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Research article

# Impact of climate change on freshwater macronutrients and agricultural yields across Britain

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ABSTRACT

Climate models project higher temperatures and altered rainfall patterns in the future. This will significantly affect terrestrial and hydrological systems, with implications for agricultural yields, freshwater quality, and ecosystem health. To understand and quantify these changes, we used the Long-Term Large-Scale Integrated Model (LTLS-IM), a national-scale terrestrial and freshwater model, to simulate the effect of projected climate change on both agricultural yield and freshwater macronutrient (carbon, nitrogen, and phosphorus) fluxes and concentrations in Great Britain. To generate macronutrient inputs to rivers, the LTLS-IM combines predictions of nutrient losses to water from the semi-natural landscape model N14CP and the agricultural Rothamsted Landscape Model (RLM), with inputs from groundwater, urban runoff, sewage, and septic tanks. These inputs are routed through a freshwater model that simulates water flow and in-stream processes responsive to changes in temperature. Using 12 realisations of the UK Climate Projections 2018 (UKCP18) under the high-emission Representative Concentration Pathway (RCP) 8.5 scenario, we compared recent past (1980–2010) with near-future (2020–2050) conditions. Our projections indicate that for most crops, yields drop by 5-20% due to climate change alone and that despite relatively stable annual nutrient loads, freshwater macronutrient concentrations could increase by 20–30% because of reduced river flows.

## 1. Introduction

Globally, food production is responsible for more than half of the anthropogenic inorganic nitrogen entering freshwater and marine environments (Lee et al., 2016). For the UK, anthropogenic influences such as land-management change and population growth have been identified as the dominant drivers of increased macronutrient (carbon (C), nitrogen (N) and phosphorus (P)) fluxes to freshwaters over the last 200 years (Bell et al., 2021). In this region, agriculture is currently the source of approximately 78% of nitrogen inputs to rivers (Bell et al., 2021), emphasising the importance of judicious agricultural management for maintaining freshwater quality. In the coming decades, anthropogenic influences will undoubtedly continue to impact on the freshwater environment, despite the sewage treatment systems and legislative targets established during the 20th Century to protect waterways (Naden et al., 2016). However, projected changes to our climate, such as warmer drier summers and wetter winters (Murphy et al., 2018), are also expected to influence agricultural productivity (Rial-Loveral et al., 2017), posing potential threats to food security, rural livelihoods, and freshwater systems (Whitehead et al., 2009). While macronutrients are important for freshwater ecosystem health, excess N and P is a wasted resource and can lead to problems including eutrophication (Dodds et al., 2016) and biodiversity loss. This study aims to estimate the impact of projected changes to our climate on freshwater quality and agricultural yields across Great Britain, while keeping anthropogenic influences such as agricultural management the same as for the present day. The analysis presented here enables the impact of climate change to be isolated from direct anthropogenic impacts (agriculture and sewage) and quantified.

We use projected climate changes for Great Britain derived from the UK Climate Projections 2018 (UKCP18, Murphy et al., 2018), developed under the Met Office Hadley Centre Climate Programme. UKCP18 provides projections based on various greenhouse gas emission scenarios, known as Representative Concentration Pathways (RCPs), which

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correspond to different radiative forcing targets by 2100. This study uses RCP8.5, representing a ‘business as usual’ future of rising emissions, with a projected temperature increase of 1.7 °C for the UK in 2020–2050 relative to 1980–2010. While this scenario is considered to be unlikely, it provides us a with a worst-case scenario for projected changes.

The impacts of UKCP18 projected climate change on hydrology in Great Britain have been extensively studied (Lane and Kay, 2021; Kay et al., 2020, 2021; Hannaford et al., 2022). These studies suggest slight increases in mean winter river flows and significant (45%) reductions in mean summer flows. We extend this analysis with projections of concentrations and fluxes of macronutrients in freshwater, as well as agricultural productivity. By including key soil and freshwater processes, the model generates responses to temperature and hydrological changes. To isolate the impact of climate change, the model assumes no changes in land use, no mitigation strategies, and no changes in contributions from urban runoff, sewage, and septic tanks.

Previous studies have examined the impact of climate change on macronutrient fate at various scales, from catchment to global. Catchment-scale results (Buonocore et al., 2021; Čerkasova et al., 2021; Dallison et al., 2022; Seidenfaden et al., 2022) vary by region and model, while global studies predict increased inorganic nitrogen exports to the coast under climate change (Seitzinger et al., 2002). Reviews by Whitehead et al. (2009) and Achat et al. (2016) indicate that in the UK, without intervention, mean nitrate concentrations in rivers are expected to rise, in response to reduced river flows. However, these studies stress that the scale and nature of impacts vary by region, and no other national-scale model currently exists for Great Britain.

Rial-Lovera et al. (2017) reviewed potential responses of UK crops to climate change, showing high variability in projections depending on the model used. While higher temperatures may accelerate crop development and reduce time to maturity, thereby reducing yields, elevated $CO_2$ levels could lead to increased yields, assuming sufficient nutrient and water availability. Projected extreme weather events such as droughts and water stress, particularly in the south and south-east of the UK (Gosling et al., 2011), would also reduce yields.

The Long-Term Large-Scale Integrated Modelling framework (LTLS-IM) used here (Davies et al. (2016), Muhammed et al. (2018); Bell et al. (2021)) dynamically combines terrestrial and freshwater sub-models to simulate the fate of key macronutrients: dissolved organic carbon (DOC), N as nitrate ($NO_3$-N), and total dissolved phosphorus (TDP). Initially developed to understand historical anthropogenic impacts on nutrient cycling and ecosystem health, the LTLS framework's introduction of climate change scenarios marks the next step in its evolution. Few models integrate both anthropogenic and climatic drivers and estimate impacts on both crop yields and freshwater quality, making this approach a novel contribution to the field. While anthropogenic drivers are included (agriculture, urban runoff, sewage, and septic tanks), projected *changes* in these drivers are not, as this work is intended as a sensitivity analysis to climate change alone.

Our results help to quantify the impact of a projected warmer climate (2020–2050) on both agricultural productivity and freshwater quality. In this paper we summarize the LTLS-IM and assess model performance against measured freshwater quality and agricultural yield data across Great Britain. We then apply the model to projected future periods associated with the UKCP18 RCP8.5 scenario, to estimate how projected climate change alone could impact on freshwater quality and agricultural production.

## 2. Method

### 2.1. Model input and measurement data

The LTLS-IM uses several input datasets to simulate terrestrial and freshwater systems across Great Britain at a 5 km × 5 km resolution. These include climate data, spatial terrain data, macronutrient inputs, and measurement datasets for model performance assessment.

#### 2.1.1. Climate data

Historical daily weather data were sourced from the UK Centre for Ecology & Hydrology (UKCEH) CHESS datasets via the UKMO-MIDAS database of the UK Centre for Environmental Data Analysis (CEDA). Future climate scenarios were generated using the UKCP18 regional projections, consisting of a 12-member perturbed parameter ensemble. To account for inherent biases in the climate model outputs, we used the delta change method by Kay et al. (2020), which uses monthly change factors relative to a historical ‘baseline’ (Arnell, 2003; Kay et al., 2020).

Kay et al. (2020) derived gridded change factors for each month and year based on multiple future 30-year slices, relative to the baseline period December 1980 to November 2010. Variables included precipitation, temperature, potential evaporation, solar radiation, humidity, atmospheric pressure, and wind speed. Future scenario runs used the same initial conditions for 1980, followed by a 30-year sequence of climate inputs for 2020–2050 (“2030s”). These were compared to model runs with baseline climate inputs from 1980 to 2010 (“1990s”).

One advantage of the delta change approach is its flexibility, allowing individual climate change factors to be applied separately. Alongside full climate change runs, we ran simulations applying only precipitation or only temperature-related changes, enabling assessment of their relative impact on model outputs.

Climate change projections include an average temperature increase of 1.7 °C, drier summers (−10% rainfall) and wetter winters (+4% precipitation) between 2020 and 2050 relative to 1980–2010 across Great Britain (see SI, Fig. S1–S2). Changes are most pronounced in England and Wales, where median summer rainfall decreases (12–15%) and temperature increases (2.0 °C) are higher than in Scotland ( −4% and 1.6 °C).

#### 2.1.2. Spatial and terrain data

River flow directions were derived from elevation data provided by the UKCEH Digital Terrain Model (Morris et al., 1990). Soil texture grids, used to estimate soil hydrological process rates, came from the Harmonised World Soil Database (Fischer et al., 2008). Land use data were sourced from the UKCEH Land Cover Map (see Fig. 1, Morton et al., 2011) and kept constant throughout simulations.

#### 2.1.3. Macronutrient data

Initial soil organic carbon values came from the International Soil Reference and Information Centre (Hengl et al., 2017). Macronutrient input sources included atmospheric deposition, derived from the FRAME model dataset (Tipping et al., 2017; Tomlinson et al., 2020), fertilizers (DEFRA, 2018), and population-based estimates of nutrients in sewage effluent, sourced from water treatment works and septic tanks (Naden et al., 2016). Fertilizer application rates were obtained from the British Survey of Fertiliser Practice (see El Fartassia et al., 2025).

