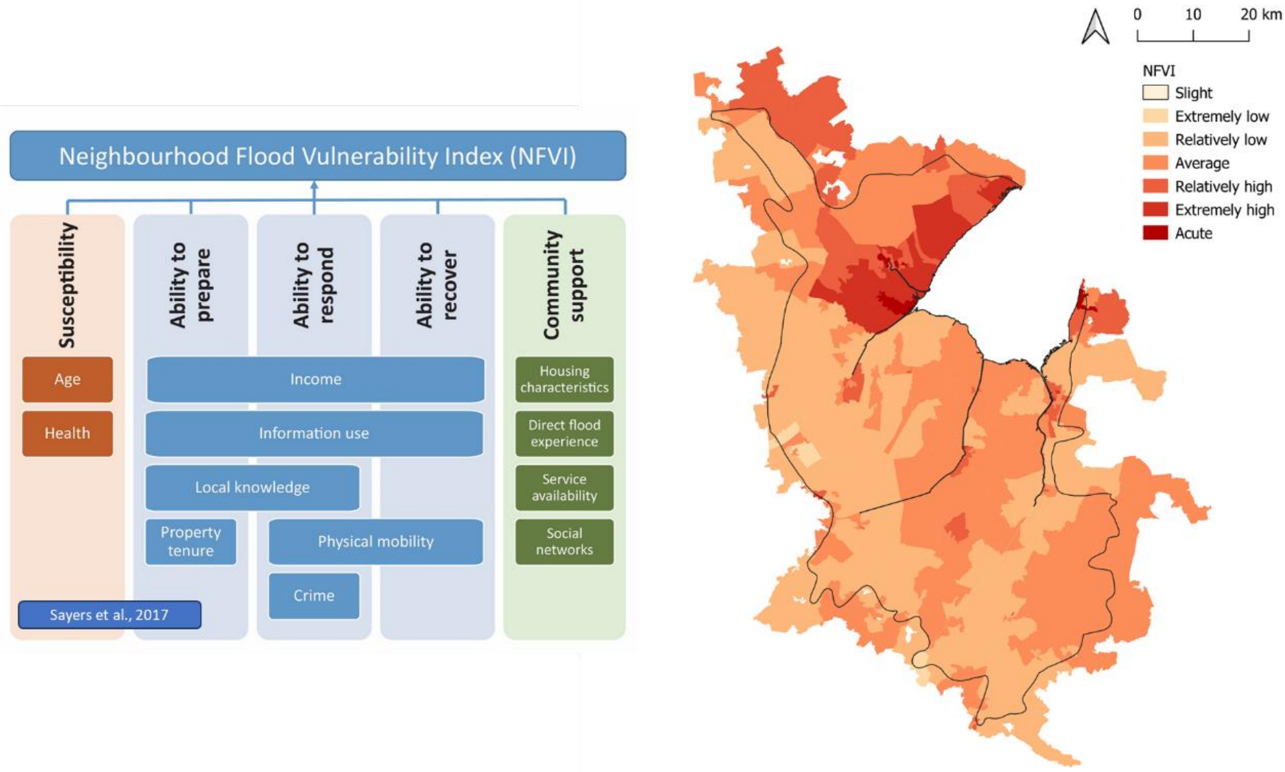
The cost of adaptation is also impacted by climate change. Climate change may, for example, make some existing operational practices such as costs for pumping, hard to maintain. As sea levels rise this may rule out gravity discharge by the end of the century, requiring all drainage channels and fluvial flows to be pumped out to sea, for example. In the shorter term, the higher sea levels may tide-lock increased fluvial flows causing the rivers to back-up (Environment Agency, 2020).

Increased exposure to more frequent and changing loads may also impact the rate of deterioration of flood defences and increase associated management costs (e.g. Sayers *et al.,* 2015). Given the significant lengths of coastal and fluvial defences in the Fens, raising flood defences along all these lines would be a significant undertaking, potentially requiring major pump upgrades, enhanced maintenance and modifications to sea defences and the barriers. At the same time, as sea levels increase, maintaining a 'hold-the-line' may squeeze saltmarsh habitats and reduce their ability to retain sediment (Holman et al. 2005). This in turn reduces the depth-limitation of incident wave conditions, further increasing the challenge of maintaining the existing defence line (Sayers et al., 2022a).

The social distribution of flood risk

The Neighbourhood Flood Vulnerability Index (NFVI, (Sayers et al., 2018)) enables the impacts of flooding on different communities to be explored. The NFVI integrates various indicators of social vulnerability that relate specifically to the challenges faced by the most vulnerable in preparing for, responding to and recovering from, a flood event at a neighbourhood scale (where 'neighbourhoods' are defined by 2011 Lower Super Output Area geographies). Figure 9 details multiple domains of social vulnerability that are integrated in the NFVI, including income, health, physical mobility and housing characteristics.

The assessment of social flood vulnerability for the Fens reveals significant variation across the Fens (shown in the map on Figure 9). NFVI levels are found to be extremely high and acute in areas in the north of the Fens in particular. Further analysis should consider updating this assessment to the 2021 Census and the exploring systematic disadvantage across the figures to support fair investment in future adaptation decisions.



Left: Multiple domains of social vulnerability integrated into the NFVI, which quantifies the social vulnerability to floods in an area

Right: Spatial pattern of NFVI values the Fens, showing some areas are much more vulnerable than others.

Source: Sayers et al., 2017

Figure 9: Neighbourhood Flood Vulnerability Index.

A portfolio of measures will be needed

The long-term approach to the Fens will require careful consideration, demanding innovation in how present and future flood risks should be managed alongside other demands. As with any approach, a portfolio of measures will be required, including investment in defences and/or barriers, potential realignments, and changes in planning etc. As sea levels rise existing practices will be increasingly challenged; gravity discharge may become impossible requiring extensive pumping. Foreshores may lower and salt marshes may become smaller, reducing the natural tidal flood protection provided to human-made defences.

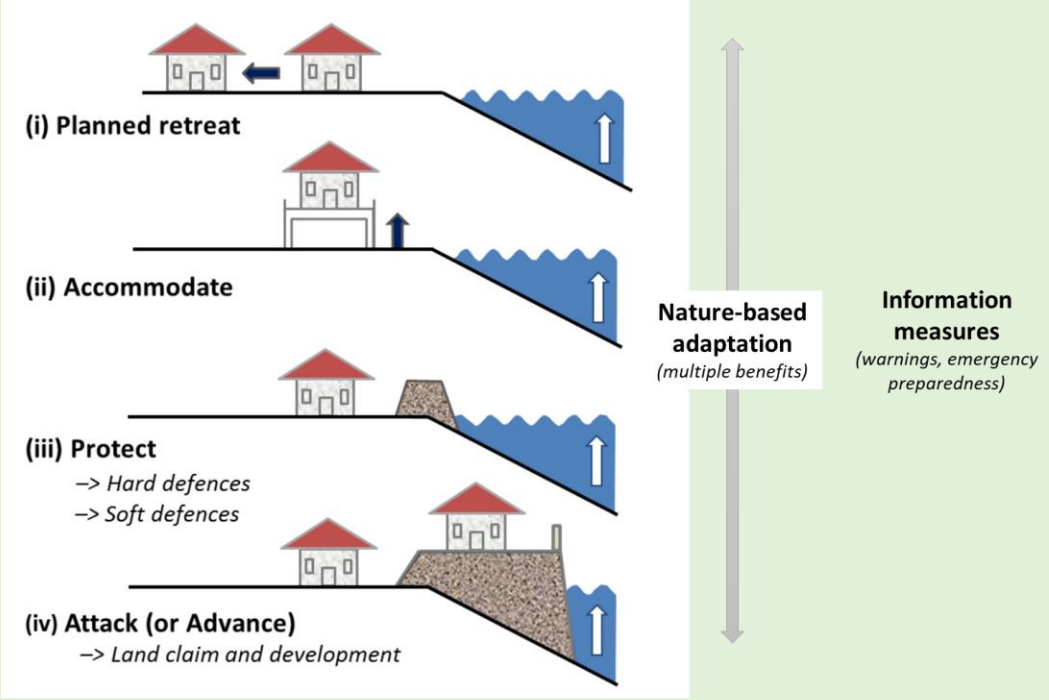
There may be opportunities for innovative responses, including the use of Nature-Based Solutions to stabilise foreshores and for Natural Flood Management (NFM) measures to slow and store water within the catchments that flow into the Fens, and within the Fens, through the targeted reconnection of floodplain areas. Such actions can help to contribute to flood risk management whilst providing multiple other benefits, including for biodiversity and nature conservation. For example, Wicken Fen National Nature Reserve helps protect 2000 ha of farmland and 10 houses from the effects of inundation and losses due to restrictions imposed by a raised water table in a 1 in 20-year flood event (Convine and Starling, 1988; Graves and Morris, 2013). Elsewhere woodlands, in the right setting, and ponds can help reduce surface runoff.

Managing present and future flood risks in the Fens will not only rely upon choosing the ‘right’ portfolio of measures but also understanding the timing and trigger point of action. Adopting an ‘adaptation pathways’ framing, that sets a clear but flexible vision that can respond to the reality of the future as it becomes known, may enable the most important choices that need to be taken today, and those they can be delayed, to be highlighted (Box 4-2). It enables action that avoids unforeseen lock-in to costly or otherwise undesirable outcomes.

Box 4-2 Adaptation pathways – An important framing for the future flood management in the Fens

Adaptation is now recognised as a continuous and proactive process of action, review, and adjustment as the reality of the future becomes better know. This process is encapsulated through the metaphor of an ‘adaptation pathway’ with decisions made as the journey into the future proceeds and lessons are learned (e.g., Haasnoot et al., 2013; Ranger et al., 2013). Flood risk management in the Fens has always evolved, often reactively with limited appreciation of the long-term consequences of each decision in the context of an uncertain future. An adaptative approach is purposefully proactive, setting out a long-term plan that honest about future uncertainty when determining what to do today.

Incremental adaptations, that modify the existing flood system are often the focus of investment choices (see earlier Box 3-2). These decisions assume the configuration of existing defence system is ‘broadly’ fit for purpose as well as the individual assets are well maintained. In the short term this is a reasonable assumption, but in the medium to longer term transformation may be needed. This may include approaches that not only enhance the existing defences but reconfigure the existing defence system by realigning some areas (landward or seaward) or accommodating some flooding in others. Nature-based adaptations could potentially be an element within all these strategies, alongside continued investment in warnings, resilient infrastructure, and emergency preparedness, but the role of Nature-based adaptations may be more limited in a highly managed system such as the Fens (Nicholls, 2018).



Illustrative flood risk management strategies that may challenge the status quo. Source: Adapted from Nicholls (2018).

Decision time – Strategic choices for the future of the Fens

In the absence of significant commitment to adaptation, fluvial, coastal, and surface water flood risk are projected to increase significantly by the 2050s. Early action is needed but deciding how is not straightforward in the Fens. Early agreement on strategic direction will be central. Getting this right will identify:

- **Early investments to avoid lost opportunity:** Identifying those issues where unless investment (to manage risks) takes place an opportunity will be lost that cannot be recovered by future investment.
- **Timing of investments:** Identifying opportunities to bring investment forward in response to events or to align with other sectors (discussed later as part of the integrated assessment) or delay in response to imposed fiscal constraints.

The strategic framing is not simply a high-level vision, but will necessarily also need to reflect practical considerations, such as:

- **Long lead in times to realise an action:** Managing flood risk assets and infrastructure investments (such as a new barrier) as well as decisions of major change, such as relocation, all rightfully take a long time to agree and implement. Hence, a need to start earlier rather than later.

Without early decisions and associated commitments, mal-adaptation is possible, including lock-in to a particular development pathway, or lock-out of future options, such as:

- **Lock-in due to wider development choices:** For example, urban development planning and the location of new towns and industrial hubs that may face increased risks or not be protected from risks in the future.
- **Lock-out due to wider development choices:** For example, development on land that could be needed to accommodate coastal change or set back defence lines or land that can be used to provide urban or catchment flood storage.

Developing a Fens wide flood strategy will need to run alongside cross-government major infrastructure plans (transport, energy, new towns, agricultural production changes etc.) to identify the interdependence between flood risk management and broader economic development plans.

The initial analysis set out here, and across the other sectors, provides a useful starting point to explore these choices and support the development of a well-founded, shared, strategy.

5. Heat Stress – Assessment of present and future risk in the Fens

The Fens will face hotter and drier summers

In the UK climate change has already had a notable impact on land temperature. 2023 was the second warmest year on record, had the hottest ever June and joint hottest September, whilst 2022 saw *daily* maximum temperature exceed 40°C for the first time on record. The number of hot days (28°C or over) has already more than doubled from 1961-1990 to 2014-2023 whist the number of very hot (30°C or over) days has more than trebled (Kendon et al., 2024).The hottest ever *average* summer temperature was recorded in 2018, with a seasonal mean air temperature of 15.8°C, whilst 2023 was 15.4°C, the eighth hottest summer on record since 1884 (Met Office, 2024a).

The UKs CCRA3 highlighted that average and extreme temperatures are both projected to increase across the UK, including the Fens, with a shift towards hotter and drier summers and wetter and warmer winters (Climate Change Committee, 2021).

Table 1 highlights that for the Fens region, modelled average monthly temperature during the summer months is projected to increase from 17.1°C in July to 18.1°C under a 2°C warming level, which could occur between the 2030s and 2050s under a high emission scenario and to 20.5°C under a 4°C warming level, which could occur between the 2070s and 2100 under a high emission scenario. Table 2 shows that average monthly *high* temperatures (usually felt mid to late afternoon) are projected to increase from 22.0°C in July to 23.1°C under a 2°C warming level and to 25.8°C under a 4°C warming level.

	1991-2020 (observed)	**2°C**	**4°C**
Jun	15.0	15.8	17.9
Jul	17.1	18.1	20.5
Aug	17.0	18.1	20.6

Table 1: Observed and projected average monthly temperature (°C) for the Fens region. Temperatures in yellow show that the new average temperature is equivalent to a temperature only experienced 1 in 3 years in 1961-1990; those in red experienced 1 in 20 years. Source: (Price et al., 2024a).

	1991-2020 (observed)	**2°C**	**4°C**
Jun	19.7	20.8	23.0
Jul	22.0	23.1	25.8
Aug	21.9	23.1	25.9

Table 2: Observed and projected average monthly high temperature (°C) for the Fens region. Temperatures in yellow show that the new average temperature is equivalent to a temperature only experienced 1 in 3 years in 1961-1990; those in red experienced 1 in 20 years. Source: (Price et al., 2024a).

Alongside changes in average monthly temperature, extremes heat days are also projected to increase in the Fens region. Figure 10 shows days where maximum temperature exceeds 28°C will increase with global warming. Between 0-2 days per year exceeded this threshold for the region in the modelled 1981-2000 baseline. With 2°C global warming this range increases to between 0-11 days per year and with 4°C to between 2-33 days per year, with higher frequency in the south and south-west of the region. Higher temperatures and heatwaves can pose risks for infrastructure such as power networks, roads and railways, and health, wellbeing and productivity.

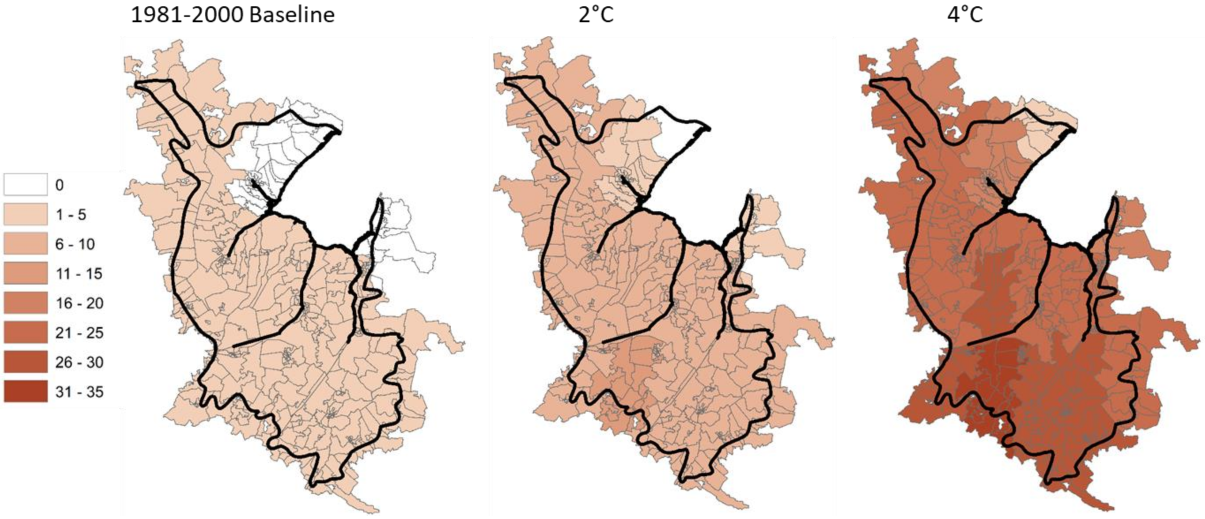


Figure 10: The number of days where maximum daily temperature exceeds 28°C, illustrating increased risk of heat stress on people, productivity and infrastructure, especially at 4°C of warming. Results are averaged across the UKCP18 12 member Regional Climate Model (RCM) ensemble. Boundaries show the Lower Super Output Area.

For example, whilst healthy individuals have efficient heat regulation mechanisms to cope with increasing temperatures, there are limits to the amount even healthy and acclimatised individuals can tolerate (Jenkins et al., 2022b). Exposure to high temperatures can cause heat exhaustion and heat stroke and increase the risk of heat-related mortality. Other consequences can include impacts on mental health, wellbeing, and increased hospital admissions (Aström et al., 2013). Older people, babies and young children, and those with underlying health conditions, are particularly at risk from heat stress (Jenkins et al., 2022b).

In 2023, it was estimated that five summer heat periods led to 209 (28-391 95% Confidence Level) excess deaths in the East Midlands, particularly those aged 85+ (UK HSA, 2024).

In the future, outputs from HARM (Heat Adaptation and Risk Model) for the Fen’s region show that additional average annual heat related deaths increase by 54 deaths per year by 2050 assuming 2°C global warming and an increase in population of 13 (compared to 14 deaths in the 1981-2000 baseline). With 4°C warming by 2080 additional average annual heat related deaths are projected to increase to 173 deaths per year with an increase in population of 25%.

It should be noted that the average annual numbers hide the potential for annual variability, with heat-related deaths lower or higher in others, placing additional strain on health services. Figure 11 presents results for the Fens and highlights that whilst climate change is a driver of increasing mortality in the region, future population growth and a larger elderly population in the region, is also a key driver of heat risk, particularly by the 2080s. Figure 12 illustrates the results spatially, aggregated to Local Authority Districts. The maps illustrate how heat related deaths are projected to increase over time with increased warming and population growth.

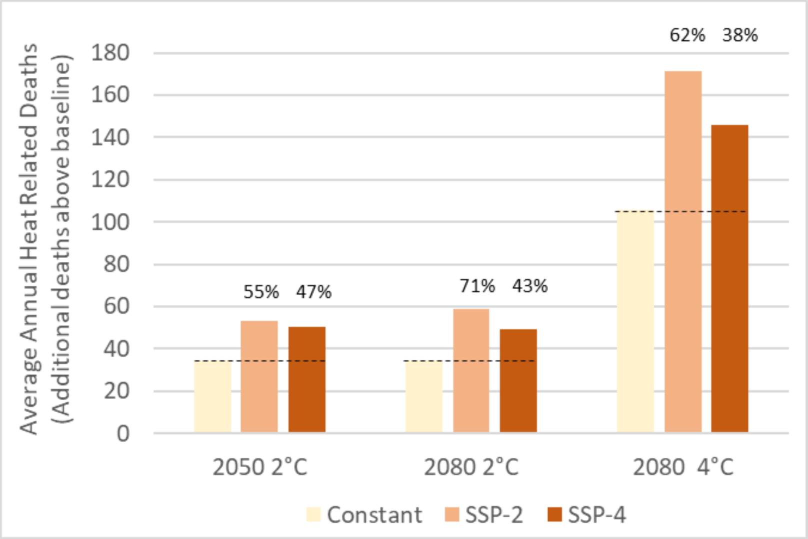


Figure 11: The additional average annual heat-related deaths above the 1981-2000 baseline in the Fens region. Results compare additional deaths under constant and changing scenarios of population and demography (SSP2 and SSP4). The annotated values show the proportion of additional heat-related deaths due to population and demographic change compared to a constant population scenario considering climate change only.

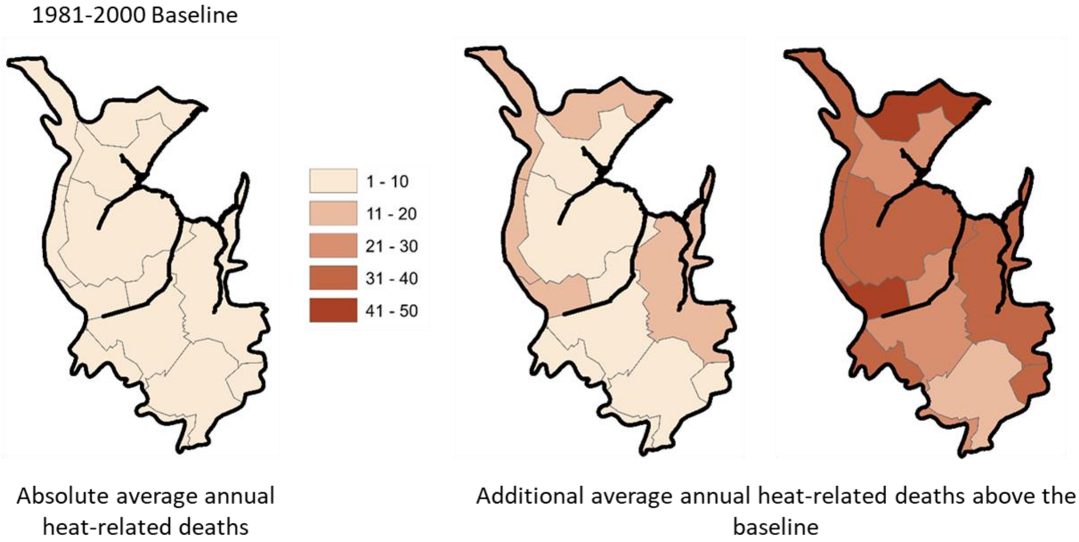


Figure 12: Additional average annual heat related deaths in the Fens (above the 1981-2000 baseline) assuming 2°C and 4°C average global warming occurring in 2050 and 2080 respectively, and assuming future population and demographic change (SSP2), demonstrating increased risk and heterogeneity of mortality rates due to heat throughout the region. Results are shown aggregated to the Local Authority District level.

A further implication of heat is the potential risk of heat stress on livestock in the area. As with humans, livestock also have ideal ambient temperature zones, above which heat stress can occur where livestock are not physiologically adapted or acclimatised to temperature conditions. For example, in the UK for cattle, the ideal ambient temperature is reported as 5°C to 25°C, with cows starting to suffer when temperature is about 19-20°C, and for shorn sheep the upper critical level is reported as 29°C (Farmers Guide, 2023; For Farmers, 2023).

Whilst increasingly warm temperatures may present some opportunities such as livestock being able to be outdoors for longer periods (Climate Change Committee, 2021) the number of days with extreme temperature and heatwave events, that can have detrimental impacts on livestock, will also increase. Key impacts include reduced welfare (i.e., discomfort) and reduced productivity (milk yields) and decreased fertility (Polsky and von Keyserlingk, 2017) leading to economic losses as well as increased susceptibility to disease, heat stroke and mortality (Climate Change Committee, 2021).

