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Research article

Impacts of reduced synthetic fertiliser use under current and future climates: Exploration using integrated agroecosystem modelling in the upper River Taw observatory, UK

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ABSTRACT

The intensification of farming and increased nitrogen fertiliser use, to satisfy the growing population demand, contributed to the extant climate change crisis. Use of synthetic fertilisers in agriculture is a significant source of anthropogenic Greenhouse Gas (GHG) emissions, especially potent nitrous oxide (N_2O). To achieve the ambitious policy target for net zero by 2050 in the UK, it is crucial to understand the impacts of potential reductions in fertiliser use on multiple ecosystem services, including crop production, GHG emissions and soil organic carbon (SOC) storge. A novel integrated modelling approach using three established agroecosystem models (SPACSYS, CSM and RothC) was implemented to evaluate the associated impacts of fertiliser reduction (10%, 30% and 50%) under current and projected climate scenarios (RCP2.6, RCP4.5 and RCP8.5) in a study catchment in Southwest England. 48 unique combinations of soil types, climate conditions and fertiliser inputs were evaluated for five major arable crops plus improved grassland. With a 30% reduction in fertiliser inputs, the estimated yield loss under current climate ranged between 11% and 30% for arable crops compared with a 20–24% and 6–22% reduction in N_2O and methane emissions, respectively. Biomass was reduced by 10–25% aboveground and by <12% for the root system. Relative to the baseline scenario, soil type dependent reductions in SOC sequestration rates are predicted under future climate with reductions in fertiliser inputs. Losses in SOC were more than doubled under the RCP4.5 scenario. The emissions from energy use, including embedded emissions from fertiliser manufacture, was a significant source (14–48%) for all arable crops and the associated GWP20.

1. Introduction

Global greenhouse gas (GHG) emissions from agriculture are increasing as a result of anthropogenic activities and contributing to the extant climate change crisis (Shakoor et al., 2021; Chataut et al., 2023). Global demand for food has also increased due to population growth and changing patterns in food consumption (Rosa and Gabrielli, 2023). In turn, this has resulted in the intensification of farming and increased nitrogen trading and use (Lassaletta et al., 2016). Whilst nitrous oxide (N_2O) and methane (CH_4) are emitted at lower quantities than carbon dioxide (CO_2), their respective global warming potential (GWP) is 310 and 21 times greater (Thangarajan et al., 2013). Agriculture is estimated to be accountable for >80% of anthropogenic N_2O emissions and ~40% of CH_4 emissions (Birch, 2014). Recent work suggested that the fertiliser industry alone contributes around 10% of agricultural emissions (Menegat et al., 2022).

As a result of the Ukraine war and sanctions imposed on Russia, global fertiliser prices rose sharply in the first half of 2022 (Arndt et al., 2023). By April 2022, fertiliser prices had more than doubled (World Bank, 2022) in response not only to the Ukraine war, but also the export ban imposed by China (Hebebrand and Laborde, 2022). In the absence of targeted subsidies to offset price hikes, it is feasible to envisage scenarios of reductions in fertiliser use in response to the sharp hikes in prices. Equally, since agroecosystems deliver important goods and services, including food, carbon sequestration and regulating services such as those for the atmosphere, it is informative to assess the technically feasible impacts of reduced fertiliser use on agricultural goods and services both under current and, indeed, future climates.

Specifically for the UK, such understanding is useful in the context of the fact that agriculture contributes ~10% of total GHG emissions (National Statistics, 2018), with emissions failing to exhibit reductions over the last decade (Committee on Climate Change, 2020). Equally, it is

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informative to understand the impacts of any potential reductions in fertiliser use in the context of the UK's ambitious policy target for net zero by 2050. One reason for this is that the land use change required for net zero, including for example, the planting of nearly 1M ha of trees in the UK by 2050, creates a potential conflict between land for production and land for net zero (Westaway et al., 2023). Consequently, we need improved understanding of the impacts of shocks, including price shocks, on current farm management of inputs including fertilisers and the associated consequences for key goods and services. Fertiliser use has a strong bearing on crop and grass yields and qualities (Mengel, 1982, Valk et al., 2000; Kohoutek et al., 2005; Tanaka and Nakano, 2019, Bhandari et al., 2020). Fertiliser rates also impact gaseous emissions (Liu et al., 2006; Smith et al., 2012; Trost et al., 2016; Bhandari et al., 2020; Kandel et al., 2020; Menegat et al., 2022) and soil organic carbon (Ladha et al., 2011; Malhi et al., 2011; Han et al., 2016).

Plot/field-scale controlled field experiments have improved our understanding of the multiple consequences, both intended and unintended, of fertiliser use and underpinned the development of biogeochemical and agroecosystem models as well as, farm/catchment decision support tools and life cycle assessments (LCAs). Such models have already been employed to optimise fertilisation rates for crop yields (e.g., Miao et al., 2006)), soil organic carbon (SOC) sequestration (Begum et al., 2017) and for informing management decisions for reducing GHG emissions (Sandor et al., 2018). Any individual model rarely simulates all of the outcomes associated with farm system management. As a result, some research has combined models to expand process or outcome representation and to take better explicit account of the uncertainties associated with model predictions. Combining models can take the form of ensembles to improve the accuracy of predictions and such an approach has featured in climate modelling for some time (e.g., Virkkala et al., 2021). Model ensembles have been applied to agroecosystems far less, although a recent example includes Hassall et al. (2022). In the case of agroecosystems, ensemble modelling faces substantial challenges including the availability of models to generate ensembles for multiple outcomes, the need to align model input and output variables, and the difficulties in aligning the spatial and temporal resolution of the outputs from the individual models (Gneiting and Raftery, 2005; Hassall et al., 2022). Here, an alternative and more pragmatic approach is to integrate the use of individual models which are selected to generate outcomes for specific components of agroecosystems, rather than for generating predictions of the same outcomes. This approach still permits exploration of scenarios for answering 'what-if?' questions including those related to potential outcomes relevant to the climate change challenge (El Chami and Daccache, 2015).

