Semiquantitative mapping of climate and land use change impacts on groundwater quality

Environmental Change, Adaptation and Resilience Programme

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Semiquantitative mapping of climate and land use change impacts on groundwater quality

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Executive Summary

This report details Task 2 ("Development of semi-quantitative national maps for assessment of potential impacts of Land Use and Climate Change and Groundwater Quality") of Phase 2 of the Environment Agency-BGS collaborative project "climate and land use change impacts on groundwater quality". This task has developed semi-quantitative maps of changes in contaminant source term risks associated with land use futures, accompanied by maps of metrics of changes in precipitation and temperature associated with climate change. The key findings of this task are as follows.

An initial scoping workshop identified a very wide range of drivers, pressures, and groundwater quality variables of interest. It also identified a wide range of users of information, covering both technical and non-technical staff and a range of scales from national down to area and local. A literature review of relevant land use and climate change datasets showed that the land use futures developed under the SPEED project (Brown et al., 2022) associated with the Shared Socioeconomic Pathways (SSPs) were the most appropriate to use for this task, accompanied by climate change projections derived from UKCP18 and CHESS-SCAPE (Robinson et al., 2022).

A semi-quantitative risk scoring methodology has been developed to link land use classes reported in the land use futures to contaminant source term risk. This methodology has been applied to land use futures under six scenarios and seven future time slices, with results summarised by EA areas and aquifers. Across the SSPs there is a divergence of changes in risk in some areas and commonality in others. Some common features across the SSPs include: stable land use (and limited change in contaminant risk) in eastern England associated with ongoing need for food production; afforestation (and reduction in contaminant risk) in southern England; urbanisation and intensification of arable land in northern England (an increase in contaminant risk).

CHESS-SCAPE data has been processed to produce maps of changes in precipitation (seasonal mean and extreme temperature, number of wet days) and temperature (seasonal mean) metrics for 10-year timesteps to 2070 for 4 Representative Concentration Pathways (RCPs). Under RCP8.5 for 2070, this results in wetter winters (particularly in northern England and coastal southern England) and drier summers (particularly in southern England), with the largest increases in extreme winter precipitation in northwest England and on the south coast. The greatest rises in mean air temperature are in greatest temperature rises in Solent and South Downs and West Thames.

The data generated in this task represent exploratory futures which are designed to support discussions with policymakers on the robustness of existing policies related to groundwater quality, and to inform spatial prioritisation of future work based on where risk is likely to be greatest. A next step would be to use the data generated in this task to inform the development of coupled water and pollutant models to quantitatively assess the impact of the land use futures on groundwater quality.

1 Introduction

This report details Task 2 (“Development of semi-quantitative national maps for assessment of potential impacts of Land Use and Climate Change and Groundwater Quality”) of Phase 2 of the climate and land use change impacts on groundwater quality project.

In Phase 1 of the project, scoping discussions with EA staff identified a wide range of potential contaminants (nitrate, pesticides, microbial contaminants, turbidity, emerging substances, phosphorus, carbon) of interest regarding the impacts of climate and land use change on groundwater quality. Improving our understanding of the long-term trajectories of these contaminants as a function of climate and land use change at the national scale is a considerable challenge. The primary constraint is that, with the limited exception of nitrate (which is addressed separately in task 3 of this project), no quantitative models exist to link changes in climate and land use with changes in groundwater quality. Further, for some pollutants, the fundamental conceptual relationships between groundwater quality variables and climate and land use change are poorly understood (Ascott et al., 2022).

In this context, this task seeks to develop an improved understanding of the potential impacts of land use and climate change on a range of groundwater quality variables using a semi-quantitative approach. The aim of this task is not to generate predictions of future groundwater quality, but to explore how alternative land use futures associated with climate and socioeconomic change may affect the overall direction of future groundwater quality at the national scale. These alternative futures can be used as tool for discussion with policymakers on prevention, mitigation, and adaptation of socioeconomic change. Further, assessment of land use futures at the national scale also acts as a screening approach to identify which areas of England and which contaminants may be most affected by land use and climate change, and acts as a pre-cursor to more detailed modelling of individual contaminants at national and area scales when such models become available (for example, through the NERC Freshwater Quality Programme Project Long Term Large Scale-Freshwater Ecosystems (LTLS-FE).

This report is structured as follows. Section 2 summarises the outputs of a workshop held with national and area EA staff to identify the future evidence requirements related to groundwater quality than can be delivered through this task, as well as the required output formats. Section 3 details a short literature review reviewing the available land use and climate change datasets for this project. Section 4, 5 and 6 present the methodology, results and discussion respectively, before providing conclusions of this task in section 7.

2 Summary of key outcomes from the workshop

On Thursday 13th October 2022 a virtual workshop was held to get inputs from national and area level EA staff regarding what would be of most relevance for their work. In the workshop participants were divided into breakout groups, and asked to address the following questions:

1. Identify and prioritise evidence requirements related to future controls on groundwater quality
2. Identify the level of detail, target audience and format of outputs

Each breakout group was allocated a recorder, who provided detailed notes on the discussions and identified a key shared message from the group. Appendix A details the transcribed outputs from workshop. The key messages from the workshop participants are summarised herein.

The evidence requirements can be divided into drivers, pressures, and groundwater quality variables of interest. The drivers of change of greatest interest to workshop participants were socioeconomic change and climate change. The pressures these drivers cause that are most of concern are land use change, changes in the seasonality and intensity of rainfall and recharge, increases in temperature, increases in sea level rise, and changes in how groundwater systems are managed (e.g. changes in abstraction, changes in policy regarding diffuse pollution). The groundwater quality variables of interest to workshop participants were nitrate, pesticides, microbial contaminants, PFAS, wastewater discharges, groundwater temperature and minewater discharges. New pollutants associated with future socioeconomic concern were of interest. It was also raised as to whether a typology-based approach can be used to group pollutants based on sources and behaviour in the environment.

The workshop participants identified that the level of detail, scale and format of any outputs is highly dependent on the user. It was stated that multiple scales and formats are needed for different users. The identified users and their requirements are shown in Table 1.

Table 1 Summary of users and output format requirements identified by workshop participants.

User	**Format required**
Technical national staff in the EA	GIS + time variant outputs, with reporting/supporting information. Gridded data at the national scale with additional aggregation to groundwater bodies
Technical area staff in the EA and other organisations (e.g. water companies)	GIS + time variant outputs, with reporting/supporting information. Catchment/local scale data needed for decision making, but national also useful for comparison between areas
National non-technical (e.g. policy makers, general public)	Images, infographics and key messages at the national scale
Local non-technical (e.g. catchment groups)	Images, infographics and key messages at the catchment/area scale

Several additional considerations were raised in the workshop; the need for consistency across scales and outputs and reflect uncertainty and confidence in data, the need for any outputs to be updatable, the need for outputs to be publicly available and also complementary to existing datasets such as groundwater vulnerability mapping.

3 Literature review

3.1 BACKGROUND

The purpose of the literature review is to identify the most appropriate datasets for mapping impacts of land use and climate change on groundwater quality in this task. This section presents the results of this literature review and is structured as follows. Sections 3.2 and 3.3 provide overviews of datasets related to climate and land use change respectively. Section 3.4 details datasets that model integrated impacts of climate and socioeconomic changes on land use. Section 3.5 provides a comparative analysis between these different datasets in the context of the EA user requirements identified in the project workshop. Conclusions on the most appropriate datasets for this project task are given in section 3.6.

3.2 CLIMATE CHANGE DATASETS

3.2.1 UK Climate Projections 2018

The UK Climate Projections 2018 (UKCP18, Met Office (2018)) represents the most up to date assessment of how the climate of the UK may change to 2100. The report from phase 1 of this project (Ascott et al., 2022) provided a review of the impacts of climate change on hydrometeorological and hydrogeological variables as derived from application of UKCP18 data. Phase 1 identified that changes in precipitation seasonality and extremes have relatively high confidence from UKCP18, and these are likely to affect groundwater quality through changes in recharge causing either contaminant spikes due or reductions due to dilution. Increases in air temperature, whilst having high confidence in the direction of change, may have relatively small direct impacts on groundwater quality, but possible indirect effects such as the warming of groundwater inputs to shallow groundwater-dependent terrestrial ecosystems.

In the context of phase 2 of the project and this literature review, the key consideration is the availability of data in relation to climate change variables (e.g. changes in precipitation) and associated metrics (e.g. changes in seasonality, extremes) that may affect groundwater quality. The key requirements are as follows:

- Data needs to be spatially coherent across England. This is required to compare and evaluate changes in climate across multiple regions
- Data needs to capture changes in seasonal behaviour and short term extremes
- Data needs to capture local detail

UKCP18 offers a range of projections (probabilistic, global, regional, local) of varying levels of suitability to meet the needs above. The probabilistic projections provide changes in future climate based on RCM uncertainties between 1961-2100. These data cover all RCPs at a 25km scale and can be used to explore the broadest range of future outcomes from UKCP18. They are not spatially coherent.

The global projections are spatially coherent at a 60 km scale, cover GCM uncertainty (13 of the 28 CMIP5 models) but only RCP8.5 (worst case scenario) and may miss local detail.

The regional projections are derived from application of a subset of the global projections as boundary conditions to the Met Office Regional Model to derive projections at a 12 km scale. The local projections are then derived from application of a subset of the regional projections as boundary conditions to the Met Office Convection-Permitting Model to derive projections at a 2.2 km scale. The regional and local projections provide a better representation of local effects due to orography, the coasts and land surface characteristics, and improved simulation of extremes.

UKCP18 data has also been used as inputs to develop derived datasets relating to both hydrometeorological and hydrogeological variables. Robinson et al. (2022) downscaled the UKCP18 regional projections to the 1 km scale and bias corrected outputs using the CHESS observational data. Alternative RCPs were also developed. This data has also been used in the development of projections of possible land use futures as a function of climate and socioeconomic changes (Brown et al. (2022), see section 3.4.1 for more information). Hannaford et al. (2022) used the UKCP18 regional projections to develop transient projections of groundwater levels, recharge and river flows.

3.3 LAND USE CHANGE DATASETS

3.3.1 GO-Science Land Use Futures

3.3.1.1 KEY FINDINGS

On behalf of the Government Office for Science, Foresight (2010) undertook a broad, overarching assessment of the future of UK land use over a 50 year timescale (2010 – 2060). The aims of the project were to identify the most important challenges and opportunities for land use, and what can be done to manage land more sustainably.

Foresight (2010) identified six drivers of future land use change, all of which interact, and may generate tensions and conflicts between sectors. These are:

- demographic change, including managing increased demand for land for housing
- economic growth and changing global economic conditions
- climate change, including use of land for climate change mitigation
- new technologies to increase land productivity and reduce pressures
- societal preferences and conflicting public attitudes
- policy and regulatory environment

Based on these drivers, three key important cross-sectoral challenges were identified:

- Rising demand for land in SE England
- Climate change and land use, including interactions between the impacts of climate change on land use and also the use of land to reduce greenhouse gas emissions
- Ensuring continued delivery of public goods and services delivered by land (e.g. biodiversity, water regulation, carbon sequestration, amenity and recreational value).

Foresight (2010) state that a major shift in approach to land use governance is required, moving away from incremental decision making on individual projects towards a coherent and consistent approach that considers the full value of land. From a water perspective the need to integrate both water quality and resources is identified, as well as the need for more systematic integration of water-related implications into decision making for land use.

3.3.1.2 FUTURE SCENARIOS

The uncertainty associated with the complex interactions between the drivers of land use change above is high, and therefore Foresight (2010) suggest that new policy interventions should be robust to a range of possible futures. To that end, three national scale scenarios are presented as plausible futures. These were developed in brainstorm workshops with land use specialists considering the six drivers of change previously identified. The workshops identified the largest uncertainties in future land use change as: the rate of climate change and extent of adaptation; the degree of societal resistance to change; the concentration of people and economic activity in the UK.

These resulted in three scenarios in which reflects these uncertainties:

- “Leading the Way”, where adaptation to environmental change is high, population and economic activity is dispersed (low concentration)
- “Valued Service”, where resistance to societal and institutional change is low and the concentration of the population and economic activity is high
- “Competition Rules”, where adaptation to environmental change is low and societal and institutional resistance to change is high.

These three scenarios are narrative based, and no data are provided. These are designed to stimulate thought, not predict the future, and represent possible backdrops against which to make decisions or policy recommendations.

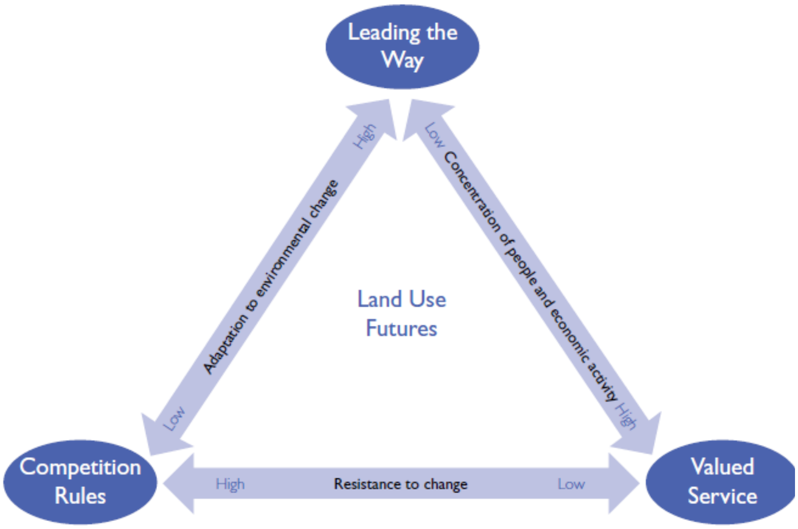

Figure 1 Narrative scenarios developed by Foresight (2010). Contains public sector information licensed under the Open Government Licence v3.0.

3.3.2 DEFRA Land Use Choices Tool (LUCT)

In 2022, DEFRA commissioned the development of the Land Use Choices Tool (LUCT). This work is ongoing and due to complete in March 2023. LUCT will allow users to determine how different land use change choices will affect environmental outcomes across a wide range of sectors (water quality, flood risk, water resources, biodiversity, forestry, net zero/greenhouse gas emissions). The tool will also allow users to calculate costs of land use interventions and run scenarios. LUCT is currently under development in the Solent and South Downs region only.

At the time of writing, no further information on LUCT was available. It is proposed LUCT is considered in future phases of this project.

3.3.3 ASSIST Scenario Exploration Tool (ASSET)

ASSET is a tool developed to explore future rural landuse change scenarios developed under the ASSIST project (Redhead et al., 2020). The ASSIST project used the InVEST Scenario Generator tool (Sharp et al., 2017) to develop scenarios associated with possible changes in rural land use in Great Britain. The tool operates at a 1 km grid cell size at the national scale, using CEH Land Cover 2007 as a baseline.

The scenarios developed focus on different components of rural land use and management: increasing agricultural land cover, afforestation, changes in cropping, changes in grassland management. Agricultural and afforestation scenarios can also be explored at 6 levels of change (5%, 10%, 15%, 20%, 25% and 30%). In total there are over 5200 possible combinations of land use change that can be explored. These scenarios are time slice-independent and represent plausible scenarios about the future at national and regional scales to be used in exploratory analyses. They are not associated with global shared socioeconomic pathways or emissions scenarios, and do not consider changes in urban expansion.

For each land use scenario, ASSET presents impacts of changes across 12 output variables modelled by InVEST (calories and income of arable crops, soil carbon stocks, nitrogen and phosphorus retention, pollinator and natural enemy richness, bird abundance, habitat connectivity). Whilst InVEST operates at a 1 km grid cell size, changes in output variables are summarised at the national and regional scale.

ASSET outputs are available via an exploratory interface (https://assist.ceh.ac.uk/asset-v2).

3.3.4 Water Resources East Natural Capital Planning

Water Resources East has developed a natural capital plan for Eastern England (Water Resources East, 2022). This consists of a plan for conservation, restoration and establishment of nature across Eastern England, through a series of priority areas for natural capital actions. The core goal of the natural capital plan is to meet the objectives of the 25 Year Environment Plan for England.

Systematic Conservation planning was used which consists of spatial prioritisation of where to implement natural capital actions, embedded within stakeholder discussions. A series of objectives, actions and targets were set in relation to environmental outcomes based on the 25 Year Environment Plan for England; habitat conservation and restoration, carbon storage, floodplain reconnection, riparian woodland, green space access, water quality. The objectives, actions and targets were implemented through a decision support tool to develop a series of 100 solutions that best meet the targets at the lowest cost. In this study, a solution is a map of the spatial priorities for natural capital actions across Eastern England.

The consolidated results for Eastern England showing where nature conservation, restoration and establishment should take place over the next 25-30 years is shown in https://wre.org.uk/wp-content/uploads/2021/05/The-Water-Resources-East-Natural-Capital-Plan-First-Iteration.pdf. Outputs are provided as regional maps, as well as county, catchment, and parish-level summaries. These outputs are designed to inform local level planning to help planners identify what actions can be undertaken to improve natural capital in their respective area.

The data generated does not consider climate change impacts, nor actual land uses. The maps are designed to provide a shared vision for nature restoration across Eastern England. They are not intended to force land use change and have no statutory basis. Consequently, no indication of when changes may be implemented are provided. A data licence from Biodiversify Ltd. is required for use of the data.

3.4 CLIMATE AND LAND USE CHANGE DATASETS

3.4.1 SPEED and the UK SSPs

The SPEED project (Spatially explicit Projections of EnvironmEntal Drivers) has generated several projections that are of relevance to the impacts of climate and land use change on groundwater quality.

The core of work under SPEED has been the development and subsequent application of UK-specific Shared Socioeconomic Pathways (SSPs). SSPs provide five narrative-based storylines representing plausible futures of socioeconomic challenges associated with mitigation and adaptation to environmental change. These have previously been developed and widely used at the global scale within integrated assessment models (Popp et al., 2017). The relationship between the five global SSPs are shown in Figure 2 and can be briefly summarised as follows:

- SSP1 – Sustainability. A gradual shift towards sustainability and reducing inequality
- SSP2 – Middle of the Road. A world where socio-economic and technological trends no not change from substantially from historical patterns
- SSP3 – Regional rivalry. Concerns on regional competitiveness and conflicts force increased focus on domestic concerns, resulting in strong environmental degradation.