The Temperature Humidity Index (THI) can be used to assess thresholds above which livestock would become vulnerable to heat stress. THI values of 70 or more (with 70 equivalent to average temperature of around 21 °C and relative humidity of 75%) is often considered the threshold above which risks develop. Figure 13 indicates that days where THI exceeds 70 will increase with global warming. Between 1-6 days per year exceeded this threshold for the region in the modelled 1981-2000 baseline. With 2°C this range increases to between 7-25 days per year and with 4°C this range increases to between 31-60 days per year, with higher frequency in the south of the region. Hence, the number of days per year when livestock would be at risk of heat stress and consequences of this on animal welfare, morbidity and mortality and fertility will increase in the future in the Fens. Whilst the region is predominantly arable, the risks to livestock would include not only direct impacts but indirect impacts such as the subsequent economic losses of changes in productivity of livestock, additional demands for clean and plentiful water during heat events, and potential compounding effects due to the interaction of heat with the suitability of pasture and forage. Pests may also increase with warmer temperatures, for example the insect vectors for the bluetongue virus which affects cattle/sheep (APHA, 2022), further compounding the risks farmers may face and need to adapt to.

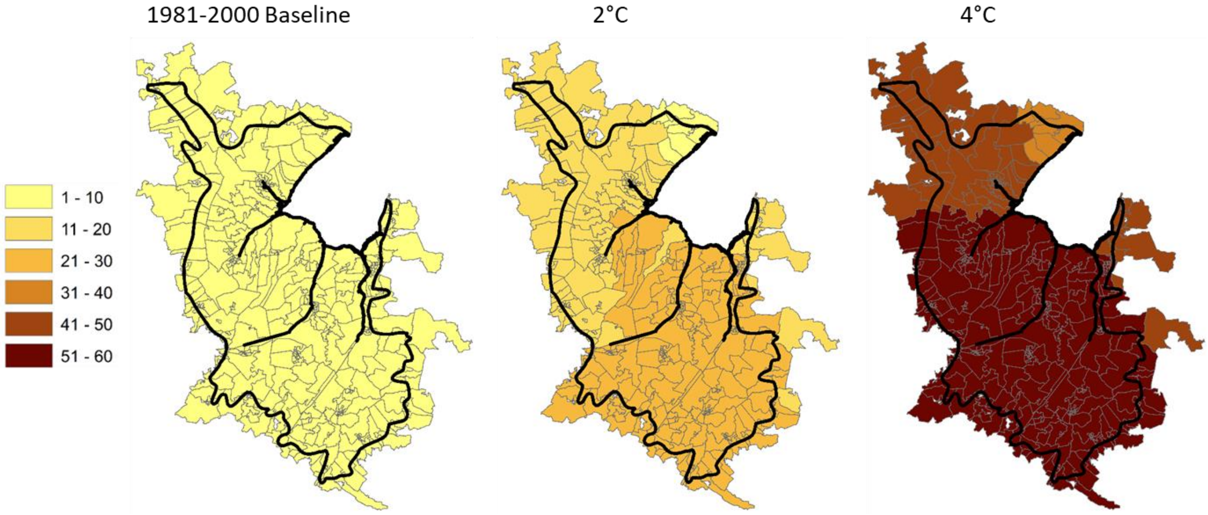


Figure 13: The number of days where the Temperature Humidity Indicator (THI) exceeds 70 in the Fens, highlighting a risk of heat-stress to livestock in that area. Boundaries show Lower Super Output Areas.

6. Drought, Water Scarcity and Water Resource Management- Assessment of present and future risk in the Fens

Drought events can be characterised by their gradual onset, potentially extensive geographical reach, and capacity to persist for weeks, months, or years. Droughts can be classified in various ways depending on meteorological or hydrological conditions or links to agricultural and socio-economic impacts (Sayers et al., 2015b). Whilst the primary driver is a decline from average rainfall levels, other factors such as high temperatures can also exacerbate the severity of events as can human interventions such as increased water demand (Van Loon et al., 2016). Therefore, while different definitions of drought exist, it is important to note the potential for drought impacts to cascade and escalate through freshwater and human system (Sayers et al., 2015b) and the related link to water scarcity, broadly defined as the mismatch between the demand for fresh water and its availability, given the strong implications of drought for water resource management.

In the UK, meteorological, agricultural and hydrological droughts are all expected to become more severe over the 21st century (Slingo, 2021). The UK's third Climate Change Risk Assessment highlighted potential risks arising from droughts, including reduced soil health, risks to crops, trees and livestock; loss of pollinator species; adverse effects on riverine bird populations; and risks to river ecology and freshwater habitats (Berry and Brown, 2021). Furthermore, both water quantity and quality can decline during a drought or water scarcity event. The useability of water for different sectors is dependent on suitable water quality e.g., increased water salinity can affect irrigation and crop production, whilst high levels of pollutants can affect the quantity of water available for abstraction due to the need for wastewater treatment (van Vliet, 2023).

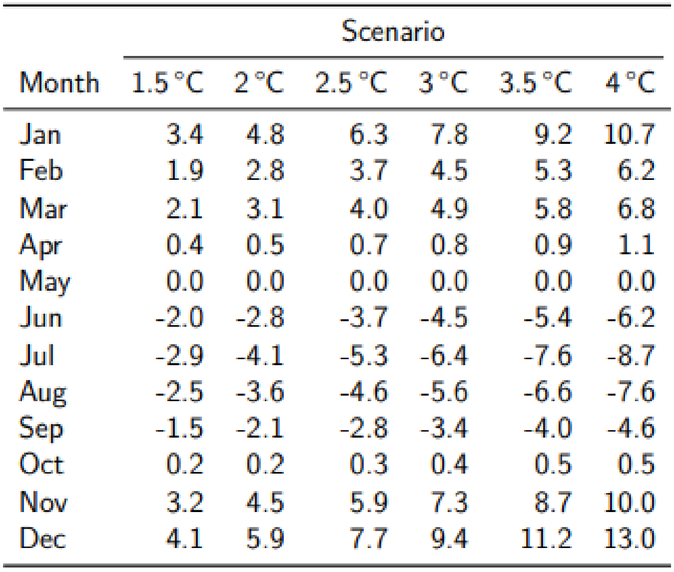
The impacts of droughts on restored natural areas may be dependent on their history, as locations with a long and recent history of agriculture and drainage are more sensitive to water scarcity, with frequent water deficits already inhibiting their ability to foster diverse wetland vegetation (Stroh et al., 2013).

Irrigation intensity is increasing in the Fens (Weatherhead et al., 2014), and the highest irrigation abstractions in England are in Lincolnshire and East Anglia (Knox et al., 2020). The water scarcity issues associated with this presented themselves in the 2018 agricultural drought, when restrictions and irrigation bans came into force in parts of the Fens (NFU, 2019). Although restrictions were also imposed on other sectors, farmers were reported to be particularly affected (Defra, 2019).

Simultaneous to any changes in climate will be socio-economic changes, such as population growth and urbanisation, which can lead to increased domestic and industrial water demand (He et al., 2021). As such, water resource management plans need to be sufficiently ambitious to cope with growth in demand, unprecedented and high impact drought events under climate change, and potentially significant trade-offs between human and natural systems (*Ibid*.). This is paramount for the fens given the Anglian Water area for East Anglia is classed as an area of serious water stress.

Meteorological Drought – projections of change

In the UK some of the driest areas are in the Fens with less than 600mm of rainfall a year (1991-2020 average) (Met Office, 2024b). Table 3 illustrates that climate change will lead to wetter winters and drier summers in the Fens, with risks accruing with each additional increment of global warming.

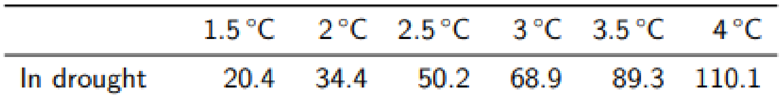


	Scenario					
Month	1.5 °C	2 °C	2.5 °C	3 °C	3.5 °C	4 °C
Jan	3.4	4.8	6.3	7.8	9.2	10.7
Feb	1.9	2.8	3.7	4.5	5.3	6.2
Mar	2.1	3.1	4.0	4.9	5.8	6.8
Apr	0.4	0.5	0.7	0.8	0.9	1.1
May	0.0	0.0	0.0	0.0	0.0	0.0
Jun	-2.0	-2.8	-3.7	-4.5	-5.4	-6.2
Jul	-2.9	-4.1	-5.3	-6.4	-7.6	-8.7
Aug	-2.5	-3.6	-4.6	-5.6	-6.6	-7.6
Sep	-1.5	-2.1	-2.8	-3.4	-4.0	-4.6
Oct	0.2	0.2	0.3	0.4	0.5	0.5
Nov	3.2	4.5	5.9	7.3	8.7	10.0
Dec	4.1	5.9	7.7	9.4	11.2	13.0

Table 3: Projected average monthly precipitation change (mm) from the 1961-1990 baseline for global warming levels of 1.5 to 4°C for the Fens illustrating a trend towards wetter winters and drier summer. Source: Price et al. (2024a).

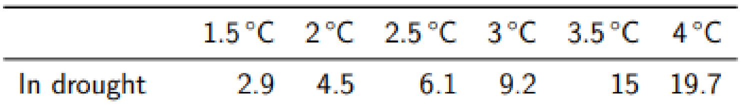
Model outputs also highlight that the probability of meteorological drought in the Fens is projected to increase. Importantly, evapotranspiration will be a main driver of drought (due to projected higher temperatures).

Tables 4 and 5 show projected consequences of climate change on severe meteorological drought in the Fens, calculated using the Standardised Precipitation Evapotranspiration index (SPEI12, -1.5) that considers both precipitation and potential evapotranspiration in determining drought. It is the metric often used when looking at potential drought issues for agricultural and natural lands as it captures the main impact of increased temperatures on water demand. The results illustrate that the number of months that are classed as being in severe drought will increase for the Fens with each increment of global warming, highlighting increasing risks from drought that will compound water scarcity issues in the region.



	1.5 °C	2 °C	2.5 °C	3 °C	3.5 °C	4 °C
In drought	20.4	34.4	50.2	68.9	89.3	110.1

Table 4: Projected number of months in severe drought (SPEI12, -1.5) or waterlogged (SPEI12, +1.5) in a 30-year period. Source: Price et al. (2024a).



	1.5 °C	2 °C	2.5 °C	3 °C	3.5 °C	4 °C
In drought	2.9	4.5	6.1	9.2	15	19.7

Table 5: Projected maximum number of consecutive months in severe drought (SPEI12, -1.5) or waterlogged (SPEI12, +1.5) in a 30-year period. Source: Price et al. (2024a).

Hydrological drought – projections of change

Hydrological drought conditions are also projected to worsen with climate change in the UK. As noted in section 3, analysis undertaken for the UK CCRA3 (Sayers et al., 2020) highlights that the change in return period of peak flood flows will vary across the Fens region. Under a 4°C rise in global mean surface temperature by 2100 (based on RCP8.5, which represents increasing greenhouse gas emissions over time and high greenhouse gas concentration levels), extreme flows are projected to increase in some locations, but are also projected to decline in other regions, namely the central Fens by as much as 15%, highlighting the spatial variation in change.

The distribution of changes in river flows will also depend largely on socio-economic futures, as rivers which pass through urban centres can be recharged by wastewater returns, while areas with low population density and high-water availability could see larger abstractions and therefore reduced river flows (Harrison et al., 2008). The implications of water resource management in the Fens are considered below.

Figure 14 highlights how minimum river flows are projected to change from the baseline (1980-2010) with warming of 2°C and 4°C, for the three NRFA catchments located within the Fens. The indicator Q95 is defined by the UK Centre for Ecology and Hydrology as the flow in m^3/s equalled or exceeded for 95% of the flow record, thus a low flow indicator. It is ecologically important and relevant for assessing river water quality and is often used as the characteristic value for minimum river flow.

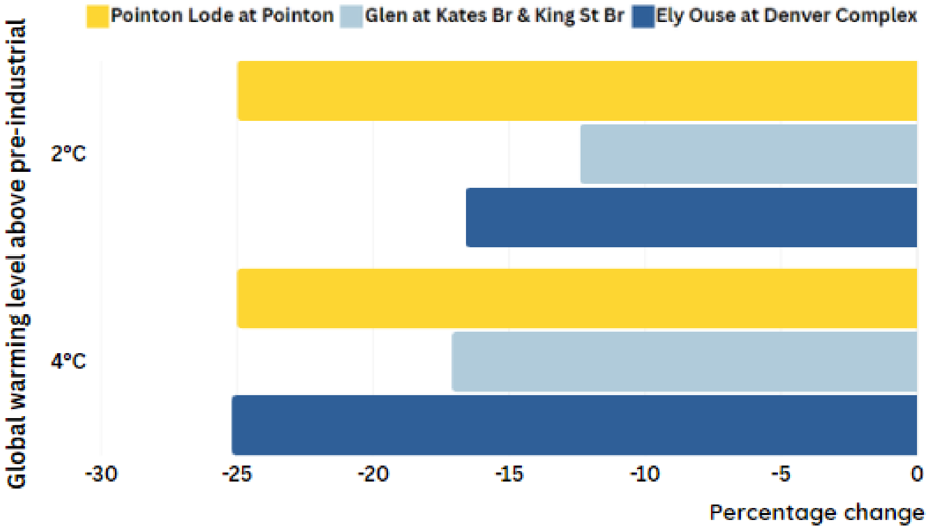


Figure 14: The percentage change in minimum river flow at the Q95 (mean) from the 1980-2010 baseline with warming of 2 and 4°C. Coloured bars represent the percentage change for the three catchments in the Fens, Pointon Lode at Pointon; Glen at Kates Br & King St Br; and Ely Ouse at Denver Complex. The percentage decrease from the baseline indicates the reduction in low flow river discharge compared to the present baseline condition.

Figure 14 shows the projected percentage change in river low flow Q95 under global warming scenarios of 2°C and 4°C above pre-industrial levels for Pointon Lode at Pointon (yellow), Glen at Kates Br & King St Br (light blue), and Ely Ouse at Denver Complex (dark blue). For both warming scenarios, all three catchments show a reduction in low flow discharge, with more significant decreases at 4°C. Ely Ouse experiences the largest reductions, especially at 4°C, approaching a 25% decrease. A larger percentage decrease suggests a more significant reduction in river flow under projected global warming scenarios, which can impact water availability, ecosystems, and overall environmental health of the river systems.

Challenges for current and future water resource management

Water resource management is challenging given the need to account for and adapt to evolving and multifaceted climate risks, socio-economic pressures and competing water demands.

Even with clear management strategies and investment in options such as reservoirs; desalination plants; inter-basin water transfers; enhanced water-use efficiency and land use management, this may not always reduce drought impacts sufficiently, considering the increase in populations or exposure of assets at risk, and particularly where drought magnitude exceeds past historical experience (Kreibich et al., 2022). Additionally, climate change may increase evaporation from reservoirs (Holman, 2011).

As such, water resource management plans need to be sufficiently ambitious to cope with unprecedented and high impact events whilst recognising the potentially significant environmental trade-offs associated with large-scale water scarcity solutions (He et al., 2021).

In England and Wales a comprehensive and systematic approach to water resource planning aims to manage water availability, quality, distribution and environmental needs with water companies required to be resilient to a drought return period of 1 in 500 years by 2040 or earlier (Defra, 2023; EA, 2023b) through Water Resource Management Plans (WRMPs) as well as operational Drought Plans. Alongside this the government's recent Environmental Improvement Plan (EIP) sets targets to drive water companies to provide clean and plentiful water to meet the needs of society, the economy, and the environment in a sustainable manner (Defra, 2023).

Larger-scale strategic supply-side options will be essential for meeting future water needs, with water companies investing around £470 million in 2020 to 2025 in options such as reservoirs, water recycling, desalination and water transfers (Defra, 2023). A strategic analysis of the drought resilience of water companies in England and Wales by Murgatroyd et al., (2022) using the Environment Agency's National System Simulation Modelling (NSSM) found that it possible to achieve a 1 in 500 year resilience standard in locations where strategic resource options are implemented, including the planned Lincolnshire and Fenland Reservoirs network. Jenkins et al., (2024) also used NSSM to further explore the trade-off between socio-economic and environmental adaptation under higher climate change and environmental ambition scenarios, highlighting that while risks of water shortages are reduced with enhanced adaptation, some water companies see declining but still large probabilities of shortfalls that the modelled adaptation actions do not resolve, particularly when enhanced environmental targets are modelled (e.g., Anglian Water). In reality, smaller scale or supporting supply side options, not modelled, are likely to be combined with larger-scale strategic supply-side options to provide additional supply, particularly in regions like Anglian Water's.

The Fens region falls under the remit of Water Resources East (WRE), a regional water resource planning group, including Anglian Water, aiming to create a regional water resource plan for eastern England to 2050 and beyond. This includes Anglian Waters Strategic Pipeline Alliance, developing a 300km-long strategic water transfer pipeline to deliver water from the wetter north to the drier south of their region by 2025 (WRE, 2023). Other planned strategic supply-side options for the region include a new Lincolnshire Reservoir and Fens Reservoir. The Fens Reservoir, based in the Cambridgeshire Fens will supply Anglian and Cambridge Water to provide additional supply between 2035-2037, supplying ~250,000 houses and supporting reduced abstraction and environmental destination targets. The Lincolnshire Reservoir is of a similar size with plans to enter supply between 2039-2041 to support aims to achieve the 1 in 500-year resilience target and environmental destination targets (WRE, 2023).

Water companies have a long history of planning and adapting for growth and climate related-risks (Jenkins et al., 2022a). WRE highlight the flexibility included in strategic and longer-term plans given the 25-year plus outlook and need to be adaptable to different adaptation pathways, as well as the potential opportunities such as benefits from new reservoirs for recreation, biodiversity and flood protection. Yet some trade-offs may occur between abstraction from existing sources and environmental needs (WRE, 2023, Figure 3.2). Additional pressures that may grow from significant 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.

At the farm level a variety of adaptation options have been highlighted for the agricultural sector to cope with drought and water scarcity. For example, enhanced irrigation, better contingency planning among farmers to understand risks of water supply disruption and how to manage them, and incentives to encourage investment in farm reservoirs and water efficiency measures (NFU, 2019).

Whilst not all crops are routinely irrigated in the Fens area, without access to secure water supplies in the longer-term, it has been suggested that growers may relocate their businesses elsewhere, probably overseas, given the lack of suitable alternative sites in the UK (NFU, 2019). Many current irrigation practices are inefficient and a switch to less wasteful irrigation practices is another adaptation option.

Availability of water for abstraction is likely to be inhibited by a projected reduction in groundwater recharge (Holman, 2006), but also largely depends on aquifer type. Unconfined sandy coastal aquifers are highly vulnerable to saline intrusion due to increased tidal surges and groundwater flooding, which are both exacerbated by climate change and land subsidence (Moulds et al., 2023). Risk of saltwater seepage is increased if water abstraction occurs, especially in areas of the Fens such as the South Holland-Holbeach Marsh where the freshwater-saline boundary and groundwater level is very shallow (*Ibid*). This could result in soil salinification, reducing the yield of most crops grown in the area (Gould et al., 2021).

Consequently, agriculture in the Fens is projected to face enhanced risks from salination of groundwater exacerbated by drought and water resource management practices and through flooding, especially coastal flooding (*ibid.*). Crop losses can have a large direct impact on farmers as well as indirectly affecting employment within the sector and production of dependent sectors such as food processing. Such impacts will be particularly hard-hitting in the Fens given its intensive agricultural landscape and high strategic value in terms of its contribution to the UKs total agricultural production. The following section focuses more specifically on the challenges of present and future risks to agriculture in the Fens.

7. Agriculture- Assessment of present and future risk in the Fens

The Fens is the largest contiguous area of lowland peat in the UK and lowland peatland is one of the most carbon-rich ecosystems in the country. However, the peat rich soils and open, readily managed landscapes also mean that The Fens are one of the most agriculturally productive regions of the UK. Despite occupying less than 3% or the total land area of England, The Fens contains nearly over 7% of the total arable land (UK Centre for Ecology and Hydrology Land Cover *plus*: Crops 2021) and almost half of England's best and most versatile agricultural land (i.e. Agricultural Land Classification Grade 1, (Natural England, 2012). This reflected in the areas of crops grown there – the Fens contributes over a quarter of England's sugar beet, 20% of its potatoes and over 30% of its fresh vegetables (Mulholland et al., 2020). The agricultural sector is a fundamental part of the Fenland economy, employing 80,000 people and generating around £3 billion a year for the regional economy in 2020 (Page et al., 2020). Many agricultural supply chains rely on the close juxtaposition of growing land, processing infrastructure and transport hubs that have developed in the region.

The importance of agriculture to the Fens, and the importance of Fenland agriculture to the rest of the UK, bring unique risks and challenges associated with climate change. The degradation of peat soils has been ongoing since the original drainage of the Fens over a century ago, due to compaction, erosion, extraction and oxidation, driven by the conversion of semi-natural wetland into productive arable land. This degradation causes net releases of greenhouse gases, issues with water availability and flooding, subsidence and a reduction in the ability of the soil to sustain agricultural production. Over the last 200 years, 84% of fertile peat topsoil has been lost from East Anglia. The Fens could lose the remainder in just 30-60 years given current land management practices and a changing climate (EA, 2020a).

When process-based models of crop yield (CropNet) under climate chance are explored (Hayman et al., 2024), on average, climate change is likely to bring moderate increases in the yield of several current major crops (winter wheat, oilseed rape, ryegrass) (Figure 15). This is consistent with the results of other crop modelling projects in the region (Gibbons and Ramsden, 2008; Holman et al. 2005). But the same models show an increasing effect of water limitation, especially at levels of warming beyond +2C above pre-industrial (Figure 16). These impacts are also not projected to be spatially consistent – water limitation is likely to be sufficient to result in decreased yields for current major crops on lowest lying Grade 1 agricultural land associated with degraded peats in the southern half of the Fens, whilst the more northerly areas are projected to show greater resistance of yields to climate change – especially evident for wheat yields as seen in Figure 15. Ultimately, these models suggest that temperatures and/or water availability are likely to become limiting for current crops in the Fens, whilst other areas of the UK are more stable or increase under climate change (Slater et al. 2022), potentially decreasing the agricultural importance of the Fens.

It is also important to note that these models predict maximum 'potential' yields under ideal field conditions under climatic constraints. They do not account for reductions imposed by imperfect management, pests and diseases and crop nutrient requirements. They are also likely to underestimate the compound effects of climate on such factors and pests and diseases, or inability to apply management at the optimal timings (e.g., sowing and harvest). These factors can combine with direct impacts of climate on the crop to exacerbate climate-driven impacts or constrain climate-related opportunities. The reliance of current systems on irrigation for some crops may also further impact yields if water availability becomes more restricted at critical times.

Cost and availability of irrigation could also have an impact on crop choice, as farmers will favour higher value irrigated crops such as potatoes over lower value irrigated crops such as sugar beet (Gibbons and Ramsden, 2008; Henriques et al., 2008) changes such as this combined with the increase in potential yield are likely to increase nitrogen fertilizer demand over East Anglia (Holman et al. 2008), which could have knock-on effects for climate change and water quality.

Furthermore, increased flood frequency and extent may render large tracts of arable land unsuitable (Holman et al. 2008). This may have important consequences for future land-use and agricultural production if the defence line is not maintained, as areas of arable land would be converted to grazing marsh (often used for pasturing cattle or cutting hay/silage in summer), but also many areas of coastal grazing marsh would be encroached on by saltmarsh (Richards et al., 2008). Even with yield increases, concurrent increases in land-use demand for non-food products such as biofuels may make it difficult to achieve regional food production targets in East Anglia (Audsley et al., 2008).