#### 2.1.4. Validation data

Freshwater quality measurements were sourced from the Great Britain Harmonised Monitoring Scheme (HMS, 2014), which provided monthly water samples primarily from larger rivers near their sea outflows from 1984 to 2013. Samples were analysed for DOC, $NO_3$-N and TDP using consistent nationwide protocols (Blake et al., 1984). Each HMS was associated with a nearby flow gauging station by pairing those with similar catchment sizes. The distances between the sites were not explicitly considered in the pairing but they were generally in close proximity (median distance 2.2 km). These differences in location may add to the uncertainty in the results.

Crop yields were sourced from farming statistics from the Department for Environment, Food and Rural Affairs (DEFRA), including UK-wide annual dry matter yields for 1980–2010 (DEFRA, 2022) and cereal (wheat, barley, and oats) and oilseed rape yields by International Territorial Level from 1999 onwards (DEFRA, 2016). National yield uncertainties were estimated at ±0.1 t/ha, and regional variations at ±0.3 t/ha. For improved grassland and maize, yields were compared to a

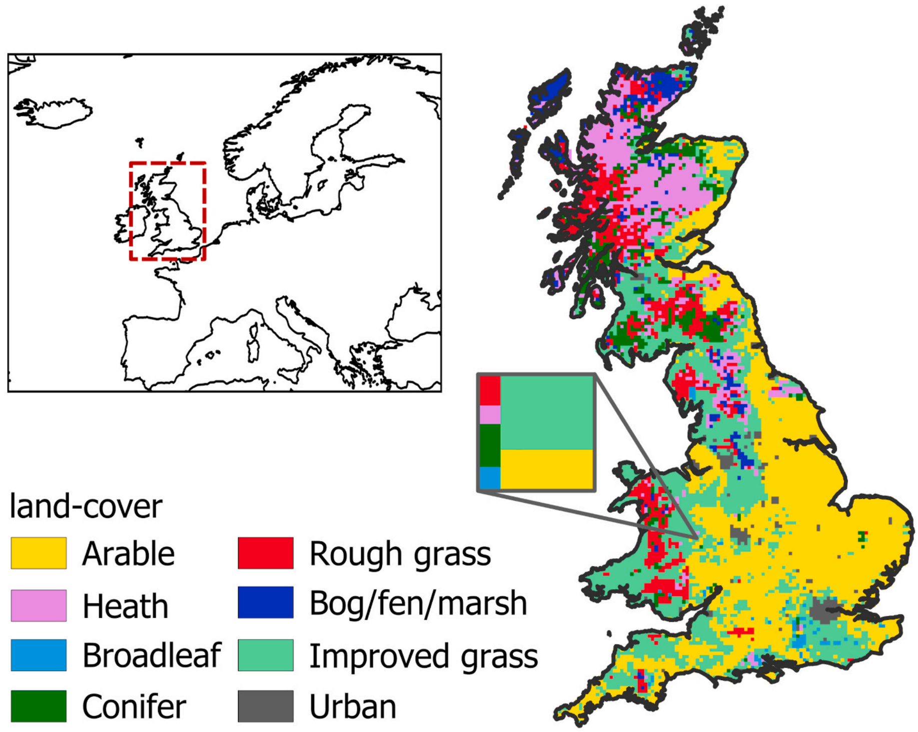


**Fig. 1.** Dominant land cover map of Great Britain in 2007. The square inset shows an example of the land cover fractions contained in a 5 km grid square.

national average of 7 t/ha (ADHB, 2024) and 12 t/ha (PDA, 2023) respectively.

### 2.2. Terrestrial and freshwater modelling

Each 5 km × 5 km grid cell of the LTLS-IM (Bell et al., 2021) is divided into land cover fractions (see SI, Fig. S3) based on the 1 km × 1 km UKCEH Land Cover Map 2007 (LCM2007, Morton et al., 2011), as shown in Fig. 1. The LTLS-IM dynamically integrates two soil-vegetation sub-models to simulate terrestrial macronutrient outputs: N14CP (Davies et al., 2016a; 2016b) for semi-natural land cover (bog, fen/-marsh, rough grassland, heath, coniferous and deciduous woodland) and the Rothamsted Landscape Model (RLM) (Coleman et al., 2017; Muhammed et al., 2018) for agricultural areas (arable land and improved grassland). Urban nutrient inputs (sewage, septic tanks, and urban runoff) were kept constant across scenarios to isolate the effect of climate change on diffuse pollution from land cover and agriculture.

Surface and sub-surface runoff from soils are estimated using the probability distributed model (PDM) (Moore, 1985) for semi-natural land, and by the RLM for agricultural land. Along with the terrestrial macronutrient outputs, these are passed to the freshwater model, which routes water and nutrients through the 5 km resolution flow network to the sea. The model assumes nutrients travel at the same speed as water and simulates key chemical processes within rivers. Fig. 2 presents a schematic of the LTLS-IM.

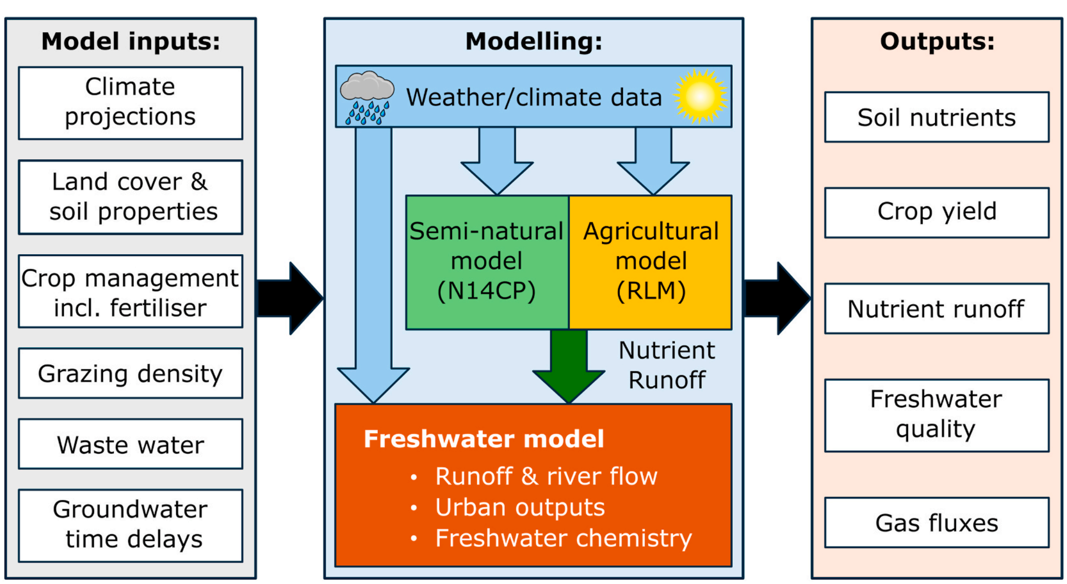


**Fig. 2.** Schematic of the Long-Term Large Scale Integrated Model framework.

#### 2.2.1. Terrestrial models

The N14CP model simulates macronutrient dynamics in seminatural soils, including plant growth, nitrogen fixation, denitrification, P weathering and sorption/desorption, rotting of coarse plant litter, incorporation of fine litter into soil organic matter (SOM), and decomposition of SOM. These processes lead to the release of dissolved organic and inorganic carbon, nitrogen and phosphorus, with temperature-dependent rate coefficients as used by Bell et al. (2021). The model outputs seasonal nutrient fluxes, which are disaggregated to daily values to align with hydrological inputs to the freshwater model, ensuring that nutrient concentrations vary with hydrological conditions. N14CP models a total soil depth of 200 cm, maintaining nutrient ratios for the “slow,” “fast,” and “passive” soil components as used by Davies et al. (2016a,b), and fixed nutrient ratios in soil and plant compartments according to Bell et al. (2021). To achieve equilibrium, N14CP was spun up from 1940 to 1980, and the resulting state variables were used to initialize subsequent runs.

The RLM simulates daily macronutrient and water dynamics, livestock production, and crop growth on agricultural land. It incorporates weather variables—temperature, rainfall, solar radiation, vapor pressure, and windspeed—to simulate canopy development and resource accumulation. The model simulates several commercial crops, including cereals (wheat, barley, oats), oilseed rape, field beans, sugar beet, forage maize, potatoes, and improved grass, while quantifying soil carbon changes, nutrient exports, and greenhouse gas emissions. The model components are derived from established models including RothC (Coleman and Jenkinson, 2014), LINTUL (Wolf, 2012), SUCROS (van Laar et al., 1997), and Century (Parton et al., 1994), as described in Coleman et al. (2017) and Muhammed et al. (2018). The RLM, modelling three soil layers (0-23 cm, 23-46 cm and 46-100 cm), was initialised so that all nutrient pools were at equilibrium before subsequent simulations. Because the agricultural sub-model runs at a daily timestep, it captures the crop response both to gradual changes in climate and to acute stressors from extreme weather events.