- SSP4 – Inequality. Increased inequality between and across countries, with environmental policies only considering local issues around middle- and high-income areas.
- SSP5 – Fossil-Fuelled Development. Competitive markets and innovation lead to rapid global economic growth. Environmental issues are managed, including by geo-engineering if necessary.

Under SPEED, downscaled, UK-specific versions of the SSPs have been developed through participatory workshops, interviews and questionnaires with key stakeholders (Harmáčková et al., 2022). For each of the SSPs, key categories of socioeconomic drivers, extended scenario narratives and semi-quantitative trends of socioeconomic indicators have been developed (see Figure 3).

Figure 2 The five SSPs. Reproduced after O'Neill et al. (2014).

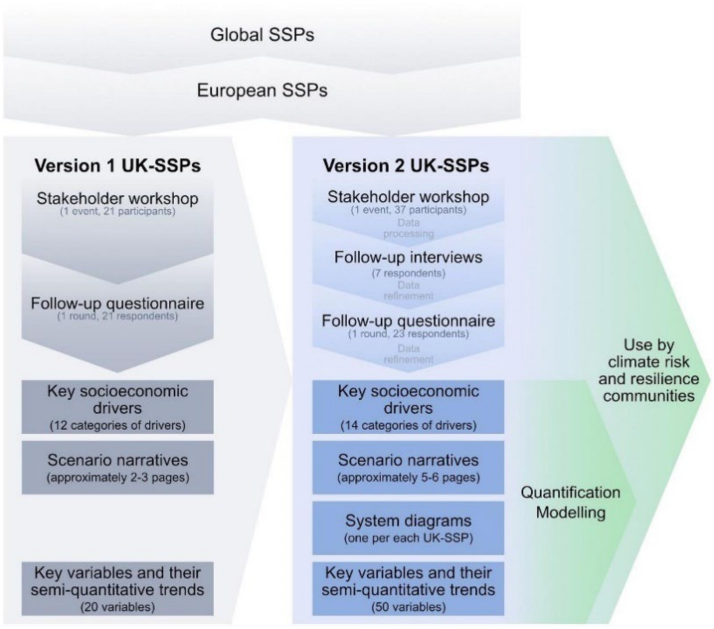

Figure 3 Development of UK SSPs. Reproduced after Harmáčková et al. (2022).

Recently, work has been undertaken to bring together the UK-SSPs with UKCP18 data and land use change models to develop plausible alternative land use futures for Great Britain as a function of both climate and socioeconomic change (Brown et al., 2022). Brown et al. (2022) combined the UK-SSP data from Harmáčková et al. (2022) with climate change data from the UKCP18 (based on Robinson et al. (2022)) under different Representative Concentration Pathways (RCPs). Six combinations of RCPs and SSPs were used: RCP2.6-SSP1, RCP4.5-SSP2, RCP4.5-SSP4, RCP6.0-SSP3, RCP8.5-SSP2, and RCP8.5-SSP5. These cover a broad range of climate and socio-economic futures and allows for analysis of the impact of different SSPs in the same RCP and vice versa.

The RCP-SSP combinations were applied to a novel agent-based modelling framework of the British land system, CRAFTY-GB. CRAFTY-GB operates at a 1km grid resolution for the whole of Great Britain and produces gridded land use futures at decadal time slices to 2070. Modelled land use futures are shown in Figure 4, and varies widely between the different RCP-SSP combinations. Socio-economic changes had a greater impact than climate change on land use futures, although this study did not consider climate extremes. For example, in SSP1 (Sustainability) there is a substantial decrease in intensive agriculture due to novel sustainable agriculture and lower demand, in contrast to SSP5 (Fossil-fuelled development) where very high levels of intensification of agriculture occur due to increases to support increases in production.

Brown et al. (2022) also highlight that the land use futures are not predictions, but plausible alternative futures envisioned by stakeholders to support the development of robust policymaking.

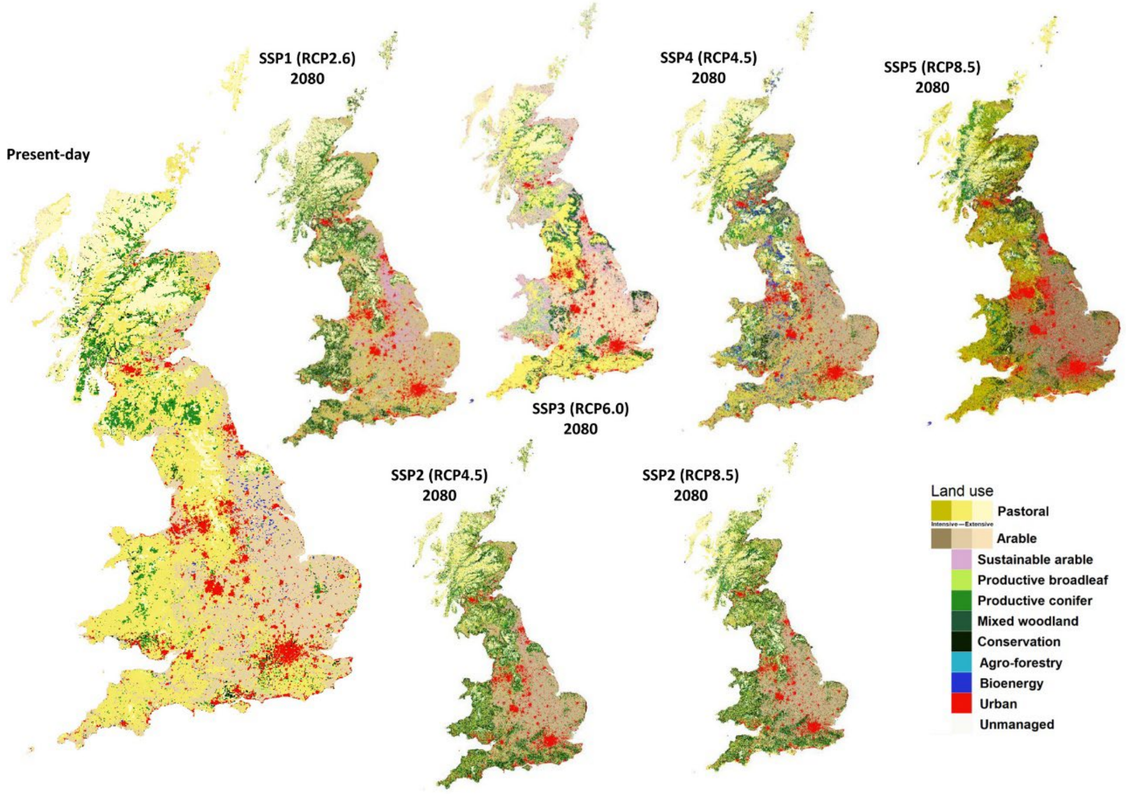

Figure 4 Land use futures generated by application of the UK SSP-RCP combinations to the CRAFTY-GB model. Reproduced after Brown et al. (2022).

3.5 SUITABILITY OF DATASETS FOR DEVELOPMENT OF SEMI-QUANTITATIVE GIS FRAMEWORKS OF IMPACTS OF CLIMATE AND LAND USE CHANGE ON GROUNDWATER QUALITY

Table 2 summarises the key attributes of the datasets reviewed in this document. All the datasets have advantages and disadvantages.

The DEFRA Land Use Futures are highly detailed futures developed with extensive stakeholder consultation. However, these data are only descriptive, and do not consider climate change or temporal variations. The ASSIST data, whilst quantitative in nature at 1 km grid scale, only covers changes in rural land uses only and does not consider climate change impacts. The WRE natural capital planning data focusses specifically on the conservation status of habitats in Eastern England only, and does not consider climate change or temporal variations. The EA's LUCT is at a national scale and considers benefits of land use choices across a range of impacts but is unavailable until March 2023. The SPEED data is advantageous as it operates at a national scale, is quantitative, gridded data at a 1 km resolution for multiple time slices for a number of climate and socio-economic futures. All land uses based on CEH Landcover mapping are considered.

Table 2 Summary of climate and land use change datasets reviewed in this report.

Dataset Name and Reference	**Scale**	**Type**	**Resolution (km)**	**Land use approach**	**Climate Change**	**Land Use Change**	**Time-variant**
DEFRA Land Use Futures	National	Descriptive	-	-	N	Y	N
ASSIST	National	Quantitative	1	Rural land uses only	N	Y	N
WRE Scenario Mapping	Regional	Quantitative	vector data	Conserve, restore, establish classification	N	Y	N
SPEED	National	Quantitative	1	All land uses based on UKCEH Landcover	Y	Y	Y
DEFRA LUCT	Regional	Quantitative	unknown	unknown	unknown	Y	unknown
UKCP18	National	Quantitative	variable	-	Y	N	Y

3.6 CONCLUSION ON WHICH LAND USE CHANGE DATASET TO EMPLOY

As detailed in the workshop summary in section 2 there are a wide range of users of information related to land use and climate change impacts on groundwater quality. These cross a range of scales (national, area) and levels of technical expertise (technical specialists, non-technical policymakers and members of the public). For these different users there is also a range of different drivers, pressures, and groundwater quality variables of interest. The need for detailed local-scale information on climate and land use predictions is also somewhat conflicted with the available datasets. The futures reviewed are designed to be exploratory and plausible, not predictions of the future.

In this context, given this project is at a national scale and considers both climate and land use change impacts on groundwater quality, the SPEED land use futures dataset in conjunction with the CHESS-SCAPE UKCP18 meteorological data are the most appropriate datasets for this project, and will be used in in the rest of this report. This provides advantages as the national scale coverage allows for consistency and comparison between areas, as well as across different RCPs, SSPs and time slices. Use of the SSP approach also frames this analysis in a global change context through the scaling down of the global SSPs to UKSSPs and subsequent use in the CRAFTY-GB model.

4 Methodology Co-design

4.1 LAND USE FUTURES

4.1.1 Datasets and scoring risks of changes in source terms

Based on the conclusions of the literature review (section 3) and discussions with the EA project steering group, it was agreed that the SPEED dataset was the most appropriate dataset of land use futures as a function of climate and socioeconomic change. We used the SPEED data for all RCP-SSP combinations for all 10-year time slices to 2080. To evaluate the implications of changes in land use for groundwater quality, it was necessary score the different SPEED land use classes in terms of potential changes to contaminant source terms. This scoring can then be applied to the land use maps for any future scenario or time slice. The SPEED data divides land use into the following classes: Pasture and arable (both subdivided from very extensive to intensive and arable further divided between food, fodder and sustainable), Forest (divided between conifer, broadleaf, native and non-native), Native and Mixed Woodland, Bioenergy, Agroforestry and Urban. Participants at the task workshop identified the following groundwater quality variables of interest: Nitrate, Pesticides, Microbial contaminants, PFAS, Wastewater discharges, groundwater temperature, minewater discharges, new pollutants that are not currently an issue.

Following discussion with EA staff leading the PFAS risk assessment project, it was agreed that there is a substantial knowledge gap regarding PFAS source terms as a function of land use. In conjunction with the rapidly changing regulatory framework related to PFAS, this means that no sensible assessment of the impact of climate and land use change on PFAS source terms can be made at this time. It was therefore not considered further in this task.

The land use classes also do not provide any differentiation in terms of minewater discharges. These are also likely to be highly localised in nature and therefore mapping at the national scale is unlikely to be appropriate. Minewater discharges were therefore also not considered further in this task.

For the remaining groundwater quality variables of interest, the SPEED Land use classes were ranked as shown in Table 3 using the following methodology. Given the uncertainty in the exact magnitude of contaminant fluxes associated with each land use, a simple 3 class scoring was used. In this approach 1 represents the lowest risk, and 3 represents the highest risk.

To estimate the scores associated with nitrate, we overlaid the baseline (2020) SPEED land use map on 1 km gridded nitrate leaching derived from NEAP-N and presented in the EA's Lines of Evidence shapefile for NVZ designation. For the SPEED agricultural land use classes (the subdivisions of pasture and arable), we extracted the mean nitrate load from agricultural sources from the Lines of Evidence shapefile. This showed that intensive arable had much higher loads than intensive pasture and extensive arable, which were higher again than extensive/very extensive pasture (Table 3, column "Agricultural N load"). These differences in load were used as a basis to score extensive/very extensive pasture as low risk, intensive pasture and extensive arable as medium risk, and intensive arable as high risk. In addition to the agricultural land use classes, all woodland landuse classes were scored as low risk, agroforestry and sustainable arable were scored as medium risk, bioenergy and urban high risk.

The same scoring was used for pesticides, except for urban which was scored as medium risk. For the remaining groundwater quality variables (microbial contaminants, groundwater temperature and wastewater discharges), the primary land use effect is likely to be urbanisation. For microbial contaminants, urban sources represent an increase in risk, and so this was scored as high risk and all other land use classes were scored as medium risk. For groundwater temperature, urbanisation can result in increasing groundwater temperatures due to the subsurface urban heat island effect (Zhu et al., 2015). Consequently, urban was scored as medium risk for groundwater temperature and all other land uses scored as low risk. Wastewater discharges may increase as a function of urbanisation (Astaraie-Imani et al., 2012) and so this was scored as a medium risk and all other land use scored as low risk.

Table 3 Original SPEED Land Use Classes, agricultural N loads for agricultural land use classes, and estimated risk scores for groundwater quality variables, and simplified landuse classes used for visualisation.

		Groundwater quality risk score					
Land Use Class	**Agricultural N load (mg/L)**	**Nitrate**	**Pesticide**	**Microbial contaminants**	**Groundwater temperature**	**Wastewater discharges**	**Simplified Land Use Class**
Mixed Woodland	-	1	1	2	1	1	Forest
Native Woodland for Conservation	-	1	1	2	1	1	Forest
Productive Native Broadleaf	-	1	1	2	1	1	Forest
Productive Native Conifer	-	1	1	2	1	1	Forest
Productive Non-Native Broadleaf	-	1	1	2	1	1	Forest
Productive Non-Native Conifer	-	1	1	2	1	1	Forest
Very Extensive Pasture	1.52	1	1	2	1	1	Extensive Pasture
Extensive Pasture	1.81	1	1	2	1	1	Extensive Pasture
Agroforestry	-	2	2	2	1	1	Forest
Extensive Arable	4.15	2	2	2	1	1	Extensive Arable
Intensive Pasture	5.72	2	2	2	1	1	Intensive Pasture
Sustainable Arable	-	2	2	2	1	1	Extensive Arable
Bioenergy	-	3	3	2	1	1	Intensive Arable
Intensive Arable (Fodder)	12.62	3	3	2	1	1	Intensive Arable
Intensive Arable (Food)	12.62	3	3	2	1	1	Intensive Arable
Urban	-	3	2	3	2	2	Urban

4.1.2 Analysis and interpretation

The methodology detailed above produces a large amount of spatiotemporal data. The seven time slices, seven futures (6 RCP-SSP combinations and the baseline) and five contaminants results in the generation of 245 rasters associated with changing land use at 1 km scale for England. These processed datasets are a powerful source of information for users to interrogate and understand the potential range of impacts of land use on groundwater quality and it's uncertainty across different geographical areas, contaminants, futures and time slices of interest. It is beyond the scope of this report to provide a detailed evaluation of the impacts of land use for each individual future, time slice and contaminant. Moreover, the SSPs are designed to be an exploratory tool working at the national scale to support prevention, mitigation, and adaptation. In this context, we developed an approach to the analysis and interpretation of the data generated which highlights and explains the broad spatial and temporal patterns of risk at the national scale across the different futures. This approach is described herein.

To produce land use change maps that were easy to interpret, we first simplified the SPEED land use classes. This principally consisted of combining the different woodland/forest land uses into a single class "forest". The simplified land use classes are shown in Table 3.

We then plotted each modelled land use as a function of the RCP-SSP future and time slice and evaluated changes in land use across the futures by visual inspection. Maps were produced for each RCP-SSP future and time slice and just for 2080 for clarity. For each future and time slice, the proportion of different land uses was calculated and plotted for all of England. This was repeated for outcrop aquifers only based on simplified hydrogeological mapping for England. The land use maps were then divided by aquifer outcrops based on simplified hydrogeological mapping (the Chalk, Devonian/Carboniferous, Jurassic, Magnesian, Permo-Trias), and divided by EA areas (further split between outcrop aquifers only and all EA areas), and for each division, the proportion of different land uses was calculated and plotted for each future and time slice.

This approach was then repeated to assess changes in contaminant source term risk. Generation of maps and plots of changing risk for each of the five contaminants in Table 3 for each future and time slice would be an intractable amount of figures to interpret. We therefore simplified the risk scoring in Table 3 further based on the similarity in scoring between the different contaminants. The scoring for nitrate and pesticides is very similar, so these were grouped as "agricultural" dominated contaminants, using the scoring for nitrate. The scoring for microbial contaminants, groundwater temperature and wastewater discharges are very similar (only urban has a higher score), and these were groups as "urban" dominated contaminants. A change in contaminant source term risk was calculated based on the difference in the scoring in Table 3 between the baseline landuse in 2020 and the modelled landuse under a given RCP-SSP future and time slice. This change in risk can range from -2 (a large decrease) to +2 (a large increase). For example, a change from intensive arable to forest would result in a change in risk for agricultural contaminant risk based on Table 3 of -2 (a large decrease). Using this approach, for the "agricultural" and "urban" dominated contaminants, we produced the following:

1. Maps of changes in contaminant source term risk for each RCP-SSP future and time slice
2. The proportion of English land that has a change in risk in comparison to the 2020 baseline for each RCP-SSP future and time slice
3. As (2), but for outcrop aquifer areas only
4. As (2), but divided by outcrop aquifers
5. As (2), but divided by EA areas, and further divided by outcrop aquifers only and all EA areas

4.2 CLIMATE CHANGE IMPACTS ON PRECIPITATION AND TEMPERATURE

4.2.1 Dataset processing

The SPEED dataset uses CHESS-SCAPE (Robinson et al., 2022) as driving climate data. For consistency, it was therefore agreed to use CHESS-SCAPE to produce maps of changes in precipitation and temperature. National scale changes in precipitation and temperature associated with the underlying UKCP18 projections and their potential groundwater quality implications have already been reported by Ascott et al. (2022), and used to generate projections of recharge and groundwater levels Hannaford et al. (2022). In this context, the purpose of including the results of CHESS-SCAPE in this task is to generate maps of changes in precipitation and temperature metrics as supporting information that can be interrogated by end users alongside land use change and contaminant source term change maps. The metrics calculated for precipitation and temperature were as follows:

- Change in seasonal mean precipitation
- Change in seasonal extreme precipitation (95th and 99th percentiles)
- Changes in number of wet days (> 1 mm/day) by season
- Change in seasonal main air temperature

Each metric was calculated using 20-year time slices on a 10 year timestep to 2080 (e.g. 2030 = 2020-2040, 2040=2030-2050 etc) for each RCP (2.6, 4.5, 6.0 and 8.5), averaging across the 4 CHESS-SCAPE ensemble members. This is consistent with the time slices in the SPEED data. In line with previous UKCP18 publications (Met Office, 2018) changes in rainfall were presented as percentage changes and changes in air temperature and wet days as absolute changes.