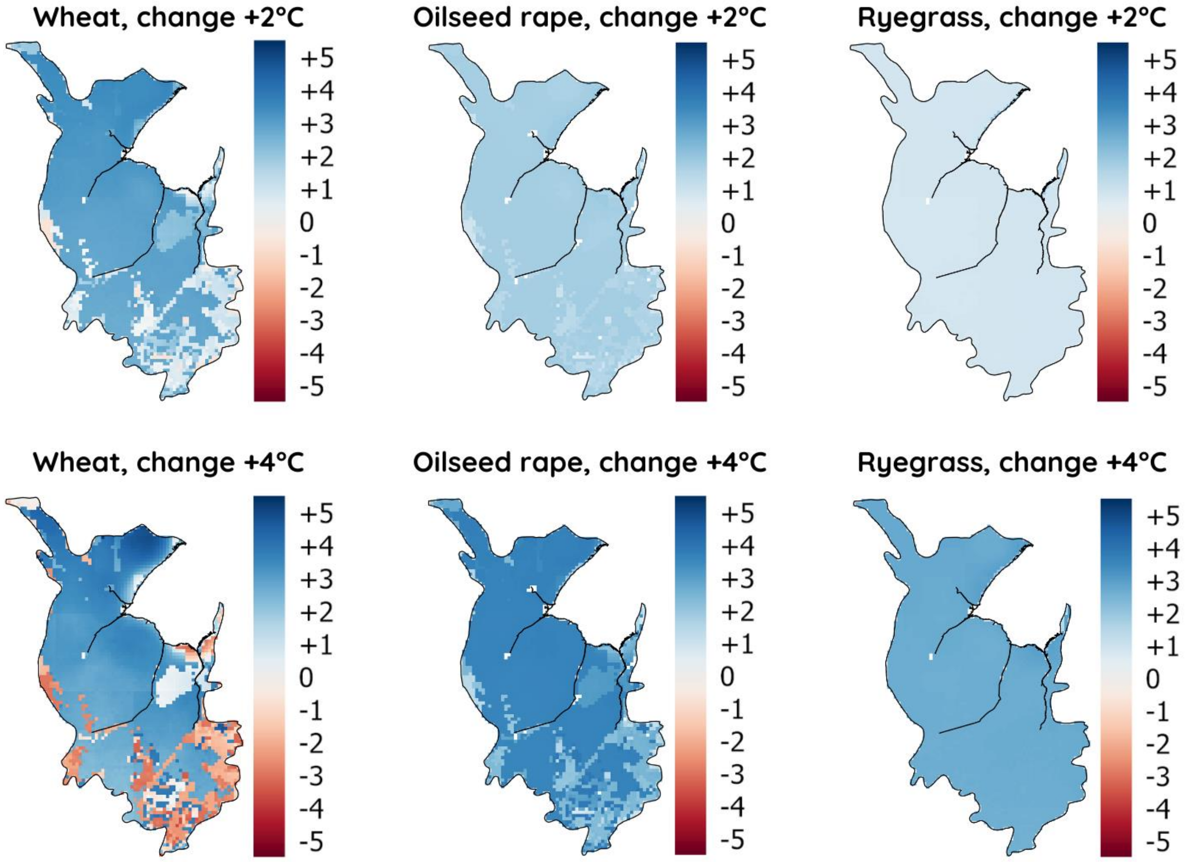
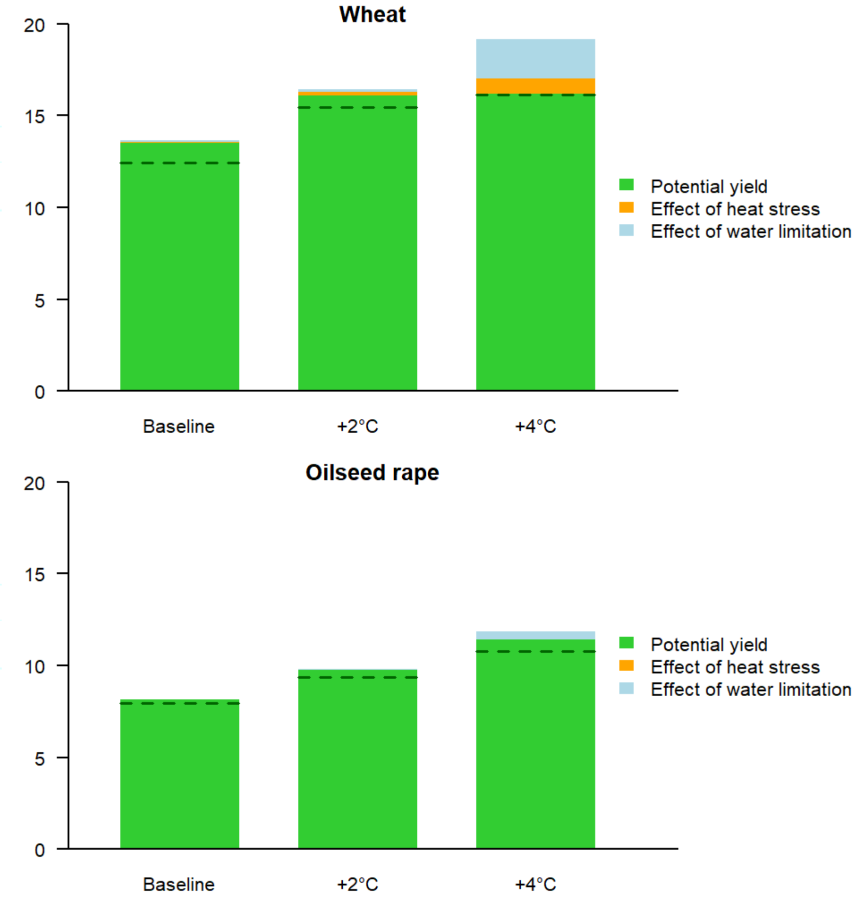


Figure 15: Modelled change in potential yield (tonnes per hectare) for the Fens, under 2 and 4°C warming scenarios, for three major crops, derived from the process-based CropNet models. On average the potential yield of all 3 crops is increased, but there is spatial variation as to the extent of this and some areas to the south may experience yield declines for wheat. Note: potential yield is modelled yield under climatic constraints and ideal field conditions, not accounting for imperfect management, pests and diseases and crop nutrient requirements.



Wheat

Oilseed rape

Figure 16: Mean potential yields for the Fens under a 2 and 4°C warming scenarios for winter wheat and oilseed rape, showing limitation due to water availability and direct heat stress. The horizontal dashed bar indicates the UK mean yield for the relevant warming scenario. Yield increases are inhibited by water limitation and heat stress at higher levels of warming. Note that the models for grass yields does not allow separation of limiting factors in an equivalent way.

One potential route for adaptation is to switch to growing crops which are better suited to the changing local climate. Indeed, because of the UK's generally temperate climate, climate change is likely to bring opportunities to grow many crops which are currently limited by low temperatures, and which can handle dryer conditions imposed by reduced water availability.

For assessing potential future crops, especially those not currently grown in the UK, parameterising process-based models like CropNet is challenging. Running such models over a large number of potential crops is also computationally expensive in terms of processing time and power. Instead, it is possible to run simpler approaches to produce indices of relative suitability. Using a model of generalised climate suitability based on the FAO EcoCrop database (FAO, 2022) for around 160 current and potential future crops allows the identification of crops for which the climate is likely to become more or less suitable (Table 6).These include both current crops and those not currently grown (at least commercially) in the UK, but which may become viable additions or replacements for current crops under a changing Fens climate.

	+2°C	+4°C
Current crops: strong increases in suitability (min. change in temperature and precipitation scores > 5)	Horseradish, hop, sugarbeet	Hop, horseradish
Current crops: moderate increases in suitability (min. change in temperature and precipitation scores between 0 and 5)	Broad bean, **blueberry**, maize, potato, cabbage, **linseed**, asparagus, rye, barley, oats, rhubarb, **celery**	Sugarbeet, **blueberry**, potato, cabbage, asparagus, **celery**
Current crops: decreases in suitability (min. change in temperature and precipitation scores < 0)	Onion, parsnip, wheat, strawberry	Onion, **linseed**, parsnip, barley, wheat, maize, broad bean, rye, strawberry, oats, rhubarb
Example potential future crops: strong increases in suitability (min. change in temperature and precipitation scores > 5)	Durum wheat, bulbous barley, sesame	Sunflower, **hemp**, durum wheat, bulbous barley, okra, sesame, chickpea, oca, tef, **club rush**
Example potential future crops: moderate increases in suitability (min. change in temperature and precipitation scores between 0 and 5)	Grape, sunflower, **hemp**, safflower, cow pea, buffalo bean, okra, oca, Algerian oat, **bur reed**	Grape, safflower, cow pea, buffalo bean, **cranberry, wild rice**, Algerian oat, sweet potato, **bur reed**

Table 6: Climatic suitability scores for the Fens derived from the EcoCrop model for selected crop species, grouped by modelled level of change in suitability score under +2°C and +4°C warming levels above pre-industrial. Example potential future crops chosen as those with positive change under both warming levels and an increase of at least 5 in the combined score in the Fens. Crops suitable for growing under paludiculture or raised water table conditions are indicated in bold

Examining the suitability scores from the EcoCrop model (Table 6) suggests that several current crops are likely to show decreases in suitability in the Fens even under moderate warming (e.g. onions, parsnips, wheat, strawberries). However, many others show moderate to strong increases at levels of warming up to +2°C. However, these changes are exacerbated by higher warming levels. At +4°C the number of current crops showing decreases is higher than those showing increases. Whilst decreases in the suitability score do not necessary indicate that continuing growth of a crop is rendered commercially non-viable, they do indicate an increasing climatic barrier that must be overcome by either management practices (irrigation, protection, germination under cover etc) or plant breeding to produce new varieties that can tolerate higher temperatures and/or reduced water availability. Both these solutions tend to require substantial investment, so switching to more resilient crops may make better economic sense.

Crops showing increases in suitability (Table 6) include many crops currently associated with more Mediterranean climates of continental European climates (e.g. wine grapes, sunflowers, hemp, chickpeas). The Fens are comparatively well-placed to take advantage of new crops, in that they already 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. However, there is also potential risk in growing crops that are associated with drier average climates, as they may well be more vulnerable to seasonal flooding when it occurs. There may also be other parts of the UK where these crops do better, given that many are not especially associated with peat soils. Market demand and socioeconomic factors will also influence the viability of new crops as a solution to improving climate resilience - previous studies which have modelled farm decision-making in East Anglia have suggested that sunflower, currently an exotic crop for the UK, is unlikely to outcompete oilseed rape as a between-cereals break crop by the 2050s (Gibbons and Ramsden, 2008). However, socioeconomic scenario is likely to have a greater impact on cropping type than at least the lower levels of climate change (Holman et al. 2005).

Even within the Fens, these risks and opportunities brought by climate change are not spatially uniform. Examining the average EcoCrop suitability score across all 160 crops (Figure 17), reveals that the median climatic suitability shows generally increasing suitability in terms of temperature and more moderate increases or zero changes for precipitation (zero change values are driven by the number of crops for which changes in precipitation become more suitable being approximately equalled by crops for those becoming less suitable). Southern areas on the Fens on deep peat soils appear more limited when temperature and precipitation are combined into a single index of suitability, driven by higher projected rises in temperature and greater reductions in rainfall, whilst in northern areas the opportunities potentially outweigh the decreases (with all the above caveats on the barriers to adopting new crops).

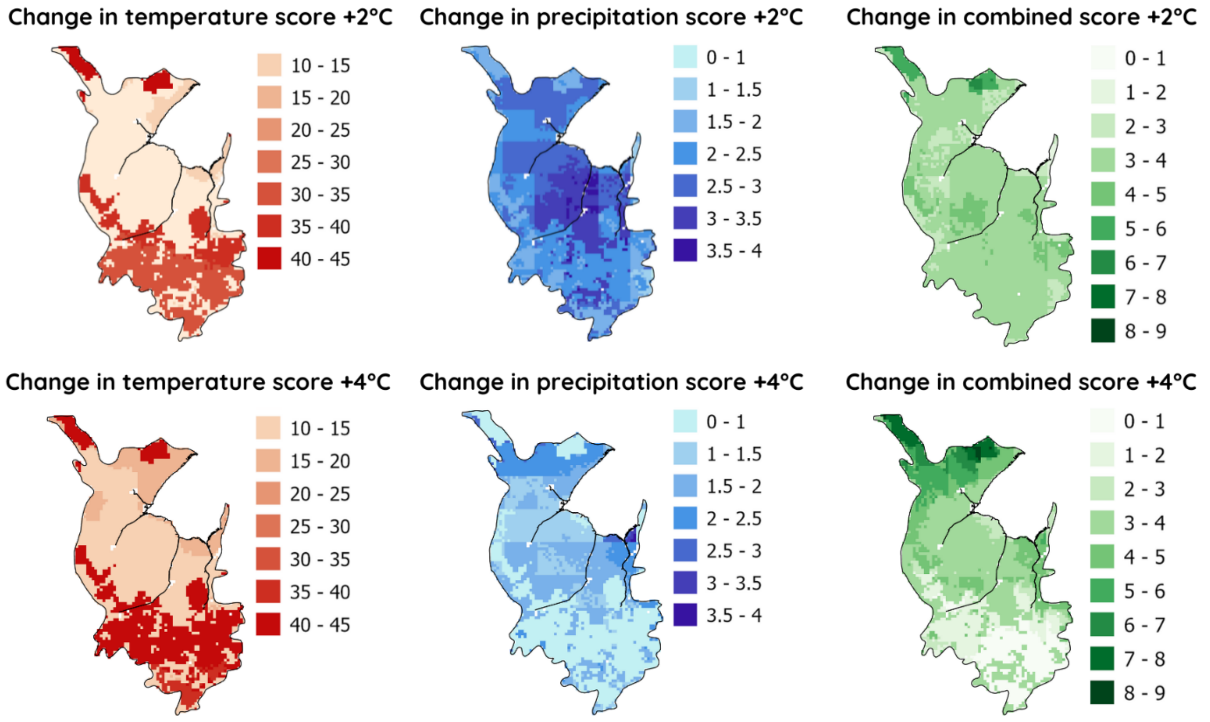


Figure 17: Median change in climatic suitability for over 160 food crops for the Fens under a 2 and 4°C warming scenario, suggesting that, on average, increase in the suitability of many new crops that may become viable in the Fens under climate change equals or exceeds the decreases in the suitability of current crops. However, opportunities are not spatially uniform - the deep peats in the south have more limited suitability increases due to greater reductions in rainfall – and even become more localised under higher levels of warming.

There is a subset of crops that may increase in suitability under climate change and help to resolve the underlying issue of peatland degradation. These are ‘paludiculture’ crops, namely those species associated with (or tolerant of) wetland conditions and thus capable of maintaining agricultural production in a re-wetted peat system (Mulholland et al., 2020). Some of these crops are projected by the EcoCrop model (Table 6) to do well under climate change (e.g. cranberries, wild rice, club-rush, bur reed). Although adequate water is required to re-wet the soil in the first place, paludiculture can help regulate water availability by acting as a reservoir, storing excess water in flood conditions and releasing some of it when water availability is reduced. Paludiculture crops have been extensively investigated as a viable route for peatland agriculture and experiments with it are planned as part of the Great Fen Project (McKie, 2023), but have a variety of challenges, including the fact that many produce products other than foods, so new supply chains and markets must be established, and a pathway found for their integration into existing agricultural systems. The same challenges apply to growing saline-tolerant crops in areas at increased risk of coastal flooding – although such crops exist (e.g. samphire), the pathways towards making them a viable replacement for current cropping systems are unclear.

A compromise may be found in the production of some current crops on raised water tables without full conversion to paludiculture. The effects of this are crop-specific. For example, raising water tables from –50cm to –30cm on soil samples from the Fens have been shown to increase radish yield (Musarika et al., 2017), but reduce romaine lettuce yield by a third (Matysek et al., 2022). Raising water tables could also offer co-benefits of mitigating carbon dioxide emissions (Musarika, 2017; Matysek, 2022) and helping to preserve fen vegetation by mitigating the formation of a rainwater lens (Schot et al., 2004). Notwithstanding, raising water tables to differential levels is a complex process, and Wicken Fen National Nature Reserve requires constant upkeep to maintain the hydraulic gradient against surrounding farmland (Lloyd et al., 2023).

Even without wholesale change in crop types or systems there are some options for adaptation that may allow agricultural systems to remain productive. Agroecological practices, such as agroforestry, more diverse crop rotations, reduced tillage and the use of cover crops can help to reduce greenhouse gas emissions, regulate water availability and reduce erosion. There are also likely to be some technical fixes that may help maintain current agricultural systems under moderate climate change (Burgess et al., 2023). Trickle irrigation has been trialled for celery, potatoes, soft fruits and lettuce production and this has produced up to 50% savings in water usage.

More technical solutions include a shift to vertical farming or low carbon glasshouse farming. In effect, this would allow the relocation of agricultural food production to flood-safe land under controlled climatic conditions, thus maximising efficiency and resource use. This could be coupled with other solutions (e.g. using paludiculture-produced sphagnum as a growing medium). However, these solutions require radical restructuring of the agricultural industry to adopt at scale, alongside significant investment in the required infrastructure.

8. Terrestrial biodiversity - Assessment of present and future risk in the Fens

Existing literature has shown that climate change will have a variable impact on species in the Fens depending on their sensitivities to pressures such as drought and waterlogging and their current relative position within their climatic envelope (suitable climates). Reducing the vulnerability of biodiversity to climate change requires an understanding of the projected magnitude of the risks. In areas where the future climate change is projected to exceed the modelled 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, and we classify these as refugia (areas remaining climatically suitable for >75% of the terrestrial biodiversity in that area). These may be the best places to protect to conserve biodiversity (also known as no-regrets action) in the future despite climate change.

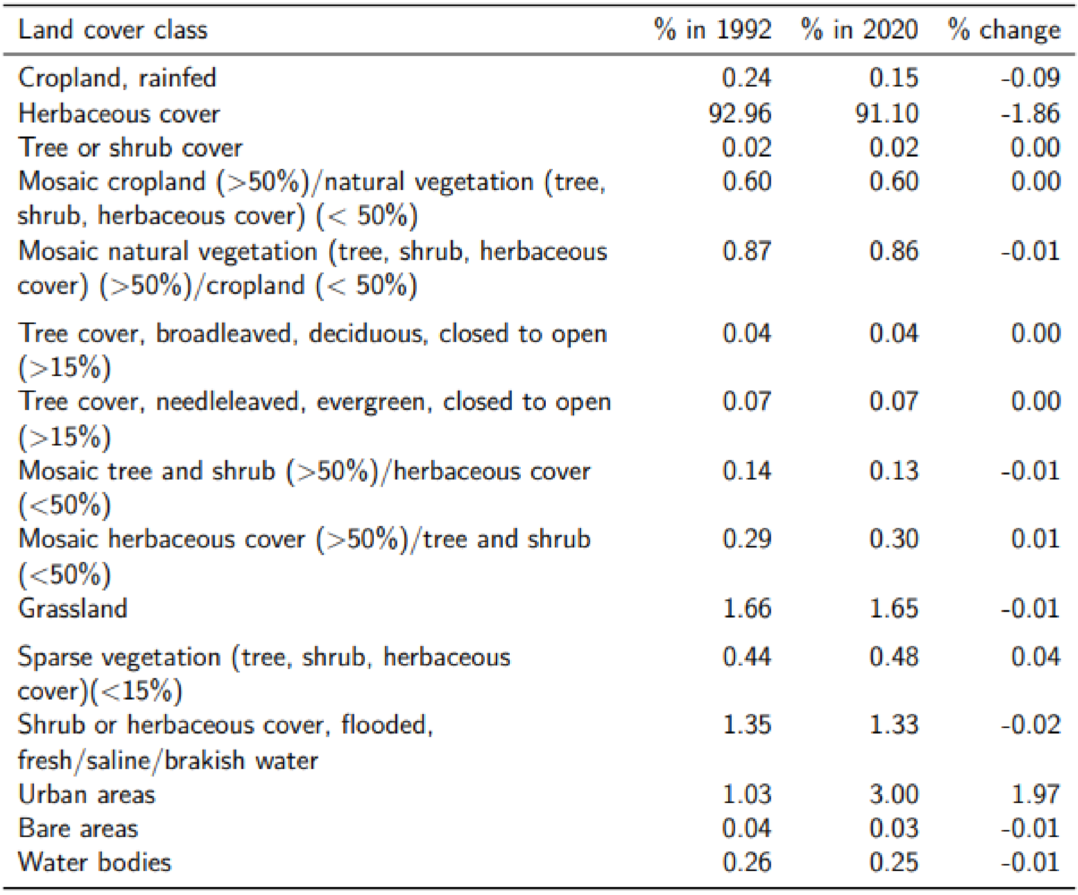
Preserving biodiversity, and space for biodiversity, is not just about the species that are being conserved, but also the ecosystem services they provide. For example, acting as seed banks, providing natural food resources, nurseries for wild species, and homes for pollinators, as well as performing important processes that have large scale benefits such as carbon storage, air purification, water collection and purification, flood prevention and soil conservation (Price et al., 2024c).

The current impacts on biodiversity in the Fens are already large, owing to past habitat conversions. These changes to habitat can drastically limit the ability of an area to persist under the additional pressures from climate change. The following sections present an assessment of present and future risks to terrestrial biodiversity for the Fens, carried out to support this report (Price et al., 2024c).

Interactions between landcover, biodiversity and socioeconomic change

Satellite data show that, between 1992 and 2020, the Fens has seen changes in landcover, with main changes in the landcover types of suburban/urban areas (+1.97%) and herbaceous cover (-1.86%) (Table 7). This is additional landcover changes on top of all the changes that have occurred over the previous hundred or more years.

Even without considering climate change, landcover change and particularly changes in agriculture will continue to have significant consequences for biodiversity. This has given rise to a debate over whether agriculture should be intensified and separated from wildlife (i.e. land-sparing) or managed to allow coexistence with wildlife (i.e. land-sharing). However, this dichotomy lacks ecological understanding of the complex interactions between species and ecosystems. In the land sparing model, if agricultural land is too distant from natural land, then the loss of critical ecosystem services can reduce yields in insect pollinator crops. If the Fens region were to lean heavily in either direction, there would be a significant change in species composition. For example, it has been projected that an extreme land-sparing approach would benefit 59% of breeding birds (Finch et al., 2019). However, these would be largely made up of breeding birds which thrive solely in nature reserves, whereas many popular species such as the blackbird (*Turdus merula*) which have benefited from the conversion towards an agricultural landscape would fare better under land-sharing.



Land cover class	% in 1992	% in 2020	% change
Cropland, rainfed	0.24	0.15	-0.09
Herbaceous cover	92.96	91.10	-1.86
Tree or shrub cover	0.02	0.02	0.00
Mosaic cropland (>50%)/natural vegetation (tree, shrub, herbaceous cover) (< 50%)	0.60	0.60	0.00
Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%)/cropland (< 50%)	0.87	0.86	-0.01
Tree cover, broadleaved, deciduous, closed to open (>15%)	0.04	0.04	0.00
Tree cover, needleleaved, evergreen, closed to open (>15%)	0.07	0.07	0.00
Mosaic tree and shrub (>50%)/herbaceous cover (<50%)	0.14	0.13	-0.01
Mosaic herbaceous cover (>50%)/tree and shrub (<50%)	0.29	0.30	0.01
Grassland	1.66	1.65	-0.01
Sparse vegetation (tree, shrub, herbaceous cover)(<15%)	0.44	0.48	0.04
Shrub or herbaceous cover, flooded, fresh/saline/brakish water	1.35	1.33	-0.02
Urban areas	1.03	3.00	1.97
Bare areas	0.04	0.03	-0.01
Water bodies	0.26	0.25	-0.01

Table 7: Percent land cover in 1992 and 2020 and change in land cover at a 300m resolution (ESA CCI), showing how urban areas have been expanding while herbaceous cover has been shrinking. These land cover changes are in addition to those that have occurred prior to 1992.

When anthropogenic landcover change is combined with climate change, species then face multiple threats, and their potential adaptation space is reduced. If the arable land area in East Anglia is reduced due to managed realignment, cereal field margin species such as the small-flowered catchfly (*Silene gallica*) and long-headed poppy (*Papaver dubium*) suffer combined effects of habitat fragmentation and climate change (del Barrio et al., 2006). Even if climate change implies an extension of some species' suitable climate envelopes within the Fens, some species which have specific habitat requirements such as nightingales (*Luscinia megarhynchos*) may require intervention to encourage northward colonisation of new territory (Wilson et al., 2005). The ability of species to move, especially those species that are less mobile, requires carefully designed and placed corridors between habitat patches suitable for these species. These corridors could potentially be designed to accompany any future water transfer schemes (e.g., canals).

Future policy priorities could alter how climate change and sea level rise effects entire habitats. In scenarios where environmental protection is prioritised, saltmarsh and coastal and fluvial grazing marsh habitats could expand in the Fens as the removal/abandonment of coastal defences allows for floodplains to extend inland (Richards et al., 2008). However, if environmental protection is reduced, significant areas of coastal grazing marsh and related freshwater habitats would also likely be lost (Holman et al., 2005), and if agricultural and urban land does not retreat to allow for habitats to convert, large areas of fluvial grazing marsh will be lost due to salinification as fluvial and tidal floodplains overlap (Richards et al., 2008). Increased flooding could benefit some fenland species, but downstream the gains would be restricted to those with salt tolerance (Holman et al. 2005). Any of these changes will have impacts on biodiversity, be they positive or negative, and need to be considered in a broader landscape level context.