#### 2.2.2. Freshwater model

The freshwater sub-model (Bell et al., 2021) simulates water and macronutrient transport through the gridded flow network on a 2-h timestep. It has two conceptual flow paths between grid cells: surface flow and sub-surface flow. Outputs from N14CP and RLM are disaggregated to 2-hourly values, with interflow (“drainage”) directed to the slower sub-surface path and surface flow (“runoff”) to the faster surface path. The freshwater processes include $CO_2$ exchange with the atmosphere, conversion of DOC to $CO_2$, denitrification, conversion of ammonia and dissolved organic nitrogen to nitrate, and seasonal algal dynamics (growth, grazing, decay nutrient uptake and release).

Long-term groundwater storage effects are approximated through a delay applied to leached nitrate. This geology-dependent delay (Wang et al., 2013), accounts for nitrate residence times of up to several decades. Delayed nitrate re-enters the flow grid where it was leached. Initial model runs from 1800 to 2010 were used to generate delayed groundwater nitrate inputs reflecting historical agricultural practices and their continued release into the future. To isolate the effects of climate change, pre-1980 groundwater nitrate inputs remained unchanged in scenario runs compared to baseline values. For example, 1950 groundwater nitrate input with a 30-year residence time is released in 1980 during baseline runs and in 2020 during scenario runs. Realistically, groundwater nitrate levels are expected to drop in the future, reducing nitrate inputs to rivers.

### 2.3. Model assessment: Approach and criteria

Model outputs of crop yield, river flow and macronutrient concentrations for the baseline period of 1980–2010 were evaluated against historical measurements (see section 2.1.4). To assess the model's performance for predicting annual averages over this 30-year baseline period, two statistical measures were used: the Nash-Sutcliffe efficiency coefficient (NSE) and the coefficient of determination ($R^2$) with respect to a linear regression line on a log-log scale. The Nash-Sutcliffe efficiency (NSE) is defined as:

$$NSE = 1 - \frac{\sum_{i=1}^{n} (\text{measured}_i - \text{modelled}_i)^2}{\sum_{i=1}^{n} (\text{measured}_i - \overline{\text{measured}})^2} \quad \text{(eq. 1)}$$

Where i represents a measurement date and location, $\text{measured}_i$ represents observed values, $\text{modelled}_i$ represents predicted values (model outputs), $\overline{\text{measured}}$ is the mean of the measured values, and $n$ is the number of measurements.

To examine spatial biases in the model, the mean percentage error (MPE) of the modelled annual averages was calculated relative to observations. The MPE is expressed as:

$$MPE = \frac{100\%}{n} \sum_{i=1}^{n} \frac{\text{modelled}_i - \text{measured}_i}{\text{measured}_i} \quad \text{(eq. 2)}$$

For the climate change impact analysis, percentage changes were computed for the future period average (2021–2050) relative to the baseline period average (1981–2010). These percentage changes were calculated using the formula:

$$\%\ \text{change} = \frac{100\%}{n} \sum_{i=\text{year}}^{n} \frac{\text{future}_i - \text{baseline}_i}{\text{baseline}_i} \quad \text{(eq. 3)}$$

Where i iterates over the n = 30 model years, and $\text{future}_i$ and $\text{baseline}_i$ represent annual averages. The percentage changes vary across the 12 ensemble members of the climate scenario, and the median value was used to summarize future projections, 25th and 75th percentile grids are shown in SI. For regional assessments, spatial means were calculated to represent area-wide trends.

## 3. Results

### 3.1. Model performance

#### 3.1.1. Agricultural yields

Fig. 3 compares modelled annual crop yields to reported annual averages of dry matter yields for 1981–2010. Median percentage errors (MPE) between modelled and observed yields are: improved grassland: 23%, oats: 21%, barley: 19%, wheat: 7%, oilseed rape: 34%, field beans: 17%, peas: 21%, potato: 1%, maize: 28%, sugar beet: 26%. Overall, the model tends to overestimate crop yields, except for improved grassland and potatoes. This overestimation likely reflects the absence of yield reducing factors like crop damage from extreme events, diseases and pests.

The MPE in average annual yields for 1999-2010 for cereals (oats, wheat, barley) and oilseed rape were also mapped across different ITL regions (see SI, Fig. S4). Average cereal yields (oats, barley and wheat, in t/ha) are most overestimated in the north and west, where arable land use is lower (see SI, Fig. S3). Oilseed rape yields, however, are most overestimated in arable-intensive areas of England.

#### 3.1.2. Freshwater quality

To assess model predictions of freshwater quality, we compared annual averages of modelled flow-weighted macronutrient concentrations:

$$\text{weighted conc} = \frac{\sum_{i}^{n} \text{conc}_i \times \text{flow}_i}{\sum_{i}^{n} \text{flow}_i} \quad \text{(eq. 4)}$$

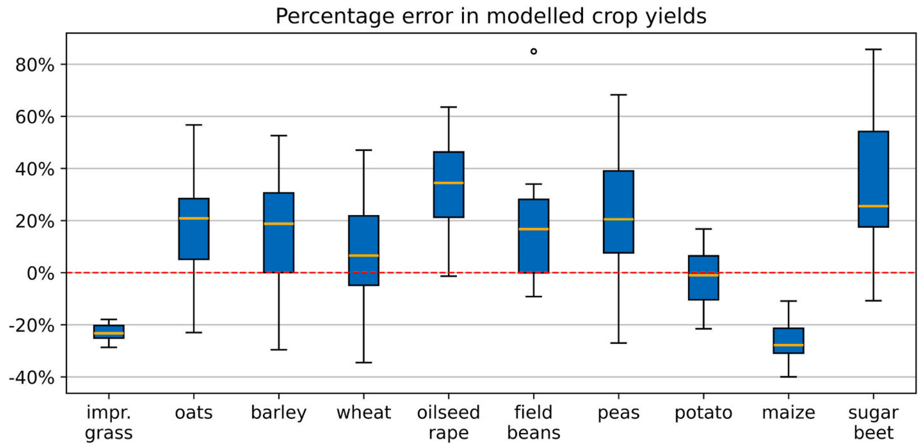


**Fig. 3.** Comparison of modelled annual yield averages between 1981 and 2010 across Great Britain against DEFRA crop yield statistics.

where i iterates over n days within a model year, against annual averages of flow weighted measured values at HMS sites between 1981 and 2010 (Fig. 4). We also mapped MPE across Great Britain at individual HMS sites and as regional averages (See SI, Fig. S5). The model performs well at predicting flow, with $R^2$=0.84, NSE=0.83, and MPE=1.3% across HMS sites.

Modelled nitrate concentrations are highly correlated with measurements ($R^2$=0.85, NSE=0.77), but are generally underestimated (MPE=-11.5%), especially in the west. In the East of England, where nitrate concentrations are highest (due to agricultural intensity), nitrate concentrations are slightly overestimated. Modelled TDP concentrations also correlate well ($R^2$=0.76, NSE=0.73) with observations indicating good overall model performance, but can exhibit high over- and underestimation, with median and mean percentage errors across HMS sites of −30% and 10%, respectively. TDP concentrations are strongly influenced by sewage treatment works, for which the inputs are estimated on a population basis rather than from observations. The impact of individual water treatment works at observed locations is not considered, which may be responsible for the underestimations of TDP in some locations. Performance for DOC across HMS sites is less robust ($R^2$=0.28, NSE=−0.03). Although there is a positive correlation ($R^2$) between simulated and measured DOC values and the MPE for DOC is small (−2.1%), the negative NSE indicates that the mean value of the data gives a lower residual mean square than the 1:1 line.

The LTLS-IM captures large-scale trends in flow, and concentrations of $NO_3$-N & TDP across Great Britain, but with some variability in accuracy at individual monitoring sites arising from uncertainty in present day model simulations and (arguably) sparse observations. The subsequent focus on how climate change impacts on *relative* changes in future freshwater flows and chemistry ensures that the analysis provides valuable insights into future trends.