4.2.2 Analysis and interpretation

Similar to the processing of the SPEED data, processing the CHESS-SCAPE climate data to produce the metrics above results in a large number of rasters. Calculating the four metrics, split by season and for all seven time slices and four RCPs produces in 560 rasters in total. Given the extensive previous results presented by Ascott et al. (2022) and Hannaford et al. (2022), in this report we highlight results only from the RCP8.5 scenario for the 2070s, as this provides the greatest climate change signal to noise ratio. For each metric we present the following:

- National maps of the metric for RCP8.5 in 2070
- National maps of the change in the metric for RCP8.5 between 2020 and 2070
- Plots of the change in the mean value for each metric for each EA area

4.3 DEVELOPMENT OF GIS FRAMEWORK

Land use change data processing was undertaken in the R statistical computing environment (R Development Core Team, 2016) and CHESS-SCAPE data was processed in Python. Core outputs of the analysis (rasters of simplified land use and contaminant risk, rainfall and temperature metrics for each RCP/SSP and time slice) were saved in ascii format for use within GIS software by end users and are provided with this report.

5 Results

5.1 NATIONAL LAND USE FUTURES

For a detailed evaluation of the land use futures for Great Britain produced in the SPEED project the reader is referred to previous work by Brown et al. (2022). Here we provide a brief overview of the modelled land use futures for England as context to the estimated changes in contaminant source terms presented in section 5.2. Note that the descriptions of land use change reported here diverge somewhat from the results reported by Brown et al. (2022) as the latter discuss results for Great Britain as a whole, not England. Figure 5 shows maps of modelled land use futures for England split by timestep and RCP-SSP combination as produced by Brown et al. (2022). The same data are presented in Figure 6 but only for 2080 for clarity. Figure 7 presents the total breakdown of land use types in England for each RCP-SSP scenario and timestep, for both all of England and for aquifer outcrop areas only. Figure 8 shows the breakdown of modelled land use changes across different aquifer outcrops in England. Both the baseline land use and changes in land use vary across the different aquifer outcrop areas. Figure 9 shows the breakdown of modelled land use changes across different EA areas in England, for outcrop aquifers only. The same plot is presented in appendix B for both non-aquifer areas and outcrop aquifers.

SSP1 (and associated RCP2.6) represents a low emissions and sustainability scenario, with the UK becoming a low carbon, circular economy with a high capacity to adapt to climate change. In this scenario novel sustainable agriculture is developed with high societal support, and there is a low demand for meat products. This results in reduced livestock production, and a decreased area of intensive arable and pasture, and increases in extensive arable and forested areas (see Figure 7). In 2080, much of eastern England is extensive arable (Figure 6). In SSP1 there are increases in forest land cover on the Devonian/carboniferous (present in Northern England only) and decreases in intensive pasture. Across the other aquifers, the predominant feature of SSP1 is the reduction in intensive arable land and replacement with extensive arable land (Figure 8). This is present across all EA areas (Figure 9) except for Cumbria and Lancashire where intensive arable land area increases (albeit from a very low initial proportion of total land use).

SSP2 (and associated RCP4.5 and RCP8.5, note that both RCPs were tested using one SSP in the SPEED project, and limited differences in the choice of climate scenario were found (Brown et al., 2022)) represents a "middle of the road" scenario in which socioeconomic futures are the most similar to the present day. Society is highly regulated and reliant on fossil fuels, with moderate economic growth and persistent inequality. There are with moderate adaptation and mitigation challenges. In this scenario forms of agriculture are largely the same as today (albeit with some intensification), but with a reduced demand for livestock products, and there is an increased demand for timber and forest-based carbon sequestration. This results in large increases in forested areas, reduced areas of intensive pasture and intensive arable land (see Figure 6 and Figure 7). These increases in forest area are on the outcrops of the Devonian/carboniferous, Chalk and Jurassic aquifers (Figure 8), associated with a reduction in intensive arable (on the Chalk) and pasture (on the Devonian/Carboniferous and Jurassic) land areas. On the magnesian limestone and the Permo-Trias there is a small change from pasture to a mix of extensive arable and forest. In contrast to SSP1, there is divergence across the EA areas in the magnitude of changes in land use (Figure 9). Small changes in land use in this SSP are present in Eastern areas when land uses associated with food production remained dominant (Cambs and Beds, Essex Norfolk Suffolk, Lincs and Northants) and EA areas dominated by urban land use (Gtr Mancs, Mersey and Ches). Large changes occurred in all other EA areas, most notably in a groundwater context within EA areas where the Chalk outcrop is a large component (Herts and North London, Kent and South London, Solent and South Downs, West Thames, Wessex). There is very little difference in the breakdown of land use types by EA areas when SSP2 is applied using the two different climate scenarios (RCP4.5 and RCP8.5)

SSP3 (and associated RCP6.0) is a dystopian scenario where the UK breaks apart due to regional tensions and barriers. Regional rivalry results in an entrenched reliance on fossil fuels and limited capacity to adapt to climate change. This resulted in large extensification of agriculture, and a large initial change from intensive pastoral to extensive arable land. Food production dominated land uses. In SSP3 in all aquifers apart there is an initial change from

2020-2030 in intensive arable and pastoral land coverage to more extensive agriculture and forest (Figure 7). From 2030-2080 there is a general increase in agricultural extent (intensive pasture on the Chalk, intensive arable on the Magnesian, both on the Jurassic and Permo-Trias, Figure 8). Like SSP2, the changes in land use are smallest in Eastern areas (Cambs and Beds, Essex Norfolk Suffolk, Lincs and Northants, Figure 9) where existing agricultural land uses remain dominant. There is interesting local variability in southern England (see Figure 9), with Wessex and Solent and South Downs having large proportions of intensive pastureland to 2080, in contrast to nearby EA areas (West Thames, Kent and South London) which show a more balanced land use breakdown. This also clear in Figure 6 (bottom right plot, note the spatial variation in green vs. light red).

SSP4 (and associated RCP4.5) is a scenario where society is dominated by inequality, with large income differences across UK society leading to limited adaptive capacity of much of the UK population. This scenario results in large scale agricultural development but low demand for livestock products. Modelled land use futures show large homogeneous agricultural areas forming, with a decline in pasture and an overall increase in the area and the intensity of arable farming. In SSP4 there is a large increase in intensive arable land area over the Devonian/carboniferous aquifers of Northern England at the expense of pasture (Figure 8). Across the other aquifers the temporal trends in this SSP are all small and relatively similar; a small decrease in intensive arable land area to the 2050, before increasing again to 2080. This relatively limited variability across the aquifers reflects the development of large homogeneous agricultural areas forming in this scenario. Similar to SSP2 and SSP3, land use changes appear to be smallest in eastern areas (Cambs and Beds, Essex Norfolk Suffolk, Lincs and Northants, Figure 9). Across many areas a small trend of decreasing intensive pasture is evident, accompanied by decreases in intensive arable in 2050, then increases to 2080. Cumbria and Lancashire, Gtr Mancs Mersey and Ches and the West Midlands show increases in intensive arable areas.

SSP5 (and associated RCP8.5) is a scenario where the UK becomes a technologically advanced with a strong economy but with a heavy reliance on fossil fuels and a high capacity for climate change adaptation. In this scenario there is a large increase urban areas and intensive agriculture land becomes more productive. Whilst there is an initial increase in forested areas to 2050, more land is converted to food production towards the end of the century. In SSP5 a key feature is the increase in urban areas, which is present across all aquifers (Figure 8). This is at the expense of intensive arable and pastureland across the aquifers, although extensive arable land does appear to increase as well. The increase in forested area to c. 2050 then decrease to 2080 is also evident across all aquifers. Increases in urban area appear to be most significant in EA areas with a relatively high baseline urban land use (Gtr Mancs, Mersey Ches, West Midlands, Herts and North London, Kent and South London, Figure 9).

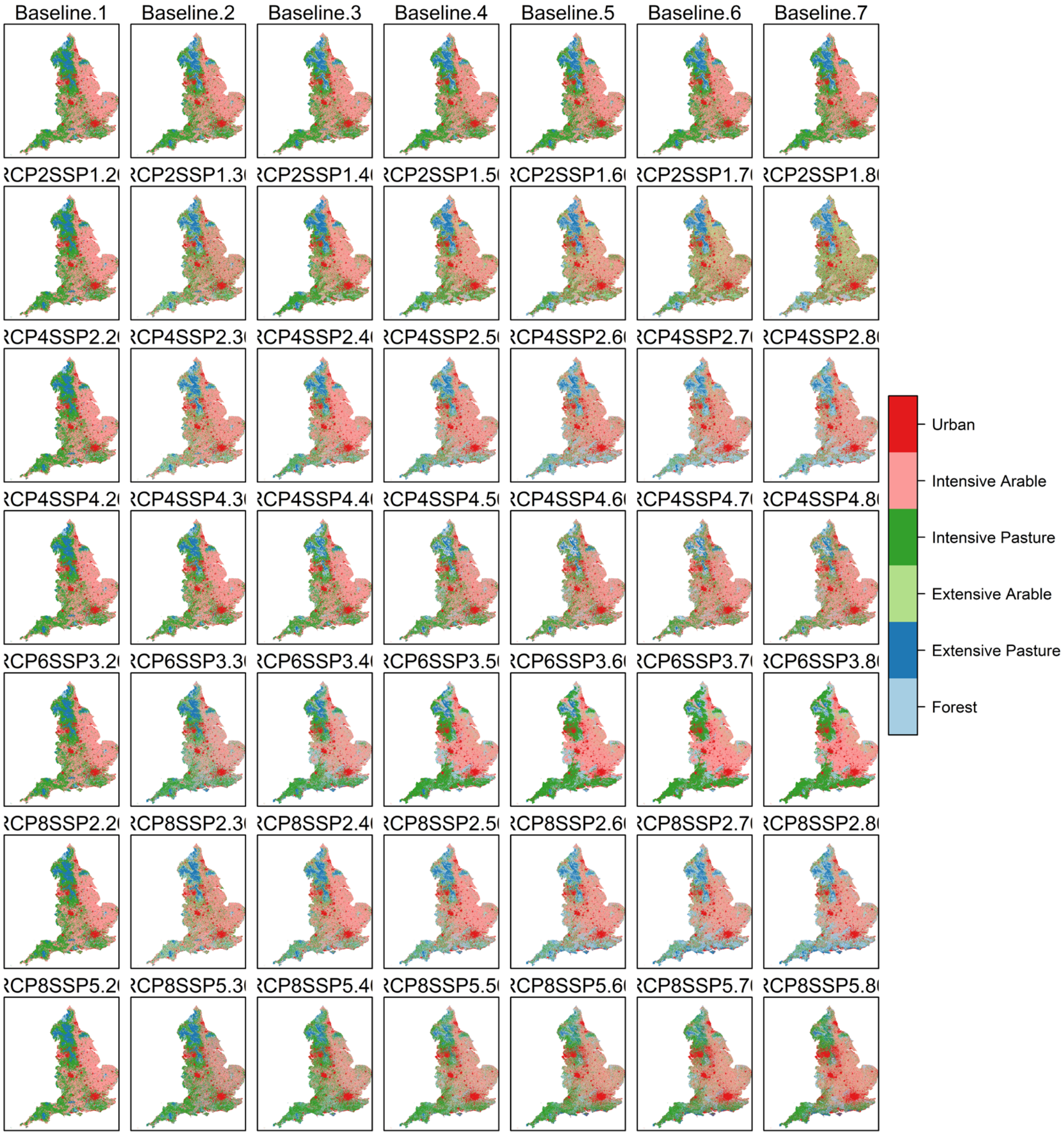

Figure 5 Modelled land use futures for England for each RCP-SSP combination (rows) for 10 year timesteps from 2020-2080 (columns), derived from Brown et al. (2022).

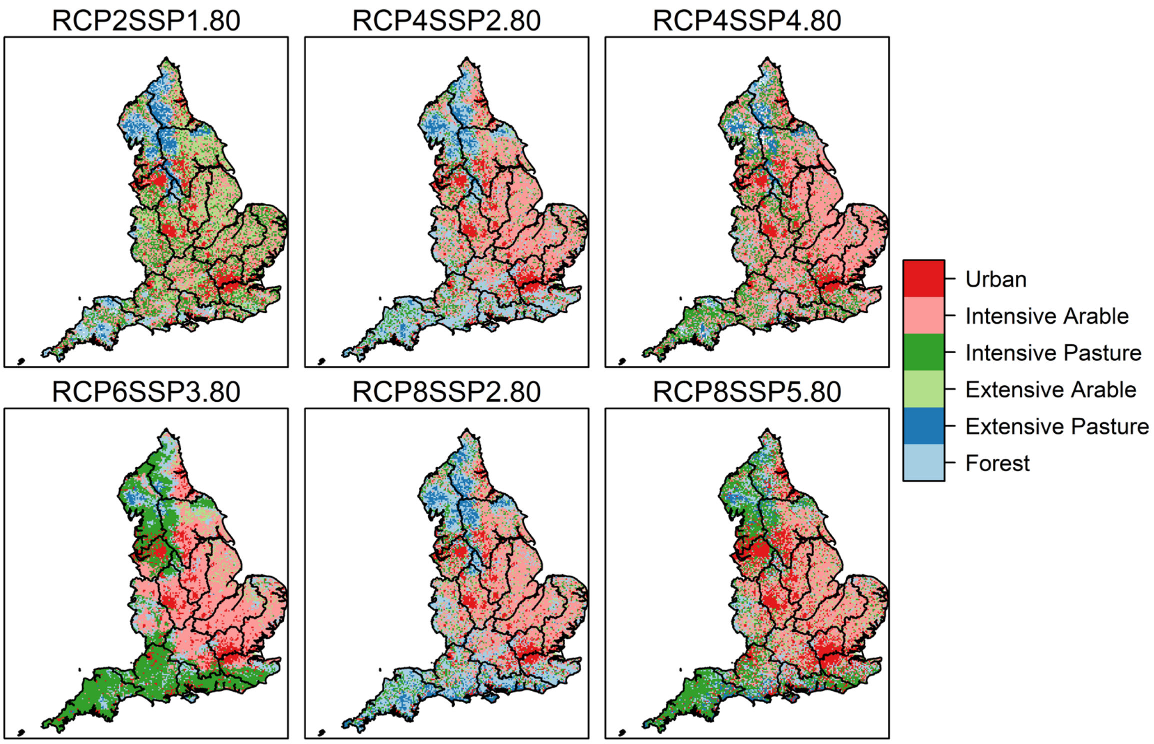

Figure 6 Modelled land use futures (Brown et al., 2022) for England for each RCP-SSP combination for 2080 and EA areas (black lines). EA areas © copyright Environment Agency and/or database right 2016. All rights reserved.

Figure 7 Fraction of modelled land use at the national scale under different RCP-SSP scenarios and timeslices for all of England (top) and outcrop aquifers only (bottom).

Figure 8 Fraction of modelled land use at the national scale under different RCP-SSP scenarios and time slices, split by aquifers.