With the shift in policy focus in the UK from the provisioning of food to the delivery of multiple ecosystem services, there is a demand for making full use of existing agroecosystem models to generate timely and site-specific evidence to support sustainable agriculture. Our work used the integration of established agroecosystem models (SPACSYS, RothC and CSM) to explore the technically feasible impacts of reduced fertiliser use under both current and future climates on multiple outcomes spanning GHG emissions, SOC sequestration and energy use. All three models simulate the interactions among climate, soil, plant and field management, but have strengths in representing different components of the processes involved. Here, for example, SPACSYS has physically-based representation of processes associated with plant growth and nitrogen cycling, RothC has parsimonious input data requirements and well calibrated SOC parameters for UK settings. CSM can account for embedded emissions associated with fertiliser use and on-farm activities. Further details on the individual models are provided in supplementary information. The main objective of the study was to couple the selected agroecosystem models for undertaking both farmer and policy relevant scenario runs in a sentinel study catchment and, in so doing, to generate new quantitative data for supporting decision-making in the study area using a novel ensemble to answer the following specific questions: how will major crops respond with proportional fertiliser inputs now and will these responses remain the same in the changing climate in the near future?

2. Study site

The study was undertaken using the lowland agricultural area (~30 km^2) of the Upper River Taw Observatory (URTO) in the southwest of England, where mixed land use and diverse farming types are present. Land cover, soil series and the distribution of major crops are shown in Fig. 1. For a 30-year (1981–2010) observation period, average annual rainfall was estimated to be 1200 mm, ranging between 1009 mm and 1501 mm. Average air temperatures were estimated at 9.9 C^o, varying between 9.0 C^o to 10.3 C^o (Met Office; Hollis et al., 2018). Lower rainfall and higher temperatures tend to be found further to the north in the upland area of the URTO. Soils are mainly represented by Denbigh, Hallsworth and Halstow series. Small patches of Neath series (<1.3 km^2) are also found. While the Hallsworth series has a clayey soil texture (clay content 36%), the other soil series are all clay loams with variable (26%–33%) clay contents. Other more fragmented and insignificant soil types include Alun, Moor Gate, Laployd and Parc series, but these are generally not in agricultural use. Based on the June Agriculture Survey in 2021, the study area is dominated by lowland grazing holdings but with some cereal and general cropping farms. Recent field scale mapping suggests that 64% of the land cover is improved grassland, 12% arable and 16% woodland (Morton et al., 2021). As illustrated in Fig. 1, major crops in the study area include winter wheat, winter barley, spring barley, maize, oilseed rape and winter oats. Other crops present include field beans and spring oats. Maize is grown as livestock feed. Based on the period 2010–2015, and using a resolution of 1 km^2, these cropping areas could have up to 86.7 kg ha^{-1} of nitrogen fertiliser applied (Osório, et al., 2019). With projected temperature and rainfall pattern changes for the study area (Met Office, 2019), some land use change could be anticipated, including the introduction of more arable cropping to areas used previously for livestock grazing. The study catchment is representative of lowland farming landscapes and land uses therein for ~9000 km^2 of the farmed area in England and Wales (Lovett et al., 2018), and includes a UK National Bioscience Research Infrastructure - the North Wyke Farm Platform (NWFP) where site-specific data on soil, climate and monitored flow and both water and air pollutant emissions are available for model parameterisation, calibration and validation. Both SPACSYS and CSM have already been applied using the available data (Wu et al., 2022; Zhang et al., 2022b). Some preliminary analysis on the workability and trafficability of soils subjected to land use change in response to future climate has already been reported (Wu et al., 2022).

3. Methodology

3.1. Scenario design

The modelling scenarios targeted those crops present in the study area under business-as-usual (BAU) and with relatively higher nitrogen demand. On this basis, nitrogen-fixing field beans and oats which typically demand lower application rates were not considered. The crops included in the modelled scenarios therefore comprised winter wheat (WW), spring barley (SB), winter barley (WB), winter oilseed rape (WOSR), maize for forage (MZ) and improved grassland (IG). The last two were included because of their strong connections with dominant farming activities in the area, i.e., lowland grazing. Since projected climate change could shift the spatial patterns of the main crop types, it was assumed that modelled crops can be grown in all major soil series, namely: the Denbigh (D), Hallsworth (H1) and Hastow (H2) series. No crops were grown in the Neath series as currently only IG can be found in those areas of the study catchment.