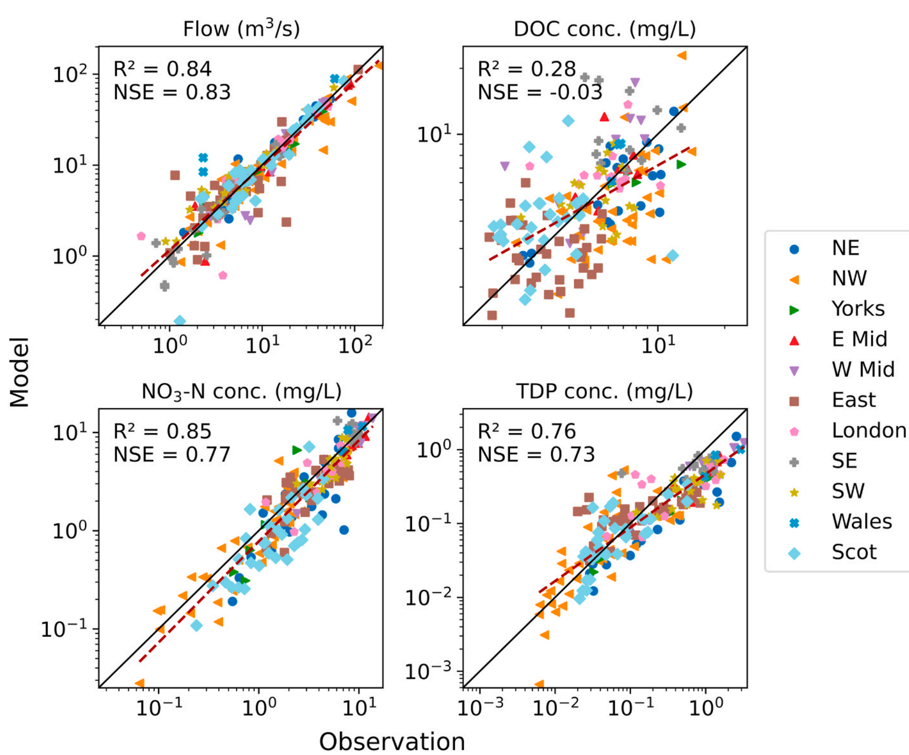


**Fig. 4.** Comparison of simulated daily mean flows and flow-weighted concentrations against HMS measurements averaged between 1981 and 2010, grouped by NUTS region. Nash-Sutcliffe efficiency (NSE) is with respect to the 1-1 line (solid). $R^2$ is with respect to the linear regression line (dashed).

### 3.2. Climate change impact

#### 3.2.1. Agricultural yields

Under the UKCP18 projected climate change RCP8.5 scenario, improved grassland yields would increase (4−8%) in Scotland, Wales, and Northern England, and decrease slightly (1−4%) in the southeast (Fig. 5). Arable crops show varying responses: oats, winter barley, winter wheat, field beans, peas, and potato yields are projected to drop by 10–15% in England and Wales, and 1–5% in Scotland. Spring barley and spring wheat yields also reduce in England and Wales but increase slightly (0–5%) in Scotland. Oilseed rape yields are projected to increase by 14% in Scotland, decrease by 5% in England, and remain stable in Wales. Sugar beet yields in England are projected to decrease by 12%. Maize yields, however, are projected to increase substantially: by approximately 20% in England and Wales, and 60% in Scotland.

Absolute changes in yields over the 30-year period reveal similar trends, with more pronounced reductions in the south and east of Great Britain where agricultural land use is most intensive (see SI, Fig. S3 and S6). Overall, these projections indicate a tendency for yields to decrease in the south of Great Britain, with smaller decreases or even increases in Scotland. The range of these changes across ensemble members are shown in Fig. 5, with 25th and 75th percentile grids shown in Fig. S10–11). The sign of the projected changes is consistent across ensemble members.

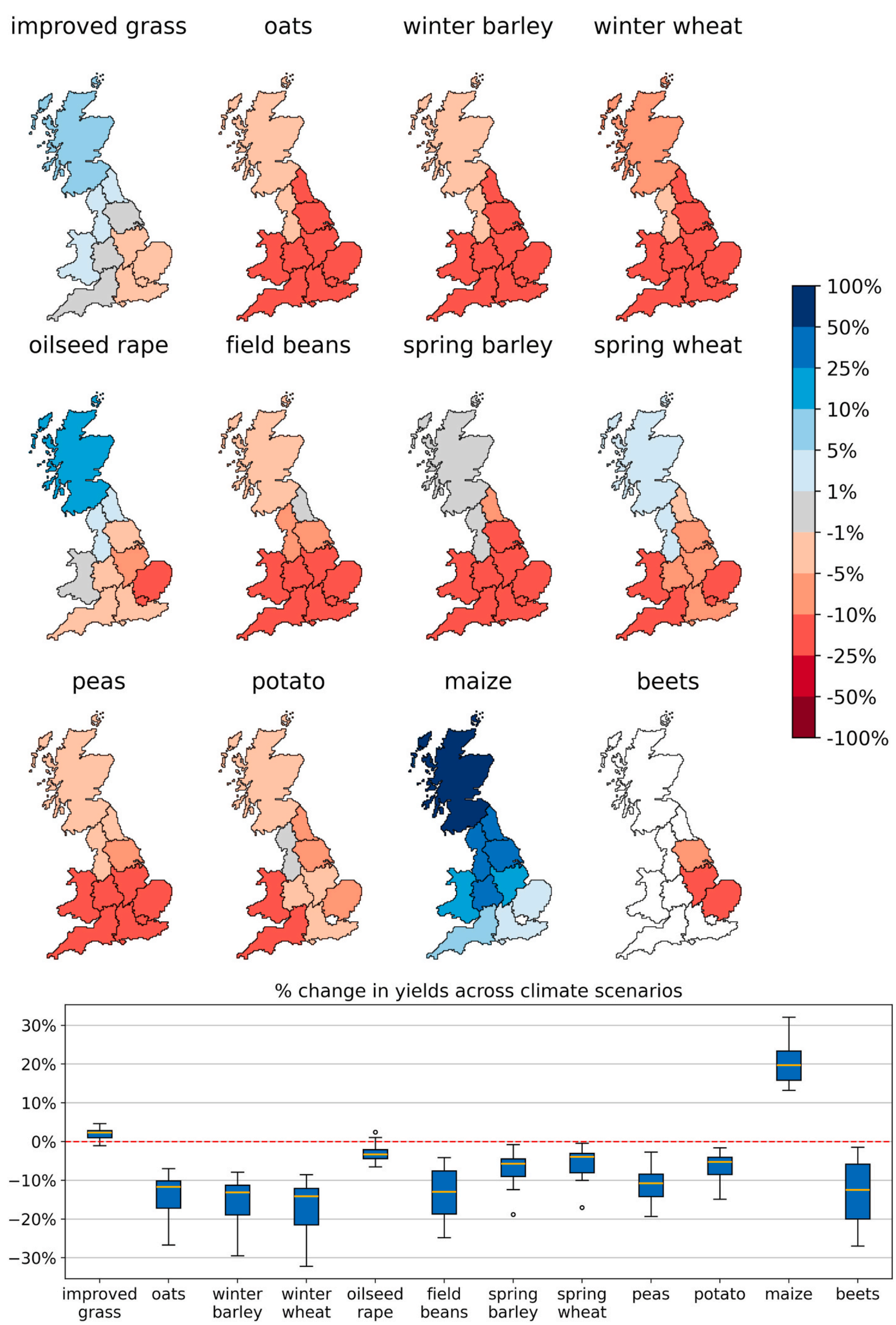


**Fig. 5.** Percentage changes in mean annual yields across future climate scenario ensemble members (2021-2050) with respect to the baseline period (1981-2010). Top: Ensemble medians of NUTS region average change in yield. Bottom: Ensemble distribution of percentage changes.

### 3.2.2. Freshwater quality and flow

Under projected climate change, nitrate fluxes from soils to rivers (Fig. 6, first column, see also Fig. S12–S13 for ensemble 25th and 75th percentiles), are projected to decrease in England (30%) but increase in Scotland (3%) and Wales (18%). Nitrate exports to freshwater are highest in intensively farmed areas, and reductions, sometimes as much as 65%, reflect reduced leaching of fertiliser in drier conditions. TDP fluxes from land to freshwaters are projected to decrease by 7% in England, and 1% in Wales, but increase by 4% in Scotland. DOC fluxes from soils in Scotland are estimated to increase by 8%. Conversely, reduced rainfall in southern regions is expected to lower DOC fluxes to rivers by 3%. The relative increases in terrestrial fluxes are primarily driven by faster soil dynamics at higher temperatures in seminatural soils.

Annual changes in river fluxes (Fig. 6, second column) are modest (DOC: 1%, $NO_3$-N: 2%, TDP: −3%), but vary seasonally (Fig. 7). Across Great Britain, a decrease in summer (DOC: 21%, $NO_3$-N: 18%, TDP: 13%) is followed by an increase in autumn (DOC: 17%, $NO_3$-N: 19%, TDP: 5%), reflecting macronutrient accumulation in soils in drier summer conditions followed by elevated fluxes from soils to rivers in the subsequent seasons, when the nutrients are mobilised by rainfall. Projected changes to coastal outputs (Figs. 6 and 4th column) reflect the changes in upstream river fluxes, with DOC flux increasing by 6% along the Scottish and western coasts and decreasing by 5% along the southeast coast. Nitrate and TDP coastal fluxes are projected to rise marginally (0–1%), but with a distinct divide of decreases ($NO_3$-N: 13%, TDP: 3%) in the East and increases ($NO_3$-N: 10%, TDP: 3%) in the West, primarily due to the projected changes in rainfall (Fig. S1).