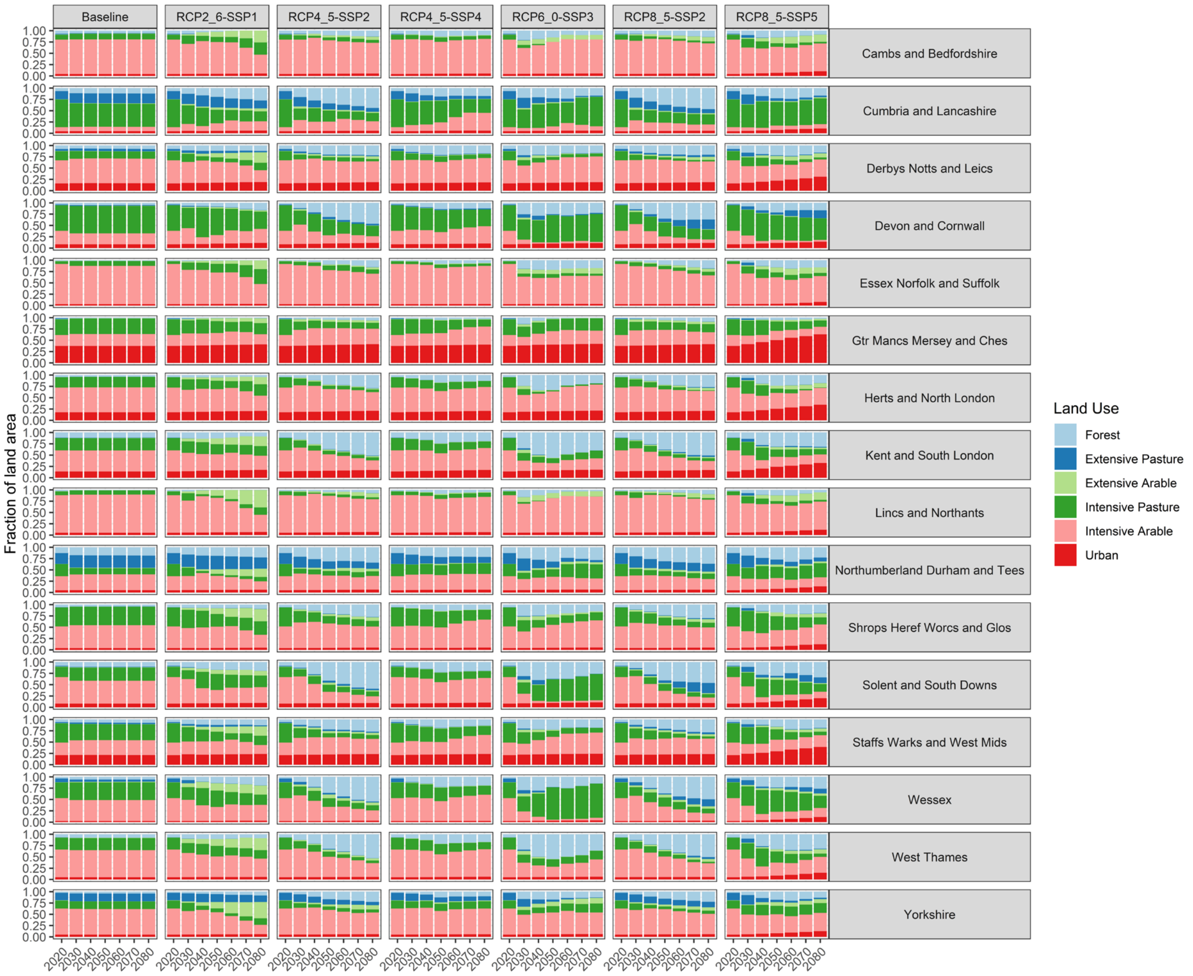

Figure 9 Fraction of modelled land use under different RCP-SSP scenarios and time slices for each EA area, on outcrop aquifer areas only.

5.2 NATIONAL FUTURES OF CONTAMINANT SOURCE TERM CHANGES

Figure 10 shows the estimated change in contaminant source term risk for agricultural-dominated contaminants (nitrate and pesticides) for England for each RCP-SSP combination and time slice. Figure 11 presents the same maps for urban-dominated contaminants (microbial contaminants, groundwater temperature, wastewater discharges). For clarity, Figure 12 and Figure 13 show the same data as Figure 10 and Figure 11 respectively but for the change between 2020 and 2080 only.

Figure 14 summarises these maps, showing the proportion of modelled land use that results in changes in agricultural and urban dominated contaminant risk under different RCP-SSP scenarios and time slices, for all of England and only on outcrop aquifers. Figure 15 shows the same as Figure 14 for agricultural-dominated contaminants but divided by aquifers. Figure 16 and Figure 17 show the same as Figure 14 for agricultural and urban-dominated contaminants respectively but divided by EA areas for outcrop aquifers only. The same plots for EA areas covering both aquifer outcrops and non-aquifers are shown in Appendix B (Figure 28 and Figure 29).

In SSP1, there are large areas of Eastern and Northwest England where there are estimated to be decreases in the risk from agricultural contaminants (Figure 12). This is associated with land use changes from intensive to extensive and sustainable arable and pasture.

These trends are also evident across all aquifers (Figure 15) and EA areas (Figure 16). There are very small areas where there are large decreases in risk, principally conversion to forest land use on the Chalk southern England (notably in the Solent and South Downs and Wessex areas, Figure 16). Small increases in risk are present over parts of Southeast England, the west country, the west midlands and northeast England. The largest increases by aquifer are on the Permo-Trias (Figure 15), which is also evident from the increases in risk in the Gtr Mancs Mersey and Ches, West Midlands EA areas (Figure 16). Overall, at the national scale, there is a more of a decrease in risk than an increase, and large changes in risk (either increasing or decreasing) are very limited.

In SSP2, large increases in forested areas for timber and carbon sequestration resulted in decreases in risk from agricultural contaminants (Figure 12). These decreases in risk were large (dark blue in figures) when associated with loss of intensive arable land (principally in Southern England, and particularly on the Chalk within SSD, West Thames, Wessex, KSL (Figure 15, Figure 16)) and small (light blue) when associated with loss of pasture (southwest England (Devon and Cornwall), the northwest England (Cumbria and Lancashire)). Small increases in risk occurred in areas of the west midlands (on the Permo-Trias and in EA region Gtr Mancs Mersey and Ches (Figure 15, Figure 16)) associated with intensive arable land, and parts of Eastern England (Cambs and Bedfordshire, Lincs and Northants, Essex Norfolk Suffolk, Figure 16) showed little change in risk over time due to the relatively stable land use where food production remained dominant. When applying RCP8.5 and RCP4.5 to SSP2, the spatial distribution of risk changes is very similar. Overall, at the national scale there is more of a decrease in risk than an increase.

SSP3 shows the largest increase in risk nationally, but there are also substantially areas of decreasing risk and areas with no change (Figure 12). Similar to SSP2, there is limited change in risk in parts of Eastern England (Cambs and Bedfordshire, Lincs and Northants, Essex Norfolk Suffolk, Figure 16) associated with continuous use of land for food production. Increases in risk occur in the west midlands and northern England (on the Devonian/Carboniferous and Permo-Trias, and in EA regions Cumbria and Lancashire, Gtr Mancs Mersey and Ches, Northumberland, West Midlands (Figure 15, Figure 16)) associated with increased arable land coverage. Decreases in risk occur in southern England associated with land use changes to pasture from arable and some areas to forest (which results in large decreases in risk (dark blue, Figure 12)). These areas are principally on the Chalk of the Solent and South Downs, West Thames, Kent and South London and Wessex areas. The trajectories of risk change differ between aquifers. The proportion of land with a reduced risk decreases over time on the Jurassic and Magnesian limestones, but this is relatively stable across the other aquifers.

SSP4 shows the smallest overall change in risk at the national scale (Figure 14). This is associated with agricultural land use in eastern England (Cambs and Bedfordshire, Lincs and Northants, Essex Norfolk Suffolk, Figure 16) being largely constant over time associated with large scale farming and food production, as also noted in SSP2 and SSP3. However, nationally there are more areas of increasing risk than decreasing risk. Areas of increasing risk are in the northwest and west country (the Devonian/Carboniferous and Permo-Trias, particularly in Cumbria and Lancashire, Gtr Mancs Mersey and Ches, Shropshire, see Figure 15 and Figure 16) and small areas of southeast England. These areas are associated with increasing intensive arable land at the expense of pasture.

Across SSP1-SSP4, the change in urban pollutant risks at the national scale is very low. The only notable changes are for SSP5 (Figure 11, Figure 13). In SSP5 there are both increases and decreases in agricultural contaminant risk, and some increases in urban contaminant risk. Overall, increases in agricultural risk are present the west midlands, the north west and central England (often on Devonian/Carboniferous aquifers) associated with arable intensification (see Figure 15 and Figure 16). Increases in urban risk are greatest in EA areas around existing cities (Gtr Mancs, Mersey and Ches, West Midlands, Herts and North London, Kent and South London, Figure 16). Decreases in agricultural risk are associated with increasing forest cover, principally in southern and Eastern England (including large decreases on the Chalk in Kent and South London, Solent and South Downs, West Thames and Wessex).

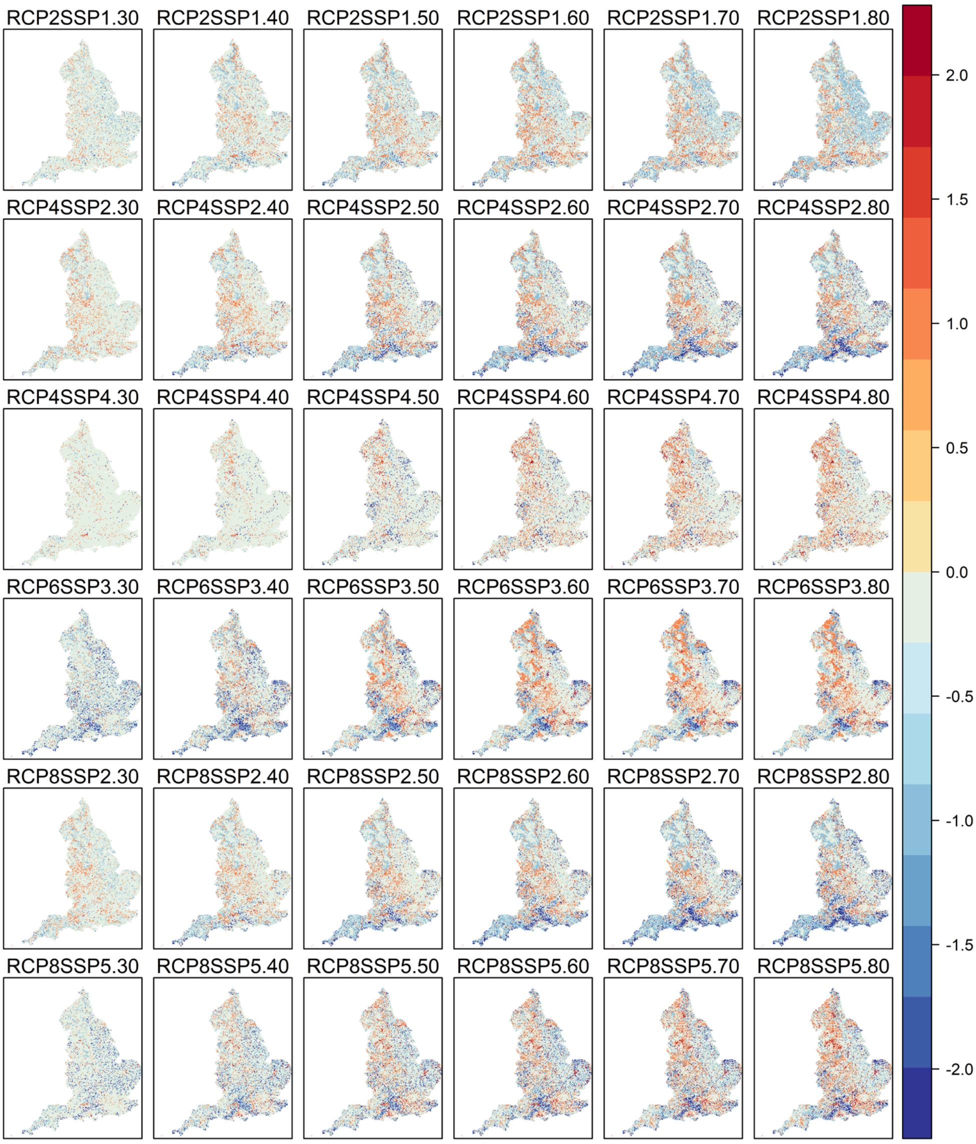

Figure 10 Estimated change in source term risk (red increasing, blue decreasing) for agricultural-dominated contaminants (nitrate and pesticides) for England for each RCP-SSP combination (rows) for 10-year timesteps from 2020-2080 (columns). Red.

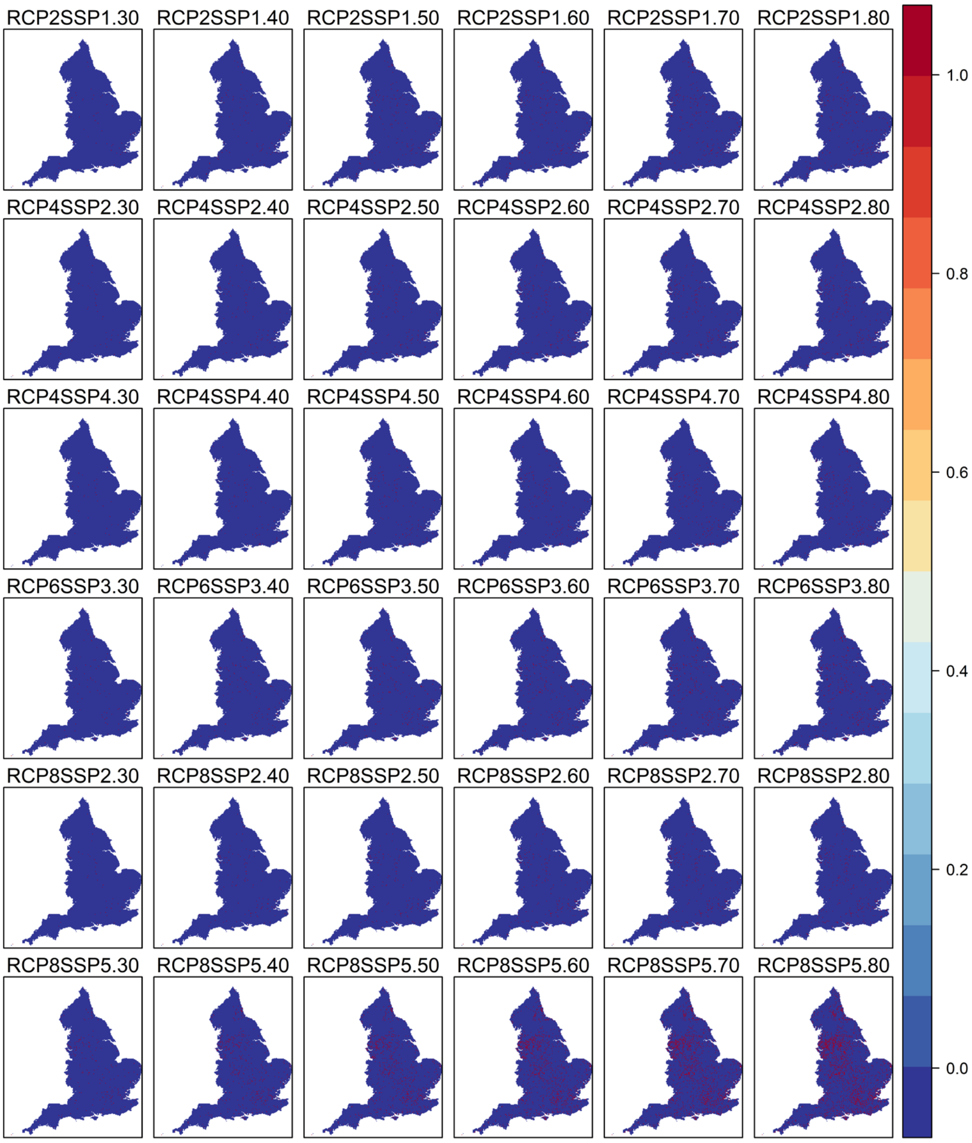

Figure 11 Estimated change in source term risk (red increasing, blue no change) for urban-dominated contaminants (microbial contaminants, groundwater temperature, wastewater discharges) for England for each RCP-SSP combination (rows) for 10-year timesteps from 2020-2080 (columns).

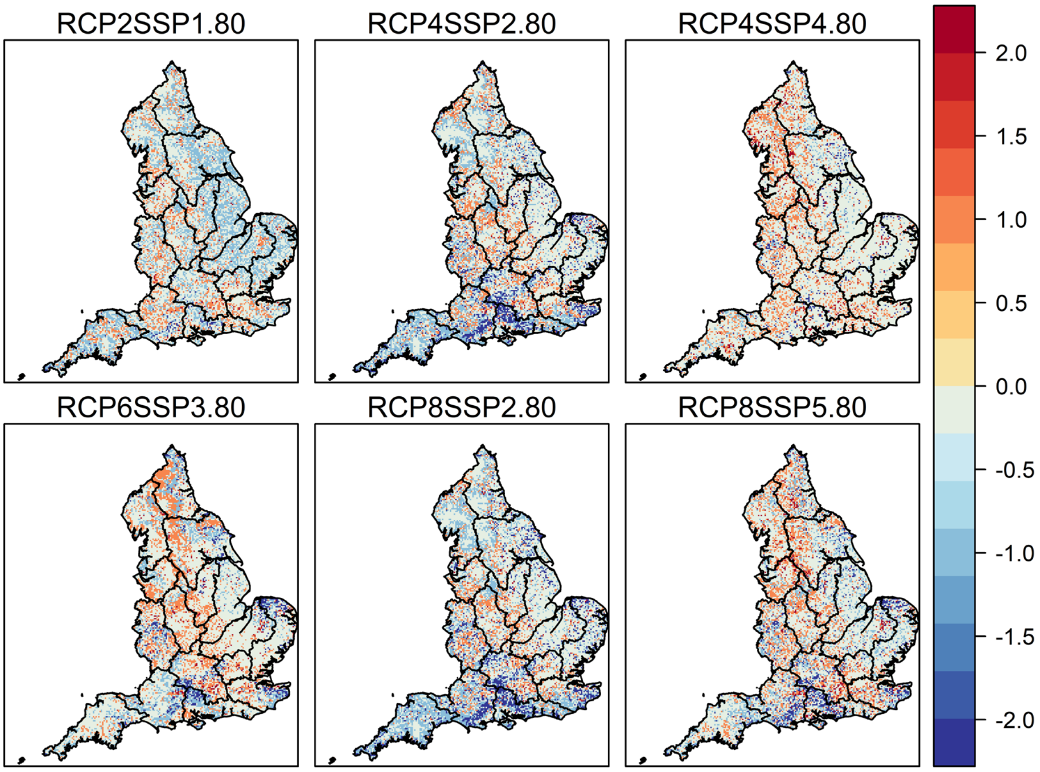

Figure 12 Estimated change in source term risk (red increasing, blue decreasing) for agricultural-dominated contaminants (nitrate and pesticides) for England for each RCP-SSP combination between the 2020 baseline and 2080 and EA areas (black lines). EA areas © copyright Environment Agency and/or database right 2016. All rights reserved.