To evaluate the effects of projected climate change, the scenario

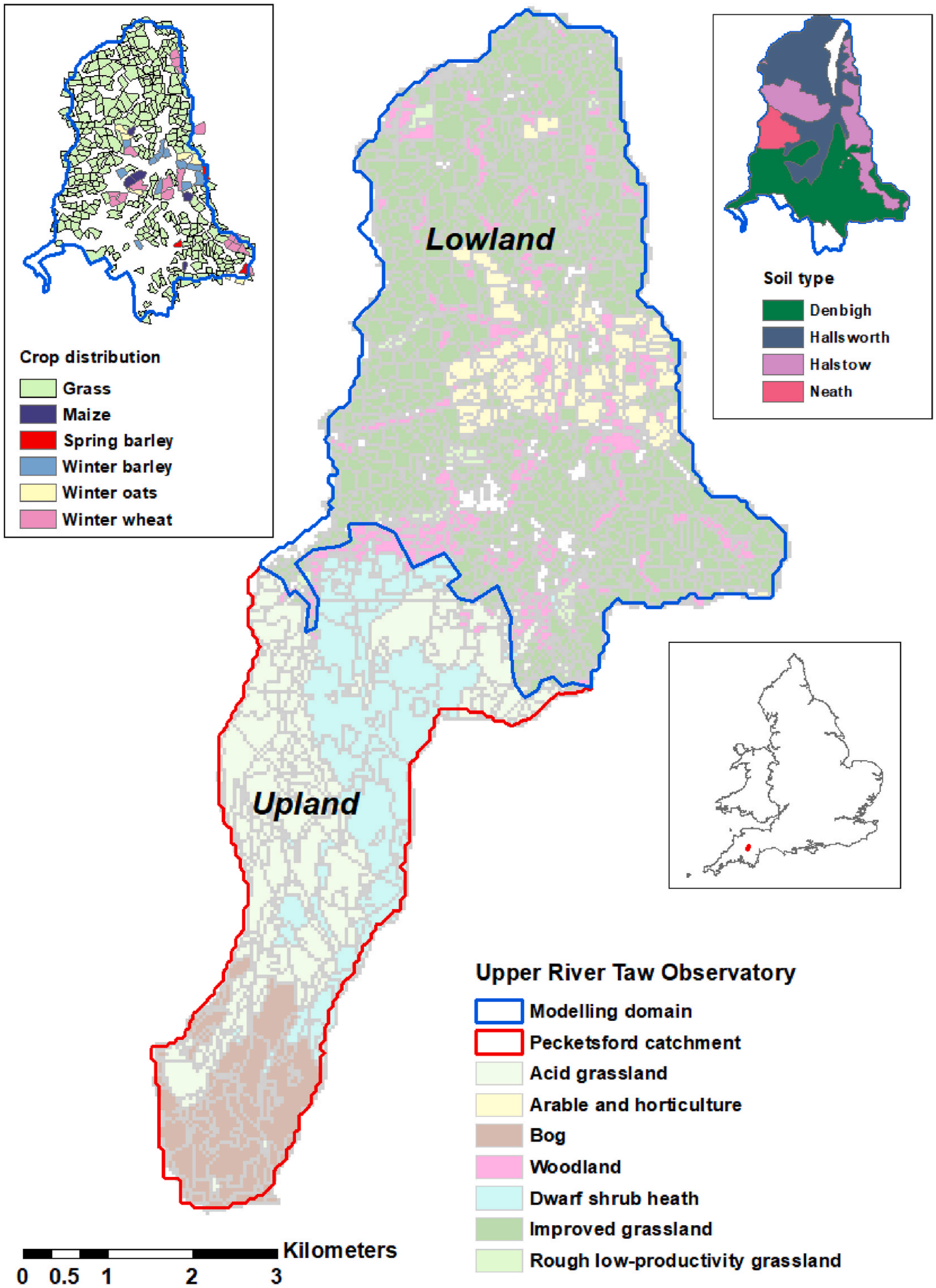

Fig. 1. Land cover, soils and major crop distribution in the study area.

modelling was performed for two representative time periods: (i) a baseline period spanning 1985 to 2015 (time period selected to represent the best available data for the study site) and (ii) a near-future period spanning 2021 to 2050. The selection of the near-future period was based on a desire to coincide with the timeline for the UK government net zero ambition by 2050. Three climate change scenarios were considered, namely: RCP2.6, RCP4.5 and RCP8.5. The daily bias-corrected weather data for future climate scenarios were based on the HadGEM2-ES model and downloaded from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP, 2022). Only data generated by the first realization, initialization, and physics (r1i1pi) of the climate model were used without considering its uncertainty. The atmospheric CO_2 concentration was set to 402 ppm initially in 2020 and increased progressively to 454, 489.3 and 539.8 ppm for RCP2.6, RCP4.5 and RCP8.5 in 2050, respectively.

For fertiliser applications to each crop, four rates were considered: BAU rates; low (10%) reduction of BAU rates; medium (30%) reduction of BAU rates, and high (50%) reduction of BAU rates. The BAU rates were estimated from published 5-year (2017–2021) average rates for individual crops for ‘Cereal’ farms and for IG on both lowland grazing and less favoured area (LFA) farms (Fertiliser Usage, 2022). The respective nitrogen fertiliser rates were 190, 146, 106, 178, 72, and 79 kg ha^{-1} for WW, WB, SB, WOSR, MZ and IG. In addition to synthetic fertiliser, 20 t ha^{-1} of fresh cattle farmyard manure (FYM) was assumed to be applied each year on the area of IG to account for the presence of livestock in the study area and the concomitant need to utilise manure. The nutrient content of this FYM was based on the UK nutrient management guide (AHDB, 2021) and assumed a nitrogen content of 6 kg t^{-1}, and an organic carbon content of 2400 kg ha^{-1}. Expert knowledge was used to adjust application frequency and timing dependent on the crop type involved and the actual annual rates applied. The actual dates used for the modelling simulations are provided in Table S1. The application rates of other nutrients, including phosphorus and potassium were assumed not to change for any of the fertiliser application rate scenarios. Accordingly, the application rates of these nutrients were estimated using multi-year averages (P_2O_5 of 39 kg ha^{-1} for MZ, 17 kg ha^{-1} for IG and between 25 and 29 kg ha^{-1} for the other crops included). On IG, the of FYM application rate was assumed not to change for any of the alternative fertiliser application scenarios.

On the basis of the above, there were 4 different climate scenarios (including one baseline for comparison), 3 different soil types, and 4 fertiliser application rates for each crop. This totalled 48 unique combinations for each crop. For IG, one extra soil series (i.e., Neath) was considered to account for the presence of this combination in the study area.

3.2. Model parameterisation and integration

To quantify multiple ecosystem services associated with the fertiliser application scenarios, an integrated modelling approach using the established agroecosystem models was adopted. In doing so, common input data were shared among the models and, more importantly, intermediate data and information were exchanged between the teams using each individual model to ensure internal consistency and to make full use of the modelled process dynamics at relevant temporal scales. The models comprised SPACSYS (Soil Plant Atmosphere Continuum System), CSM (Catchment Systems Model) and RothC. The interrelationships among the three agroecosystem models and their parameterisation are illustrated in Fig. 2.