Projected reductions in annual mean river flows by 9% (England: 12%, Scotland: 3%, Wales: 7%), with mean summer flows reducing by 38% (see Fig. 7 and SI, Fig. S7–9), align well with findings by Kay (2021). These reductions cause projected macronutrient concentrations to rise nationwide. DOC concentrations (Fig. 6, third column) are projected to increase by 19% (England: 13%, Scotland: 21, Wales: 38), $NO_3$ by 19% (England: 21%, Scotland: 10%, Wales: 46%) and TDP by 24% (England: 28%, Scotland: 14%, Wales: 28%) on average (based on the ensemble median). Autumn sees the most significant increase in DOC concentrations (34%), while summer experiences the largest rise for nitrate and TDP (40−50%) (see Fig. 7 and SI, Fig. S7–9 for seasonal ensemble median, 25th and 75th percentiles).

Spatial means of projected percentage changes in freshwater quality across Great Britain show a reduction in river flows and an increase in macronutrient concentrations year-round (Fig. 7). Winter flows are slightly higher (3%), with nutrient fluxes and concentrations rising by 0–10%. In spring, reduced rainfall results in 20% lower flows, with slight reductions in nutrient fluxes (0–5%) and a 10–20% increase in concentrations. The projected warmer and drier summer conditions lead to a 40% average reduction in river flows, a 20% decrease in nutrient fluxes, and a 20–40% increase in concentrations. Autumn projections indicate a 6% reduction in flow, a 5–18% increase in macronutrient fluxes, and a 16–28% increase in concentrations compared to the baseline period. Fig. 7 shows the distribution of these projected changes across ensemble members.

### 3.2.3. Relative impact analysis

To understand whether these projected climate impacts are predominantly due to change in future temperatures or rainfall patterns, we compared model outputs under future simulations incorporating only precipitation or only temperature-related changes to the baseline climate (Fig. 8). When only precipitation changes are applied, yields of oilseed rape, potato, and sugar beets increase slightly (1−3%), while yields for peas and field beans decrease by 10%, and other crops experience minor decreases (1−5%). In contrast, applying temperature

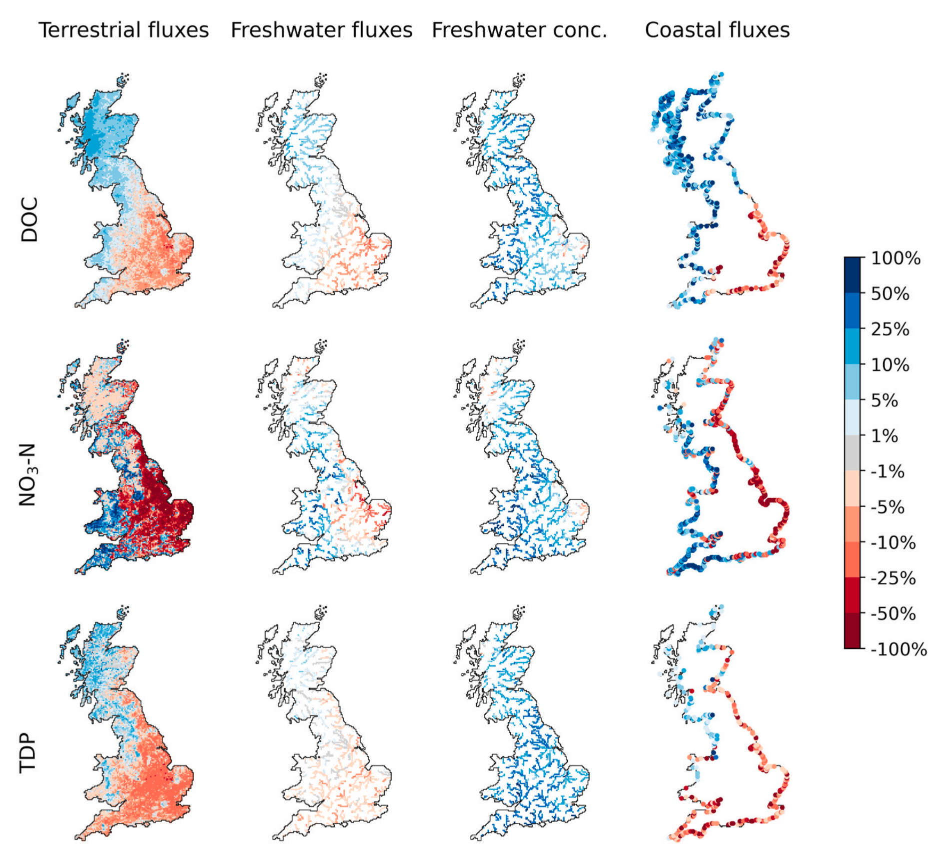


**Fig. 6.** Ensemble median of percentage changes in annual average terrestrial, freshwater and coastal macronutrient fluxes for future scenarios (2021-2050) with respect to baseline conditions (1981-2010). Increases in future fluxes are shown in blue, decreases in red. Results are shown only for river pixels with a catchment area exceeding 250 km$^2$. The points along the coastline show changes in nutrient fluxes to sea.

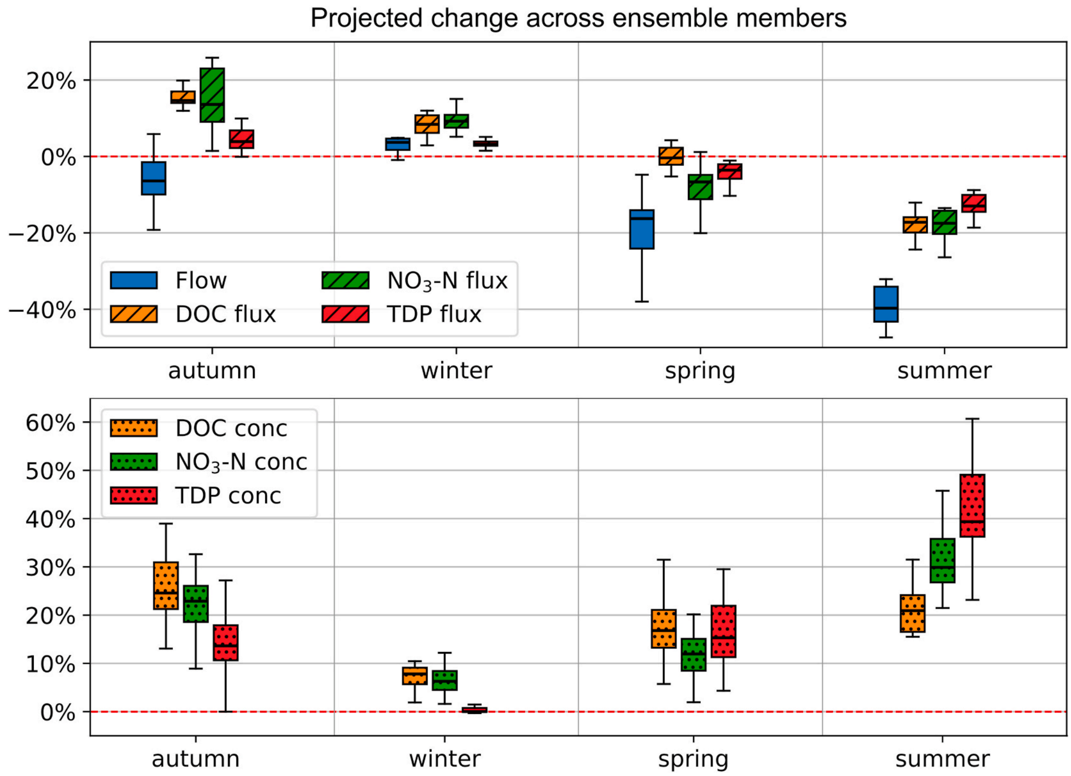


**Fig. 7.** Boxplots of the projected percentage changes across climate scenario realisations for river flows, nutrient fluxes and concentrations in Great Britain.