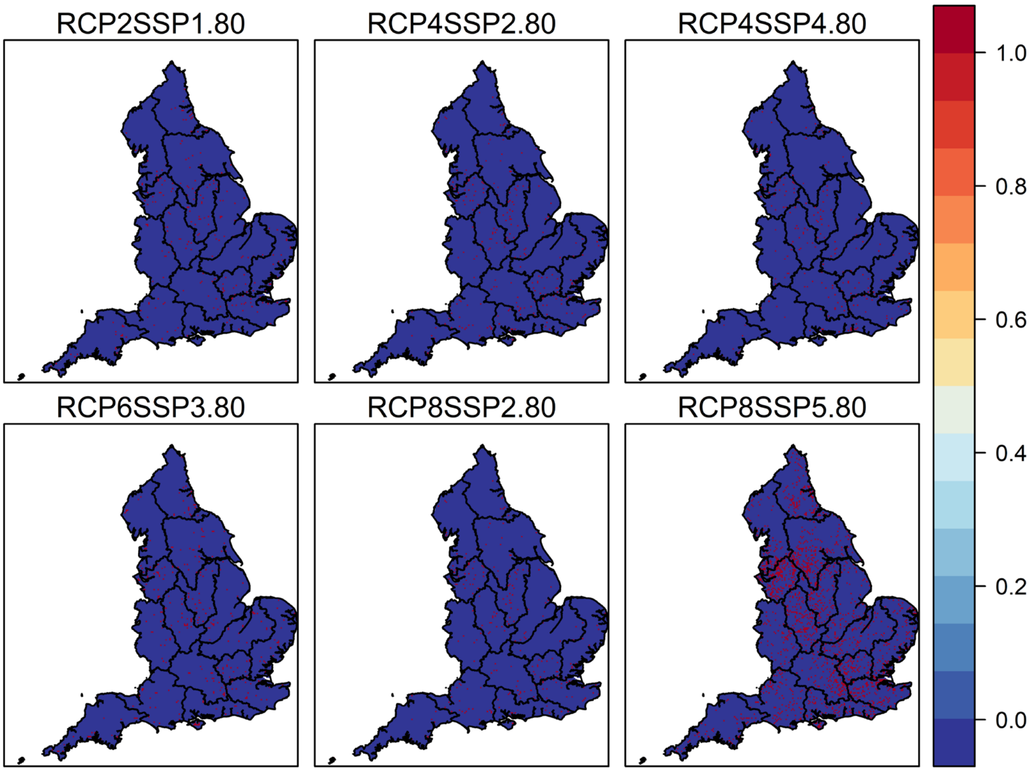

Figure 13 Estimated change in source term risk (red increasing, blue no change) for urban-dominated contaminants (microbial contaminants, groundwater temperature, wastewater discharges) for England for each RCP-SSP combination between the 2020 baseline and 2080 and EA areas (black lines). EA areas © copyright Environment Agency and/or database right 2016. All rights reserved.

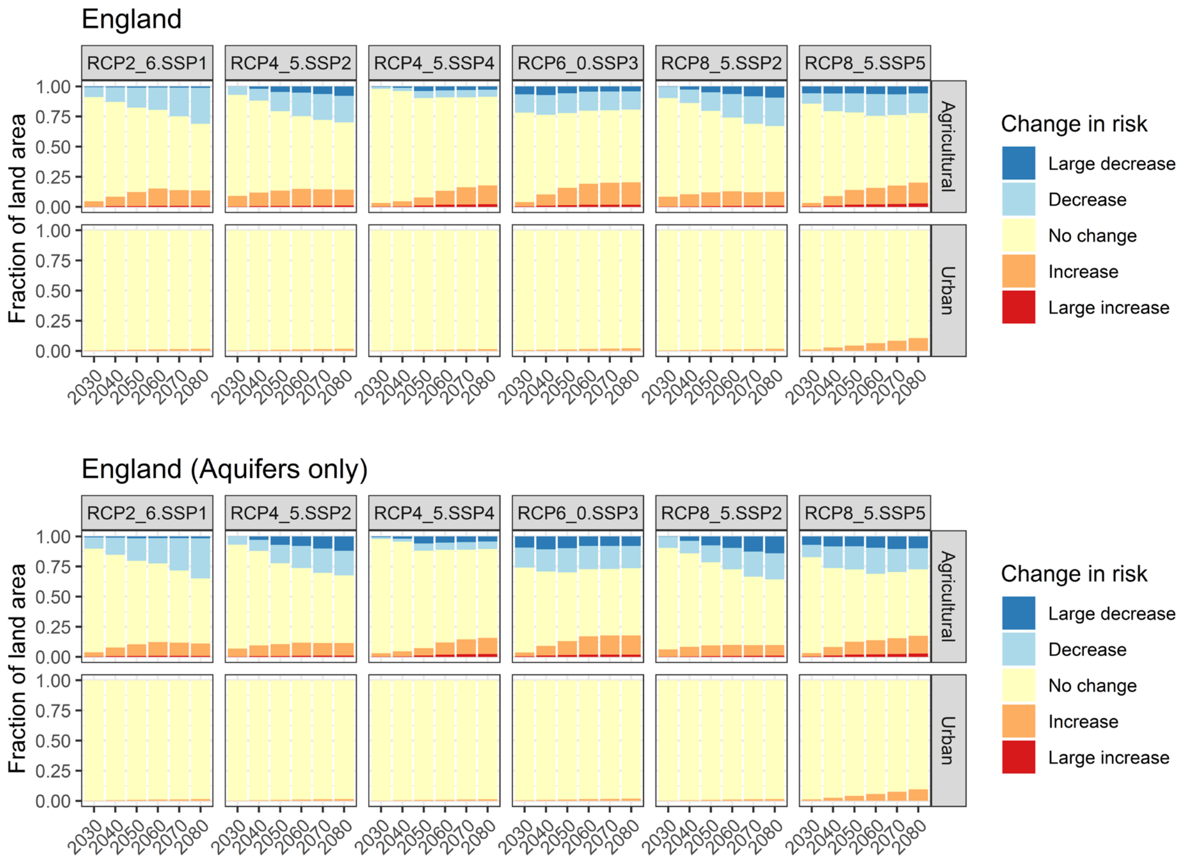

Figure 14 Fraction of modelled land use that results in changes in contaminant risk at the national scale under different RCP-SSP scenarios and time slices for all of England (top two rows) and outcrop aquifers only (bottom two rows), divided between agricultural and urban dominated contaminants.

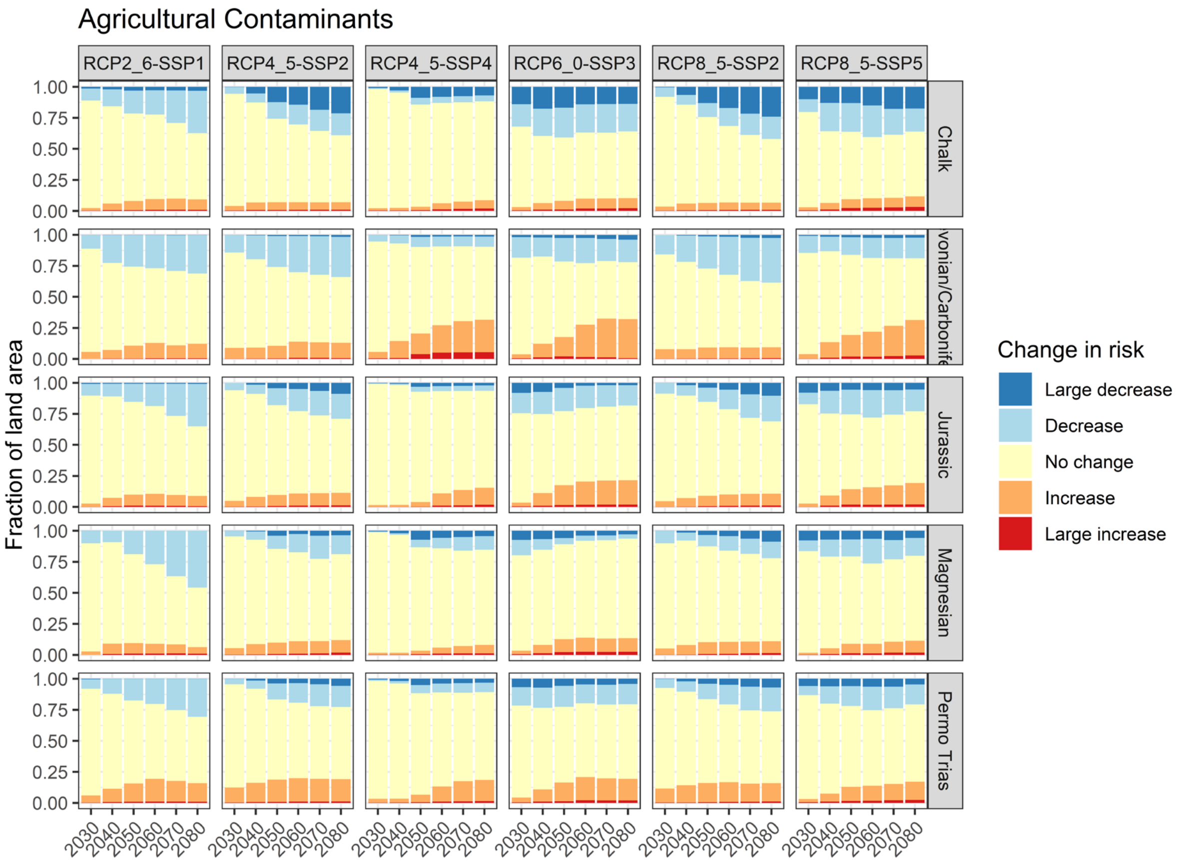

Figure 15 Fraction of modelled land use that results in changes in agricultural dominated contaminant risk at the national scale under different RCP-SSP scenarios and time slices divided by aquifers.

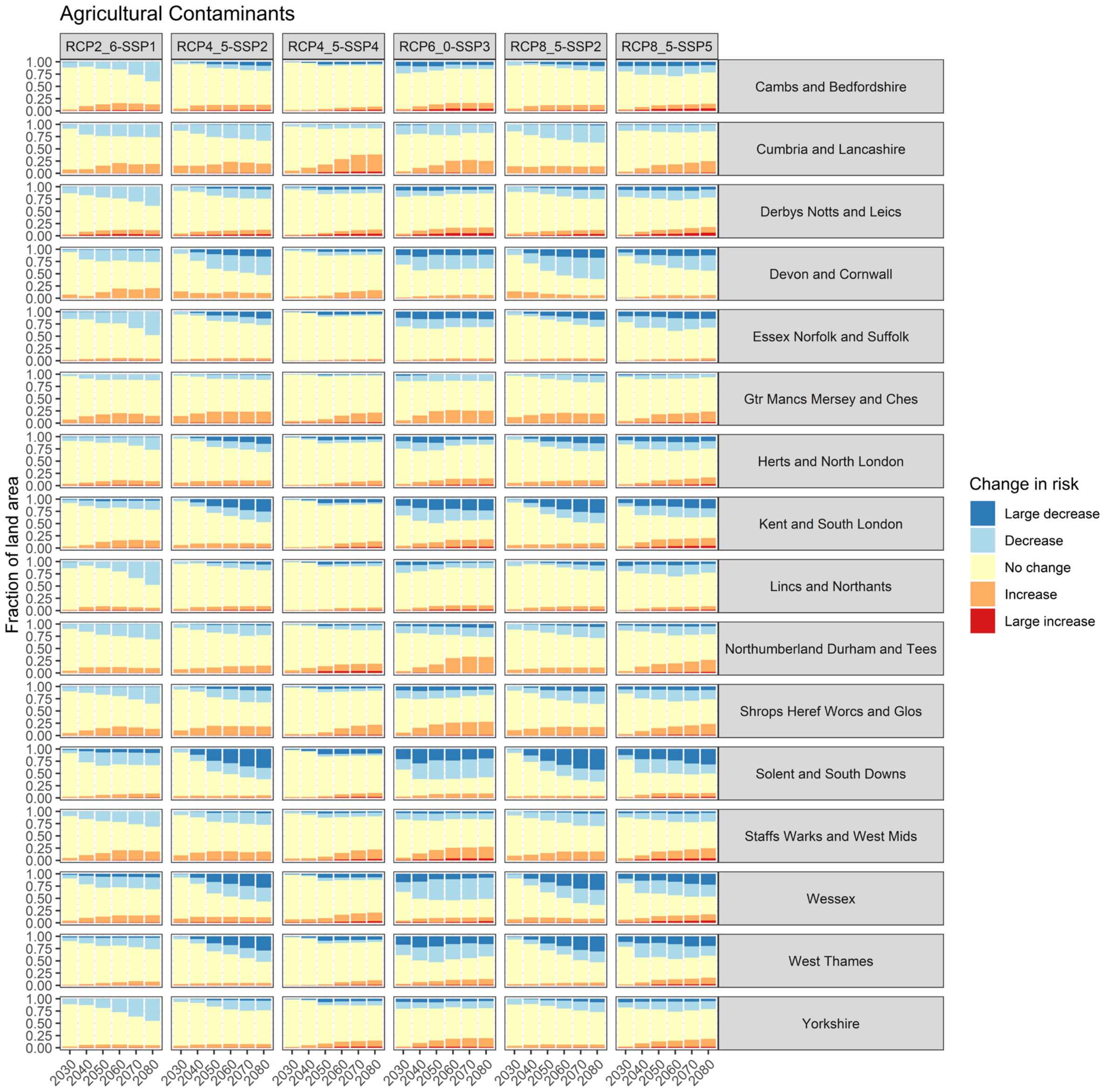

Figure 16 Fraction of modelled land use that results in changes in agricultural dominated contaminant risk at the national scale under different RCP-SSP scenarios and time slices divided by EA areas for outcrop aquifers only.

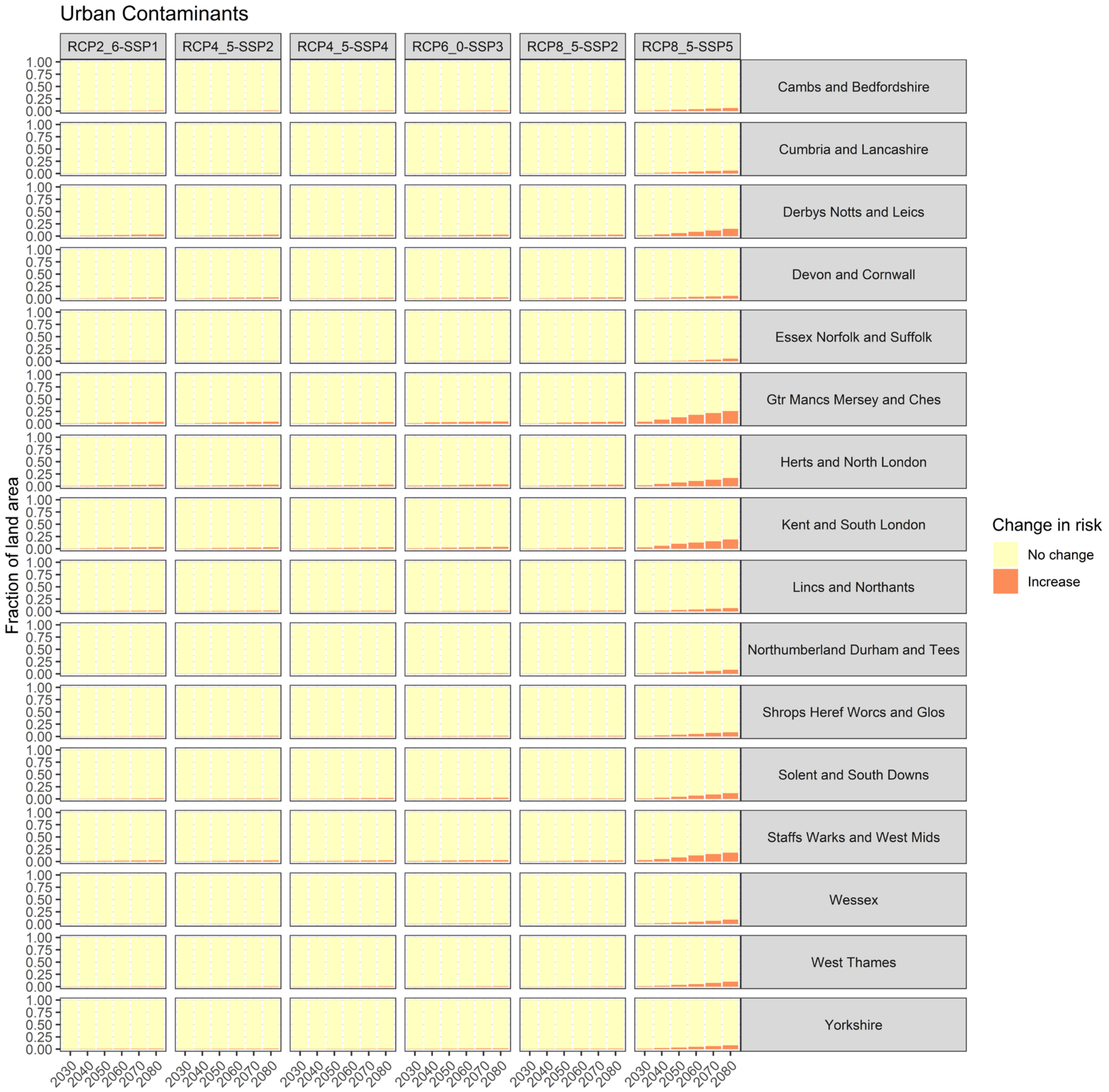

Figure 17 Fraction of modelled land use that results in changes in urban dominated contaminant risk at the national scale under different RCP-SSP scenarios and time slices divided by EA areas for outcrop aquifers only.

5.3 CHANGES IN PRECIPITATION AND TEMPERATURE FROM CHESS-SCAPE

Figure 18 shows seasonal mean precipitation (mm/day) from the CHESS-SCAPE data for the RCP8.5 2070 (2060-2080) time slice. This shows seasonal mean precipitation rates ranging from a minimum of 0.74 mm/day in the summer for Devon and Cornwall to a maximum of 19.42 mm/day in the winter for Cumbria and Lancashire.