The SPACSYS model required soil type and soil layers specific data to

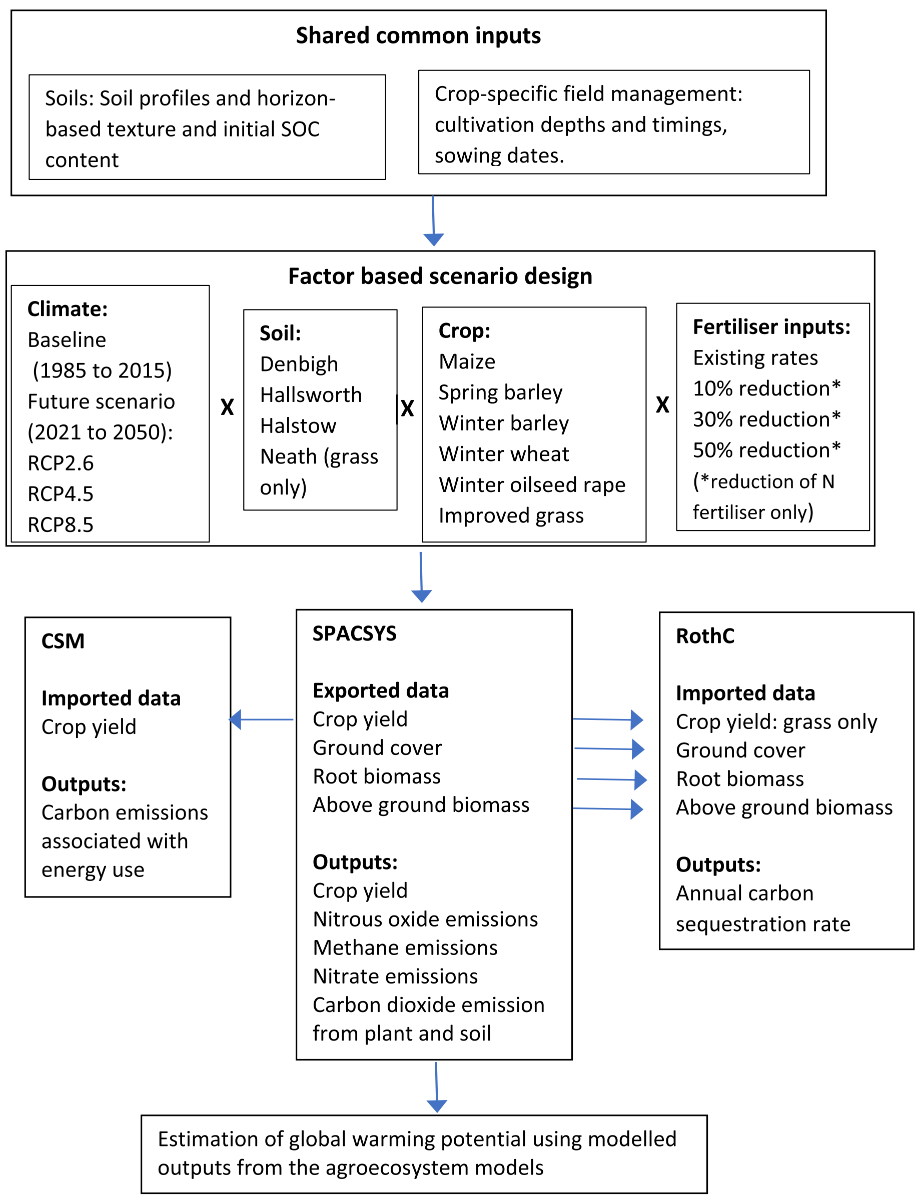

Fig. 2. Overview of the integration of the three agroecosystem models.

predict water, nutrient and gas movement through the soil-plant-atmosphere continuum. Full parameter descriptions for SPACSYS can be found in Wu et al. (2007). Soil physical (e.g., soil texture, bulk density, clay content), chemical (e.g., C and N contents) and hydraulic properties (e.g., saturated hydraulic conductivity, fitted van Genuchtens parameters for soil water release) for horizons A to C were taken from NatMapVector (NatMapVector, 2021). Soil depths varied from 75 cm for the Halstow series, to 90 cm for the Neath series and 135 cm for the Hallsworth and Denbigh series. For SPACSYS-based modelling, the soil profiles were divided into 7 to 8 subsections, with the upper 4 subsections being 10 cm in thickness and the remaining subsections varying between 20 and 35 cm. Soil data and parameters were interpolated based on the horizon-based data available. For carbon sequestration, only the topsoil layer (0–25 cm) was considered as it is the most dynamic part of the soil complex. Parameterised values for plant characteristics and growth patterns in SPACSYS were used without modifications for this study.

A single and dominant species of grass (i.e., ryegrass) was used to represent the vegetation on IG in the study area. All annual crops were ploughed to a depth of 20 cm on a selected date (10th September for WW and WB; 30th January for SB; 20th Apr for MZ; 30th July for WOSR). Sowing dates were a few weeks after ploughing and were fixed annually. Harvest dates were determined for each SPACSYS simulation as defined by physiological maturity. Because maize is used for silage in the study area, its harvesting date coincided with maximum aboveground biomass for each growing season. No scheduled ploughing and re-seeding were considered for the IG since surveys in the study area suggest significant variability in the frequency, timing and methods among lowland grazing farms. The SPACSYS simulations assumed two silage cuts a year on the 25th May and the 25th August.

For simulations using CSM (Zhang et al., 2022b), the arable crops were assumed to be grown on a typical cereal farm in a local waterbody (GB108050008250) with drained soil for arable and grassland use in an area with average annual rainfall between 900 and 1200 mm. For IG, typical management practices on a lowland grazing farm were adopted. These comprised three fertiliser applications per year, with the number of field passes adjusted to reflect the reductions in application rates. An extra field pass was added to account for spraying for weed control for all scenarios. Waterbody scale attributes within the CSM model, such as field boundary types and field drain efficiency were used without modification. Relevant field management, such as field passes associated with fertiliser application, were modified based on the scenario-specific fertiliser application regimes. All crops were assumed to have typical field and farm management routines, such as pesticide usage, harvesting dates, drying and crop storage. For the estimation of energy use associated with crop production for the different modelled scenarios, the embedded emissions from production of fertilisers and pesticides were included. The coefficients used for the conversion of fuel use to equivalent carbon emissions were 2.66 kg CO_2/litre for diesel, 0.52 kg CO_2 eq/kWh for electricity, 0.30 kg CO_2 eq/kWh for gas oil and 0.23 kg CO_2 eq/kWh for LPG.

The modified version of the RothC model was used in order to consider the specific quality of plant residues for the different crops under the humid temperate climatic conditions (Jebari et al., 2021). To evaluate soil carbon sequestration trends under the different scenarios, existing SOC concentrations for different soil horizons from the 'NatMap Carbon' data layer (Natmap Carbon, 2022) for arable and grass crops were combined with corresponding soil depth and bulk density to calculate SOC stocks. The estimated values for different combinations of soil types and arable and grass crops were used as the initial stocks for continuous cropping during the modelled time periods. Established pedo-transfer functions (Falloon et al., 1998; Weihermuller et al., 2013) were employed to allocate the total stocks to various carbon pools specified by the RothC model. Monthly carbon temporal distribution input patterns was based on earlier work by Smith et al. (2005) and DMP/RPM ratios were estimated using plant specific Neutral Detergent Fibre (NDF) values as described by Jebari et al. (2021) The NDS values were sourced from the feedpedia website (Heuzé et al., 2019) and ranged from 37 to 64% for WW, 42–62% for WB and SB, 13–31% for WOSR, 55–82% for MZ and 43–49% for IG.

SPACSYS predicted green leaf area index was used to characterise the land cover status, i.e., to specify if a month has vegetation cover or not for RothC. Annual root biomass and above ground biomass for different crops provided by SPACSYS were used to derive annual fresh carbon inputs. Here, predicted crop yields with BAU fertiliser rates, under baseline weather conditions, were used as inputs to existing empirical relationships (Hillier et al., 2009; Johnston et al., 2017) to calculate the annual fresh carbon inputs. The estimated fresh inputs were then compared against the corresponding total biomass (including above ground and root) with BAU fertiliser rates under baseline climate condition to quantify the proportion of biomass that becomes fresh carbon input for the year for each crop included in the RothC simulations. These proportions were assumed not to change among the different modelled scenarios. Scenario-specific crop yields predicted by SPACSYS were used in conjunction with the CSM model to estimate emissions associated with energy use on farm for product storage and necessary post-harvesting processing.