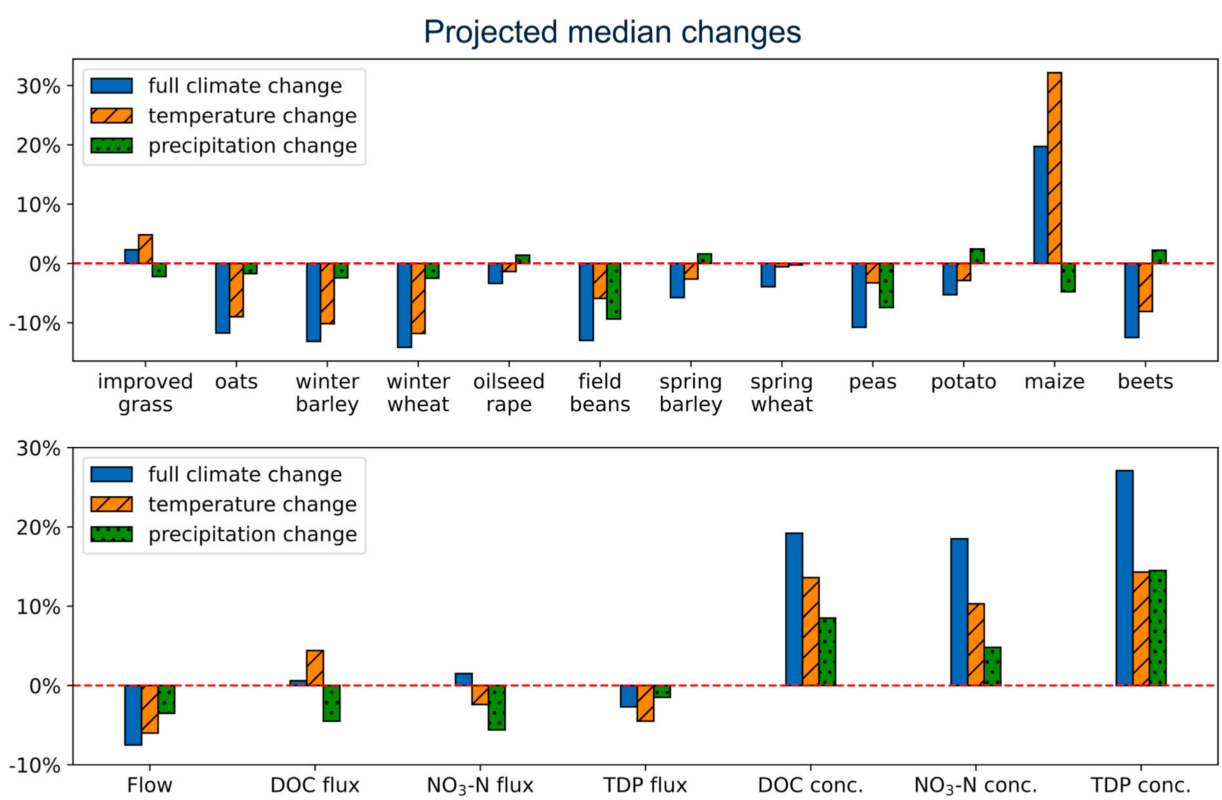


**Fig. 8.** Projected median percentage changes in future (2021-2050) yields (top), flow and freshwater quality (bottom) with respect to baseline conditions (1981-2010) for the full climate change model, temperature changes, and precipitation changes.

changes results in a 5% increase in improved grassland yields, a more than 30% increase in maize yields, and a 2−12% decrease in other crop yields. Temperature changes generally lead to more substantial impacts on crop yields compared to precipitation changes, except for field beans and peas, which are more sensitive to changes in precipitation.

Both applying only temperature-related and only precipitation changes lead to reduced river flows and increased macronutrient concentrations, with temperature being the main driver behind the projected changes. Changes in temperature and rainfall both lead to slightly reduced macronutrient fluxes, except for DOC fluxes, which increase by about 5% when only temperature changes are applied, due to increased soil decomposition rates.

## 4. Discussion

In the combined agricultural and hydrological modelling presented here, we estimated the effect of projected climate change on agricultural productivity, river flows, and their combined impact on freshwater quality. The projected reductions in river flows, altered nutrient fluxes, and increased concentrations of DOC, TDP, and $NO_3$-N in British rivers under the UKCP18 RCP8.5 scenario are consistent with previous findings (Kay, 2021; Whitehead et al., 2009; Achat et al., 2016). Note that the RCP8.5 scenario is a worst-case scenario, and results should be interpreted as such. A more plausible scenario like RCP4.5 still comes with an average projected temperature increase of 1.4 °C (rather than 1.7 °C) for the future period and would likely result in similar projections, albeit to a lesser extent. Nevertheless, the projected reductions in crop yields and river flows, and the increase in nutrient concentrations stress the importance of developing adaptive strategies to mitigate adverse effects of climate change and enhance resilience in both agricultural and water management.

Under this climate-only future scenario, our agricultural modelling indicates that by 2050, Britain would see a decline in agricultural yields for the crops considered, except for improved grassland and maize. In practice, by 2050 there will be other influencing factors such as changes to land-management, adaptive agricultural practices (Rial-Lovera et al., 2016), and improved sewage treatment (Cooper et al., 2022). However, the projected climate change impacts alone highlight the extent to which adaptation will be required even to maintain current levels of agricultural production in a warmer climate. “Net zero plus” farming practices (Rehberger et al., 2023) such as regenerative agriculture and land-sharing or land-sparing strategies could help mitigate greenhouse emissions, limiting more extreme climate changes, and may improve crop yield through enhanced soil health. Consequences for terrestrial biodiversity and freshwater health should also be considered, not least because healthy biodiversity (e.g. plentiful pollinators, soil microbes) is a necessary requirement to support agriculture (Aizen et al., 2009; Mishra et al., 2016).

Higher temperatures in the south of Great Britain would likely accelerate crop maturity, leaving less time for crops to intercept radiation and accumulate biomass (Wheeler et al., 1996). Crop yields are likely to be further reduced by projected changes in rainfall seasonality. In the north of Great Britain, crop yields are projected to decrease less, and yields of improved grassland, maize, oilseed rape, and spring wheat could even increase. The projected yield reductions, particularly in the south, could pose a threat to food security, food prices, and farm incomes unless changes in agricultural practices can mitigate these losses. However, the modelling presented here also indicates potential opportunities: crops like maize may benefit from warmer temperatures, agreeing with findings on climate-resilient crop suitability in the UK (Redhead et al., 2025; Coleman et al., 2021). Unlike the other crops modelled here, maize is a C4 crop and is temperature-limited in the UK (Sanchez et al., 2014). C4 crops excel in warmer climates because they need to open their stomata less than C3 plants to obtain $CO_2$ and so lose less water. Consequently, maize would benefit substantially from warmer conditions in Great Britain. Maize can be high-risk in terms of soil erosion, particularly on sloped terrain, thus, although maize could become a more important crop in Great Britain under climate change, it will be important not to cultivate it on erosion-prone fields near watercourses (Gregar et al., 2024).

Our modelling does not include all potential factors affecting future yields. The $CO_2$ fertilisation effect, for example, where higher future atmospheric $CO_2$ levels could improve the rate of photosynthesis in plants and improve crop retention of water by causing plants to close their stomata (Li et al., 2004). This would mitigate the reduction in yields from shorter growing periods for certain crops (Putelat et al., 2021). Studies generally report yield increases of 10-20% for C3 crops (such as wheat and barley) grown in Europe from a 200–300 ppm $CO_2$ rise under non-limiting N and water. These studies caution that warming (+2 °C), heat stress at anthesis or severe drought can reduce this by up to 10%, even producing net losses (Asseng et al., 2019). While C4 crops, such as maize, show no yield increase except under drought conditions (Erbs et al., 2015). Farmers are also likely to adapt to a warmer climate by changing sowing and harvesting times (Parent et al., 2018) and growing different crops. This would mitigate some of the detrimental impacts of projected climate change on agricultural production.

Projections of freshwater quality generally show increased concentrations of DOC, $NO_3$-N and TDP in Britain's rivers, but often for different reasons in different places. In Scotland, terrestrial DOC fluxes rise due to increased decomposition in semi-natural soils. In more agricultural English catchments, DOC leaching from soils is projected to decrease under drier conditions, but lower river flows still lead to higher projected DOC concentrations. However, our DOC outputs show weak correlation to observations, so future projections are uncertain. Nitrate and TDP concentrations in rivers are both projected to increase for most of Britain, except for southeast England and northwest Scotland during winter. The projected reductions in terrestrial nitrate fluxes across England are due to reduced soil runoff and leaching in drier conditions, and increased soil microbial denitrification in a warmer climate (Stanford et al., 1975). TDP exports to freshwater are predominantly from farmland and direct sewage inputs, and projected future changes show similarities with nitrate. Projections indicate a decrease in TDP exports from arable land to freshwaters associated with reduced leaching. However, despite projected decreases in terrestrial fluxes to rivers, lower river flows still lead to increased concentrations of nitrate and TDP, except during winter months.

For this sensitivity study of nutrient fluxes to climate change alone, fluxes from urban sources and groundwater contamination have been kept constant. However, a higher population would lead to higher urban fluxes, while groundwater nitrate levels are decreasing. Future model development could include different socioeconomic and climate scenarios for a wider range of projections, and human adaptation strategies to mitigate impact. Other limitations of the model include a limited treatment of extreme events, which lead to crop damage and acute nutrient fluxes.

The projected impacts of climate change on freshwater quality and agricultural productivity for 2020-2050 indicate an urgent need for proactive and integrated management strategies. A parallel study by Rothamsted Research (El Fartassia et al., 2025) has isolated the impact of different land-management strategies on freshwater quality and agricultural yields, allowing for a comparison to be made of the relative impacts of climate change and agricultural management on yield and water quality. Such a comparison will be able to identify parts of Britain most likely to be affected by near-future climate or land-management change, and identify where particular agricultural management can best mitigate adverse impacts of projected climate change. Addressing both ecological and socio-economic challenges will require coordinated efforts to develop effective responses. Agricultural resilience to climate change could be enhanced through crop diversification (Slater et al., 2022; Redhead et al., 2025) and adaptation strategies, improving water management practices to mitigate elevated nutrient concentrations, and implementing robust regulatory frameworks to manage anthropogenic inputs.