Figure 19 shows the percentage change in seasonal mean precipitation for the RCP8.5 2070 time slice from the seasonal mean precipitation for the RCP8.5 2030 time slice. These plots show that the greatest winter change across the time period for RCP8.5 is in the Cumbria and Lancashire area and on in coastal southern England. There is also a north-south split in changes in summer precipitation, with the greatest decreases in summer precipitation occurring in southern England.

Figure 20 shows seasonal extreme precipitation (mm/day) from the CHESS-SCAPE data for the RCP8.5 2070 (2060-2080) time slice. These plots show seasonal extreme precipitation rates ranging from a minimum of 3.25 mm/day in the summer for Devon and Cornwall to a maximum of 40.74 mm/day in the winter for Cumbria and Lancashire. Figure 21 shows the percentage change in seasonal extreme precipitation for the RCP8.5 2070 time slice from the seasonal extreme precipitation for the RCP8.5 2030 time slice. These plots show that in winter there is a general increase in 95th percentile winter rainfall across England. This is spatially heterogeneous, with the largest increases in northwest England, the south coast and the smallest in western and northeast England. There is a decrease in the 95th percentile rainfall in summer. As previously noted by Ascott et al. (2022) this contradicts the results of convection permitting climate model runs, which are likely to be more reliable in generating predictions of extreme summer precipitation.

Figure 22 shows seasonal mean temperature (Degree Celsius) from the CHESS-SCAPE data for the RCP8.5 2070 (2060-2080) time slice. These plots show seasonal mean temperature ranging from a minimum of 1.82 Degree Celsius in the winter for Cumbria and Lancashire to a maximum of 22.98 Degree Celsius in the summer for Hertfordshire and North London. Figure 23 shows the absolute change in seasonal mean temperature for the RCP8.5 2070 time slice from the seasonal mean temperature for the RCP8.5 2030 time slice. These plots show a general trend of warming across all seasons with an increase in seasonal mean temperature ranging from 1.16 Degree Celsius to 3.05 Degree Celsius. The greatest degree of change across the time period for RCP8.5 is in the Solent and South Downs and West Thames areas, which would see a potential increase in summer mean temperatures of just over 3 Degree Celsius.

Figure 24 shows the seasonal number of wet days (>1mm) from the CHESS-SCAPE data for the RCP8.5 2070 (2060-2080) time slice. These plots show the seasonal number of wet days ranging from a minimum of around 17 days in summer (JJA) for the Devon and Cornwall area and a maximum of around 88 days in winter(DJF) for the Cumbria and Lancashire area and the Northumberland Durham and Tees area. Figure 25 show the absolute difference in seasonal number of wet days across the time period of data processed (2020-2080). These plots show a general trend of a decrease in the number of wet days across all seasons, with the greatest decreases in summer and autumn. The greatest degree of change across the time period in summer for RCP8.5 is in the Devon and Cornwall area, which would see a potential decrease in the number of wet days in summer of up to 17 days.

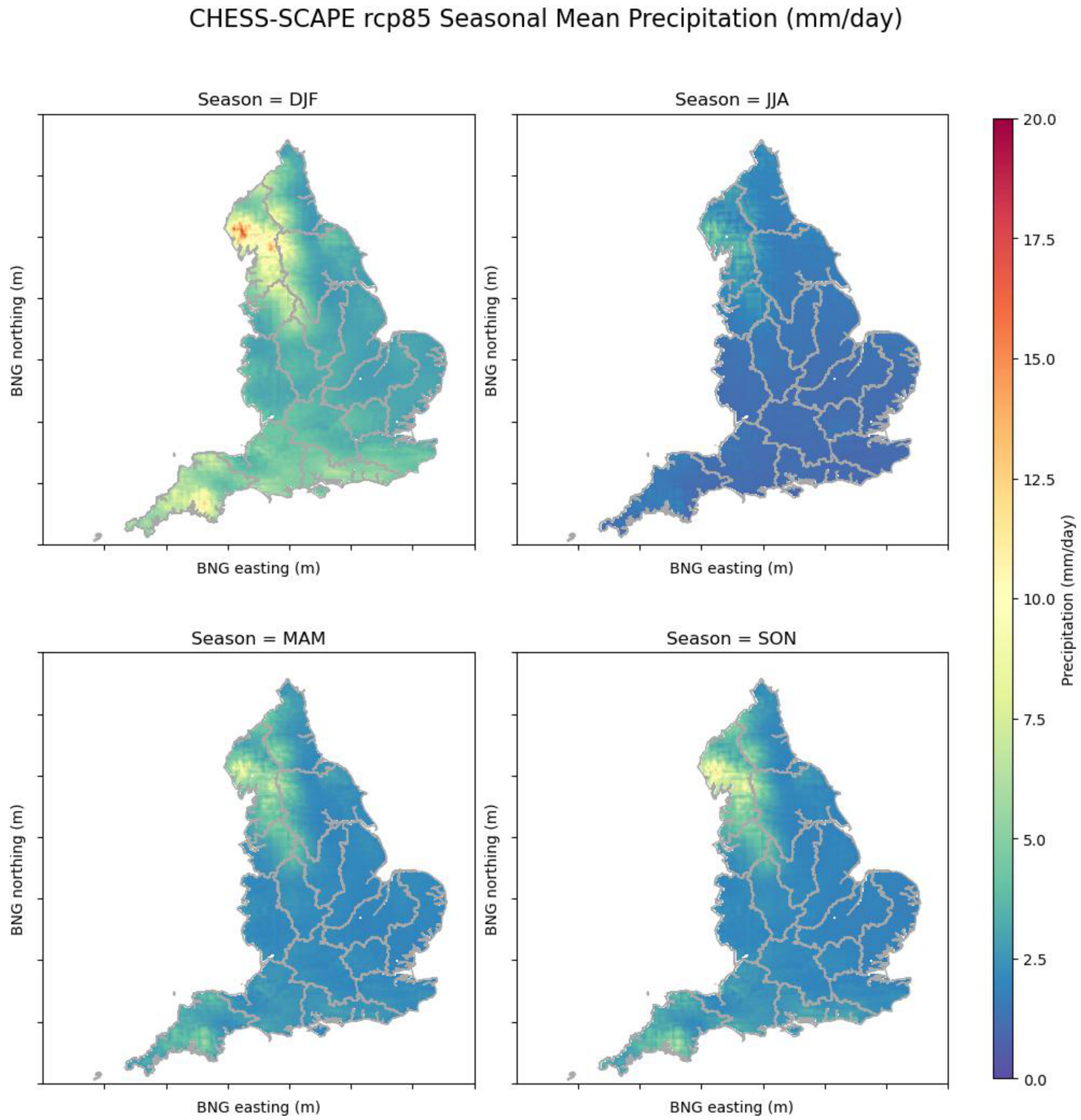

Figure 18 Seasonal mean precipitation (mm/day) for England for the RCP8.5 2070 time slice derived from CHESS-SCAPE (Robinson et al., 2022), showing the EA areas (grey lines). EA areas © copyright Environment Agency and/or database right 2016. All rights reserved.

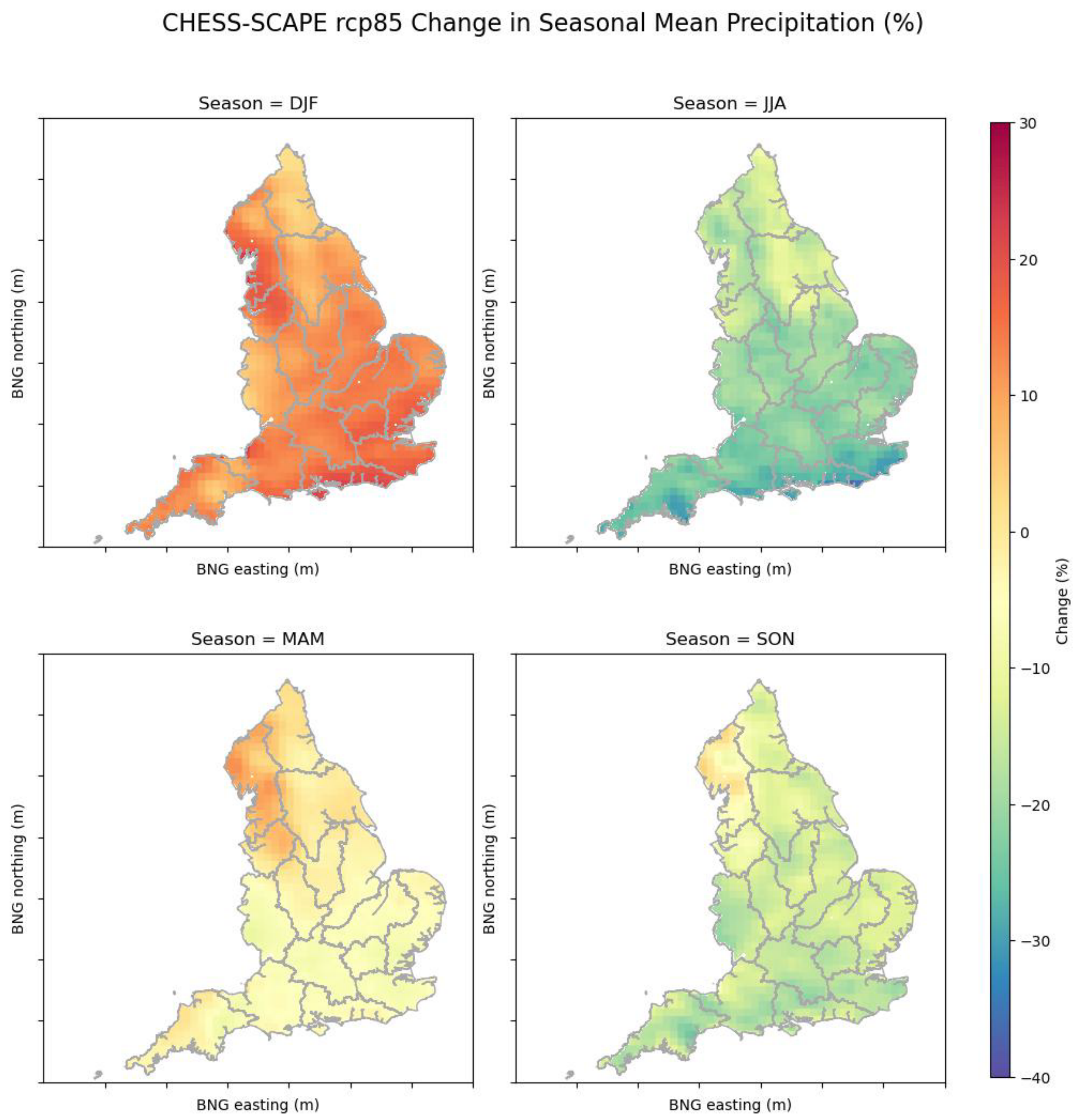

Figure 19 Percentage change in seasonal mean precipitation (mm/day) for England between the RCP8.5 2030 time slice and the RCP8.5 2070 time slice derived from CHESS-SCAPE (Robinson et al., 2022), showing the EA areas (grey lines). EA areas © copyright Environment Agency and/or database right 2016. All rights reserved.

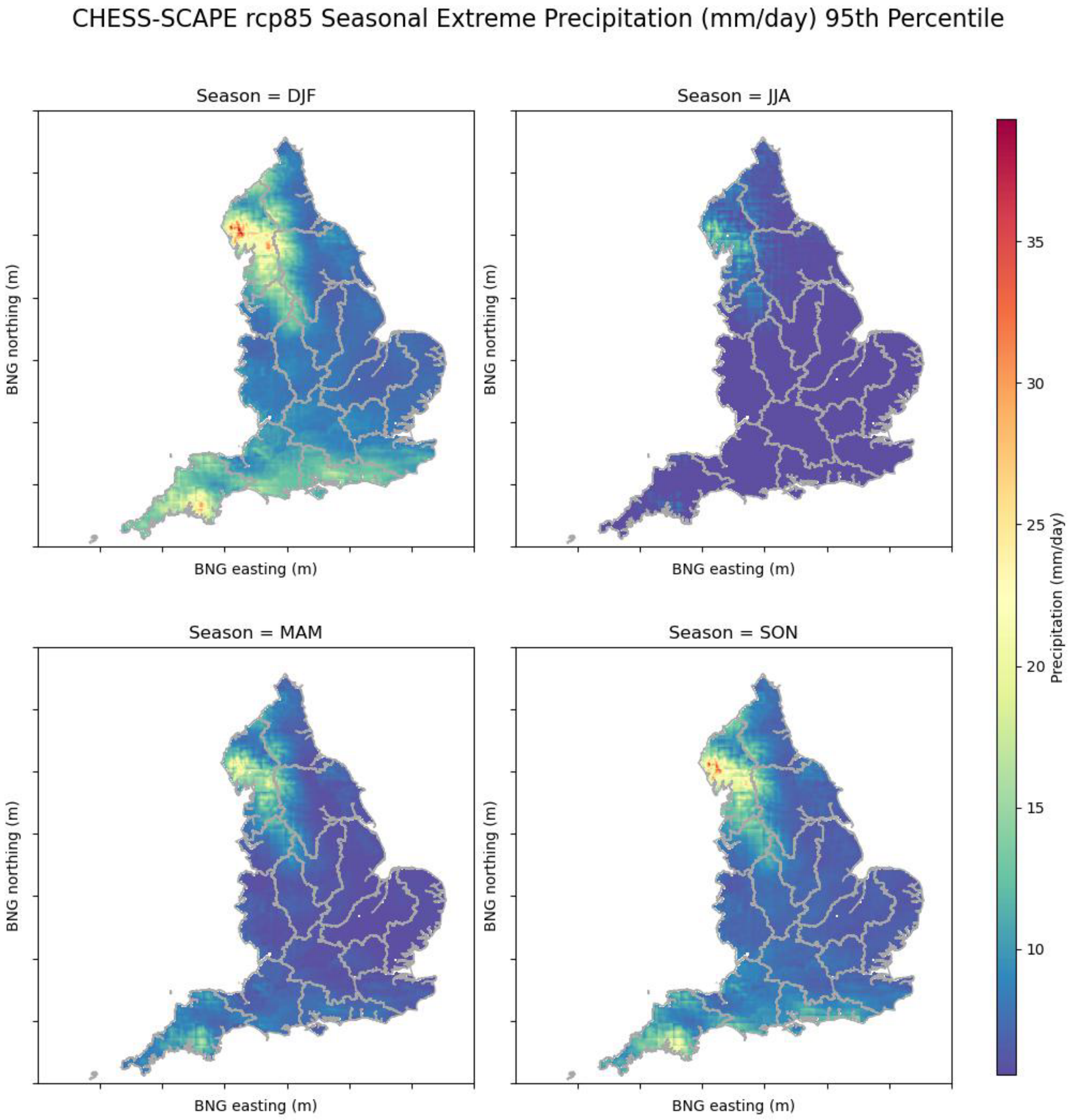

Figure 20 Seasonal extreme (95th percentile) precipitation (mm/day) for England for the RCP8.5 2070 time slice derived from CHESS-SCAPE (Robinson et al., 2022), showing the EA areas (grey lines). EA areas © copyright Environment Agency and/or database right 2016. All rights reserved.

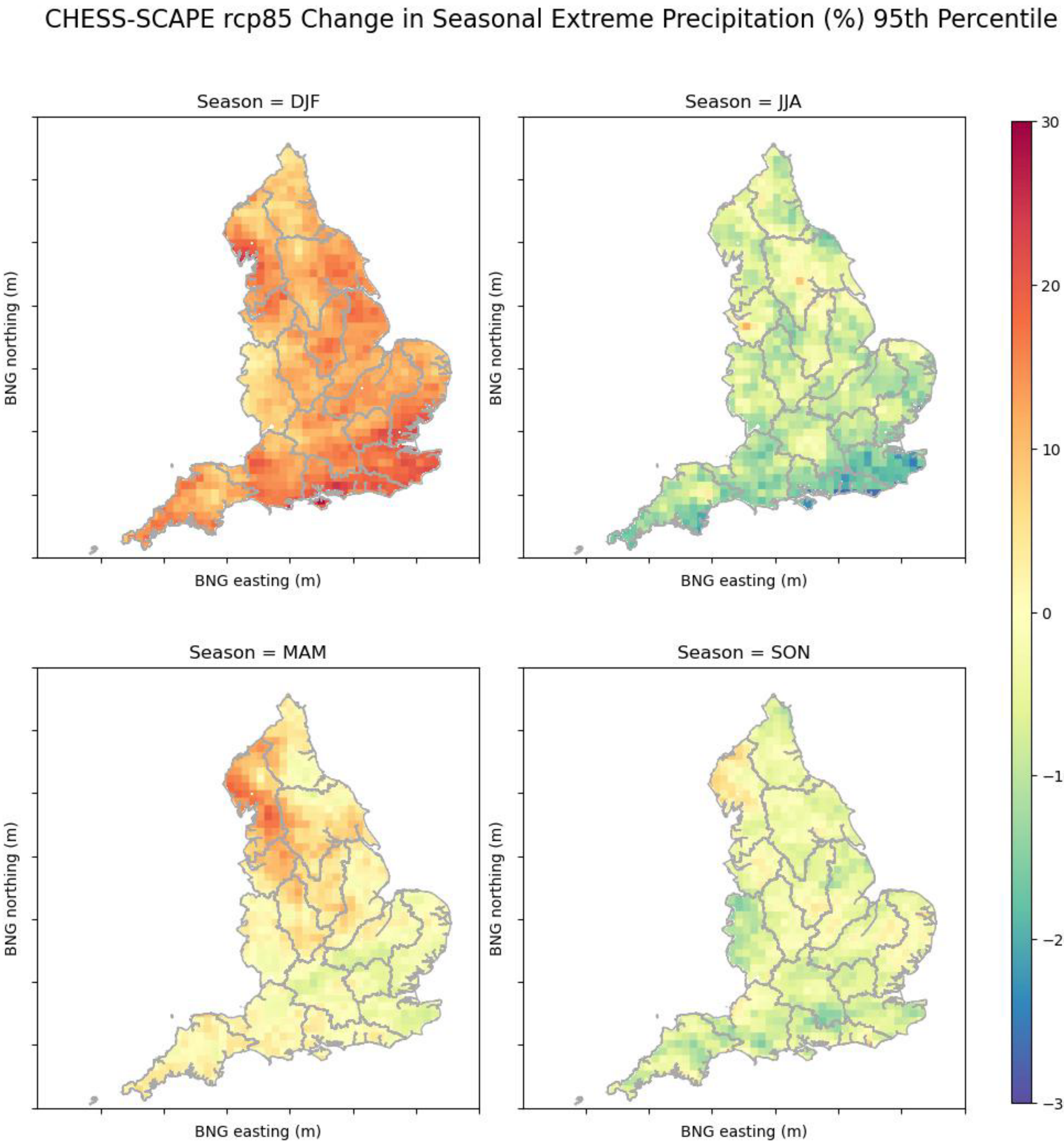

Figure 21 Percentage change in seasonal extreme (95th percentile) precipitation (mm/day) for England between the RCP8.5 2030 time slice and the RCP8.5 2070 time slice derived from CHESS-SCAPE (Robinson et al., 2022), showing the EA areas (grey lines). EA areas © copyright Environment Agency and/or database right 2016. All rights reserved.