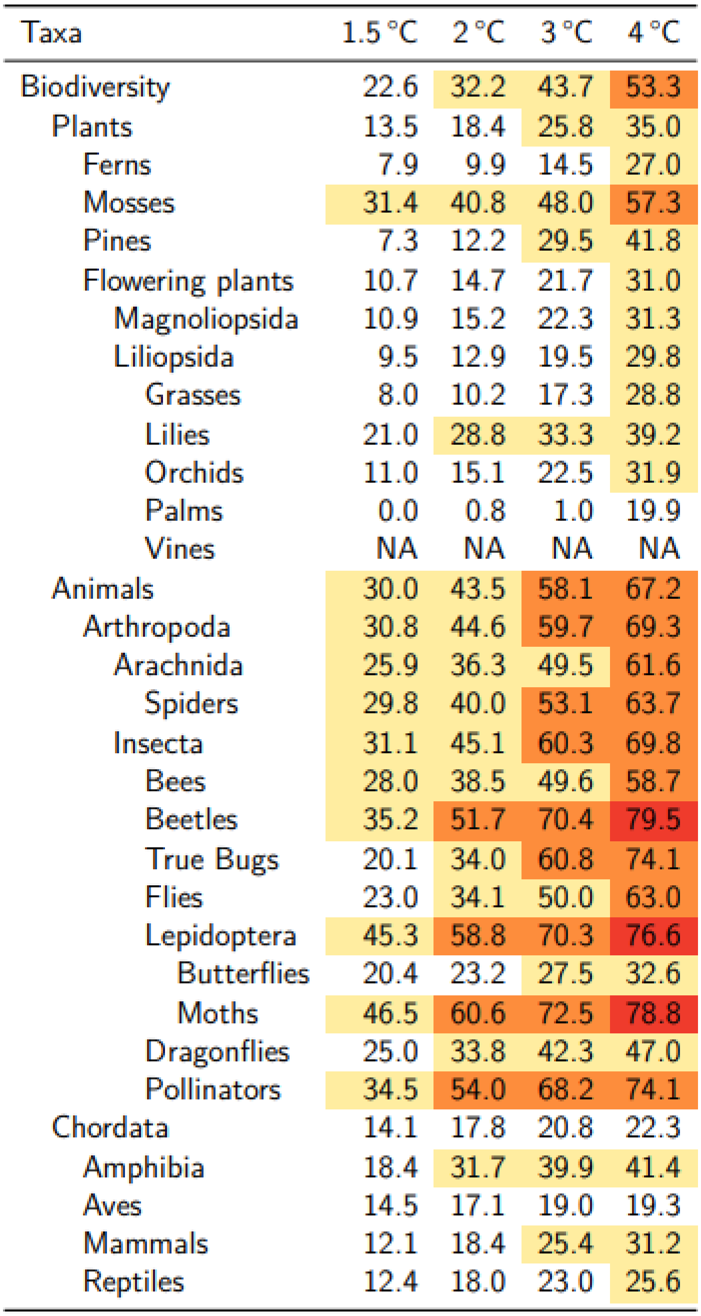
The response of the agricultural sector to the threats and opportunities brought by climate change can also bring about secondary impacts on species. For example, some species such as shepherd's needle (*Scandix pecten-veneris*) may experience no change in climate space in East Anglia (at 2.3°C of temperature increase), but increased nitrogen fertilizer application linked to cropping changes in response to climate change would cause large areas to become marginal (Audsley et al., 2008). This is exacerbated by competition from species which react positively to increased nitrogen such as cleavers (*Galium aparine*) (*Ibid.*).

Local extinction risk in the Fens

Local extinction is defined as the percentage of species in a cell/region where their climate tolerance (defined by the climate envelope) is exceeded. In Table 8, once the climate for 25% of the species in a given taxa is projected to be exceeded, the cell is shaded in yellow. This means, for that species' group, it is no longer a climate refugia. If it is shaded in orange, then the climate for more than 50% of the species in that group is projected to be exceeded. This means that the ecosystem services provided by species in that group are more disrupted and it may be hard to maintain functioning ecosystem services. If a cell is shaded in red, then more than 75% of the species in that group have had their climate envelope exceeded and loss of ecosystem services would be large.

For example, the refugia threshold for overall biodiversity is crossed by 2°C, but for animals it is 1.5°C (mostly owing to projected impacts on insects). This is especially true for pollinators (moths in particular) who are projected to cross the 50% loss and loss of ecosystem services line with less than 2°C warming. These losses are already occurring and rapidly increasing. The loss of moths would lead to a mixed set of impacts. For example, moth caterpillars are crop pests but also major food resources for many vertebrates, while the loss of adult moths would have an impact on crop pollination and also loss of food for many vertebrates.

Table 8 shows the percentage of species in different taxonomic groups projected to be at risk of local extinction owing to changes in climate alone. In the Fens area, moths and beetles are two of the groups most exposed to climate change (Price et al., 2024a).



Taxa	1.5 °C	2 °C	3 °C	4 °C
Biodiversity	22.6	32.2	43.7	53.3
Plants	13.5	18.4	25.8	35.0
Ferns	7.9	9.9	14.5	27.0
Mosses	31.4	40.8	48.0	57.3
Pines	7.3	12.2	29.5	41.8
Flowering plants	10.7	14.7	21.7	31.0
Magnoliopsida	10.9	15.2	22.3	31.3
Liliopsida	9.5	12.9	19.5	29.8
Grasses	8.0	10.2	17.3	28.8
Lilies	21.0	28.8	33.3	39.2
Orchids	11.0	15.1	22.5	31.9
Palms	0.0	0.8	1.0	19.9
Vines	NA	NA	NA	NA
Animals	30.0	43.5	58.1	67.2
Arthropoda	30.8	44.6	59.7	69.3
Arachnida	25.9	36.3	49.5	61.6
Spiders	29.8	40.0	53.1	63.7
Insecta	31.1	45.1	60.3	69.8
Bees	28.0	38.5	49.6	58.7
Beetles	35.2	51.7	70.4	79.5
True Bugs	20.1	34.0	60.8	74.1
Flies	23.0	34.1	50.0	63.0
Lepidoptera	45.3	58.8	70.3	76.6
Butterflies	20.4	23.2	27.5	32.6
Moths	46.5	60.6	72.5	78.8
Dragonflies	25.0	33.8	42.3	47.0
Pollinators	34.5	54.0	68.2	74.1
Chordata	14.1	17.8	20.8	22.3
Amphibia	18.4	31.7	39.9	41.4
Aves	14.5	17.1	19.0	19.3
Mammals	12.1	18.4	25.4	31.2
Reptiles	12.4	18.0	23.0	25.6

Table 8: The percentage of species in different taxonomic groups projected to be at risk of local extinction owing to changes in climate alone, with moths and beetles most exposed to climate change. Yellow shading indicates areas projected to become climatically unsuitable for >25% of the species studied (by group); orange shading indicates areas projected to become climatically unsuitable for >50% of the species studied; and red shading indicates areas projected to become climatically unsuitable for >75% of the species studied. NA means there is insufficient data for that group in that area.

Figures 18 to 20 show the average percent of the species (species richness) remaining within the boundaries of the Fens for selected groups. The maps highlight the spatial variability in the potential patterns of biodiversity loss, and also the severe nature of potential biodiversity loss under 2 and 4°C of warming. Figure 18 highlights that at 2°C approximately 60-70% of overall biodiversity would remain across the Fens, reducing to approximately 40-50% at 4°C. Figures 19 and 20 highlight the risk when considering insects and pollinators groups. With 4°C of warming it is projected that only 10-30% of insects would remain in the Fens and 20-30% of pollinators. The severity of reductions, especially under the higher levels of warming, could have serious implications for insect-pollinated crops and wild plants.

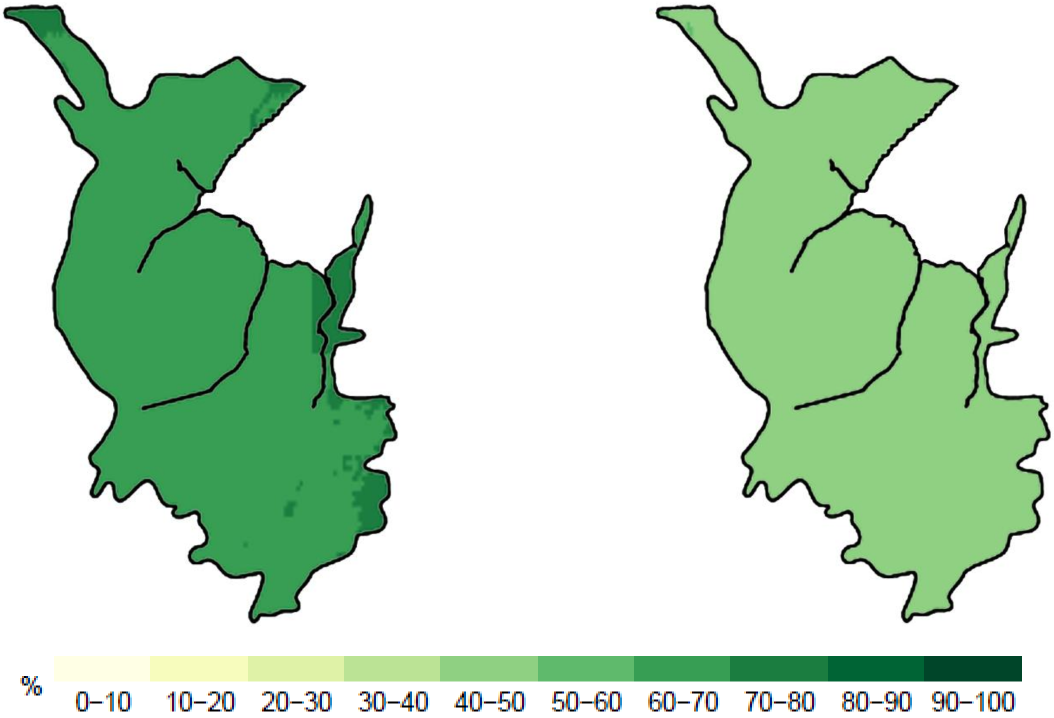


Figure 18: Overall percentage of biodiversity remaining in the Fens under 2°C (left) and 4°C (right).

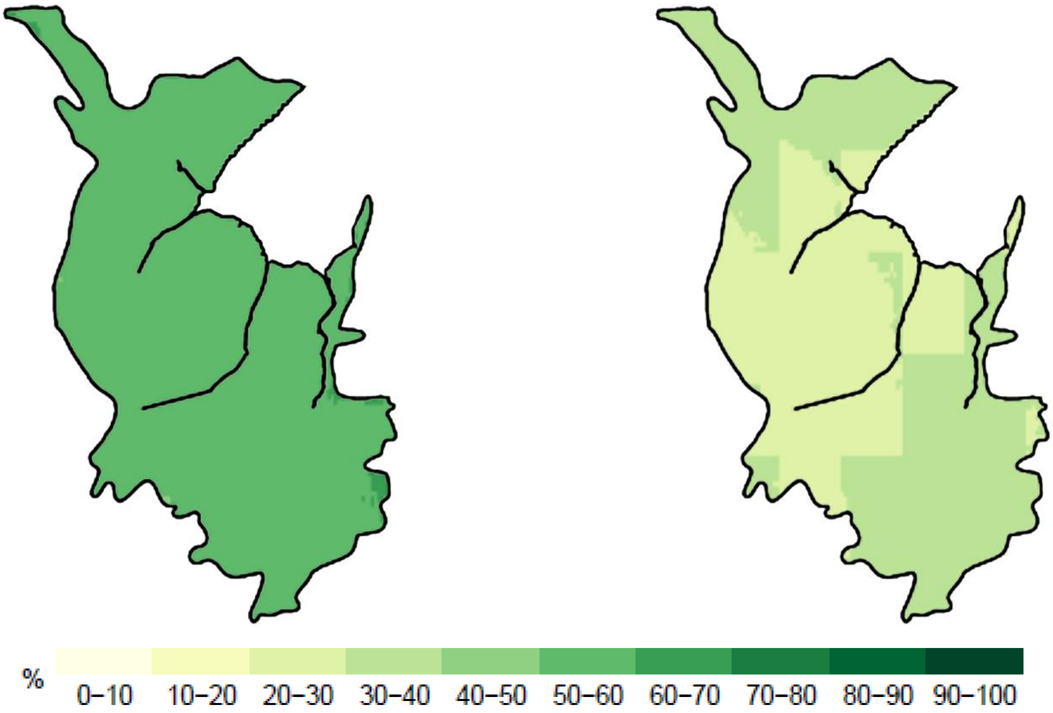


Figure 19: Overall percentage of insects remaining in the Fens under 2°C (left) and 4°C (right).

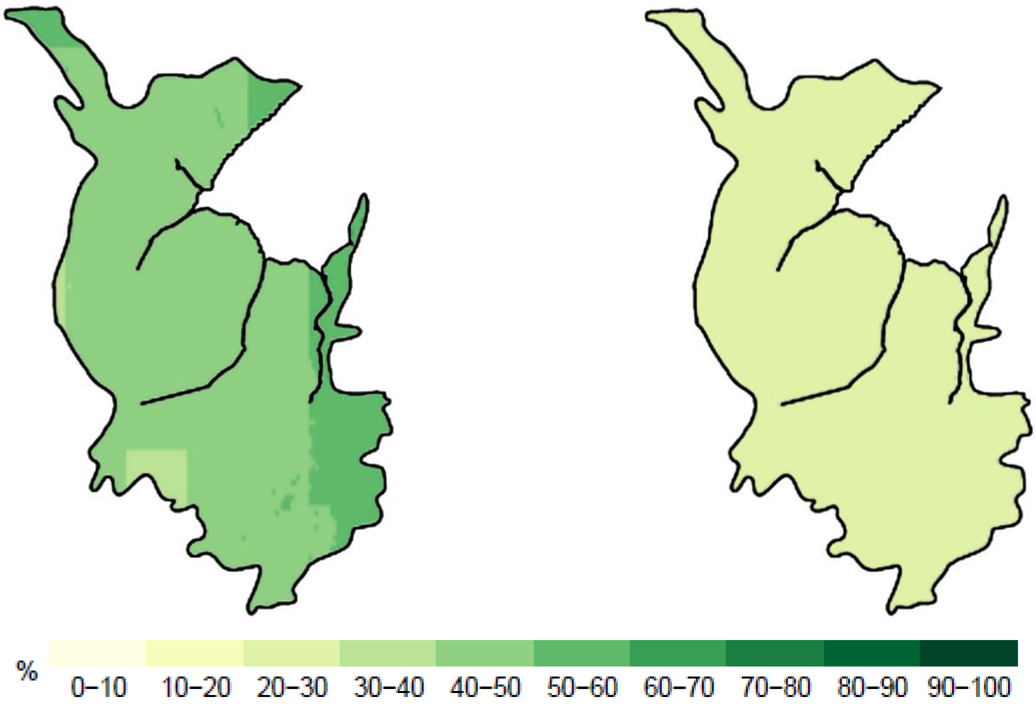


Figure 20: Overall percentage of pollinators remaining in the Fens under 2°C (left) and 4°C (right). The severity of reductions especially under the higher levels of warming could have serious implications for insect-pollinated crops and wild plants.

Remaining areas of climate refugia in the Fens will become very limited

Climatic refugia are defined as areas remaining climatically suitable for >75% of the species in each group. Figures 21 to 24 show the number of climate models agreeing that a particular pixel (cell) is a refugium for the taxa indicated. Table 8 provides the same information in a tabular form. These maps provide a spatial representation of the agreement in the models (or areas with potentially lower uncertainty) to be refugia for the different groups as well as how this potentially varies within the area of study. The legend refers to the number of climate models (out of 21) agreeing that the area is a refugia. Very little of the Fens is projected to remain refugia for most taxa (essentially none if a standard threshold of at least half of the models in agreement is used). However, if the focus is solely on birds or mammals then more of the Fens would be suitable refugia, at least at 2°C, but there is projected to be large losses of species richness in many invertebrate groups, and some plants, meaning that food and habitat resources would be lost.

Figures 21 to 24 illustrate that even if global average temperature is kept to 2°C almost none of the Fens is a refugia with any certainty (as measured by models in agreement). Given the agricultural importance of the area, the risk to insect pollinators needs to be considered, as this potentially hampers the ability to grow certain crops, and potentially impacts the yields of the insect pollinated crops.

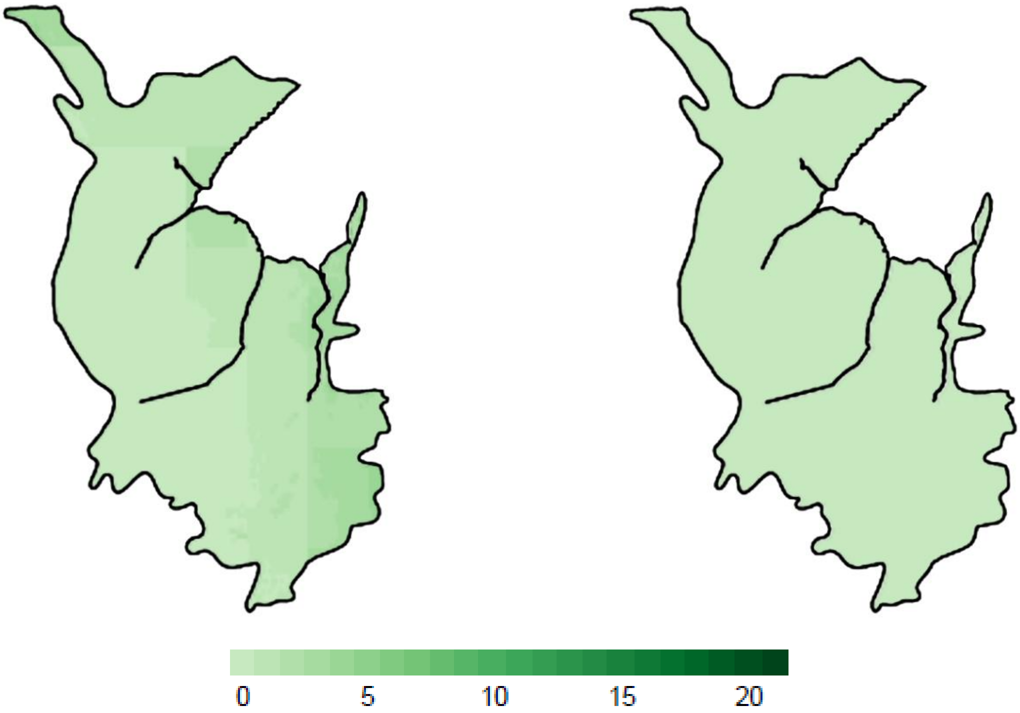


Figure 21: Overall biodiversity refugia in the Fens under 2 and 4°C, demonstrating how even under 2°C climate change, most of the Fens is unlikely to retain >75% of the species in each group.

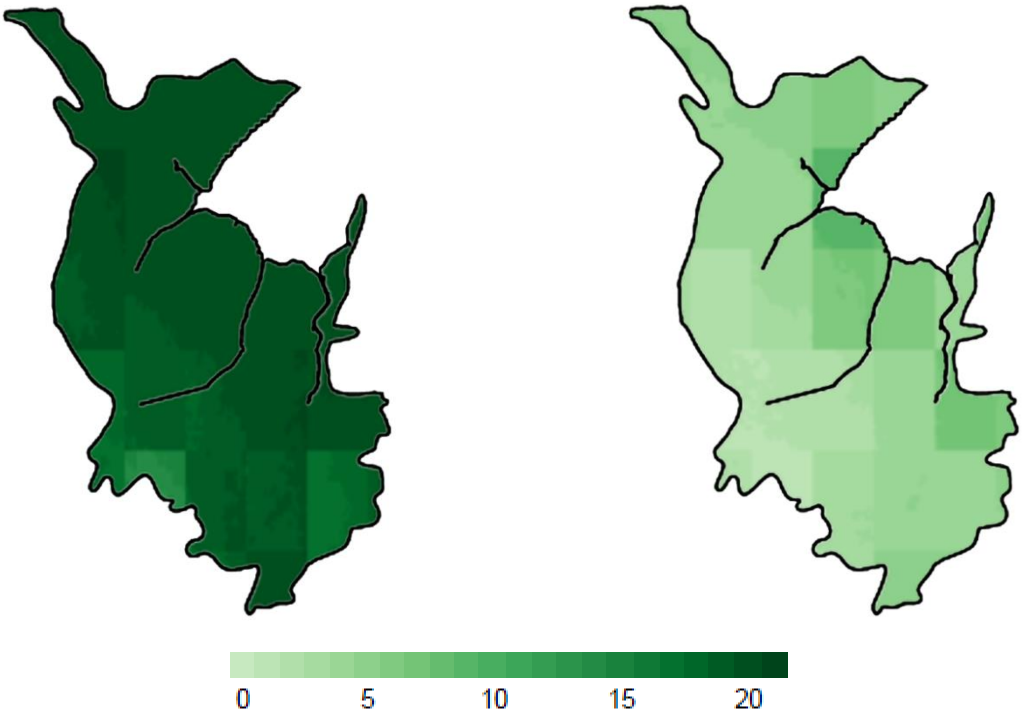


Figure 22: Mammal refugia in the Fens under 2 and 4°C.

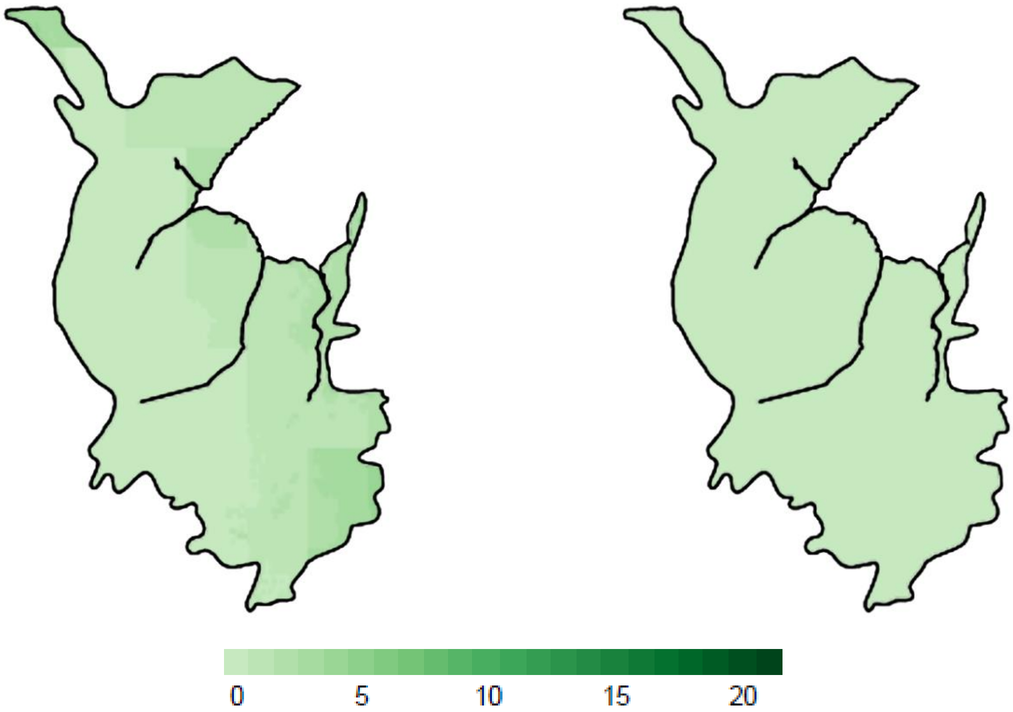


Figure 23: Insect refugia in the Fens under 2 and 4°C.