SPACSYS and RothC are field scale models, while CSM can generate multiple scale model outputs, i.e., it can generate outputs at field, farm and catchment scales. Virtual fields with unique crop, soil, climate and fertiliser application combinations were the base modelling unit for this work. SPACSYS, RothC and CSM operate at daily, monthly and annual time steps, respectively. Individual model outputs were aggregated to appropriate temporal scales to facilitate their integration with the other models, e.g., SPACSYS outputs were summarised to monthly scale to facilitate integration with RothC and to annual scale for integration with CSM.

3.3. Post-modelling data processing and statistical analysis

For SPACSYS and RothC modelling, annual estimates of all modelled outputs were extracted and then multi-year averages were calculated. To demonstrate the combined effects of multiple GHG emissions, the 20-year GWP (GWP20) was calculated using the following formula, since the time horizon for this better matched the policy target date of 2050 for net zero:

$$GWP20 = N_2O_{load} * 273 + CH_{4\,load} * 81.2 + EG + ER$$

where N_2O load and CH_4 load are the estimated annual emissions in kg ha^{-1} for nitrous oxide and methane, respectively. The coefficients used for the conversion of loads to GWP20 were based on the recent IPCC (Intergovernmental Panel on Climate Change) recommendation (Smith et al., 2021). EG represents the carbon emissions from in-field and on farm energy use expressed in kg CO_2-equiv. ER accounts for ecosystem respiration, including CO_2 emissions resulting from plant respiration and various soil carbon pools, including fresh organic matter, humus and associated microbial activity.

To examine the impacts associated with the fertiliser scenarios, the multi-year means from the model runs with BAU fertiliser rates under baseline climate conditions for different soils were used as the reference values. The ratios of scenario-based outputs to the corresponding reference values were estimated to assess relative change. Multifactor variance analysis, Spearman correlation and simple linear regression analysis were undertaken using SPSS between fertiliser rates and various outputs to assess the relationships and the effects of reductions in BAU fertiliser use.

4. Results

This section will firstly describe the characteristics of the selected climate data timeseries used for the scenario modelling and then summarise the effects of the fertiliser reduction scenarios under baseline weather conditions and future climate scenarios.

4.1. Baseline and projected climate data

The monthly temporal patterns for two key climate drivers, namely rainfall and air temperature, for the baseline period and near-future climate scenario are shown in Fig. 3. The baseline data match well with the monitored long-term (1981–2010) rainfall and temperatures at the North Wyke weather station which is inside the study area (North Wyke station). The maximum monthly differences were <8 mm for rainfall and <0.5 °C for temperature.

Temperature increases were predicted for all months relative to baseline conditions. The most noticeable increases were predicted between June and September, wherein an increase of >2 °C was predicted for the RCP2.6 and RCP8.5 scenarios. Similar magnitudes of increase were only predicted for August and September in the case of the RCP4.5 scenario. The overall annual increase was predicted to be between 1.3 and 1.6° for all scenarios and the biggest increase was, as expected, predicted for RCP8.5. These projected changes are in similar ranges to those reported by UKCP18 for the southwest administration area where the study catchment is located (UKCP18, 2022); estimated median increase of between 1 and 1.3°c and a corresponding 95th percentile increase of between 1.9 and 2.3 °C for the 3 scenarios. As for rainfall, a substantial increase was predicted across the year, with mean annual increases of 48%, 35% and 35% relative to baseline for RCP2.6, RCP4.5 and RCP8.5, respectively. These increases are much higher than the UKCP18 projections for the study region, which suggest an increase in winter rainfall of ~28% and in summer a rainfall increase of ~20% (95th percentiles), respectively. These differences are partly due to the potential influences of localised factors, including elevated terrain and the effects of the Dartmoor upland microclimate in the headwaters of the study catchment. The highest increases in rainfall were projected to be in the winter period. This seasonal trend agreed with the UKCP18 projections. In summary, the climate data used suggest increases in average temperatures and higher rainfall, as projected by UKCP18.

4.2. Modelled outputs under baseline climate conditions with BAU fertiliser rates

Modelled key annual outputs under baseline climate with BAU fertiliser management are shown in Table 1. Variations for individual crops reflect the effects of growing individual crops in different soil types in the study area. Relatively speaking, the predicted yields for WOSR and