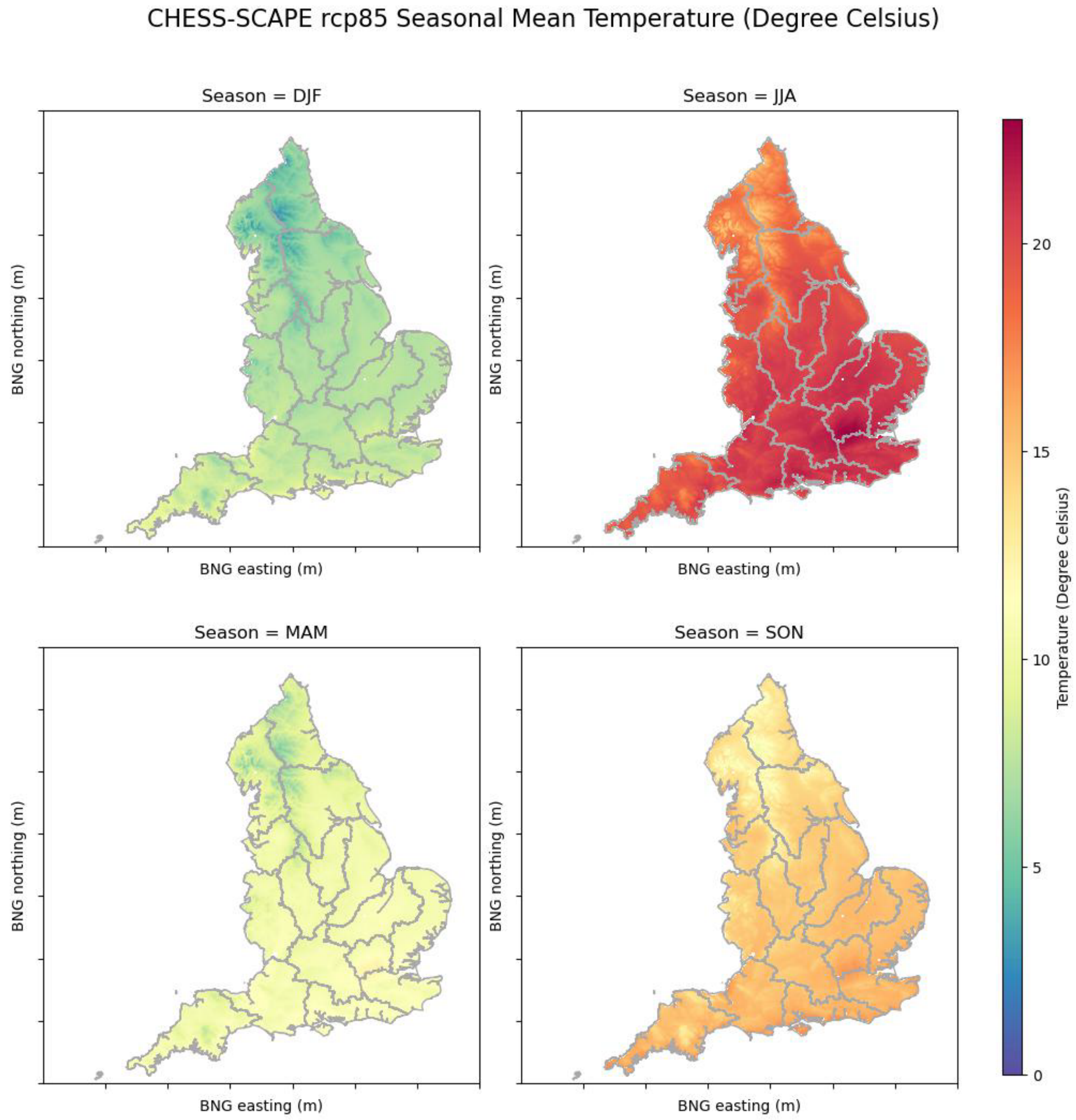

Figure 22 Seasonal mean temperature (Degrees Celsius) for England for the RCP8.5 2070 time slice derived from CHESS-SCAPE (Robinson et al., 2022), showing the EA areas (grey lines). EA areas © copyright Environment Agency and/or database right 2016. All rights reserved.

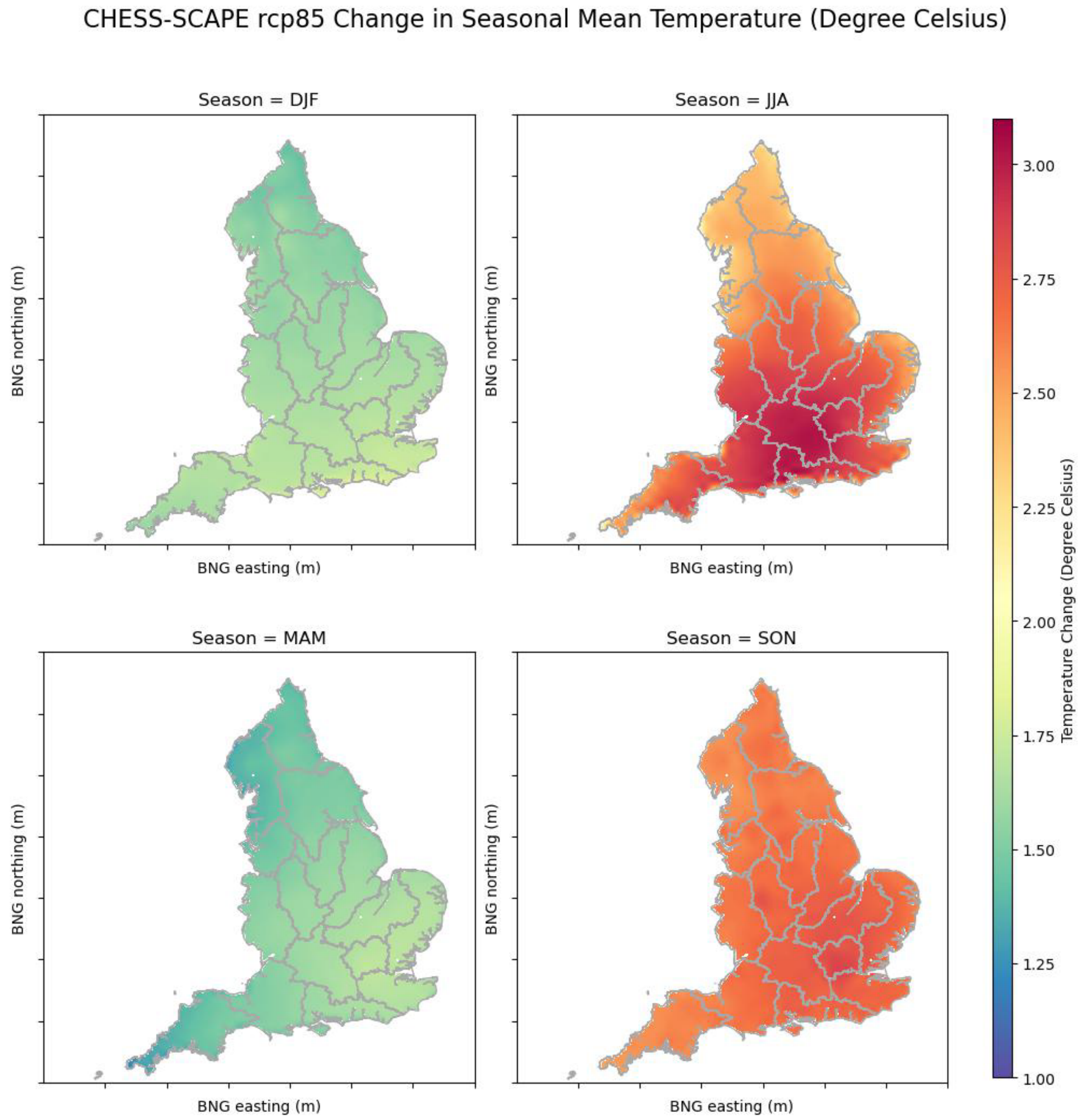

Figure 23 Absolute change in seasonal mean temperature (Degrees Celsius) for England between the RCP8.5 2030 time slice and the RCP8.5 2070 time slice derived from CHESS-SCAPE (Robinson et al., 2022), showing the EA areas (grey lines). EA areas © copyright Environment Agency and/or database right 2016. All rights reserved.

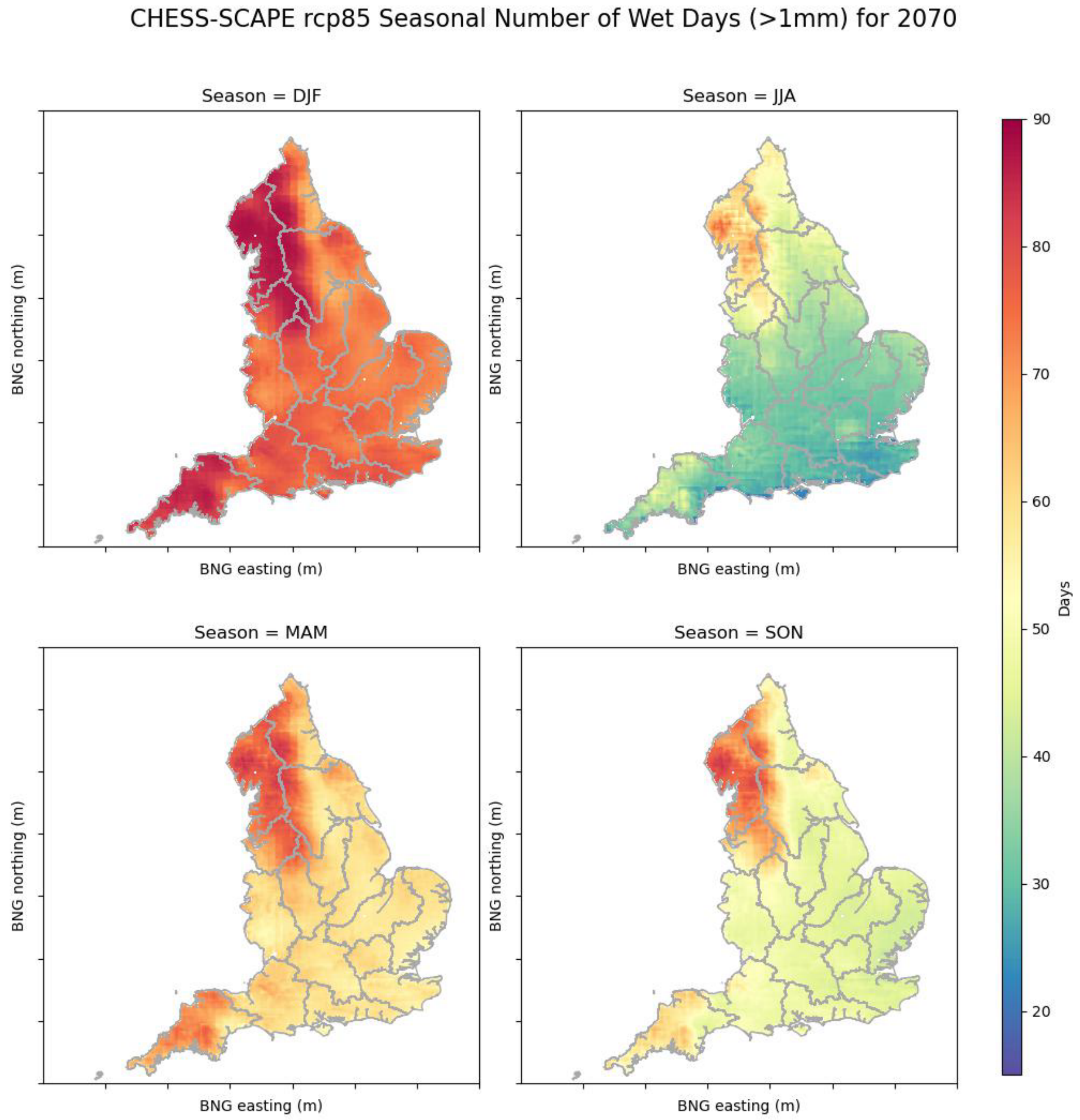

Figure 24 Seasonal number of wet days for England for the RCP8.5 2070 time slice derived from CHESS-SCAPE (Robinson et al., 2022), showing the EA areas (grey lines). EA areas © copyright Environment Agency and/or database right 2016. All rights reserved.

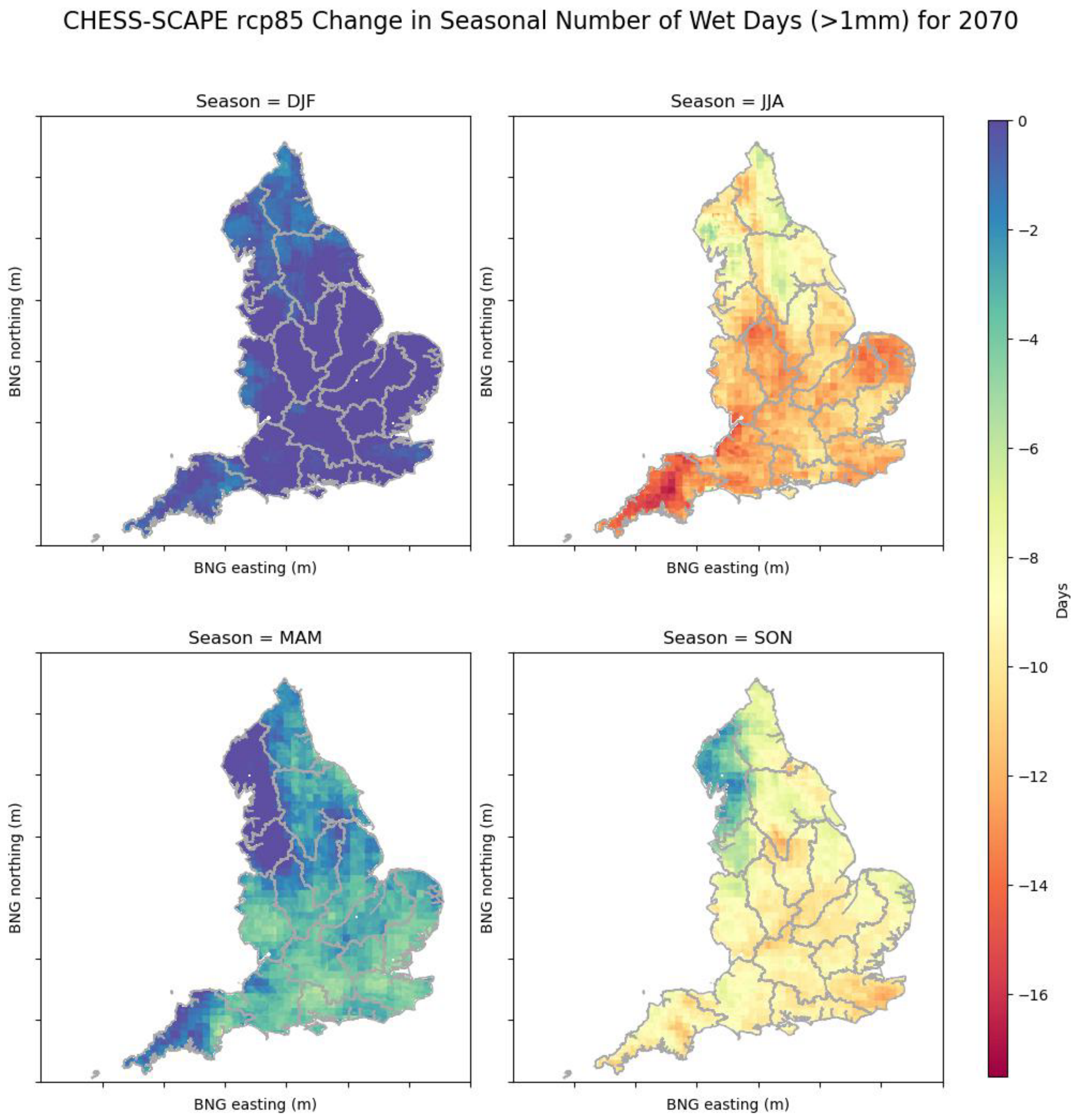

Figure 25 Change in the seasonal number of wet days for England between the RCP8.5 2030 time slice and the RCP8.5 2070 time slice derived from CHESS-SCAPE (Robinson et al., 2022), showing the EA areas (grey lines). EA areas © copyright Environment Agency and/or database right 2016. All rights reserved.

Figure 26 summarises the changes in the precipitation and temperature metrics presented in this report by EA area. In terms of mean precipitation, the CHESS-SCAPE data predicts wetter winters across all EA areas in 2070. The largest increases are in southern EA areas such as Solent and South Downs and the smallest are in western England (Shropshire). Based on mean precipitation the CHESS-SCAPE data shows drier summers across all EA areas. The largest decreases are in the South (Solent and South Downs, Kent South London) and South West (Devon and Cornwall), and the smallest are in the north (Cumbria, Northumberland).