## 5. Conclusions

A new dynamically coupled terrestrial and freshwater model, LTLS-IM, which includes a spatially distributed agricultural model (Coleman et al., 2017; Muhammed et al., 2018), is presented and applied across Great Britain to explore the impact of projected future changes in climate on crop yield and freshwater quality while assuming present day management of sewage and agriculture continues. A "delta-change" factor approach to climate change impact modelling is used here, based on a 12-member ensemble of UKCP18 RCP8.5 climate model projections for a historical (1980 – 2010) and near-future (2020-2050) periods (section 2.1.1). The LTLS-IM projections indicate near-future reductions in annual river flows, increases in freshwater concentrations of DOC, $NO_3$-N and TDP in many areas, and decreased agricultural yields for most crops, which we summarize here with the 25th-75th quantile range of the ensemble members.

Agricultural yields (section 3.2.1) are projected to decline across Great Britain for oats (10-17%), winter wheat (12-22%), spring wheat (3-8%), winter barley (11-19%), spring barley (4-9%), oilseed rape (2-4%), field beans (8-19%), peas (8-14%), potato (4-9%), and sugar beet (6-20%). However, if the $CO_2$ fertilization effect is accounted for these declines are likely to be smaller. Conversely, some crops are projected to benefit from warmer temperatures, with an increase of projected yields for maize (16-23%) and improved grassland (1-3%). In England, where intensive agricultural land use is highest, relative decreases in yields are greatest and relative increases are lowest due to the higher change in temperature and net rainfall. In Scotland, climate change impacts are projected to be less severe and projected decreases in yields are lower, while projected increases are higher.

Freshwater macronutrient concentrations (section 3.2.2) are projected to rise significantly, with annual average DOC concentrations increasing by 17-22%, nitrate concentrations by 17-22%, and TDP concentrations by 21-31%. These increases are driven by the combination of changes in seasonal flows and macronutrient fluxes. In summer, projected changes in temperature and rainfall lead to reduced flows (34-43%), while reduced soil leaching leads to lower terrestrial macronutrient fluxes (DOC: 16-20%, $NO_3$-N: 14-20%, TDP: 10-15%). In winter, projected river flows are slightly higher (2-5%), while a build-up of soil macronutrients leads to a projected increase in macronutrient fluxes (DOC: 6-11%, $NO_3$-N: 8-11%, TDP: 3-4%). Averaged annually, projected river flows are 8-12% lower, while macronutrient fluxes are similar to those of the baseline period. Marine outputs are projected to decrease in the south and east, while an increase is projected along the west coast. These projections represent the effect of climate change alone, for an extreme RCP8.5 climate change scenario and without accounting for adaptation strategies and changing urban fluxes. Ongoing research will continue to refine model predictions, assess the effectiveness of various adaptation strategies, and investigate the effect of different socio-economic pathways to better prepare for and respond to the challenges posed by climate change.

## CRediT authorship contribution statement

**Nathan Missault:** Writing – original draft, Visualization, Validation, Investigation, Formal analysis. **Victoria A. Bell:** Writing – review & editing, Supervision, Software, Methodology, Funding acquisition, Conceptualization. **David M. Cooper:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis. **Ryan T. Sharp:** Validation, Software, Investigation, Formal analysis. **Andrew P. Whitmore:** Writing – review & editing, Supervision, Software, Methodology, Funding acquisition, Conceptualization. **Alice E. Milne:** Writing – review & editing, Supervision, Software, Methodology, Funding acquisition, Conceptualization. **Helen N. Davies:** Resources, Data curation.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.128927.

## Data availability

Data will be made available on request.

## References

Achat, D.L., Augusto, L., Gallet-Budynek, A., Loustau, D., 2016. Future challenges in coupled C–N–P cycle models for terrestrial ecosystems under global change: a review. Biogeochemistry 131 (1), 173–202.
AHDB - Agriculture and Horticulture Development Board, 2024. Grassland reseeding. https://ahdb.org.uk/knowledge-library/grassland-reseeding.
Aizen, M.A., Garibaldi, L.A., Cunningham, S.A., Klein, A.M., 2009. How much does agriculture depend on pollinators? Lessons from long-term trends in crop production. Ann. Bot. 103 (9), 1579–1588.
Arnell, N.W., 2003. Relative effects of multi-decadal climatic variability and changes in the mean and variability of climate due to global warming: future streamflows in Britain. J. Hydrol. 270 (3-4), 195–213.
Asseng, S., Martre, P., Maiorano, A., Rötter, R.P., O'Leary, G.J., Fitzgerald, G.J., Girousse, C., Motzo, R., Giunta, F., Babar, M.A., Reynolds, M.P., 2019. Climate change impact and adaptation for wheat protein. Glob. Change Biol. 25 (1), 155–173.
Bell, V.A., Naden, P.S., Tipping, E., Davies, H.N., Carnell, E., Davies, J.A.C., Dore, A.J., Dragosits, U., Lapworth, D.J., Muhammed, S.E., Quinton, J.N., 2021. Long term simulations of macronutrients (C, N and P) in UK freshwaters. Sci. Total Environ. 776, 145813.
Blake, S., Gardner, M., Hunt, D., 1984. Co-ordination of analytical quality control for DOE harmonised monitoring scheme. WRC Environ. Marlow SL7 2HD, UK.
Buonocore, C., Pascual, J.J.G., Cayeiro, M.L.P., Salinas, R.M., Mejías, M.B., 2021. Modelling the impacts of climate and land use changes on water quality in the Guadiana basin and the adjacent coastal area. Sci. Total Environ. 776, 146034.
Čerkasova, N., Umgiesser, G., Ertürk, A., 2021. Modelling framework for flow, sediments and nutrient loads in a large transboundary river watershed: a climate change impact assessment of the Nemunas River watershed. J. Hydrol. 598, 126422.
Coleman, K., Jenkinson, D., 2014. RothC - A model for the turnover of carbon in soil: model description and users guide. Harpenden, UK, Lawes Agricultural Trust (Updated June 2014).
Coleman, K., Muhammed, S.E., Milne, A.E., Todman, L.C., Dailey, A.G., Glendining, M.J., Whitmore, A.P., 2017. The landscape model: a model for exploring trade-offs between agricultural production and the environment. Sci. Total Environ. 609, 1483–1499.
Coleman, K., Whitmore, A.P., Hassall, K.L., Shield, I., Semenov, M.A., Dobermann, A., Bourhis, Y., Eskandary, A., Milne, A.E., 2021. The potential for soybean to diversify the production of plant-based protein in the UK. Sci. Total Environ. 767, 144903.
Dallison, R.J.H., Williams, A.P., Harris, I.M., Patil, S.D., 2022. Modelling the impact of future climate change on streamflow and water quality in Wales, UK. Hydrol. Sci. J. 67 (6), 939–962.
Davies, J.A.C., Tipping, E., Rowe, E.C., Boyle, J.F., Graf Pannatier, E., Martinsen, V., 2016a. Long-term P weathering and recent N deposition control contemporary plant-soil C, N, and P. Glob. Biogeochem. Cycles 30 (2), 231–249.
Davies, J.A.C., Tipping, E., Whitmore, A.P., 2016b. 150 years of macronutrient change in unfertilized UK ecosystems: observations vs simulations. Sci. Total Environ. 572, 1485–1495.
DEFRA, 2016. Regional crop yield dataset: united Kingdom cereal yields 1885 onwards. https://www.data.gov.uk/dataset/76ca636f-a449-44ba-ac2f-f8febecec2a2/cereals-and-oilseeds-production-harvest.
DEFRA, 2018. The British survey of fertilizer practice: fertilizer use on farm crops for crop year 2018. www.gov.uk/government/statistics/british-survey-of-fertiliser-practice-2018.
DEFRA, 2022. Chapter 7: crops. https://www.gov.uk/government/statistics/agriculture-in-the-united-kingdom-2021/chapter-7-crops.
Dodds, W.K., Smith, V.H., 2016. Nitrogen, phosphorus, and eutrophication in streams. Inland Waters 6 (2), 155–164.

El Fartassia, I., Sharp, R.T., Bell, V.I., Whitmore, A.P., Metcalfe, H., Missault, N., Redhead, J., Cooper, D.M., Davies, H., Jackson, T., Coleman, A., Storkeya, J., Milne, A., 2025. Rethinking Land-Use Strategies: a Multi-Objective Analysis of Sparing and Sharing Approaches Applied Variably Across Great Britain. *submitted for publication*.

Erbs, M., Manderscheid, R., Hüther, L., Schenderlein, A., Wieser, H., Dänicke, S., Weigel, H.J., 2015. Free-air CO2 enrichment modifies maize quality only under drought stress. Agron. Sustain. Dev. 35 (1), 203–212.