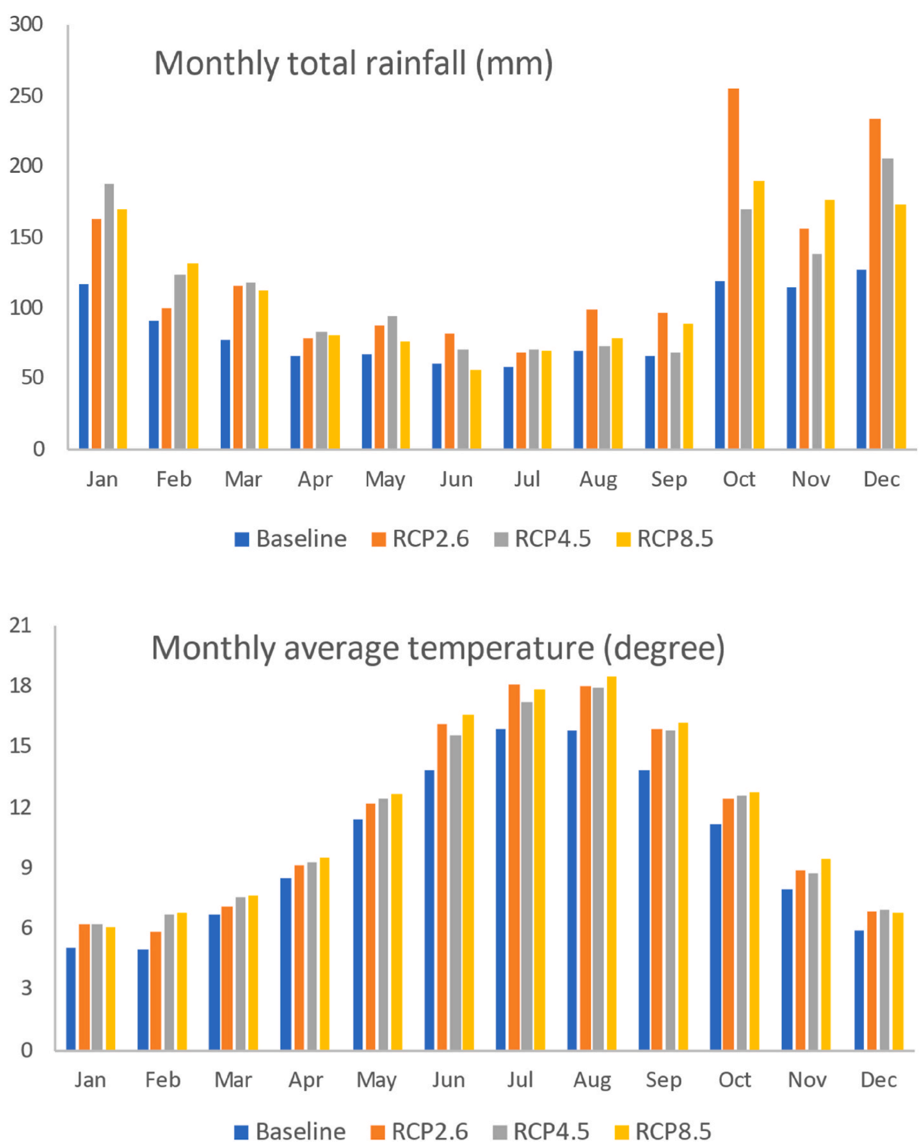

Fig. 3. Monthly rainfall and air temperatures for the baseline and near-future climates.

Table 1
Modelled annual impacts (per hectare) of BAU fertiliser management under baseline climate.

Crop[a]	Summary statistics	Yield t	N_2O emissions kg N	CH_4 emissions kg C	SOC rate*** kg C	Energy use kg CO_2-eq	GWP20 kg CO_2-eq
WW	Minimum	7.0	0.31	1.1	−236.0	1890	8772
	Median	7.5	0.80	1.2	−125.6	1900	8850
	Maximum	7.6	0.92	1.5	22.2	1901	9192
	STD	0.3	0.32	0.2	129.6	5.8	223
	CV (%)	4.4	40.3	16.9	103.2	0.3	2.5
SB	Minimum	4.9	0.39	2.2	−457.1	961	6456
	Median	5.0	0.86	2.2	−340.8	963	6863
	Maximum	5.5	1.40	2.3	−213.2	979	7574
	STD	0.3	0.51	0.0	122.0	10	566
	CV (%)	6.8	58.5	2.1	35.8	1.0	8.2
WB	Minimum	5.9	0.31	0.9	−378.6	1681	6705
	Median	6.1	0.92	1.0	−266.7	1816	7008
	Maximum	6.3	1.31	1.3	−117.8	1929	7576
	STD	0.2	0.50	0.2	130.8	124	442
	CV (%)	3.6	54.6	19.0	49.1	6.8	6.3
WOSR	Minimum	2.4	0.28	0.2	−150.6	1759	3642
	Median	2.5	0.29	0.2	−123.9	1764	3665
	Maximum	3.1	0.41	0.3	54.7	1780	4130
	STD	0.4	0.07	0.1	111.7	11	276
	CV (%)	14.7	23.5	33.4	90.1	0.6	7.5
MZ[b]	Minimum	8.4	0.17	0.9	−138.3	1860	5807
	Median	9.1	0.34	0.9	−65.1	1960	6754
	Maximum	10.9	0.50	0.9	25.0	2191	7725
	STD	1.3	0.17	0.0	81.8	170	959
	CV (%)	14.2	48.4	1.9	125.6	8.7	14.2
IG	Minimum	9.3	1.06	34.2	1123.6	768	20336
	Median	9.3	2.89	36.3	1308.6	768	22493
	Maximum	10.2	2.99	99.1	1309.4	768	25394
	STD	0.5	1.09	36.9	107.1	0	2121
	CV (%)	5.7	37.56	101.7	8.2	0	9.4

[a] WW = winter wheat; SB = spring barley; WB = winter barley; WOSR = winter oilseed rape; MZ = maize and IG = improved grass.
[b] MZ yield includes both grains and above ground biomass; *** negative values indicate the loss of SOC and positive values indicate an increase in SOC.

MZ exhibited higher coefficients of variation (∼14%) than the other crops included in the scenarios (∼5%). More detailed examination suggested that higher yields of WOSR and MZ are expected at sites with Denbigh soil than those with Halstow soil.

Simulated GHG emissions, especially for N_2O, exhibited much higher coefficients of variation. The lowest variation (24%) was associated with WOSR, and the corresponding variations for all other crops were >37%. For crops in the latter group, the emission rates were ranked in the following order: Denbigh > Hallsworth > Halstow. WOSR was predicted to have the lowest emission rates. The highest rate was predicted for IG, which can be attributed to the addition of FYM. The reported low NDS values for WOSR (Thiebeau et al., 2021) can contribute to its low emissions as suggested by recent studies (e.g., Abalos et al., 2022). Apart from IG, the predicted emission values were low. Clear seasonal variations were evident in the predictions with winter crops have higher values (>15%) than spring crops (<5%), such as MZ and SB.

The role of crop-specific residue management introduces another uncertainty for the SOC sequestration rates. For some crops, switches from the loss of SOC to the sequestration of SOC were predicted. In contrast, the predicted energy use associated with the production of each crop exhibited consistently smaller variation (coefficients of variation all <10%). Low variations were also generally observed for the

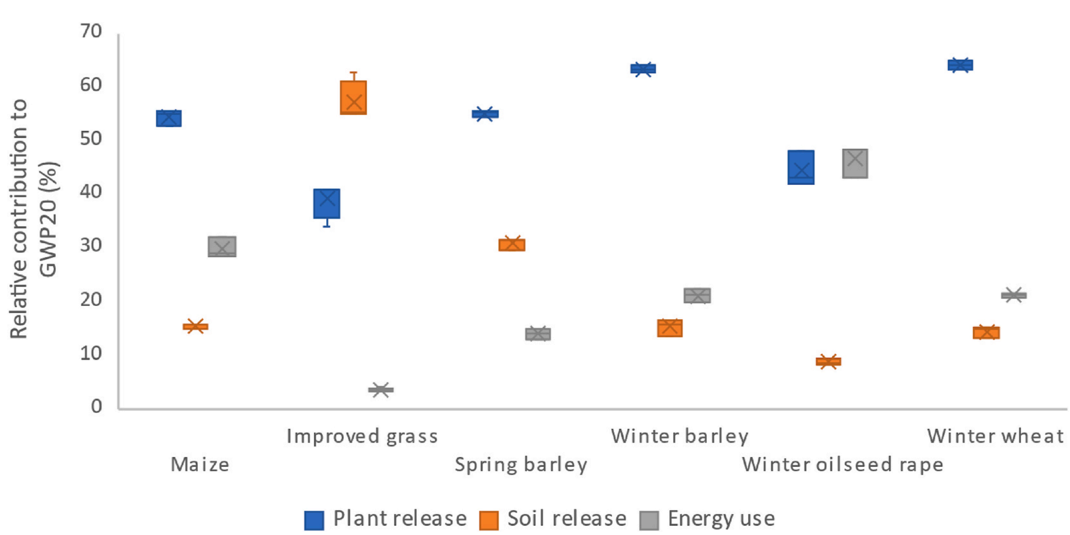

Fig. 4. Relative contribution of different sources to GWP20 under baseline climate.

calculated GWP20 though there was some variation among crops. The relative contributions from multiple sources to GWP20 are shown in Fig. 4 wherein CO_2 emissions were grouped into three broad categories: plant release, soil release and energy use. While plant release is the dominant source for most crops, energy use from in-field and on-farm activities are also significant, especially for MZ and WOSR (>30%).