A similar pattern across EA areas is present for extreme (95th percentile) precipitation, albeit with greater spatial heterogeneity. The largest increases in winter extreme precipitation are in the Solent and South Downs, Kent South London and West Thames EA areas. In general, there is a very small change in the number of wet days over winter. The number of wet days decreases during summer, with larger decreases in southern England EA areas than those in northern England. There are relatively consistent increases in mean air temperature across EA areas. The largest increases are in summer and autumn. Spatially, the increases are greatest in southern and central England (Herts and North London, West Thames, Shropshire).

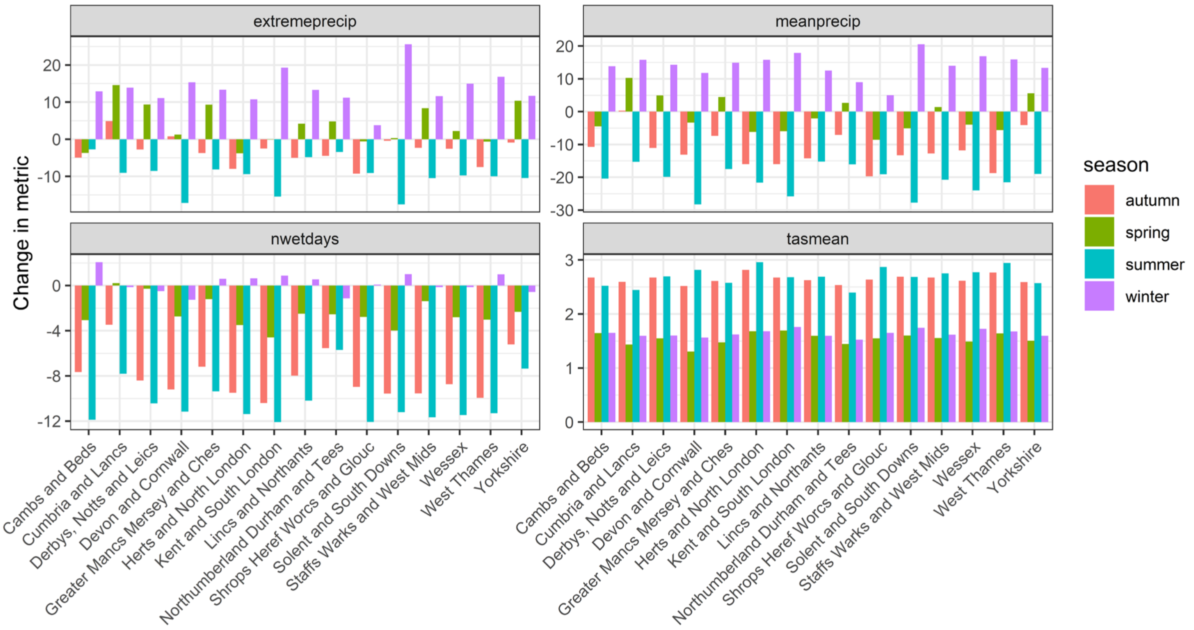

Figure 26 Change in extreme (95th percentile) precipitation (top left), mean precipitation (top right), number of wet days (bottom left), and mean air temperature (bottom right) for each EA divided by season, between 2030 and 2070 under RCP 8.5. Changes for precipitation metrics are percentage changes and for number of wet days and air temperature these are absolute.

6 Discussion

6.1 VARIABILITY IN CHANGES IN CONTAMINANT SOURCE TERM RISKS ACROSS FUTURES

The results presented in section 5 show that between the SSPs, there is divergence in changes in risk some areas and commonality in others. At the national scale, changes in contaminant source term risk varies between the SSPs, with SSP1 and 2 showing more decreases in risk than increases, increases in SSP3 and 5, and little change in SSP4.

Spatially, there are several interesting patterns evident across multiple SSPs. For example, the SPEED land use futures have limited changes in land use in much of Eastern England in SSP2, 3 and 4, due to the ongoing need for food production, which results in limited changes in agricultural contaminant risks in these SSPs. This contrasts with SSP1 in this area, where there is a widespread reduction in agricultural contaminant risk associated with conversion of arable land from intensive to extensive.

SSP1, SSP2 and SSP5 all show that afforestation in parts of southern England, and on the Chalk in particular. This results in a large decrease in risk when the baseline land use is intensive arable. In SSP5 there is a reduction in this forest cover towards the end of the 21st century.

Across SSP1, 2, 3 and 4 it is notable that the increases in risk are generally in the Midlands and Northern England, and generally associated with increased intensive arable land and urbanisation. Urbanisation generally only occurs around existing urban centres only.

An interesting observation to note is also the conversion of arable land to extensive pasture in the dystopian scenario, SSP3. This extensification results in a decreased risk for agricultural-dominated contaminants.

6.2 IMPLICATIONS AND USE OF RESULTS

The spatial consistency in risk changes across the SSPs (e.g. relatively stable land use in Eastern England, increasing risk in northern England, some areas of decreasing risk in southern England) has important implications for future work. These differences in risk could support the prioritisation of more targeted modelling work at regional and catchment scales. This could focus on, for example, intensification of agriculture in Northern England. Moreover, the lack of long-term groundwater nitrate time series in WIMS in this area may make monitoring any impact of changing climate and land use challenging (see Ascott and Gooddy (2023)).

The SPEED land use change data and associated mapping of groundwater contaminant source term risks developed in this research represent exploratory futures, and not predictions. These can be used as a basis for discussion with EA policymakers. Some of the questions that this data can be used to address are as follows:

- How can we prevent, mitigate, or adapt to certain futures?
- Given the range of uncertainty in the SSPs, and the deep uncertainty associated related with the relationships between drivers of change and impacts on some groundwater quality variables (Ascott et al., 2022),
    - How robust are existing groundwater quality policies to alternative futures?
    - Are there any “no regrets” policy interventions that could be implemented now that would be of benefit across the SSP futures?
    - How can groundwater quality policy be aligned to realise the more positive/least impactful scenarios (e.g. SSP1)
    - Is “anticipatory” governance and policymaking (Boyd et al., 2015) in relation to groundwater quality possible given this uncertainty?

6.3 LIMITATIONS AND FURTHER WORK

This research has made a first evaluation at the national scale of the implications of different climate and socioeconomic futures on land use change and associated risks to groundwater quality. There are several limitations to the approach used here. The SPEED outputs used here provide the dominant land use for each 1 km grid cell across the UK. Brown et al. (2022) report that in some SSPs, intensification occurs with an existing land use class. Such intensification is not captured in this analysis, and in technologically advanced futures (e.g. SSP5) intensification of agriculture may not necessarily result in increased fluxes of agricultural pollutants. Further, the simplification of land uses means that some local heterogeneity in risk is not captured. This is particularly pertinent for forest land uses, which were merged (see Table 3). Brown et al. (2022) also report that under SSP3, land use changed frequently with sub-optimal food production. Analysis of the long-term changes at decadal time scales to 2080 is unlikely to capture this short term detail.

This approach has taken a semi-quantitative approach to estimation of contaminant source term risk associated with the SPEED land use classes, building on existing agrochemical leaching maps, literature, and heuristic assessment. Maps of changes in precipitation and temperature metrics from CHESS-SCAPE have also been produced as supporting information to help the user. A next step to build on this would be to quantitatively evaluate how changes in land use and climate affect pollutant and water fluxes. This requires a coupled water and pollutant modelling framework at the national scale. These are currently under development by BGS PhD students and through the NERC Freshwater Quality programme project LTLS-FE.

The extensive afforestation under SSP1, 2 and 5 also warrants investigation from a groundwater resources perspective. On the Chalk this would require dividing the “forest” land use back into coniferous and broadleaved woodlands, as these have different water use characteristics. Use of tools such as a national groundwater recharge model (Mansour et al., 2018), the British Mainland groundwater model and the EA's Woodland and Water Resources tool would be of benefit here.

7 Conclusions

This task has developed semi-quantitative maps of changes in contaminant source term risks associated with land use futures, accompanied by maps of metrics of changes in precipitation and temperature associated with climate change. The key findings of this task are as follows.

An initial scoping workshop identified a very wide range of drivers, pressures, and groundwater quality variables of interest. It also identified a wide range of users of information, covering both technical and non-technical staff and a range of scales from national down to area and local. A literature review of relevant land use and climate change datasets showed that the land use futures developed under the SPEED project (Brown et al., 2022) associated with the Shared Socioeconomic Pathways (SSPs) were the most appropriate to use for this task, accompanied by climate change projections derived from UKCP18 and CHESS-SCAPE (Robinson et al., 2022).

A semi-quantitative risk scoring methodology has been developed to link land use classes reported in the land use futures to contaminant source term risk. This methodology has been applied to land use futures under six scenarios and seven future time slices, with results summarised by EA areas and aquifers. Across the SSPs there is a divergence of changes in risk in some areas and commonality in others. Some common features across the SSPs include: stable land use (and limited change in contaminant risk) in eastern England associated with ongoing need for food production; afforestation (and reduction in contaminant risk) in southern England; urbanisation and intensification of arable land in northern England (an increase in contaminant risk).

CHESS-SCAPE data has been processed to produce maps of changes in precipitation (seasonal mean and extreme temperature, number of wet days) and temperature (seasonal mean) metrics for 10-year timesteps to 2070 for 4 RCPs. Under RCP8.5 for 2070, this results in wetter winters (particularly in northern England and coastal southern England) and drier summers (particularly in southern England), with the largest increases in extreme winter precipitation in northwest England and on the south coast. The greatest rises in mean air temperature are in greatest temperature rises in SSD and West Thames.

The data generated in this task represent exploratory futures which are designed to support discussions with policymakers on the robustness of existing policies related to groundwater quality, and to inform spatial prioritisation of future work based on where risk is likely to be greatest. A next step would be to use the data generated in this task to inform the development of coupled water and pollutant models to quantitatively assess the impact of the land use futures on groundwater quality.

Appendix A – Transcribed workshop outputs

See attached report.

Appendix B – Land use changes by EA area covering aquifers and non-aquifers

Figure 27 Fraction of modelled land use under different RCP-SSP scenarios and time slices for each EA area, covering both aquifer outcrop areas and non-aquifers.

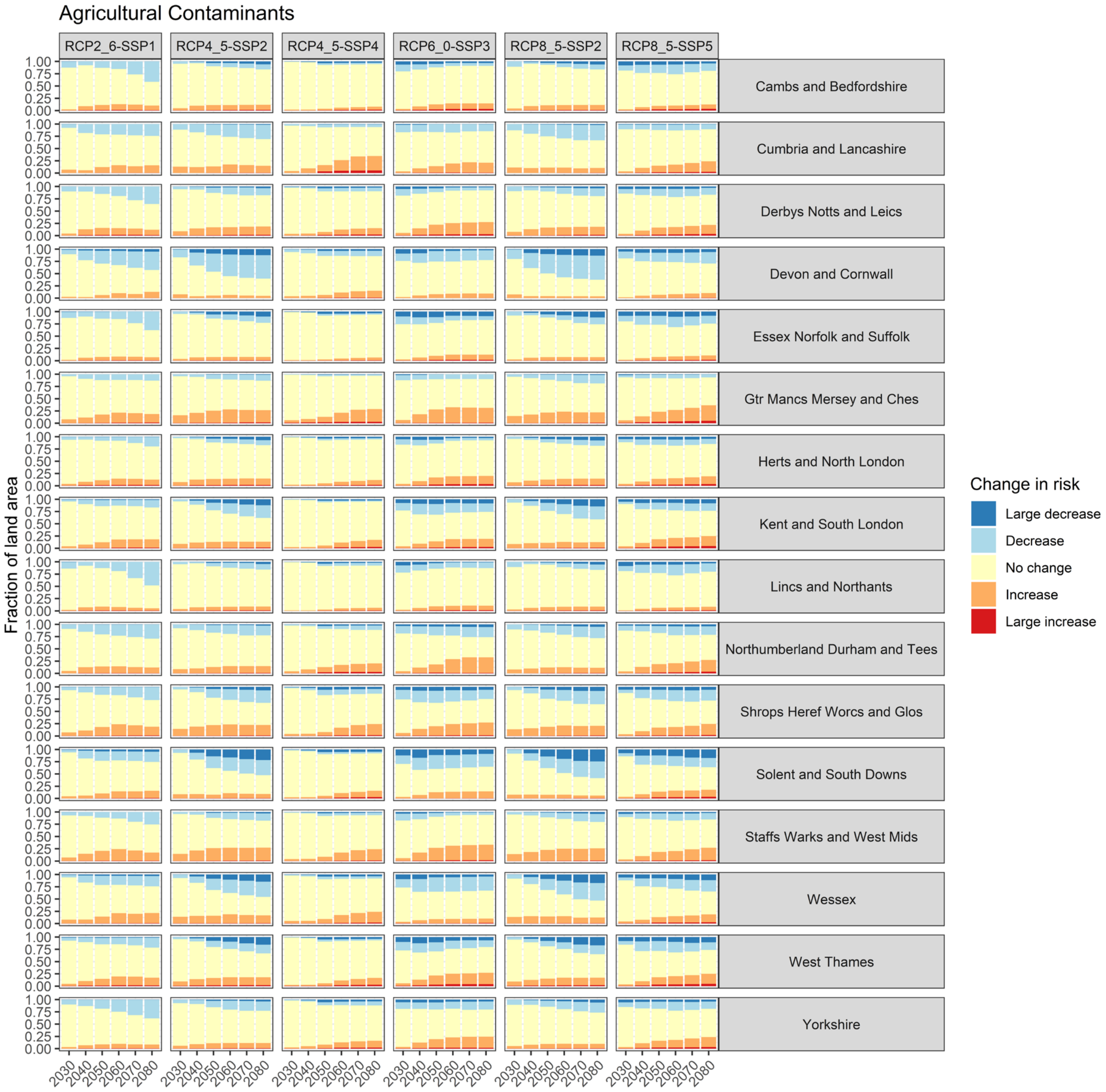

Figure 28 Fraction of modelled land use that results in changes in agricultural dominated contaminant risk at the national scale under different RCP-SSP scenarios and time slices divided by EA areas covering both aquifer outcrop areas and non-aquifers.

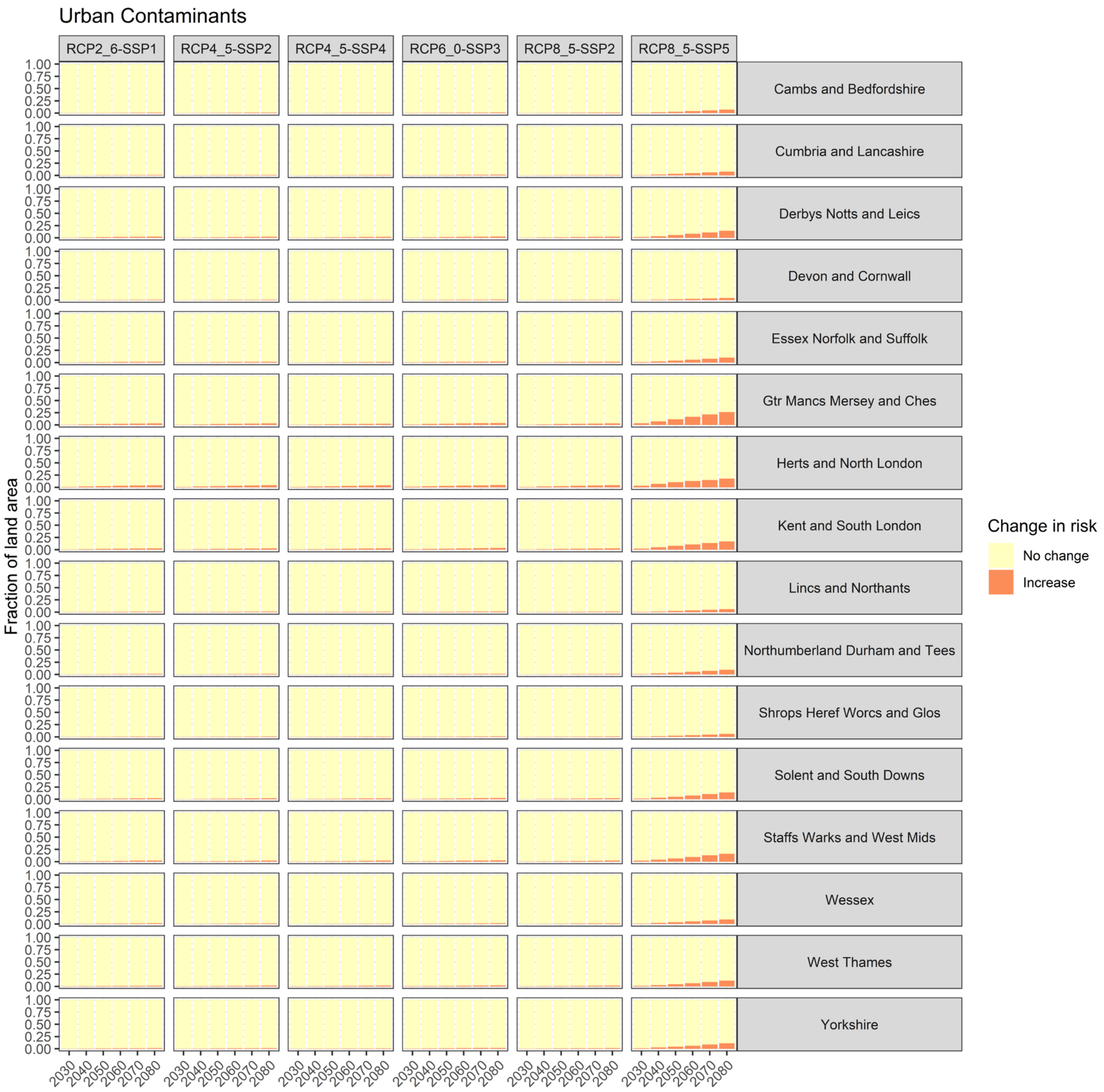

Figure 29 Fraction of modelled land use that results in changes in urban dominated contaminant risk at the national scale under different RCP-SSP scenarios and time slices divided by EA areas covering both aquifer outcrop areas and non-aquifers

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