Fischer, G., Nachtergaele, F., Prieler, S., Van Velthuizen, H.T., Verelst, L., Wiberg, D., 2008. Global agro-ecological Zones Assessment for Agriculture (GAEZ 2008), 10. IIASA, Laxenburg, Austria and FAO, Rome, Italy. https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/.

Gosling, S.N., Dunn, R., Carrol, F., Christidis, N., Fullwood, J., de Gusmao, D., et al., 2011. Climate: observations, projections and impacts. UK Met Office (UKMO), Hadley Centre, Exeter.

Gregar, J., Petrů, J., Kalibová, J., Ürge, V., Kincl, D., Vopravil, J., 2024. Impact of intercrops on soil loss and surface runoff from sloping maize fields. Soil Water Res. 19 (3).

Hannaford, J., Mackay, J., Ascott, M., Bell, V., Chitson, T., Cole, S., Counsell, C., Durant, M., Jackson, C.R., Kay, A., Lane, R., 2022. eFLaG: enhanced future FLows and groundwater. A national dataset of hydrological projections based on UKCP18. Earth Syst. Sci. Data Discuss. 2022, 1–40.

Hengl, T., Mendes de Jesus, J., Heuvelink, G.B., Ruiperez Gonzalez, M., Kilibarda, M., Blagotić, A., Shangguan, W., Wright, M.N., Geng, X., Bauer-Marschallinger, B., Guevara, M.A., 2017. SoilGrids250m: global gridded soil information based on machine learning. PLoS One 12 (2), e0169748. https://files.isric.org/soilgrids/former/2017-03-10/data/.

HMS, 2014. ENV-16 harmonised monitoring scheme datasets. https://www.gov.uk/government/statistical-data-sets/env-16-harmonised-monitoring-scheme-datasets. (Accessed 6 June 2025).

Kay, A.L., 2021. Simulation of river flow in Britain under climate change: baseline performance and future seasonal changes. Hydrol. Process. 35 (4), e14137.

Kay, A.L., Watts, G., Wells, S.C., Allen, S., 2020. The impact of climate change on UK river flows: a preliminary comparison of two generations of probabilistic climate projections. Hydrol. Process. 34 (4), 1081–1088.

Lane, R.A., Kay, A.L., 2021. Climate change impact on the magnitude and timing of hydrological extremes across Great Britain. Front. Water 3, 684982.

Lee, R.Y., Seitzinger, S., Mayorga, E., 2016. Land-based nutrient loading to LMEs: a global watershed perspective on magnitudes and sources. Environ. Dev. 17, 220–229.

Li, F., Kang, S., Zhang, J., 2004. Interactive effects of elevated CO2, nitrogen and drought on leaf area, stomatal conductance, and evapotranspiration of wheat. Agric. Water Manag. 67 (3), 221–233.

Mishra, J., Prakash, J., Arora, N.K., 2016. Role of beneficial soil microbes in sustainable agriculture and environmental management. Clim. Change Environ. Sustain. 4 (2), 137–149.

Moore, R.J., 1985. The probability-distributed principle and runoff production at point and basin scales. Hydrol. Sci. J. 30 (2), 273–297.

Morris, D.G., Flavin, R.W., Moore, R.V., 1990. A Digital Terrain Model for Hydrology. Proc 4th International Symposium on Spatial Data Handling. Zurich.

Morton, D., Rowland, C., Wood, C., Meek, L., Marston, C., Smith, G., Wadsworth, R., Simpson, I., 2011. Final report for LCM2007-the new UK land cover map. Countryside Survey Tech. Rep. No 11/07.

Muhammed, S.E., Coleman, K., Wu, L., Bell, V.A., Davies, J.A., Quinton, J.N., Carnell, E. J., Tomlinson, S.J., Dore, A.J., Dragosits, U., Naden, P.S., 2018. Impact of two centuries of intensive agriculture on soil carbon, nitrogen and phosphorus cycling in the UK. Sci. Total Environ. 634, 1486–1504.

Murphy, J.M., Harris, G.R., Sexton, D.M.H., Kendon, E.J., Bett, P.E., Clark, R.T., Eagle, K. E., Fosser, G., Fung, F., Lowe, J.A., McDonald, R.E., 2018. UKCP18 Land Projections: Science Report.

Naden, P., Bell, V., Carnell, E., Tomlinson, S., Dragosits, U., Chaplow, J., May, L., Tipping, E., 2016. Nutrient fluxes from domestic wastewater: a national-scale historical perspective for the UK 1800–2010. Sci. Total Environ. 572, 1471–1484.

Parent, B., Leclere, M., Lacube, S., Semenov, M.A., Welcker, C., Martre, P., Tardieu, F., 2018. Maize yields over Europe may increase in spite of climate change, with an appropriate use of the genetic variability of flowering time. Proc. Natl. Acad. Sci. 115 (42), 10642–10647.

Parton, W.J., Ojima, D.S., Cole, C.V., Schimel, D.S., 1994. A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. Quant. Model. Soil Form. Process. 39, 147–167.

PDA, 2023. Forage maize – fertiliser requirements. https://www.pda.org.uk/pda_leaflets/17-forage-maize-fertiliser-requirements/. (Accessed 27 November 2025).

Putelat, T., Whitmore, A.P., Senapati, N., Semenov, M.A., 2021. Local impacts of climate change on winter wheat in Great Britain. R. Soc. Open Sci. 8 (6), 201669.

Rial-Lovera, K., Davies, W.P., Cannon, N.D., 2017. Implications of climate change predictions for UK cropping and prospects for possible mitigation: a review of challenges and potential responses. J. Sci. Food Agric. 97 (1), 17–32.

Redhead, J.W., Brown, M., Price, J., Robinson, E., Nicholls, R.J., Warren, R., Pywell, R.F., 2025. National horizon scanning for future crops under a changing UK climate. Clim. Resilience Sustain. 4 (1), e70007.

Rehberger, E., West, P.C., Spillane, C., McKeown, P.C., 2023. What climate and environmental benefits of regenerative agriculture practices? An evidence review. Environ. Res. Commun. 5 (5), 052001.

Seidenfaden, I.K., Sonnenborg, T.O., Børgesen, C.D., Trolle, D., Olesen, J.E., Refsgaard, J. C., 2022. Impacts of land use, climate change and hydrological model structure on nitrate fluxes: magnitudes and uncertainties. Sci. Total Environ. 830, 154671.

Seitzinger, S.P., Kroeze, C., Bouwman, A.F., Caraco, N., Dentener, F., Styles, R.V., 2002. Global patterns of dissolved inorganic and particulate nitrogen inputs to coastal systems: recent conditions and future projections. Estuaries 25, 640–655.

Slater, L.J., Huntingford, C., Pywell, R.F., Redhead, J.W., Kendon, E.J., 2022. Resilience of UK crop yields to compound climate change. Earth Syst. Dynam. 13 (3), 1377–1396.

Stanford, G., Dzienia, S., Vander Pol, R.A., 1975. Effect of temperature on denitrification rate in soils. Soil Sci. Soc. Am. J. 39 (5), 867–870.

Tipping, E., Davies, J.A.C., Henrys, P.A., Kirk, G.J., Lilly, A., Dragosits, U., Carnell, E.J., Dore, A.J., Sutton, M.A., Tomlinson, S.J., 2017. Long-term increases in soil carbon due to ecosystem fertilization by atmospheric nitrogen deposition demonstrated by regional-scale modelling and observations. Sci. Rep. 7 (1), 1890.

Tomlinson, S.J., Carnell, E.J., Dore, A.J., Dragosits, U., 2020. Nitrogen Deposition in the UK at 1km Resolution, 1990-2017. NERC Environmental Information Data Centre.

Van Laar, H.V., Goudriaan, J.V., Keulen, H.V., 1997. SUCROS97: simulation of crop growth for potential and water-limited production situations. As Applied to Spring Wheat. Netherlands, ab-dlo.

Wang, L., Butcher, A.S., Stuart, M.E., Gooddy, D.C., Bloomfield, J.P., 2013. The nitrate time bomb: a numerical way to investigate nitrate storage and lag time in the unsaturated zone. Environ. Geochem. Health 35, 667–681.

Wheeler, T.R., Batts, G.R., Ellis, R.H., Hadley, P., Morison, J.I.L., 1996. Growth and yield of winter wheat (Triticum aestivum) crops in response to CO2 and temperature. J. Agric. Sci. 127 (1), 37–48.

Whitehead, P.G., Wilby, R.L., Battarbee, R.W., Kernan, M., Wade, A.J., 2009. A review of the potential impacts of climate change on surface water quality. Hydrol. Sci. J. J. Des Sci. Hydrol. 54 (1), 101–123.

Wolf, J., 2012. User Guide for LINTUL4 and LINTUL4V: Simple Generic Model for Simulation of Crop Growth Under Potential, Water Limited and Nitrogen Limited Conditions. Wageningen University.