4.3. Impacts of BAU fertiliser rates under future climate

Examination of the effects of continued adoption of BAU fertiliser rates under the projected future climate conditions suggested that there are subtle responses from the different soil types in the study area. Calculated average changes relative to those for the baseline climate for the different soil types are shown in Table 2. For crop yields, the model simulations suggested a slight decrease (5%) for WOSR, a reasonably substantial increase for spring crops (13–20% for SB and 31–51% for MZ) and a slight increase for other winter crops and IG. Some enhanced root and aboveground biomass accumulation were predicted for most climate scenarios, but the more substantial increases were predicted for the former (5–20% increase vs −0.4%–13% for aboveground biomass).

In the case of GHG emissions, the modelled outputs for continuation of BAU fertiliser use under future climate suggested an overall reduction in N_2O emissions but an increase in CH_4 emissions. The lowest reductions of the former were reported for WOSR, MZ and IG (mostly <15%). For the other crops, the reductions in N_2O emissions varied between 22 and 28%. For these crops, IG and WOSR were predicted to have higher increases (<35%) in nitrous oxide losses than the rest.

While most modelled outputs exhibited no scenario dependent pattern, consistent patterns were shown by SOC loss rates. While RCP8.5 based scenarios tended to have slightly higher SOC loss rates relative to those for RCP2.6, the increases in SOC loss rates were much higher under the RCP4.5 scenario. This can be attributed to the more conducive combination of soil moisture and temperature conditions for SOC decomposition under this climate scenario. The limiting effects of extreme temperatures and soil moisture conditions on SOC decomposition has also been highlighted by work at European scale (Smith et al., 2005).

In the case of the estimated GWP20, no significant changes were predicted for almost all arable crops. Here, the only exception is maize under the RCP8.5 scenario where a 14% increase is predicted. The increase in FYM-related emissions also resulted in a >10% increase in GWP20 for all scenarios.

4.4. Impacts of reductions in BAU fertiliser rates under baseline climate

Table 3 summarises the impacts of the fertiliser reduction scenarios under baseline climate, relative to BAU application rates, where root biomass and above ground biomass values for different crops from SPACSYS were also included. Though there is generally a negative linear relationship between fertiliser reduction and crop yields, the magnitudes of relative changes are, as expected, crop dependent. Limited variations were reported among the different soil types for each fertiliser reduction scenario. Simulated grass yields exhibited the least change as the maximum fertiliser reduction scenario (R50) only resulted in a ~10% yield reduction. For the other crops, the outputs suggested that the 10% reduction fertiliser scenario (R10) resulted in a ~5% reduction in crop yields. More variation was predicted for the 30% reduction scenario, ranging from 15% for barley, 20% for WOSR and MZ to nearly 30% for WW. For the R50 scenario, 30%–40% reductions in crop yields were predicted. A strong linear relationship between crop yield and aboveground biomass was observed (Fig. 5). In comparison, predicted root biomass exhibited smaller ranges of change and a weak relationship with crop yields. This means that reductions in fertiliser rates under the baseline climate could lead to significantly lower aboveground biomass accumulation and farm income.

For N_2O emissions, the predicted responses following fertiliser reduction under baseline climate are affected by the interaction of crop types, soil type and fertiliser rates. With a 50% reduction of BAU fertiliser application rates, the average reduction in N_2O emissions, relative to BAU, ranged from 36% for WOR to 55% for MZ. However, there were significant variations based on soil type. Multi-factor variance analysis for each crop indicated that the soil types have significant impacts on N_2O emissions for all crops except for WW, which has an estimated significance level at 0.071. In comparison, smaller reductions were predicted for CH_4 emissions and here, there was less influence from soil type with variance analysis indicating there were no statistically significant differences among the different soils for WW, SB and MZ. Insignificant changes were reported for CH_4 emissions from IG.

For SOC, no significant changes were predicted for IG. For arable crops, simulations with the Halstow soil series exhibited a switch from low SOC sequestration to substantial SOC loss for some crops, e.g., WW. All other arable crops followed the same ranking in terms of the predicted increase in SOC loss: Denbigh < Hallsworth < Halstow. The predicted large increases in SOC loss for the Halstow soil are attributed to the unique combination of high clay content and low initial SOC content. The roles of both soil properties have been highlighted in

Table 2
Ratios for the changes in various modelled outcomes for the continuation of BAU fertiliser applications under future climate scenarios.

Crop type[a]	Climate change scenario	Yield	Root biomass	Aboveground biomass	Nitrous oxide emissions	Methane emissions	Energy use	SOC sequestration rate	GWP20
WW	RCP2.6	1.06	1.16	1.07	0.76	1.38	1.00	0.89	1.02
WW	RCP4.5	1.06	1.10	1.04	0.73	1.25	1.00	7.69	0.99
WW	RCP8.5	1.09	1.20	1.10	0.83	1.28	1.01	1.25	1.03
SB	RCP2.6	1.13	1.10	1.07	0.78	1.21	1.02	0.52	1.04
SB	RCP4.5	1.14	1.06	1.07	0.72	1.13	1.02	1.56	1.03
SB	RCP8.5	1.20	1.16	1.13	0.84	1.10	1.03	0.65	1.06
WB	RCP2.6	1.04	1.10	1.05	0.69	1.38	0.98	0.58	0.99
WB	RCP4.5	1.03	1.05	1.02	0.70	1.32	0.98	2.29	0.99
WB	RCP8.5	1.08	1.14	1.09	0.76	1.34	1.00	0.87	1.01
WOSR	RCP2.6	0.94	1.09	1.00	0.89	1.84	1.00	2.26	1.04
WOSR	RCP4.5	0.94	1.05	0.96	1.05	2.05	1.00	6.14	1.02
WOSR	RCP8.5	0.96	1.13	1.02	0.97	1.55	1.00	3.04	1.04
MZ	RCP2.6	1.51	1.14	1.03	0.86	1.42	1.05	2.30	1.08
MZ	RCP4.5	1.31	1.06	0.98	0.81	1.22	1.01	10.05	0.99
MZ	RCP8.5	1.49	1.20	1.10	0.94	1.22	1.09	3.33	1.14
IG	RCP2.6	1.05	NA	NA	0.98	1.87	1.00	0.73	1.18
IG	RCP4.5	1.01	NA	NA	0.92	1.49	1.00	0.59	1.10
IG	RCP8.5	1.02	NA	NA	0.99	1.66	1.00	0.57	1.12

[a] WW = winter wheat; SB = spring barley; WB = winter barley; WOSR = winter oilseed rape; MZ = maize and IG = improved grass.