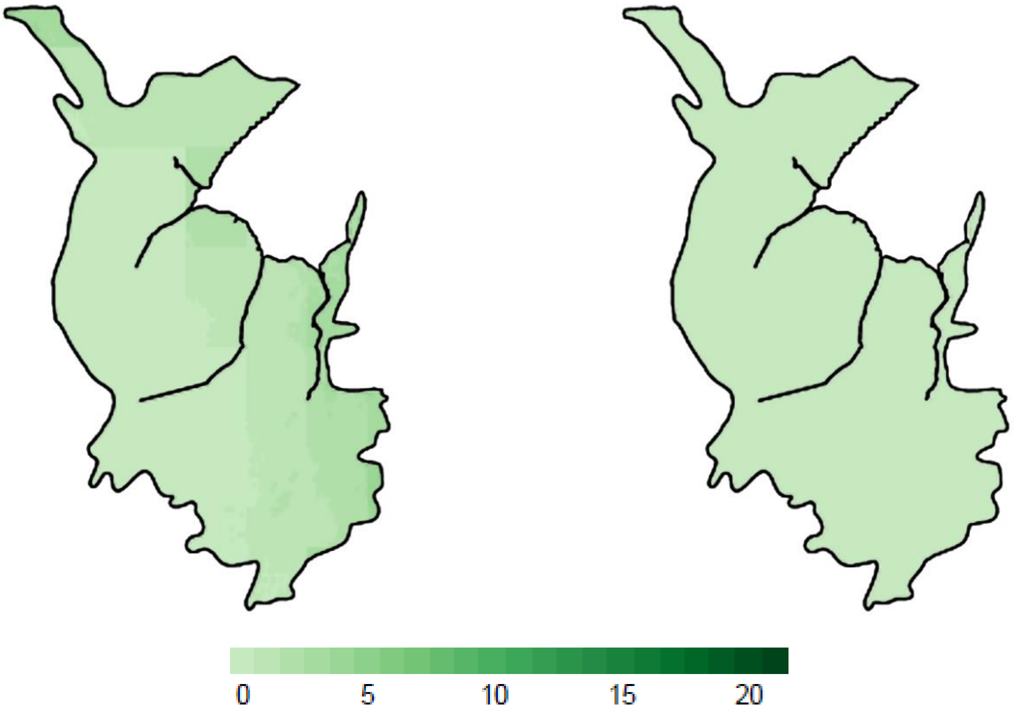


Figure 24: Pollinator refugia in the Fens under 2 and 4°C.

Adaptation Effort required to maintain biodiversity on the Fens

Figures 25 to 27 present a spatial representation of the potential ‘adaptation effort’ that might be needed to maintain at least 75% of the existing species modelled in each 1km cell (see Box 8-1).

Box 8-1: Adaptation Effort

The **Adaptation Effort Index** is a measure of how much additional adaptation effort may be required to maintain existing biodiversity (overall, or by specific groups). Higher index values indicate lower levels of additional effort will be needed while lower index values indicate increasing efforts will be needed. While there are no direct economic values associated with these values, increasing effort will require increasing resources and costs. Some of these (habitat creation or major modification) will be quite substantial.

Entire documents have been developed on biodiversity adaptation in the UK. However, these are general guidelines and, until now, there have not been any maps showing where the adaptation effort needed would be greater or lesser under differing amounts of warming. The text below provides some examples or the types of adaptation that may be needed in the Fens (and other parts of the southern UK) at different levels of adaptation effort.

Figure 25 shows results for adaptation effort for birds in the Fens under 2°C and 4°C. With an **index of +15 to +21**, as shown in Figure 25, generally most models would agree that the area remains climatically suitable for most (>75%) species. This is only applicable for a few groups of species in the Fens, and only at lower temperatures. This would largely fall in the category of what is frequently termed ‘business as usual’ conservation (assuming current conservation efforts are adequate, which may not be the case). This means conservation efforts much as they are done now (and this may still be substantial, and costly, for some habitats and species).

Although high positive values for the adaptation effort index remain even into 4°C for birds, reductions in insect and plant species (e.g. figure 27) may make it increasingly difficult for the birds to find food and thus not do as well as the model's project. Alternatively, increasing adaptation effort to try and ensure an adequate food supply (planting different seed crops, attracting more climate tolerant insects) is required.

As the Adaptation Effort Index level falls with larger increases in temperature, greater attention will also need to be placed on dealing with increases in ‘extreme’ weather such as longer, more severe droughts, or more flooding. For droughts it may require providing additional water (either directly in the form of guzzlers or ponds or indirectly through local irrigation of key food plant areas). It will also be necessary, especially in drought conditions, to be able to deal with fires.

In the case of additional flooding, it may require additional effort to more quickly move flood water off key habitats. This is an issue in the Fens as some key biodiversity sites are also areas where floodwater is redirected. In the case of increasing coastal flooding, it means being able to quickly get the seawater off the habitat to avoid salinisation. Given that changes are already occurring, then working to build resilience in the system becomes ever more critical.

These adaptation efforts are sometimes referred to as ‘Buying Time’ and first among them is to work to remove or minimize other anthropogenic stressors in the environment. These sorts of activities include minimizing other sources of pollution such as nutrient loading (e.g., from nitrogen and other chemical runoff), lead pollution from spent shot, monocultural plantings (e.g., conifer plantations), improperly sited renewable energy, disturbance from recreational activities (e.g., off-road or off-trail movements, dogs off leads), disturbance from fires and pests, etc. While pesticide and fertilizer use may continue to be necessary in the agricultural environment, overuse, spill over, run-off, and pollinator toxic pesticides need to be minimized if not avoided all together.

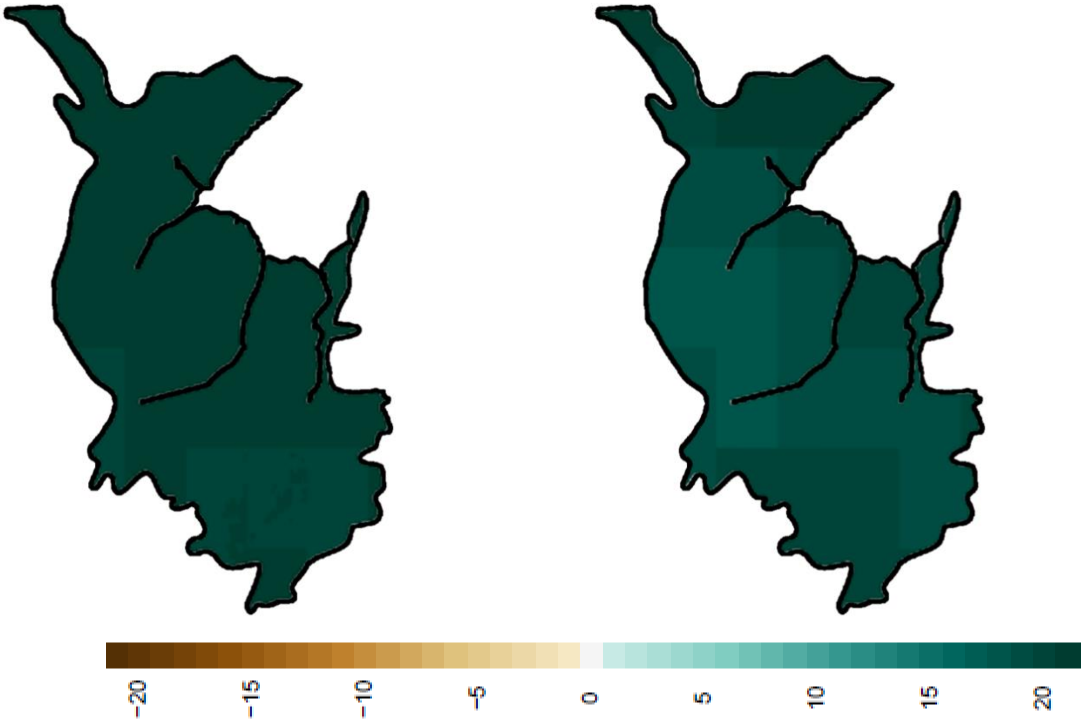


Figure 25: Adaptation effort for birds in the Fens under 2°C and 4°C. Although high positive value remain even into 4°C, reductions in insect and plant species may make it increasingly difficult for the birds to find food.

With an adaptation effort index of **+10 - +15** 'business as usual' conservation activities will no longer be adequate to maintain healthy and intact sites. All the activities mentioned above will begin to become much more important, if not critical, for the maintenance of the ecological integrity of the sites. At this stage (and with the likelihood of further increases in warming) then consideration needs to be given to expanding the size of the sites as well as the development of buffers around the sites to minimize some of the other stressors. Thought needs to be given to connectivity between sites. This does not explicitly need to be land that has been 'set-aside' but could include conservation easements and mixed land uses that blend productivity with biodiversity benefits (mixed plantings/inter-cropping for example, such as oats and fruit trees, which will also potentially provide economic resilience to the farmer).

Figure 26 presents the adaptation effort index for overall biodiversity in the Fens under 2°C and 4°C. The green shading in the 2°C map shows that only some of the coastal parts of the Fens are projected to be positive on the adaptation effort index. The areas in grey are at 0 and this would indicate the need for additional adaptation effort. By 4°C, biodiversity adaptation efforts are going to be much more expensive and may require replanting but with species more tolerant of the new climate regime, or other habitat engineering (discussed below).

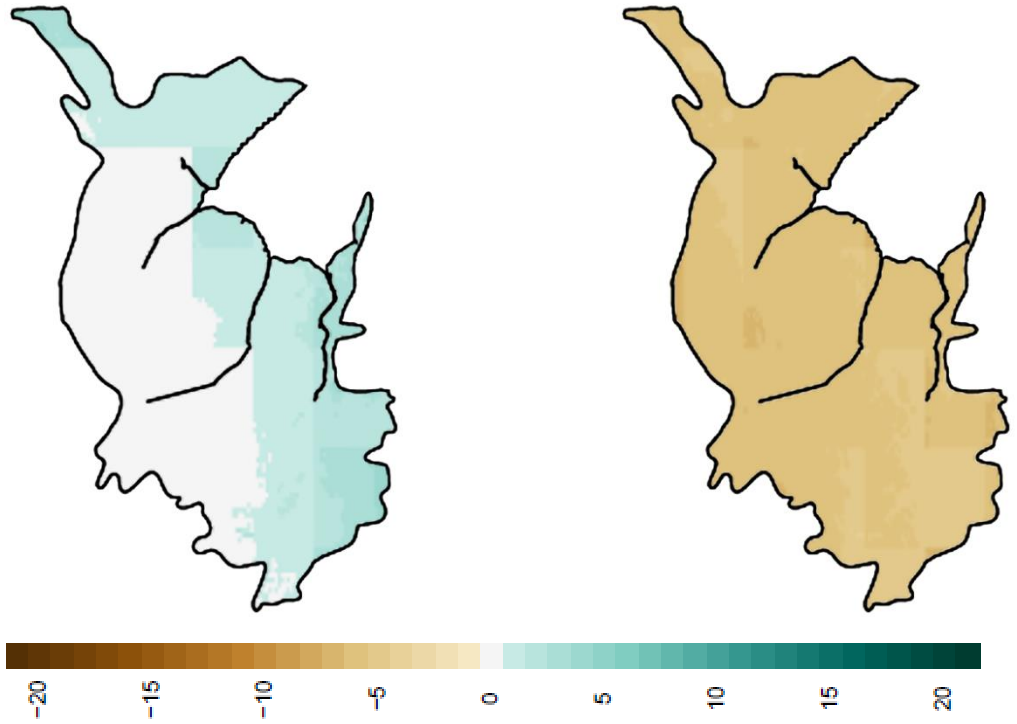


Figure 26: Adaptation effort for overall biodiversity in the Fens under 2°C and 4°C. High positive values suggest business-as-usual conservation may be sufficient to preserve biodiversity, while negative values suggest increasingly extreme adaptations will be required for the conservation effort.

An adaptation effort index between **-10 - +10** (as in figure 26) implies significant projected changes to the biodiversity in natural sites and a substantial increase in the loss of ecosystem services. The above activities already mentioned above would be necessary but are unlikely to be sufficient. Economic costs of adaptation would be expected to rise substantially. Habitat engineering would become increasingly more important.

Some examples of within site adaptation would be increased development of ponds to provide sources of water and breeding sites for aquatic species, including some pollinators (e.g., some of the hoverflies). Local engineering may be able to provide some protection for some groups of species, at least at lower levels of warming. For example, the creation of log piles or rock piles to provide cool shelters for some species (e.g., some reptiles and insects) and/or the creation of small hills to provide shaded and cooler areas (for some insects and plants) on the north side of the hill. Identification of potential microrefugia for species is vital. All of these are really 'band-aid' solutions as the number of individuals that may benefit will be smaller than the normal number of individuals that would have been able to persist in the absence of warming. They are also stop-gap measures unless mitigation of emissions has occurred with limited additional warming. Shifting and replacing habitats will be necessary.

Freshwater wetlands near the coast will be increasingly pressured by saltwater intrusion. Over time, these wetlands would be expected to convert to saltwater wetlands. Development, or protection, of replacement freshwater wetlands will be necessary. This could be the development of new freshwater wetlands (e.g., designed as part or fringes of proposed new reservoirs) or the purchase and protection of other freshwater wetlands that are less likely to face saltwater intrusion within the next century. Development of new saltwater wetlands could be allowed to occur naturally or to be encouraged to accelerate in areas that are currently freshwater wetlands (those that have been replaced) to deal with projected increases in sea-level and storm surges. The ability to control water in these areas becomes increasingly important (and expensive). This includes flushing salt out of freshwater wetlands after storm events or the ability to maintain water levels in freshwater wetlands in times of drought. As this may require pumping the costs may be substantial.

Degraded natural lands, where appropriate, need to be restored and intactness needs to be increased. In some cases, for some species, mechanical modification of the landscape will be necessary to maintain the habitats in proper condition for the species. Most conservation activities will require increasing amounts of intervention – also termed active management. Some level of active management is already required in many of the areas in the Fens, as the size of the nature reserves are too small to rely on natural processes. With increasing warming, the level of active management increases. As many of the groups who maintain these nature reserves are already stretched for resources, the levels of increased management may be outside of their ability to adequately maintain them at this level of warming.

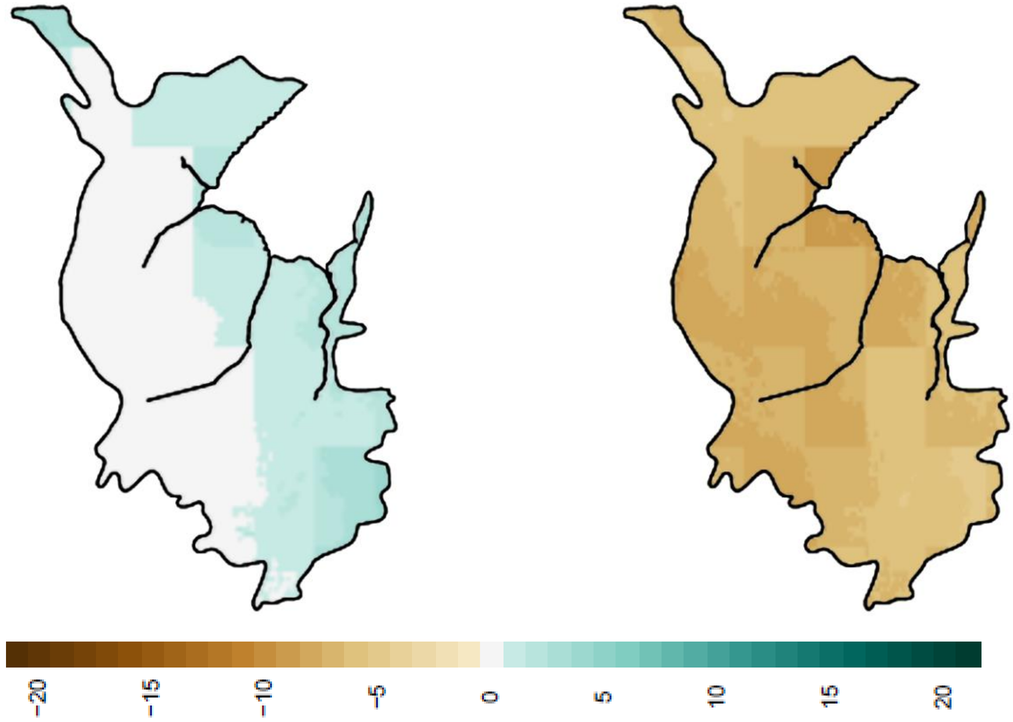


Figure 27: Adaptation effort for insects in the Fens under 2 and 4°C. These maps show that, even with 2°C warming insects will struggle and additional adaptation (e.g., removing additional stressors like pesticides) would be required. By 4°C, the adaptation effort needed has increased to the level where the building of micro-refugia, or alternative planting of different species may be required to maintain the existing insect species, and new species will be arriving that will further complicate conservation efforts.

Figure 27 shows the adaptation effort for insects in the Fens under 2°C and 4°C. These maps show that, even with 2°C warming insects will struggle given the low adaptation index values (<5) and additional adaptation (e.g., removing additional stressors like pesticides) would be required. With 4°C of warming the adaptation effort index becomes negative across the whole of the Fens for insects.

An adaptation effort index of **< -10** implies any adaptation effort at this stage will need to be substantial and the nature reserves and natural lands may not be able to be maintained to maintain existing biodiversity. As warming levels exceed 1.5°C, and especially above 2°C, the loss of critical components of the ecosystems increases. In some cases, over time, other species will move in to replace those no longer able to persist under this level of warming. The length of time this will take is dependent of the dispersal ability of the different species (relatively fast for birds, some insects (but not many), and some mammals, but slow for most plants, insects, reptiles and amphibians). It is also essential for non-flying species that natural areas be connected with corridors, and movement barriers minimized or mitigated (especially around transport systems).

As species each respond to climate change individually, some will be needing to track the new climate while others may still be able to persist in the areas they currently occur. This is much more complicated than working with farmers to start planting new crops and the idea of human-assisted movement of animals is fraught with problems (not least of which is that introduced species rarely fare well, or fare all too well, in the new areas). One way of facilitating this change is to plant similar species (usually the same genus but a different species, native if possible but this may not always be possible) that will provide the same level of structure and potentially the same types of food and nesting areas. For example, replacing an oak species that is beginning to run up against its climate limits with a similar oak that has a climate envelope more suitable for the projected levels of warming. The existing oak may be able to provide necessary ecosystem support while the new oaks become established.

At this level of effort and warming then local conservation can only be thought of in terms of a much larger landscape. These levels of changes will likely be very expensive. Currently, the 'best practice' of many conservation organizations is to allow restoration to occur naturally. While it is generally true that this level of restoration works better, it is only because it is compared to planting schemes that have not been well thought out, that often involve planting only one, or at most a few species. It would be possible to speed up restoration or transformation if it was seen from a systems point of view.

Properly planting a mix of large trees, would aid the restoration by not needing to work from one edge to another, but to allow the new area to expand in multiple ways – from the edges and from centroids of growth around parent trees. Planting large trees is much more expensive, and survival rates are lower, but it is not impossible. Relying on natural regeneration means decades (or longer with increasing warming differentially impacting species) of time will be required. The planting of parent and nursery trees may allow the regeneration to be 'head started' and potentially may allow some successional stages to be shortened or eliminated. In any of these activities, it needs to be borne in mind that the eventual community will likely be novel to what is expected, with different mixes of species than currently exist.

In the above analysis there are also many complexities. Not least that an area may remain a refugia for vertebrates and yet potentially become unsuitable for many of the species making up the habitat or food resources for these species. If the habitat becomes unsuitable, or food becomes more unavailable, then this is likely to have major implications for those taxa that a modelled cell/area remains a refugia for. With increasing warming, fewer areas remain refugia, more areas become areas of concern, and adaptation effort increases (i.e., becomes more negative).

The above figures also represent a picture based on climate only. However, the Fens are a highly modified landscape and most of the natural land cover has been lost. Figure 28 below thus highlights areas that could be restored to make space for biodiversity. These areas are generally closer to the coast so would likely be more impacted by coastal flood risk and by sea-level rise, which was not considered in this analysis.

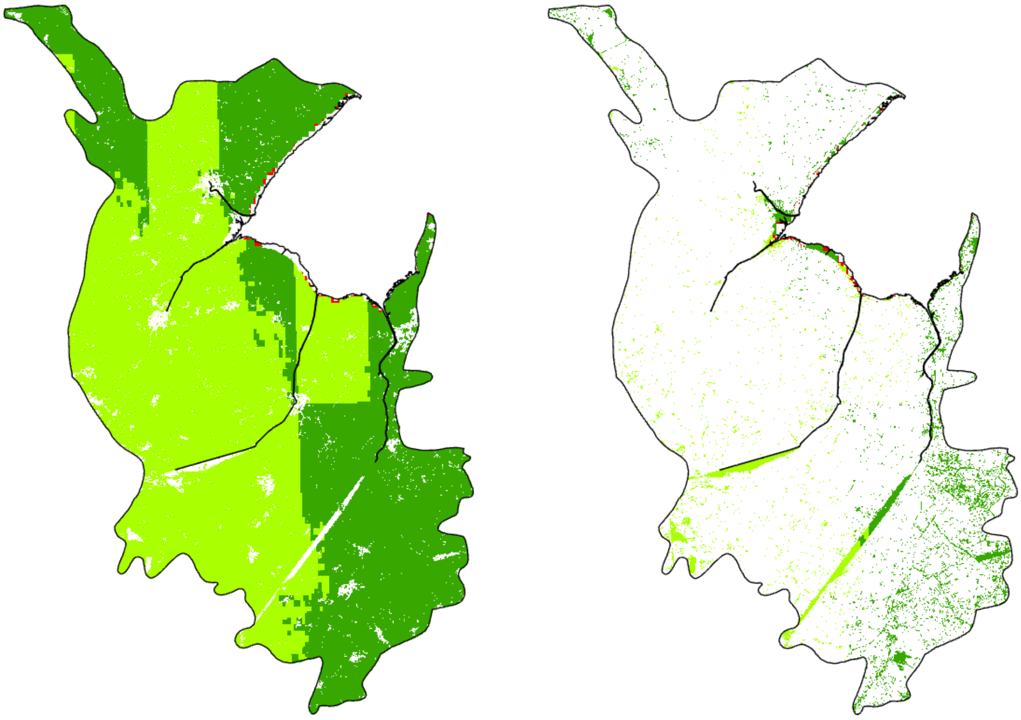


Figure 28: Areas that could be restored to make space for biodiversity, in areas classified as agricultural landcover (left) and natural landcover (right), with 1.5°C warming (light green) and 2.0°C warming (dark green).

However, figure 28 highlights that there are no areas that would remain a biodiversity refugia for more than half of the climate models at warming levels above 2°C. Considering both historical changes in landcover and climate then the ability to make a significant difference in any of the adaptation scenarios is very difficult. Biodiversity in the area fares poorly under climate change, especially at warming levels above 2°C (and even 1.5°C for some biodiversity groups).

This indicates that most of the Fens will require significant adaptation even with 2°C warming. As climate change exceeds 2°C the Fens require increasing levels of adaptation, moving into effort levels where facilitating change may be required (e.g., changing an area that is deciduous woodland into one that is more similar to the habitats seen in the Brecks). As most of the models underlying the biodiversity metric are plants and invertebrates, this indicates that even if the area remains suitable for vertebrates, they will struggle to find suitable habitats and food.

9. An integrated climate change risk assessment for the Fens

The previous sections considered the different climate risks independently. Here we draw these insights together to consider the implications of this sub-set of risks in aggregate for the Fens.

It is important to view the Fens through a systems lens, made up of different but interconnected elements such as sectors, communities, stakeholders and environments which interact and are affected by climate change and sea level rise, and which together create the characteristics and patterns of behaviour seen. For example, the Fens is a strategically important area in terms of its agricultural production, and this has a national significance. It is also important to recognise that 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 as it subsided, among other changes, especially water and flood management.

The current Fens landscape is only possible due to critical flood risk and water level management assets that underpin the management of water levels across the landscape 24 hours a day and 365 days a year, and the continued investment to maintain and enhance this adaptation. The new Boston tidal barrier and upgraded pumping station at St Germans are two recent examples of continued investment. Yet with the growth in agriculture, biodiversity across the Fens has been widely degraded and most peat deposits have been lost leading to severe loss of elevation, further compounding the flood risk, and release of soil carbon to the atmosphere.

These system-wide interconnections mean that 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. For example, whilst risks to agriculture could be viewed in isolation and areas could be identified from the above maps where there is potential to grow new crops or where current yields of crops could increase, if the same areas are projected to also see large declines in crop insect pollinators, or be adversely affected by an increase in the duration or intensity of drought, water supply restrictions and/or an increase in flood risk such assumptions or planned adaptations would be undermined (Maani, 2013).

Considering the Fens as a system is also important given climate-related risks do not happen in isolation. There is the potential for such risks to interact or cascade across or between multiple sectors (Cradock-Henry et al., 2020). There is also the potential for compound events to occur, whereby two or more weather or climate hazards occur simultaneously or in close succession which can lead to larger impacts than when occurring in isolation, for example the run of named storms in 2023/24. A transdisciplinary approach involving knowledge from all disciplines and sources is essential to tackle the complexity of the problem (VanKoningsveld et al., 2008).

The importance of why the Fens should be viewed through a system-wide and integrated lens is highlighted below. Although not definitive, as this report focused on a sub-set of modelled risks and sectors alongside a wider review of existing literature, it does provide tangible examples of why systems thinking will be needed to support climate change adaptation planning and decision making in the region going forwards:

- **The Fens is highly vulnerable to a wide range of climate hazards:** Due to the landscape and economy of the Fens it differs from many urban and rural parts of the UK where dominant risks from climate change can be identified and prioritised, such as flooding, heat stress or drought. In contrast, the Fens is highly vulnerable to a multitude of climate related risks including sea level rise, that can compound each other (Figure 29). Furthermore, climate risks and adaptation have co-developed over time and are intimately linked so it is not just climate-related risks that need to be considered but also combined with the consequences of past and future human interventions that can exacerbate or reduce risks in the future. Prioritising and adapting to one risk without considering and adapting to others in parallel is difficult.

- **A sectoral assessment, for example just focused on flood risk, is insufficient to capture multiple and cascading impacts that will affect the Fens:** The lens of residential and non-residential damage from flooding (expressed in this report through an Expected Annual Damage (EAD)) provides only a partial picture of the true risk. For example, short and long term impacts of flooding on agricultural production; soil erosion and declines in soil quality; losses to terrestrial biodiversity; damage to infrastructure such as roadways and loss of electricity supply, which will have system-wide implications, are not reflected. Understanding the 'full' picture of flood related risks will be an important next step to exploring investment choices.
- **There will be multiple, competing demands for freshwater in the Fens.** Socio-economic changes such as projected population growth and urbanisation will lead to increased domestic and industrial water demand. Drought and water scarcity are projected to increase under future projections of climate change, which can lead to reduced soil health, risks to crops and livestock, loss of biodiversity and reduced water quality. Changes in water salinity can affect irrigation and crop production whilst high levels of pollutants can reduce the quantity of water available for abstraction with any restrictions on irrigation further amplifying risks to agriculture. While agricultural land may be protected from flooding by enhanced investment in flood defences, it will only remain productive if drought and water quantity and quality issues are addressed in parallel.
- **There are potential opportunities for agriculture:** The future of agriculture in the Fens needs to be considered in a systemic way, including the direct and indirect effects of climate change (e.g. changes in drought and groundwater) and other changes such as the evolving agricultural system itself, as well as human demand. There are opportunities for agriculture in the Fens to adapt to warmer and drier conditions through investment, for example, farm-level reservoirs and increased irrigation. However, longer term this will become more challenging to align with national targets on environmental improvement, which will require reduced water abstraction alongside projected increases in temperature and drought magnitude. Continued intense agriculture would demand long-term and continued flood protection, but could be supported by a shift to vertical farming or low carbon glasshouse farming that would allow the relocation of agricultural food production to flood-safe land under controlled climatic conditions.
- **Agriculture and biodiversity are intrinsically linked:** Climate impacts and declines of insect pollinators will add to stresses facing some current crops and may limit the number of future crops that can be grown. Care needs to be taken in future plans so as not to further exacerbate biodiversity losses and to aim to reverse such losses where possible. While agricultural land may be protected from flooding by enhanced investment in flood defences, it will only remain productive if biodiversity, such as insect pollinators, is addressed in parallel. Alternatively, less intense agriculture may allow more flooding through managed rewetting and rewilding in certain areas. Alongside this, there are opportunities for agriculture in the Fens to adapt to wetter conditions through novel agricultural systems (e.g. paludiculture). This depends on successfully adapting all levels of the food supply chain, from the agronomic knowledge of farmers to local processing, distribution facilities and national markets.
- **Infrastructure underpins societal functions and is highly vulnerable:** Damage to infrastructure such as highways from flooding and drought will be exacerbated with future climate change. The proportion of class C and U roads that have little or no foundations means Lincolnshire is highly vulnerable. Cascading effects can include impacts on health and social care delivery, emergency response times and education accessibility. Likewise

impacts of extreme weather on interconnected power, water and telecommunications networks can propagate across the affected region and beyond.

Overall, the integrated assessment highlights a need for continued and enhanced investment in the flood risk management assets across the Fens. However, there are many choices in how and where that flood management investment occurs. Sea level rise is of particular concern as while the amount is uncertain, it will certainly continue into the future even with climate stabilisation. As already discussed, illustrative rises of 1m are quite plausible by the end of the century and 2 and 3 m by 2300. Hence the demand for adaptation will continue to grow and require far greater investment beyond simply maintaining current defence levels. Continuing protection will also see higher and higher defences and the consequences of failure – even if unlikely – will become much more severe for the people, communities, businesses and critical infrastructure, which in turn can lead to further cascading effects on society, the economy and environment.

Consequently, continuing to follow the present approach to flood management along the current defence lines, including along the rivers, should be reviewed as whether it is a wise long-term strategy. When the rivers (e.g., Great Ouse, Nene, Welland, etc.) are considered, there is a long defence line which will require upgrade as sea levels rise and projections of flood events show increases in magnitude and frequency, particularly after the 2050s and at higher global warming levels.

In the future a more diverse approach to the management of the Fens is possible, potentially allowing a more varied landscape and sets of activities to evolve that would enhance the resilience. Any future approaches need to recognise the interrelated nature of sectors and risks, as highlighted above, and the potential for fundamental trade-offs such as agriculture use versus other land uses in the long-term. Whilst smaller and more incremental changes to flood and land-use management practices are considered easier to implement, albeit with the outcome likely remaining closer to the current status quo of the system, addressing such system-wide change will require more transformational adaptation. Transformational adaptation will require higher ambition and may suffer from difficulties in implementation given the need to engage multiple stakeholders and institutions in the process and longer-term vision, as seen in the Dutch fen landscape (den Uyl and Munaretto, 2020).

To give an example of how the Fens could be viewed based on more traditional (incremental) adaptation and more transformational adaptation approaches, the following section reflects on the above findings from the integrated risk assessment to explore a range of possible adaptation futures. These storylines have been developed by considering a range of contrasting futures from major advance through to widespread retreat, and intermediate cases closer to the current management of flood protection assets. They are illustrative storylines to emphasise how, given the strong set of climate-related risks the Fens faces across all sectors, future adaptation planning, and solutions will need to be evaluated by considering these multiple risks and their integrated nature.

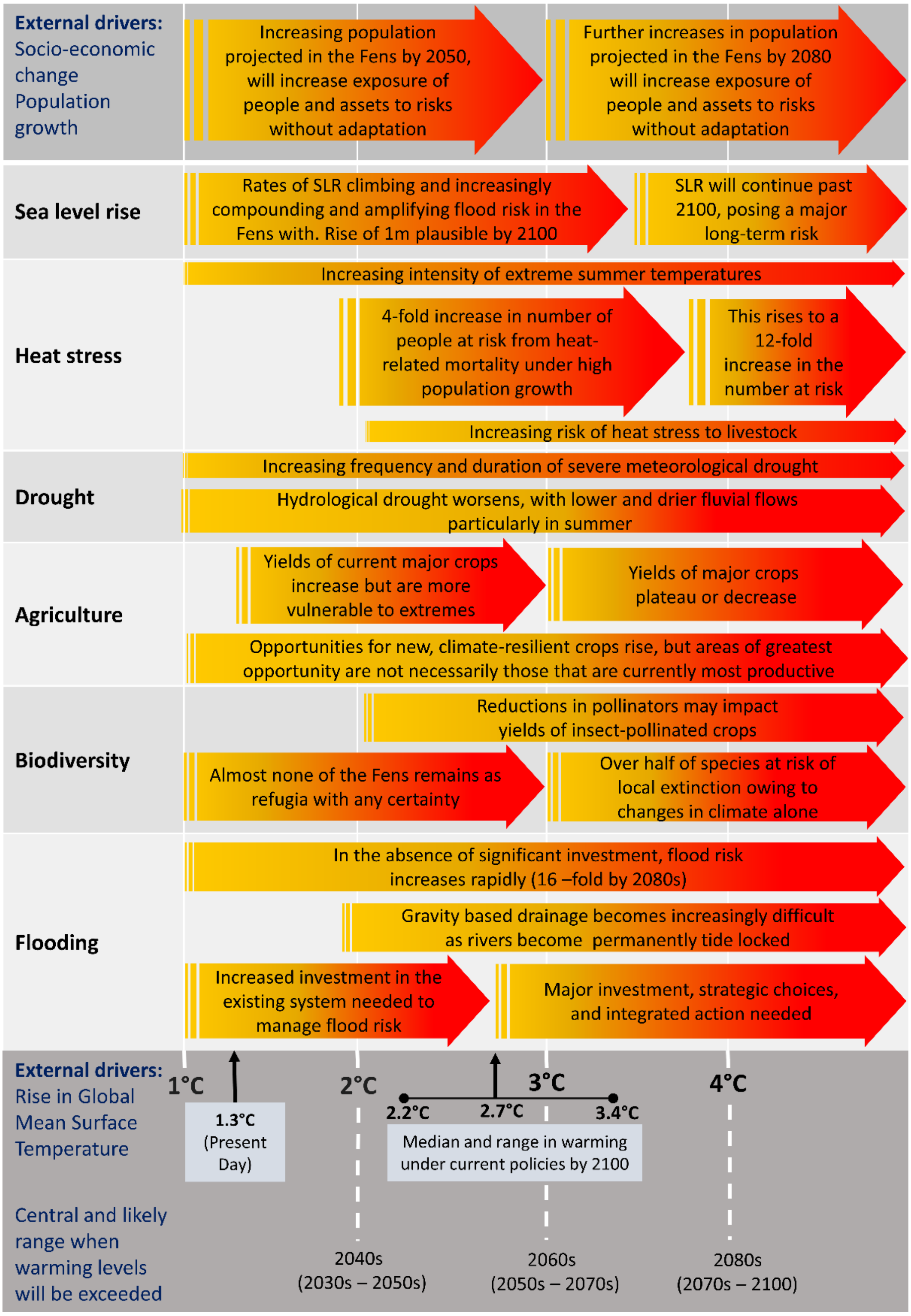


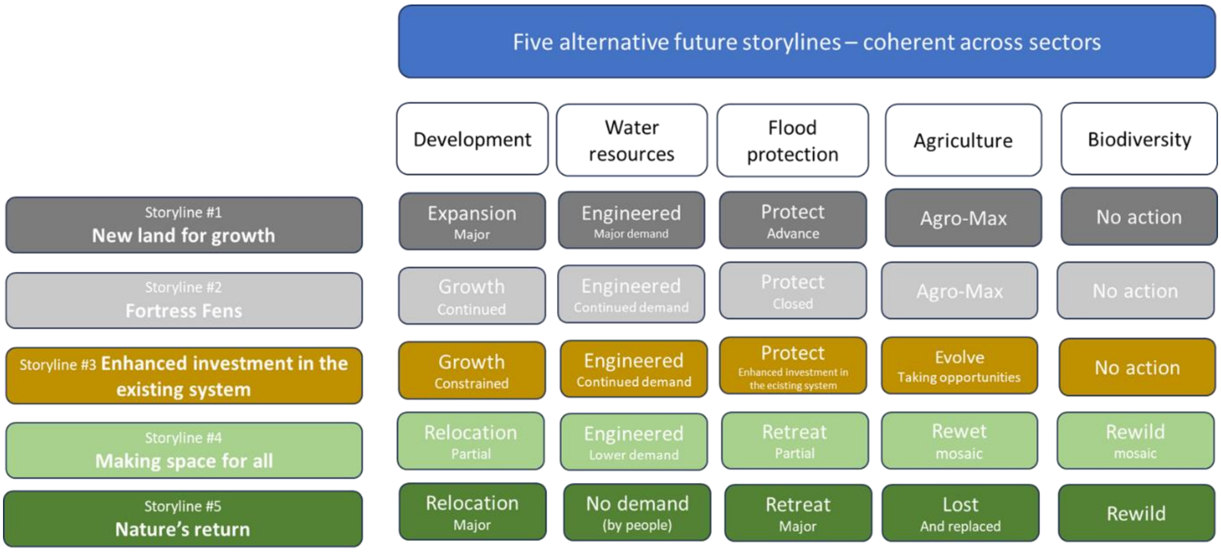
Figure 29: The myriad of risks that could impact the Fens as global mean surface temperature increases, based on the climate risk modelling presented in this report. The arrows highlight when risks may be faced based on modelled trajectories of when warming levels of 2°C, 3°C and 4°C are reached, reported by the Carbon Brief (2020) and IPCC (2023) and assuming a high emission future (note the height of arrows are for illustrative purposes only and do not depict the signifcance or size of risk). Even if current pledges of international government action are considered and assummed to be delivered, temperatures rise beyond 2°C and potentially 3°C by the end of the century, with continued increases after that date (Climate Action Tracker, 2023).

10. Imagining the future of the Fens – Alternative stories

Unlike historic adaptation in the Fens, which tended to happen in a more localised, incremental, and reactive manner, we now have foresight, and so we can think further ahead on our choices today compared to the past. The following *storylines* of how the Fens might evolve have been developed as illustrative examples by drawing on the long history of adaptation and reclamation in the Fens and the likely effects of climate change, including sea-level rise as reported in this risk assessment. Whilst the risk assessment mainly concentrated on the period up until 2100, there are longer term issues of concern given temperatures may continue to rise beyond 2100, and especially for sea level rise (Palmer et al., 2024; Weeks et al., 2023) which will continue to rise for centuries to come regardless of climate change mitigation. As such, the storylines are designed to stimulate thinking on the adaptation choices that are faced in the Fens to 2100 and further to 2200 and beyond where appropriate.

These storylines are ***not*** presented as recommendations, projections, or scenarios, but are narratives that aim to encourage thinking and consideration of the possible longer-term choices the Fens could face in the future, and what the Fens could look like under different storylines about the integrated nature of risks and adaptation. The storylines are inspired by the approach of van Alphen et al (2022) in thinking about a range of possible futures for the Netherlands under large amounts of sea level rise.

The storylines are built upon coherent messages across key elements of development, water resources, flood protection, agriculture and biodiversity, drawing on the earlier analysis presented in the risk assessment and ensuring consistency across the themes. We here describe five future narratives, others exist, all with different interactions, variables and outcomes.



Five alternative future storylines – coherent across sectors

	Development	Water resources	Flood protection	Agriculture	Biodiversity
Storyline #1 **New land for growth**	Expansion Major	Engineered Major demand	Protect Advance	Agro-Max	No action
Storyline #2 **Fortress Fens**	Growth Continued	Engineered Continued demand	Protect Closed	Agro-Max	No action
Storyline #3 **Enhanced investment in the existing system**	Growth Constrained	Engineered Continued demand	Protect Enhanced investment in the ecisting system	Evolve Taking opportunities	No action
Storyline #4 **Making space for all**	Relocation Partial	Engineered Lower demand	Retreat Partial	Rewet mosaic	Rewild mosaic
Storyline #5 **Nature's return**	Relocation Major	No demand (by people)	Retreat Major	Lost And replaced	Rewild

Figure 30: Outline of the key elements considered within the storylines.

They range in terms of levels of investment, changes in systems, focus on protection or retreat, and moves from traditional to more nature based economic opportunities, expanding from the current approach, and underscored by the CCRA elements modelled and presented in sections 4-9.

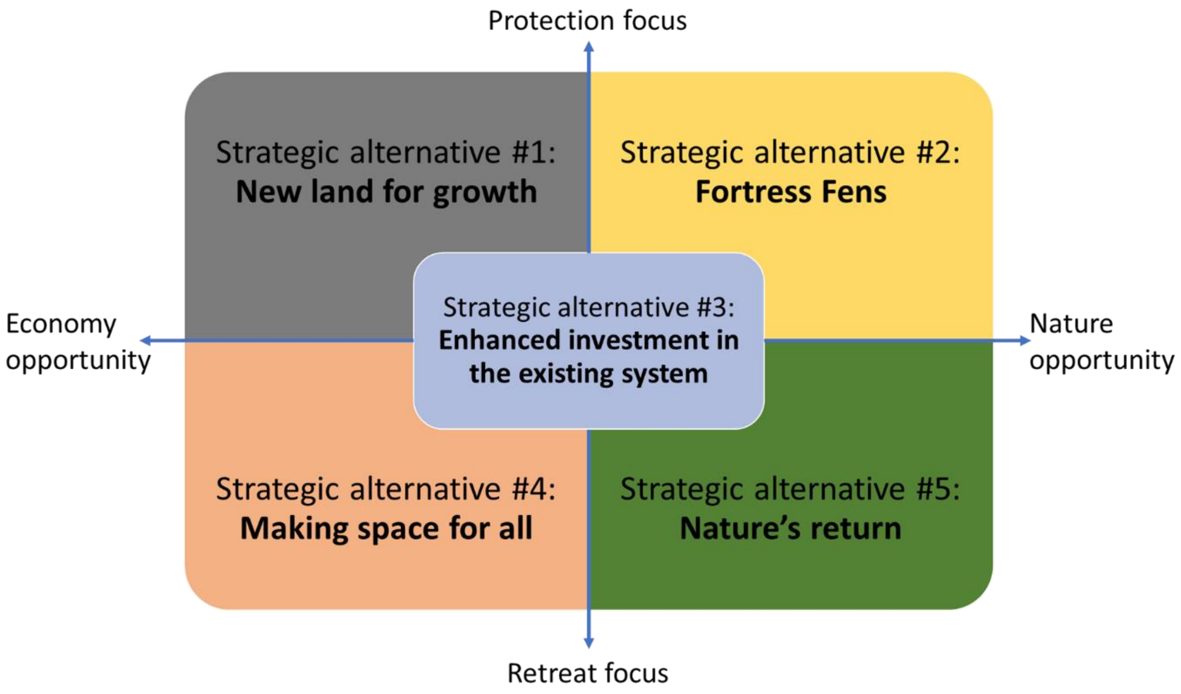


Figure 31: Matrix showing the focus of storylines on protection or retreat and moves from traditional to more nature based economic opportunities.

Storyline #1 New land for new growth

Large scale intervention with substantial investment required, providing high economic opportunities and little benefits for nature.

Development: Expansion (Major within and beyond the existing Fens): Population and the economy expand significantly across the Fens, including a focus on extensive reclamation in and around the Wash based on a highly contentious new Barrage. Development of infrastructure is paramount to economic growth and will support growth in jobs in the region. Population growth means more people will be exposed to risks from heat.

Water resources: Engineered (Major increase in demand): Coupled to the human expansion is a major growth in the demand for water and in addition to new land, strong demand-side management and new strategic supply side options are needed e.g., water storage is created including the proposed reservoir near Chatteris and especially in the Wash, linked to the Barrage.

Flood protection: Protect Advance: The flood defence strategy is centred on large scale protect and advance, under which schemes like the proposed Wash Barrage could fall, with the need for a shorter defence line inline and reclamation of land – by fill or as polders. Inland, drainage and river management would be increasingly decoupled from the sea with a growing dependence on pumping to control water levels rather than discharge by gravity. Implicit in this strategy is the assumption that the development will fund this flood protection.

Agriculture: Agro-fortress: With water levels heavily controlled and current agricultural areas protected from flooding, agricultural systems require minimal change. The creation of new water storage and distribution infrastructure is used to resolve water shortages, so that crops can be heavily irrigated where necessary. A warming climate may thus bring opportunities to grow many crops that are currently limited by temperature. Where warming climates or degraded soils reduce our ability to grow certain crops, vertical farming and glasshouses are used to maintain agricultural productivity and employment. Vertical farming may even take place on reclaimed land.

Biodiversity: No action or attempt to conserve: With no direct efforts to maintain or create new habitat for biodiversity, impacts on biodiversity are largely negative. Some species benefit in the short term (e.g. overwintering wildfowl continue to use agricultural fields close to wetland) but others lose large areas of internationally important coastal habitat to reclamation (e.g. estuarine habitats in the Wash), whilst inland biodiversity becomes increasingly restricted to the current network of protected habitat fragments. Although these fragments are largely protected from flooding or drying out by heavily controlled water regimes, they become increasingly isolated as the intervening landscape is further intensified, and increasingly vulnerable to the effects of rising temperatures and agricultural pollution.

Within the Wash, saltmarshes, tidal flats and shallow seabed are also lost due to direct destruction. Under current habitats regulations significant compensatory coastal habitat would need to be created elsewhere – i.e. under these rules, changes in the Fens/Wash will cause changes in other UK coastal lowlands/estuaries (e.g., Humber, Severn, etc.).

Storyline #2 Fortress Fens

Large scale intervention with substantial investment required, although lower than required in new land for growth, providing moderate economic opportunities and low benefits for nature.

Development: Expansion (Major within the existing Fens): Population and the economy expand significantly with continued growth and strong sprawled development of centres such as Peterborough and Cambridge and their strong footprint across the Fens. Population growth means more people will be exposed to risks from heat, particularly in urban areas.

Water resources: Engineered (Major increase in demand): Coupled to the human expansion is a major growth in the demand for water and need for strong demand-side management and investment in strategic supply side options including new water storage created within the Fens, e.g., the proposed reservoir near Chatteris. The approach to flood protection provides opportunities for freshwater storage on the Fens without displacing significant areas of agricultural land.

Flood protection: Protect: The strategy is 'hold the line' taking a strong engineering approach along the shoreline. All coastal defences are raised, while rivers are progressively decoupled from the North Sea, with mobile or fixed barriers as sea levels rise and. Discharge and drainage will ultimately need to be pumped over the defences.

Agriculture: Agro-fortress: Current agricultural areas are well protected from flooding, so agricultural systems do not require relocation. New water storage inland may help to resolve water shortages, so that crops can be irrigated where necessary. A warming climate may bring opportunities to grow many crops that are currently limited by temperature. Where warming climates or degraded soils reduce the ability to grow certain crops, vertical farming and glasshouses are used to maintain agricultural productivity and employment.

Biodiversity: No action, but the Wash is left to itself: No direct efforts to maintain or create new habitat for biodiversity, impacts on biodiversity are largely negative. Some species benefit in the short term (e.g. overwintering wildfowl continue to use agricultural fields close to wetland) but, overall, biodiversity becomes increasingly restricted to the current network of protected habitat fragments. Although these fragments are largely protected from flooding or drying out by heavily controlled water management, they become increasingly isolated as the intervening landscape is further intensified, and increasingly vulnerable to the effects of rising temperatures and agricultural pollution. Intertidal habitats in the Wash are preserved and evolve naturally depending on the availability of sediment and drivers such as the rate of sea level rise. Land cannot migrate inland meaning this critical habitat is lost.

Storyline #3 Enhanced investment in the existing system

Large scale intervention with substantial investment required, although lower than required in new land for growth, providing moderate economic opportunities and moderate benefits for nature.

Development: Expansion (Major): Population and the economy expand significantly with continued growth and strong sprawled development of centres such as Peterborough and Cambridge and their strong footprint across the Fens. Population growth means more people will be exposed to risks from heat, particularly in urban areas.

Water resources: Engineered (Increase in demand): Coupled to the human expansion is a major growth in the demand for water and need for strong demand-side management and investment in strategic supply side options including new water storage created within the Fens e.g. the proposed reservoir near Chatteris, but also displacing some agricultural land. There will be potential trade-offs in terms of achieving high environmental ambition and competing demands for water from society.

Flood protection: Protect: The strategy is ‘hold the line’ taking a strong engineering approach along the shoreline, and leaving the rivers open to the sea. All coastal and river defences are raised as sea levels rise and discharge is by gravity with pumped drainage from the Fens agricultural areas which requires progressive upgrade. The defence line is substantially longer than storyline #2. The rivers will progressively become perched above the land in the Fens.

Agriculture: Evolves to take opportunities: Ongoing climatic and land-use changes lead agricultural systems to adapt as best possible. Whilst increasing flood risks, water limitation and soil degradation may lead to some areas becoming agriculturally unviable, in many areas farmers switch to crops offering the greatest increase in production under climate change – some farmers simply swap new crops into existing rotations, others specialise in new high value crops under novel systems (including agroforestry and paludiculture). Competition for water resources between agriculture and other sectors intensifies.

Biodiversity: Maintain current action: Actions relating to biodiversity are focussed on protection of the existing protected area network, and the uptake of existing schemes to enhance the biodiversity of agricultural land (e.g. the Environmental Land Management Scheme). This results in some local increases in landscape connectivity and associated short-term increases in biodiversity. There is a high risk that such impacts are insufficient to insulate these habitats from warming temperatures, flooding and drying out.

Intertidal habitats in the Wash are preserved and evolve naturally depending on the availability of sediment and drivers such as the rate of sea level rise. Habitats cannot move inland meaning an eventual loss of habitat for coastal biodiversity. There is also marine-land connectivity along the river channels.

Storyline #4 Making space for all

Large scale intervention with substantial investment required, although lower than required in new land for growth, providing limited economic opportunities but higher benefits for nature.

Development: Decline in some areas: This involves giving up some land, but generally land with lower population density. Existing centres would be protected and continue to expand. Any migration would tend to be local – redistributing population to regions with jobs, rather than population falling. Population in urban areas are increasingly exposed to risks from heat.

Water resources: Engineered (Increased demand (society) decreased demand (Agriculture)): Coupled to the human expansion of existing urban areas will be growth in the demand for public water supply and need for demand side management and supply side options given increased drought risk. The new wetland habitat and decline in some agricultural areas will lead to a decline in water demand and natural mitigation during summer water shortages. Lower levels of environmental ambition will be required alongside increasing demands for water from society.

Flood protection: Selective - Protect and Retreat: Approaches include making space for water where possible. Coastal defences will be realigned landward where possible, creating areas suitable for salt marsh creation and enhancing nature-based defences. River defences will be set back where possible and be open to the sea and estuaries and marshes will be allowed to develop. With intelligent application of morphodynamic and hydrodynamic modelling, these changes can be designed to maximise protection benefits. However, grey protection would remain a key element in some areas.

Agriculture: Selective - rewet mosaic: Agriculture must adapt to the changing landscape, with some areas lost for agriculture altogether. Most peatland farmers re-wet peat soils, some switch to paludiculture crops or growing arable crops on higher water tables, whilst others allocate land to rewilding projects (potentially funded by carbon/biodiversity payments), helping to reconnect remnant semi-natural habitats. Rewetting does allow the land to act as a sponge, helping to mitigate both winter flooding and summer water shortages, so some areas remain potentially unaffected, and continue to produce high-yielding crops. Overall agricultural productivity remains high, though the composition of agricultural products may look very different to the present day.

Biodiversity: Rewild mosaic: The creation of large tracts of new wetland habitat offer many opportunities for biodiversity. Although future habitats and their arrangement in the landscape may eventually look quite different from the present day, the management of change allows most species and habitats to keep pace with it (facilitated by farmers still actively managing such activities as grazing and water depth in many areas). Overall, the increase in total habitat area and better connection of existing habitats are likely to outweigh losses at specific sites (e.g., where water depth becomes too high for specific species). Salinity gradients are promoted, and intertidal and saltmarsh habitats have potential to be restored and migrate inland.

Storyline #5 Nature's return

Lower levels of intervention needed with lower investment required, providing limited economic opportunities and high benefits for nature.

Development: Relocation (Major): The Fens is essentially abandoned by the existing populations and economic activities, which relocate to other regions with jobs. Certain centres such as Peterborough and Cambridge might be protected and continue to grow. Population in urban areas are increasingly exposed to risks from heat.

Water resources: Engineered (Reduced demand): Given the limited growth in the region demand for public water supply will remain relatively stable and the increased risks of drought managed through demand side options and smaller scale supply side options where necessary for remaining urban areas. There will be a decline in abstractions for manufacturing and agriculture potentially requiring lower levels of environmental ambition by water companies to maintain environmental resilience and support vulnerable water ecologies.

Flood protection: Retreat: Existing coastal and river defences are allowed to degrade and ultimately fail leading to more frequent flooding and changing habitats. This retreat or abandonment would need to be carefully planned across the region to maximise benefits and minimise risks. Some defences may be retained on the edge of the Fens and around towns and transport links are protected.

Agriculture: Lost and replaced: Large areas of land become unsuitable for agriculture as natural processes take over, including inundation from the sea. Some areas may remain suitable for paludiculture, and new enterprises may develop in specific areas (e.g. ecotourism, aquaculture, fisheries) to replace agricultural jobs, but the Fens drastically changes from one of the UK's most highly productive agricultural areas. This will have a significant impact given the high strategic value of the Fens in terms of its contribution to the UK’s total agricultural production.

Biodiversity: Rewild: Left unsupervised, the Fens returns to a vast wetland. Increased sea levels may create more brackish habitats than were present historically, with a mix of saline lagoons, swamps, marshes and reedbeds, and drier habitats (e.g. wet woodlands) on the new fenland fringes and islands. Many species are likely to benefit from this huge increase in wetland habitat area, especially those mobile groups that can rapidly colonise new wetland habitat (e.g. birds, fish), and a warming climate is likely to bring new colonising species currently associated with wetland habitats in France and Spain. Salinity gradients are promoted, and saltmarsh and intertidal habitats have the maximum potential to be restored and migrate inland.

However, the loss of agricultural management, such as grazing, and the inundation of current habitat fragments mean that some species may not be able to keep pace with change, and some habitats that depend on agricultural management such as grazing may be lost. Species that currently benefit from the juxtaposition of wetland and agriculture (e.g. overwintering wildfowl) may be negatively impacted in the short term (although the creation of new saltmarsh and wetland/agricultural boundaries along the new Fenland edge may compensate for this). Whilst biodiversity overall is likely to be much higher, it may no longer include all the species and habitats of the Fens today. This is especially true at levels of warming above 1.5°C.

11. Conclusion

What are the big challenges?

The Fens is highly vulnerable to a multitude of climate related risks including sea level rise, that have the potential to compound each other and lead to larger impacts than when occurring in isolation (Figure 29). In the worst case this can lead to 'surprises' and completely unexpected impacts.

The Fens also provides a unique landscape where climate risks and adaptation are intimately linked. As climate risks and adaptation have co-developed over time it is not just climate-related risks that need to be considered but also the consequences of past and future human interventions that can exacerbate or reduce risks that may be felt in the future.

Flood related risks and challenges

- **Without significant investment in adaptation, flood risk will increase:** Present day flood risks in the Fens may double by the 2080s given a 4°C rise in global mean surface temperature and a high population growth projection. In the case of a low adaptation future, with no further upgrades to existing defences and limited maintenance, flood risk may increase ~16-fold over the same period (with a ~7-fold increase by the 2050s).
- **The Fens is highly sensitive to climate change, taking action to mitigate climate change is an important part of flood risk management:** If climate change can be successfully limited to a rise of 2°C (current projections highlight that if emissions are not rapidly reduced, we will exceed 2°C between the 2030s and 2050s) and population growth is low, the projected increase in risk by the 2080s with limited adaptation is projected to be ~7 times the present-day risk. Although this is still significant it is less than the ~16-fold increase projected under a 4°C future. This sensitivity to climate change is also reflected in a projected rapid increase in flood risk between the 2050s and 2080s as the 2°C and 4°C climate trajectories diverge. By limiting climate change, the costs of adaptation (including the feasibility of maintaining existing systems and the scale of defences and barriers needed) are likely to be significantly less, maintaining a window of opportunity to decide how best to respond.

Temperature related risks and challenges

- **The Fens are getting hotter:** The magnitude of temperature extremes will accrue as global mean surface temperature rises. Even at 2°C, which could occur between the 2030s and 2050s, there will be multiple repercussions of increasing temperatures and heatwaves, including on transport infrastructure, the built environment, labour productivity, livestock and human health.
- **Heat related risks to human health are projected to increase:** With global warming of 2°C by 2050, heat-related deaths are projected to increase 4-fold from the 1981-2000 baseline, with 53 additional average annual deaths. With warming of 4°C by 2080, heat-related deaths are projected to increase 12-fold to 173 additional average annual deaths.

Water related risks and challenges

- **Droughts are projected to persist for longer:** Hydrological and meteorological droughts are projected to worsen under future climate change. At 2°C, which could occur between the 2030s and 2050s, the number of months in severe drought in a 30-year period is projected to be 34.3. With 4°C of global warming, which could occur by the end of the century under higher emission scenarios, this increases to 110.1 months.

Agriculture related risks and challenges

- **Significant agricultural challenges arise as temperatures increase:** At higher levels of warming (up to 4°C), many current major crops are likely to show more plateaus or decreases in yield/climatic suitability compared with the rest of the UK. Limiting warming to more moderate levels (up to 2°C, which could occur between the 2030s and 2050s) reduces this risk and may even result in increased yield for current crops. However, water availability is likely to become more limiting than in the present day even under more moderate levels of warming.
- **Some agricultural opportunities may emerge:** A warming climate brings the potential to adopt new, more climatically suitable crops with which to diversify agricultural systems. However, these are strongly conditional on adequate water availability and the ability to manage agricultural systems in an optimal way, both of which may be strongly influenced by climate change. The success of novel crops and agricultural systems as a route to keeping the Fens' contribution to UK food security more climate resilient depends on successfully adapting all levels of the food supply chain, from the agronomic knowledge of farmers to local processing and distribution facilities and national markets.

Biodiversity related risks and challenges

- **Even limited global warming poses a significant threat to terrestrial biodiversity in the Fens:** Even if global average temperature is kept to 2°C, which could occur between the 2030s and 2050s, almost none of the Fens is likely to remain as an area of refugia. The risk to insect pollinators, even at lower levels of warming could have serious implications for insect-pollinated crops and wild plants. Historical conversion of natural habitats in the Fens further exacerbates this problem.

The time to respond is now

Ultimately, the findings from this climate change risk assessment highlight that there is a crucial window of opportunity in which to respond to the risks of a 2°C world and begin planning and responding for a 3 or 4°C world. The choices that are made today will determine the future risk. As the climate continues to change, flood defences will be increasingly exposed. As salt marshes narrow in response to sea level rise, coastal defences will experience increased and frequent wave loading. Barriers and pumps will be called upon routinely, reducing the window for maintenance with attendant increases in operating costs adding further pressure to Internal Drainage Boards. Extreme storm events will be more severe, but perhaps the most profound impact will be increased severity of the more frequent extreme events. There is an urgent need to set out a strategic vision for adaptation in the Fens through the 21st Century and beyond and to act based on that plan.

A resilient Fens – Go together not alone

The future of the Fens cannot be secured through local tactical actions to improve a particular barrier or embankment, but demands a long term 'whole of Fens' strategy. This is not to suggest a detailed Master Plan, setting out detailed actions in all locations, but it does demand a coherent strategy to be set out, enabling a wide range of stakeholders to develop and implement reponses that align with that overall strategy. This will be imperative given the challenges that a 2°C world will pose in terms of future climate-related risks and the short timeframe remaining to plan and implement adaptation to manage present day and future risks. There is a crucial window of opportunity for future work to build upon this risk assessment and support the next stage choices.

- **A shared long term strategic vision**: Each activity in the Fens relies on choices made by the other activities which share the landscape. Developing a shared long term vision and understanding how to progress towards that shared vision will provide important guidance for future investment and development choices. This may include managing investments in the existing flood defence system or transitioning to an alternative configuration. This may include continuing to defend some areas into the long-term while accepting more flooding in other parts of the Fens. There are a wide range of detailed choices and options available that need to be considered.

- **An integrated management strategy and investment approach is needed:** The Fens is a highly managed system where flood management investment has delivered some of the most intensely used and valuable agricultural land in the UK. While flood risk management remains fundamental to sustaining the productive use of the Fens, the form that it takes needs to be considered, since the choices do not stand alone. Flood risk management influences, and is influenced by, development goals and associated water resources, agricultural, habitat, and infrastructure choices. A tractable integrated assessment and aligned planning process will be central to the success of the Fens as a region in the long-term.
- **Exploration of future adaptation choices must be through a system-wide lens**: There are a range of possible adaptation futures for the Fens depending on societal and management decisions in the face of climate and other changes. These can be illustrated by a range of contrasting futures from major advance through to widespread retreat and intermediate cases assuming similar but enhanced investment in the existing system. However, there will be fundamental trade-offs concerning land use in the Fens, especially agriculture versus other land uses such as biodiversity restoration or conservation and development in the long-term, as the land resource is finite. Rather than stopping at the defence line, consideration of the Wash and the intertidal areas around it is needed, as the position of the defence line may well change and the intertidal areas generally enhance protection.
- **A mosaic of different adaptation approaches could help address potential trade-offs:** The role of the Fens in national food supply and security has been key in how flooding has been managed in the region and how the government recognises this importance now and in the future. The current approach is uniform, but a more diverse and targeted adaptation approach is possible, which could be used to capitalise on different opportunities for agriculture, biodiversity, and flood risk management alongside competing demands and needs of supporting development, economic growth, and Net Zero strategies.

Advancing the knowledge – Next steps

Responding to the **big challenges** facing the Fens will require difficult decisions, trade-offs, investment, innovation and a willingness to work together to capitalise on potential opportunities. It will also require credibility and shared evidence. The analysis presented here provides some of this foundation but also highlights important areas that would benefit from enhanced knowledge. Developing a shared and detailed understanding will be crucial in developing a long term 'whole of Fens' strategy that is appropriately transformative (to address the **big challenges)** and reflects the **critical timescales needed for action**.

In this context, the future of the Fens cannot be secured through local tactical actions to improve a particular barrier or embankment. This is not to suggest a detailed Master Plan, setting out detailed actions in all locations, but it does demand establishment of a coherent 'whole of Fens' strategy to enable a wide range of stakeholders to develop and implement tactical reponses that align with that overall strategy.

Based on the analysis presented here, a series of priority areas that would enhance knowledge have emerged. Addressing these research priorities is possible, but not simple. Many of the foundational models now exist, and there is a window of opportunity for future work to build upon these and support the next stage choices (briefly discussed in Appendix D).

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Appendix A: Model Descriptions

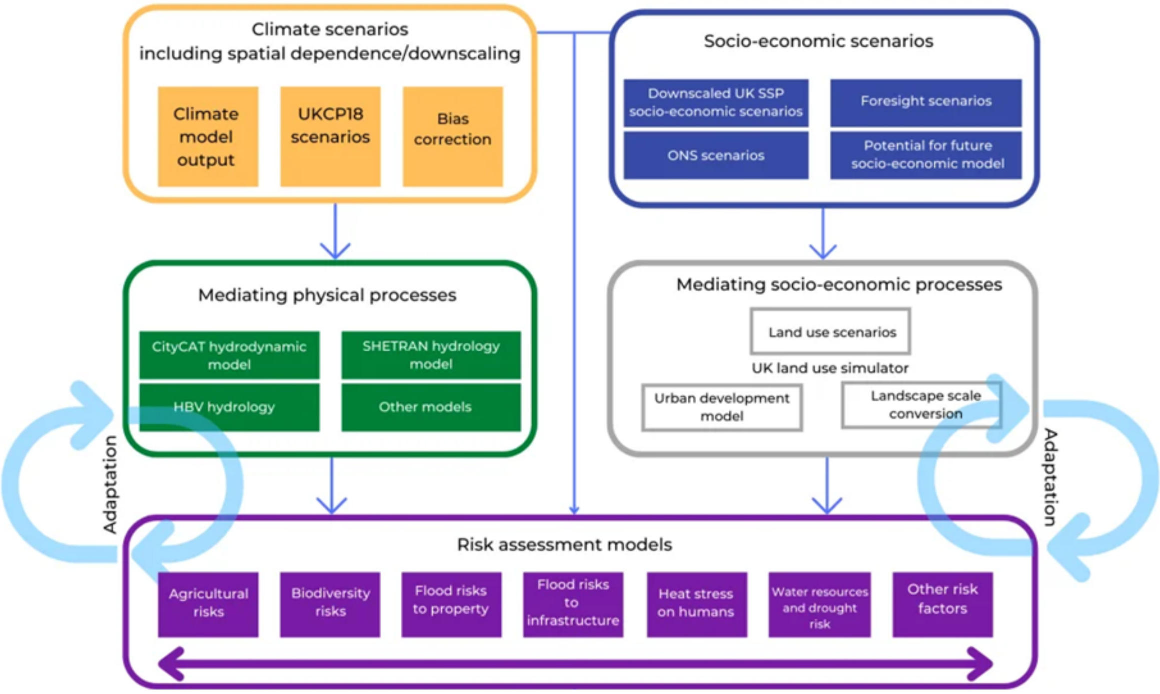

Figure A1: The OpenCLIM themes, structure, and consideration of adaptation within the framework. In this example adaptation could be i) measures aimed at mediating the physical processes, such as nature-based solutions that could help alleviate flood or drought risk and ii) measures aimed at mediating socio-economic processes such as designing new homes to reduce the risk of overheating in summer or strategic design of buildings which are more flood resilient.

A1. HARM

HARM (Heat Adaptation and Risk Model) uses a threshold-based approach to calculate exposure. Regional Linear Exposure-Response Functions (ERFs) define heat thresholds above which daily mortality will increase by a given percentage. The ERFs are based on statistical associations between daily mean temperature and epidemiologic data on mortality (described in full in Jenkins et al., 2022).

The model provides spatially explicit projections, using the latest UKCP18 regional 12 km data and incorporates socio-economic data (population, demographics, residential building numbers/type) using the UK-SSPs to reflect the exposed population and vulnerability to heat via demographic data and relationships between age and Relative-Risk (RR) values provided by the linear ERFs.

Climate data is based on the UK Met Office's UKCP18 12 member RCM (Regional Climate Model) ensemble at 12 km resolution. The data was bias corrected using ERA5 reanalysis of global climate data following the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) 2b bias correction method, as applied in Kennedy-Asser et al. (2021). For each global warming level, climate variables for each 30-year period, representative of the different levels of global warming above pre-industrial temperatures, are extracted. The 30-year time periods for each global warming level were based on start and end years published in Arnell et al. (2021), with the exact years for each global warming level varying slightly between UKCP18 RCM simulations (Kennedy-Asser et al., 2022). UKCP18 RCM simulations follow CMIP5 historical climate forcing until 2005 then representative concentration pathway 8.5 (RCP8.5) until 2080. Projected risks are compared to present day risks estimated using a modelled baseline of 1981-2000.

A2. Future Flood Explorer (FFE) – Brief description

Future Flood Explorer (FFE) toolset has been specifically designed to enable a credible exploration of how present day flood risk may change under a range of alternative climate and socioeconomic projections, and how effective different adaptation policies may be in offsetting these changes. The Future Flood Explorer (FFE) represents coastal, fluvial, surface water and groundwater sources of flooding, and can quantify risk to a wide range of receptors such as residential and non-residential properties, infrastructure sites, and transport links. Analysis uses local scale information on flood hazards, social and infrastructure vulnerable, as well as property exposure and existing flood risk management activities to enable a coherent assessment across a range of scales from multiple national, to national, to regional, to neighbourhood.

A key capability of the Future Flood Explorer is the ability to quantify the effects of adaptation strategies on risk, including defence construction, rural and urban catchment management, property level resilience measures, spatial planning and forecasting/warning, and their whole life costs. This supports adaptation investment policy choices at a range of scale. The FFE is an exploratory tool, designed to support strategy development and not scheme appraisal.

Details of data and methods used in the FFE are set out in several papers in detail. Of most relevance to this study are:

- Sayers, P.B., Ashley, R, Carr, S., Eccleston P, Horritt M, Horton, B, Miller, J (2022). Surface water – Risk and investment needs. A report by Sayers and Partners for the National Infrastructure Commission, London. Supporting the NIC Recommendations here
- Sayers, P., Moss, C., Carr, S. and Payo, A., 2022. Responding to climate change around England's coast - The scale of the transformational challenge. Journal of Ocean & Coastal Management. Volume 225, 15 June 2022, 106187. https://doi.org/10.1016/j.ocecoaman.2022.106187
- Sayers, PB., Horritt, M, Carr, S, Kay, A, and Mauz, J (2020) Third UK Climate Change Risk Assessment (CCRA3): Future flood risk. Research undertaken by Sayers and Partners for the Committee on Climate Change (using the Future Flood Explorer). Published by Sayers and Partners and the Committee on Climate Change, London.

A more complete description can be found here: Future Flood Explorer - Sayers and Partners (http://www.sayersandpartners.co.uk/future-flood-explorer.html.

A3. Terrestrial Biodiversity

The global analyses reported in Warren et al. (2013, 2018a) is based on the Wallace Initiative database and contains projections of potential climate change impacts, based on the climatically determined geographic ranges, of more than 135,000 individual terrestrial species. This study uses the most up to date version of this database to extract projections of the impacts of climate change upon plants and vertebrates in the UK, at alternative levels of global warming (specific warming levels, SWLs) of 1.5, 2, 2.7, 3.2, and 4.5°C (as well as 6°). The individual species data were then aggregated into metrics including species richness remaining (the % of species whose climatic ranges remain suitable at that warming level compared to the model baseline), local species extinction (the inverse of species richness remaining), and refugia (defined as an area (cell) containing a minimum of 75% of the species remaining). For consistency with other projects, we have subsequently interpolated linearly between these aggregations to extract projections matching SWLs of 0.5°C to 4.5°C of warming in 0.5°C increments.

The data found in the Wallace Initiative database has been widely used in the studies published in peer-reviewed journals (e.g., Jenkins et al., 2021; Manes et al., 2021; Price et al., 2024; Saunders et al., 2023; Smith et al., 2018; Warren et al., 2018a, 2018b, 2013). The results from the Wallace Initiative database should be viewed as a statistical sample to attempt to discover the underlying relationships, trends and patterns for broader populations. To that end, extensive resampling and testing have been done to assess how well it performs in terms of general trends and patterns. Results have been found to be generally robust to choice of climate model - CMIP3 vs CMIP5 (current) vs. high resolution RCM models (EU project Helix).

The methodology follows that used in Warren et al. (2018b, 2018a) and Warren et al. (2013). The global scale Wallace Initiative database was created using an established species distribution model, MaxENT, to estimate potential changes to the ranges of more than 135,000 terrestrial fungi, plants, invertebrate and vertebrate species associated with levels of global warming between 1.5 and 6°C (relative to pre-industrial levels), using 21 alternative regional climate change projections for each level of warming to incorporate uncertainty in regional climate projection, derived from the CMIP5 model inter-comparison project. As in Warren et al. (2018b, 2018a), calculations were carried out at an ~20km x20km scale. The MaxENT analyses relies on developing statistical relationships between current species distributions and current climate, and assumes this relationship holds into the future. To develop these models, species distribution data was sourced via the Global Biodiversity Information Facility (GBIF). A complete consideration of the caveats of the modelling process can be found in Price et al. (2024) and Warren et al. (2018b, 2018a, 2013).

While the original Wallace Initiative database was modelled at a spatial resolution of approximately 20km x 20km, the aggregated data were subsequently 'elevationally' downscaled to ~1km x 1km following the methodology outlined in Price et al. (2024) and Saunders et al. (2023). To match land cover maps these data were then resampled (ArcGIS Pro, RESAMPLE, nearest neighbour) to match the subsequently used land cover data - either 300mx300m (ESA-CCI, global, used in the natural capital climate risk register), or 20mx20m (CEH, used in OpenCLIM and here).

All data were spatially clipped to the Fens region before calculations were made that are presented above.

A4. Agriculture

The UK Centre for Ecology & Hydrology CropNet Wheat, CropNet OSR (Oilseed Rape) and CropNet Grass yield models simulate 'potential' yield of wheat and grass (Perennial ryegrass) growing under rainfed conditions in the UK, based on key meteorological inputs (solar radiation, temperature and precipitation). The models account for climatic variables, soil effects on water availability, and day length. The models run at daily timesteps and output annual yield per hectare (t/ha). The models have been designed and calibrated to produce estimates of crop yield impacts over relatively large spatial extents and long timescales (i.e., climate change impacts on patterns of yield across the UK).

The UKCEH CropNet Wheat model is based on approaches for simulating potential yield developed by Sylvester-Bradley and Kindred (2014) and Lynch et al. (2017), and also accounts for the impacts of variation in sowing date, of water limitation, direct heat stress and CO2 fertilisation. The model has three main stages: i) estimation of the Green Area Index (GAI) over the growing season; ii) convert this time series of GAI into biomass via an estimation of solar radiation intercepted by a wheat plant with given GAI. Water limitation is applied to the biomass conversion based on the rainfall and available soil water; iii) convert the biomass to grain yield and apply a waterlogging penalty based on the rainfall and water capacity of the soil. Patterns of predicted Wheat yields for the baseline period (1980-2010) are confirmed by Defra Wheat yield statistics. The difference between achieved and potential predicted yields appears to be consistent and represent yield loss due to factors such as pests and diseases, soil degradation and suboptimal agronomic decisions.

The CropNet OSR model works in a similar way for oilseed rape based on the approaches and equations of Habekotte´ (1997a, 1997b), Clarke et al. (2017).

The UKCEH CropNet Grass model is based on that of Brereton et al. (1996). It uses a parameterised relationship between daily temperature and the efficiency of the conversion of solar radiation to biomass to calculate the biomass accumulated each day. This is water-limited by calculating the ratio of actual to potential evapotranspiration, the former calculated using the soil moisture deficit derived from precipitation and rainfall, and the latter using the standard Penman-Monteith formulation. The yield is the sum of the water-limited biomass produced each day.

The crop suitability metric shows the relative climatic suitability (temperature and precipitation) of each 1km grid cell in the UK for over 160 annual and perennial crop species under different levels of warming. The UKCEH EcoCrop crop suitability model runs at a daily timestep and derives a suitability score based on daily temperature and daily precipitation using required and optimal temperature and precipitation ranges, and the range of the number of days within which the crop must grow (GMIN to GMAX). The temperature suitability score for a given crop is based on the average temperature and how this relates to the crop's required and optimum temperature ranges. The average score is calculated for a series of growing times between GMIN and GMAX, and the maximum taken as the final score. The precipitation suitability score is calculated in a similar way but summing the precipitation rather than calculating its average. The scores are calculated in a forward-rolling manner from each day, and then aggregated into yearly scores.

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Appendix B: Glossary

Definitions are based on those provided by the Intergovernmental Panel on Climate Change (IPCC) sixth Assessment Report (AR6) unless otherwise specified by * and referenced at the end of the section.

Adaptation: In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.

Incremental adaptation: Adaptation that maintains the essence and integrity of a system or process at a given scale.

Transformational adaptation: Adaptation that changes the fundamental attributes of a socio-ecological system in anticipation of climate change and its impacts.

Adaptation deficit: The adaptation gap between the current state of a system and the state it needs to be in to minimise the impacts of climate change to an acceptable risk threshold.

Adaptation limits: The point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions. Hard adaptation limit - No adaptive actions are possible to avoid intolerable risks. Soft adaptation limit - Options are currently not available to avoid intolerable risks through adaptive action.

Adaptation lock-in: A situation in which the future development of a system, including infrastructure, technologies, investments, institutions and behavioural norms, is determined (locked-in) or constrained (locked-out) by historical developments.

Maladaptation: Actions that may lead to increased risk of adverse climate-related outcomes, including via increased greenhouse gas emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future. Most often, maladaptation is an unintended consequence.

Agroforestry: Collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. In agroforestry systems, there are both ecological and economical interactions between the different components. Agroforestry can also be defined as a dynamic, ecologically based, natural resource management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels.

Anthropogenic: Resulting from or produced by human activities.

Biodiversity: Biodiversity or biological diversity means the variability among living organisms from all sources including, among other things, terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems.

Climate Change: A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use.

Climate extremes: The occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable.

By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classified as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., high temperature, drought or heavy rainfall over a season).

Climate variability: Deviations of some climate variables from a given mean state (including the occurrence of extremes, etc.) at all spatial and temporal scales beyond that of individual weather events. Variability may be intrinsic, due to fluctuations of processes internal to the climate system (internal variability), or extrinsic, due to variations in natural or anthropogenic external forcing (forced variability)

Global warming: The increase in global surface temperature relative to a baseline reference period, averaging over a period sufficient to remove interannual variations (e.g., 20 or 30 years). A common choice for the baseline is 1850–1900 (the earliest period of reliable observations with sufficient geographic coverage), with more modern baselines used depending upon the application.

Climate changes mitigation: A human intervention to reduce emissions or enhance the sinks of greenhouse gases.

Climate envelope/space*: Measures of the correlation between species occurrence or abundance with climate variables, used to make spatially explicit predictions of potential distribution (IPBES, 2018).

Climate refugia: A geographic area that has had a stable climate on evolutionary time scales, or that is projected to have a stable climate into the future.

Micro-refugia*: Climate refugia of <1km.

Cover crop*: Any crop grown to cover the soil and may be incorporated into the soil later for enrichment (USDA, n.d.).

Density-yield curves*: A function describing the relationship between a species population density and different levels of crop yield, based on data collected from comparable areas (Phalan et al., 2011).

Drainage (agricultural): Artificial lowering of the soil water table.

Drainage (soil)*: The natural process by which water moves through the soil and out of it due to gravity (Fausey, 2005).

Driver: Any natural or human-induced factor that directly or indirectly causes a change in a system.

Drought: An exceptional period of water shortage for existing ecosystems and the human population (due to low rainfall, high temperature, and/or wind).

Agricultural and ecological drought: Depending on the affected biome: a period with abnormal soil moisture deficit, which results from combined shortage of precipitation and excess evapotranspiration, and during the growing season impinges on crop production or ecosystem function in general.

Hydrological drought: A period with large runoff and water deficits in rivers, lakes and reservoirs.

Meteorological drought: A period with an abnormal precipitation deficit.

Blue-water Drought*: An unusual and significant deficiency in the water stored in freshwater lakes, rivers, aquifers and wetlands (Sayers et al., 2015).

Green-water drought*: An unusual and significant deficiency in the water stored in the soil layer (from which plants and crops normally draw their water) and/or in vegetation itself (Sayers et al., 2015).

Ecosystem: A functional unit consisting of living organisms, their non-living environment and the interactions within and between them. The components included in each ecosystem and its spatial boundaries depend on the purpose for which the ecosystem is defined: in some cases, they are relatively sharp, while in others they are diffuse. Ecosystem boundaries can change over time. Ecosystems are nested within other ecosystems, and their scale can range from very small to the entire biosphere.

Ecosystem services*: Ecosystem services are services provided by the ecosystems and contributing directly or indirectly to human well-being. These services play a crucial role in signalling the reliance of societies with regards to ecological systems and functions, as well as biodiversity (Roussel, 2020).

Impacts: The consequences of realized risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather/climate events), exposure, and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Impacts may be referred to as consequences or outcomes and can be adverse or beneficial.

Evapotranspiration: The combined processes through which water is transferred to the atmosphere from open water and ice surfaces, bare soil and vegetation that make up the Earth’s surface.

Exposure: The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected.

Fens (ecological)*: Fens are peat-forming wetland habitats fed by largely by groundwater or surface water which keeps the water table near the surface for much of the year (Freshwater Habitats Trust, n.d.).

The Fens (geographical)*: The UK's largest coastal lowland, reaching from Lincoln in the north to Cambridge in the south, and from Peterborough in the west across to north-western areas of Norfolk in the east. The landscape has been dramatically augmented through large-scale drainage, allowing it to host half of the best agricultural land in the UK.

Fill*: A flood risk management strategy of raising entire areas well above the expected flood levels by creating large, elevated landfills (or mounds) (Lendering et al., 2020).

Flooding: The overflowing of the normal confines of a stream or other water body, or the accumulation of water over areas that are not normally submerged. Floods can be caused by unusually heavy rain, for example during storms and cyclones.

Coastal*: Saltwater flooding normally due to a high tide or storm surge.

Fluvial*: Flooding due to waterways bursting their banks.

Pluvial*: Flooding due accumulation of rainwater over the land surface.

Groundwater* Flooding caused by the water table rising above the land surface.

Frontal rainfall*: Rainfall generated due to a cold air mass meeting warm air mass in a weather front.

Greenhouse gas: Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of radiation emitted by the Earth's ocean and land surface, by the atmosphere itself and by clouds. This property causes the greenhouse effect. Water vapour (H2O), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4) and ozone (O3) are the primary GHGs in the Earth's atmosphere. Human-made GHGs include sulphur hexafluoride (SF6), hydrofluorocarbons (HFCs), chlorofluorocarbons (CFCs) and perfluorocarbons (PFCs); several of these are also O3-depleting (and are regulated under the Montreal Protocol).

Gross Value Added*: The value generated by any unit engaged in the production of goods and services (ONS, n.d.).

Habitat fragmentation*: The process where a large, continuous habitat is divided into smaller isolated fragments due to human activities like roads, farms, and industries, leading to barriers for species dispersal and colonization, as well as changes in the microenvironment at the fragment edges (Primack, 2001).

Hard engineering/grey protection*: The use of artificial structures such as sea walls to manage coastal erosion and flood risk.

Hazard: The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.

Heat stress: A range of conditions in, for example, terrestrial or aquatic organisms when the body absorbs excess heat during overexposure to high air or water temperatures or thermal radiation. In aquatic water-breathing animals, hypoxia and acidification can exacerbate vulnerability to heat. Heat stress in mammals (including humans) and birds, both in air, is exacerbated by a detrimental combination of ambient heat, high humidity and low wind speed, causing the regulation of body temperature to fail.

Hydrodynamic modelling*: Hydrodynamic models are mathematical models that provide a physical basis for simulating a wide range of flow situations and sediment transport. These models simulate water movement by solving governing equations, which are formulated based on the laws of physics (Jahandideh-Tehrani et al., 2020).

Inter-basin water transfer*: The transfer of water from one geographically distinct river catchment or basin to another, or from one river reach to another (Davies et al., 1992).

Interflow*: The component of the runoff generation process where water flows at or near the surface without becoming part of regional groundwater system (Department: Water and Sanitation, 2011).

Land-sharing*: An agricultural system involving a patchwork of low-intensity agriculture which incorporates natural features such as ponds and hedgerows, rather than keeping agriculture and wilderness separate (Acton, 2014).

Land-sparing*: An agricultural system involving large, separate areas of sustainably intensified agriculture and wilderness (Acton, 2014).

Models: Structured imitations of a system's attributes and mechanisms to mimic the appearance or functioning of systems, for example, the climate, the economy of a country, or a crop. Mathematical models assemble (many) variables and relations (often in a computer code) to simulate system functioning and performance for variations in parameters and inputs.

Convection-Permitting Models (CPMs)*: Very high-resolution climate models which allow convection to be represented explicitly on the model grid without the need for a convective parametrization scheme (Kendon et al., 2021).

Ensemble models*: Ensemble modelling is a process where multiple diverse base models are used to predict an outcome. The motivation for using ensemble models is to reduce the generalization error of the prediction. As long as the base models are diverse and independent, the prediction error decreases when the ensemble approach is use (Kotu and Deshpande, 2019).

General Circulation Models (GCMs)*: Numerical models representing physical processes in the atmosphere, ocean, cryosphere and land surface, capable of simulating the response of the global climate system to increasing greenhouse gas concentrations (IPCC, 2013).

Process-based models*: A model in which relationships are described in terms of explicitly stated processes or mechanisms based on established scientific understanding, and model parameters therefore have clear ecological interpretation, defined beforehand. A model in which relationships are described in terms of explicitly stated processes or mechanisms based on established scientific understanding, and model parameters therefore have clear ecological interpretation, defined beforehand (IPBES, 2016).

Morphodynamic modelling*: Modelling involving fluid dynamics, geodynamics and ecodynamics with and without human interaction (Syvitski et al., 2010).

Nature-Based Solutions/Adaptations: Actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits.

Natural capital*: The world's stocks of natural assets which include geology, soil, air, water and all living things (World Forum on Natural Capital, n.d.).

Natural Flood Management*: The utilisation of natural processes to reduce the risk of flooding. These processes protect, restore, and mimic the natural functions of catchments, floodplains and the coast to slow and store water (Environment Agency and DEFRA, 2024).

Paludiculture: farming and agroforestry systems designed to generate a commercial crop from wetland conditions using species that are typical of (or tolerant of) wetland habitats (Mulholland et al., 2020).

Paris Agreement*: A legally binding international treaty on climate change, adopted at the UN Climate Change Conference (COP21) in Paris in 2015. The Agreement sets long-term goals to guide all nations to: (1) substantially reduce global greenhouse gas emissions to hold global temperature increase to well below 2°C above pre-industrial levels and pursue efforts to limit it to 1.5°C above pre-industrial levels; (2) periodically assess the collective progress towards achieving the purpose of this agreement and its long-term goals; (3) provide financing to developing countries to mitigate climate change, strengthen resilience and enhance abilities to adapt to climate impacts (UN, n.d.).

Peat: Soft, porous or compressed, sedentary deposit of which a substantial portion is partly decomposed plant material with high water content in the natural state (up to about 90%).

Peat extraction*: Physical removal of peat from the ground, usually for energy or horticulture, at a rate which substantially exceeds the original rate of deposition and accumulation (Lindsay et al., 2014).

Peatland restoration*: Returning damaged peatlands to a stable state where they are able to function naturally and support their typical wildlife. This is mainly achieved by providing the right stabilised, water level conditions to support the key peatland vegetation that is responsible for laying down and protecting the peat carbon store (IUCN UK Peatland Programme, n.d.).

Peatland rewetting*: All deliberate actions that aim to bring the water table of a drained peatland (i.e., the position relative to the surface) back to that of the original, peat-forming peatland (Convention on Wetlands, 2021).

Peatland subsidence*: A form of land subsidence, which is the downward movement of the Earth's surface due to the removal of subsurface earth materials. For peat, the main driver is the removal of groundwater from the naturally water-logged ecosystem, mostly due to the construction of canal drainage. This leads to the decline of water table depth causing peat soil to become drier and decompose faster. As a result, the previously water-logged peat layer is exposed to oxygen, increasing microbial activities and biological oxidation of the organic deposits. The oxidation of the peat ultimately leads to large carbon losses, which triggers subsidence (Sulaeman, 2023).

Peat oxidation*: The loss of organic matter in peat due to a chemical reaction caused by contact with oxygen (oxidation).

Polder*: A flood risk management strategy of surrounding the at-risk area with flood defences. A drainage system is then installed to drain excess water from the polder to the adjacent rivers or sea (Lendering et al., 2020).

Reforestation: Conversion to forest of land that has previously contained forests but that has been converted to some other use.

Resilience: The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/or transformation.

Return period: An estimate of the average time interval between occurrences of an event (e.g., flood or extreme rainfall) that exceeds a defined size or intensity. E.g. A 1 in 100-year return period event has the likelihood of occurring, on average once in 100 years.

Rewilding*: A concept which aims to restore ecosystems and reverse biodiversity declines by allowing wildlife and natural processes to reclaim areas no longer under human management (IUCN, 2021).

Risk: The potential for adverse consequences for human or ecological systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change. Relevant adverse consequences include those on lives, livelihoods, health and well-being, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species.

In the context of climate change impacts, risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards. Hazards, exposure and vulnerability may each be subject to uncertainty in terms of magnitude and likelihood of occurrence, and each may change over time and space due to socio-economic changes and human decision-making.

In the context of climate change responses, risks result from the potential for such responses not achieving the intended objective(s), or from potential trade-offs with, or negative side-effects on, other societal objectives.

Salinisation*: The process of accumulating soluble salts in soil, usually by an upward capillary movement from a saline groundwater source, followed by evaporation from the surface (Allaby, 2008).

Saline intrusion*: The incursion of saline water into the freshwater aquifer caused by natural processes or human activities (Prusty and Farooq, 2022).

Saline seepage*: The movement of saline groundwater from the upper aquifer to the surface (Oude Essink and de Louw, 2014).

Scenarios: A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are used to provide a view of the implications of developments and actions.

Representative Concentration Pathways (RCPs): Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases and aerosols and chemically active gases, as well as land use/land cover. The word 'representative' signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term pathway emphasises the fact that not only the long-term concentration levels, but also the trajectory taken over time to reach that outcome are of interest.

RCPs usually refer to the portion of the concentration pathway extending up to 2100, for which integrated assessment models produced corresponding emission scenarios. Extended concentration pathways describe extensions of the RCPs from 2100 to 2300 that were calculated using simple rules generated by stakeholder consultations, and do not represent fully consistent scenarios. Four RCPs produced from integrated assessment models were selected from the published literature and are used in the Fifth IPCC Assessment and are also used in this Assessment for comparison, spanning the range from approximately below 2°C warming to high (>4°C) warming best-estimates by the end of the 21st century: RCP2.6, RCP4.5 and RCP6.0, and RCP8.5.

(UK) Shared Socio-economic Pathways (SSPs)*: The UK SSPs describe a set of five alternative plausible trajectories of future societal development, which are based on the best current hypotheses about which societal elements are the most important determinants of challenges to climate change mitigation and adaptation specific to the UK. They are designed to be used to investigate the impacts of climate change, vulnerabilities and adaptation.

Sea level change (sea level rise/sea level fall): Change to the height of sea level, both globally and locally (relative sea level change) at seasonal, annual, or longer time scales due to (i) a change in ocean volume as a result of a change in the mass of water in the ocean (e.g., due to melt of glaciers and ice sheets), (ii) changes in ocean volume as a result of changes in ocean water density (e.g., expansion under warmer conditions), (iii) changes in the shape of the ocean basins and changes in the Earth's gravitational and rotational fields, and (iv) local subsidence or uplift of the land.

Soil degradation*: A change in soil health status resulting in a diminished capacity of the ecosystem to provide goods and services for its beneficiaries (FAO, n.d.).

Soil erosion: The displacement of the soil by the action of water or wind.

Species richness*: The number of different species present in a given area (Feest et al., 2010).

Standard of defence/protection*: The return period of a flood event against which the defence should be effective (Weller, 2018).

Storm/tidal surge: The temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place.

Storyline: A way of making sense of a situation or a series of events through the construction of a set of explanatory elements. Usually, it is built on logical or causal reasoning. In climate research, the term storyline is used both in connection to scenarios as related to a future trajectory of the climate and human systems and to a weather or climate event. In this context, storylines can be used to describe plural, conditional possible futures or explanations of a current situation, in contrast to single, definitive futures or explanations.

Subsurface flow*: The component of water flow occurring beneath the Earth's surface.

Time-sampling approach*: An approach used to estimate regional climate signals associated with global mean temperature change increments in climate projections and climate impact studies through identifying the time at which each degree of warming is reached and examining regional climate changes which occur at that date (James et al., 2017).

Tipping point: A critical threshold beyond which a system reorganises, often abruptly and/or irreversibly.

Trickle irrigation*: The method of dripping water onto the soil very close to the plant at very low rates to increase water use efficiency (Brouwer et al., n.d.).

UK Climate Change Risk Assessment (CCRA)*: A five-yearly independent risk assessment which considers and prioritises sixty-one UK-wide climate risks and opportunities cutting across multiple sectors of the economy (DEFRA, 2022).

UK Climate Projections 2018 (UKCP18)*: The latest generation of national climate projections for the United Kingdom and will provide users with the most recent scientific evidence on projected climate changes with which to plan (Met Office, 2022).

UKCP18 Probabilistic Projections*: Data from UKCP18 showing the spatial pattern of the projected climate change at a given probability level across an area such as the whole of the UK or administrative region (Met Office, 2018).

Vertical farming*: Farming on vertical surfaces, usually stacked in layers within a controlled environment.

Vulnerability: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Water Scarcity: Water scarcity can be broadly described as a mismatch between the demand for fresh water and its availability, quantified in physical terms.

Wave climate*: The long-term analysis of certain sea state parameters at a specific location over a particular period of time. A ‘sea state’ is a time interval in which the energetic conditions of the ocean free surface are uniform or pseudo-uniform (J. Méndez and Rueda, 2020).

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Appendix C: Acronymns

AR6: 6th Assessment Report
CCC: Climate Change Committee
CCRA: Climate Change Risk Assessment
CoCliCo Project: Coastal Climate Core Services
CPM: Convection Permitting Model
CReDo: Climate Resilience Demonstrator
EIES: Enhanced Investment in the Existing System
EIP: Environmental Improvement Plan
ERFs: Exposure-Response Functions
FFE: Future Flood Explorer
FFIA: Future Fens Integrated Adaptation Taskforce
GAI: Green Area Index
GBIF: Global Biodiversity Information Facility
HARM: Heat Adaptation Risk Model
ISIMIP: Inter-Sectoral Impact Model Intercomparison Project
IPCC: Intergovernmental Panel on Climate Change
NAP: National Adaptation Programme
NFVI: Neighbourhood Flood Vulnerability Index
NSSM: National System Simulation Modelling
OpenCLIM: Open CLimate IMpacts modelling framework
ONS: Office of National Statistics
(12)RCM: (twelve-member) regional climate model
RCP: Representative Concentration Pathways
RR: Relative-Risk
SWLs: specific warming levels
THI: Temperature Humidity Index
UKCP18: UK Climate Projections 2018
UK-SSPs: UK-scale shared socioeconomic pathways
WRE: Water Resources East
WRMPs: Water Resource Management Plans

Appendix D: Next steps analysis

Extensions to the modelling: The analysis presented here used existing climate models and data to provide a regional assessment of climate risks for the Fens. Overall, evolving the underlying models to reflect the Fens and the latest data and projections will be critical. In addition, more specific extensions to the modelling would help support further exploration and communication of key risks using a systems lens:

- Flood risk is presented in terms of changes in EAD (Expected Annual Damage) and provides a measure of change over time. In future iterations it could be made less abstract and support more direct communication by presenting an analysis of the number of additional properties flooded or changes in probabilities of being flooded.
- There are few places within the Fens that lie outside of the areas defined as floodplain. Exactly how many new homes have been built on the floodplain in the recent years, and how proposals for new developments could translate into increased flood exposure (and by extension) risk would be interesting to explore.
- Flood risk can include damage and loss from water logging but the impacts of groundwater and damages from this is not explored from an agricultural perspective. This will have a major impact from an agricultural perspective and an area where more modelling could be done in the future. Agricultural damages could then be combined with residential and non-residential losses.
- The report reflects on findings from the UK CCRA3 on sea level rise driven change in the standard of protection that would occur in the absence of any further adaptation. The results of the analysis for the UK CCRA3 highlighted the high sensitivity of coastal defence standards to sea level rise even in a 2°C future. This analysis could be repeated directly for the fens area.

Explicit exploration of long term strategic directions: What are the costs and benefits (social, environmental and economic) of alternative adaptation strategies – how much is it likely to cost to mainatin the existing system in the future versus the costs and benefits of advancing or retreating the line and all that implies for the rest of the Fens system. In responding to this it will be important to consider additional cross cutting issues that have received less attention to date:

- The implications of water supply for the agriculture sector
- The role of salinisation in the Fens – both groundwater and surface water
- Implications of declining insector pollinators for insect pollinated crops and agriculture. Data on crops and their specific pollinators are available and could be used to extend the analysis. However, while the major insect pollinators for many crops are known, it is less known whether the pollination might be ‘replaced’ to any degree by any remaining pollinator.
- Long-term flood management given multi-metre sea-level rise (either plausible but unlikely rapid change and/or likely more slow steady change over several centuries)
- The longer-term national significance of the Fens from the perspective of food, transport and energy which defines the values you attribute to them and what resources and approaches are available for adaptation.
- Exploring the investment case: Addressing the existing adaptation deficit, in the absence of climate change considerations, is likely to require significant and sustained investment. This investment, however, is likely to be a fraction of the investment that would be needed to adapt to 2 or 4°C of climate change.