Table 3
Ratios for the changes in various modelled outcomes between the different fertiliser reduction scenarios and BAU under baseline climate.

Crop type[a]	Fertiliser reduction scenario[b]	Soil type[c]	Yield	Root mass	Aboveground mass	Nitrous oxide emissions	Methane emissions	Energy use	SOC sequestration rate	GWP20
WW	R10	D	0.94	0.98	0.95	0.89	0.96	0.93	1.10	0.96
		H1	0.93	0.98	0.94	0.84	1.01	0.93	1.22	0.96
		H2	0.93	0.97	0.94	1.00	1.00	0.93	1.27	0.99
	R30	D	0.73	0.91	0.76	0.60	0.83	0.78	1.50	0.81
		H1	0.72	0.92	0.75	0.85	0.83	0.78	1.93	0.81
		H2	0.70	0.93	0.74	0.91	0.84	0.78	5.46	0.81
	R50	D	0.57	0.83	0.61	0.48	0.68	0.64	1.82	0.66
		H1	0.56	0.83	0.59	0.57	0.64	0.64	2.55	0.66
		H2	0.54	0.83	0.59	0.68	0.69	0.64	8.97	0.66
SB	R10	D	0.97	0.98	0.97	0.92	0.92	0.95	1.02	0.98
		H1	0.96	0.98	0.97	0.93	0.99	0.95	1.03	1.01
		H2	0.96	0.98	0.96	0.84	0.94	0.95	1.05	1.03
	R30	D	0.88	0.93	0.89	0.78	0.84	0.84	1.07	0.89
		H1	0.85	0.93	0.87	0.77	0.94	0.83	1.11	0.87
		H2	0.85	0.93	0.87	0.72	1.03	0.83	1.17	0.88
	R50	D	0.67	0.87	0.72	0.51	0.93	0.71	1.18	0.74
		H1	0.57	0.85	0.63	0.47	0.99	0.69	1.30	0.69
		H2	0.58	0.83	0.64	0.37	0.91	0.69	1.45	0.69
WB	R10	D	0.96	0.97	0.96	0.90	0.91	0.88	1.05	0.94
		H1	0.95	0.96	0.95	0.87	0.88	0.93	1.07	0.94
		H2	0.96	0.97	0.96	0.99	0.96	1.09	1.13	0.97
	R30	D	0.90	0.91	0.91	0.68	0.81	0.78	1.11	0.85
		H1	0.87	0.89	0.88	0.74	0.80	0.79	1.18	0.84
		H2	0.88	0.88	0.90	0.91	0.86	0.81	1.38	0.86
	R50	D	0.78	0.81	0.78	0.52	0.70	0.64	1.25	0.72
		H1	0.71	0.78	0.73	0.56	0.67	0.65	1.40	0.70
		H2	0.72	0.76	0.74	0.67	0.71	0.66	1.89	0.72
WOSR	R10	D	0.94	0.97	0.95	0.88	0.90	0.92	1.16	0.92
		H1	0.93	0.97	0.93	0.95	0.98	0.92	1.24	0.93
		H2	0.92	0.96	0.92	0.89	0.95	0.92	0.34	0.92
	R30	D	0.82	0.90	0.81	0.76	0.85	0.77	1.65	0.79
		H1	0.75	0.89	0.76	0.83	0.92	0.77	1.81	0.81
		H2	0.74	0.88	0.74	0.80	0.82	0.76	2.07	0.79
	R50	D	0.62	0.81	0.62	0.57	0.79	0.61	2.33	0.64
		H1	0.56	0.78	0.57	0.71	0.86	0.61	3.27	0.66
		H2	0.53	0.76	0.54	0.62	0.75	0.61	3.86	0.63
MZ	R10	D	0.94	0.97	0.94	0.93	0.93	0.94	1.21	0.96
		H1	0.95	0.97	0.95	0.87	0.95	0.95	1.33	0.96
		H2	0.94	0.97	0.94	0.97	0.96	0.94	0.09	1.00
	R30	D	0.80	0.91	0.80	0.72	0.79	0.81	1.69	0.82
		H1	0.81	0.89	0.81	0.76	0.83	0.82	2.34	0.82
		H2	0.80	0.87	0.80	0.83	0.80	0.81	3.56	0.83
	R50	D	0.65	0.81	0.65	0.57	0.64	0.68	2.27	0.68
		H1	0.70	0.80	0.70	0.56	0.72	0.71	3.30	0.71
		H2	0.68	0.76	0.68	0.70	0.68	0.70	6.11	0.72
IG	R10	D	0.98			0.92	1.07	0.93	0.99	0.99
		H1	0.98			0.89	1.08	0.93	0.99	1.01
		H2	0.98			0.99	1.02	0.93	0.99	1.01
	R30	D	0.92			0.70	1.02	0.78	0.96	0.95
		H1	0.94			0.68	1.07	0.78	0.97	0.98
		H2	0.94			0.86	0.96	0.78	0.97	0.98
	R50	D	0.88			0.55	0.97	0.64	0.93	0.91
		H1	0.89			0.51	1.05	0.64	0.95	0.95
		H2	0.89			0.77	0.94	0.64	0.95	0.95

[a] WW = winter wheat; SB = spring barley; WB = winter barley; WOSR = winter oilseed rape; MZ = maize and IG = improved grass.
[b] R10 = 10% reduction; R30 = 30% reduction and R50 = 50% reduction.
[c] D = Denbigh; H1 = Hallsworth; H2 = Halstow.

existing studies (e.g., Jebari et al., 2022). The average responses across the soil types suggested that WW exhibited the highest increase in SOC loss (3 times), whilst SB exhibited the lowest increase in SOC loss (30%).

For all the crops modelled, the expected reduction in energy use associated carbon emissions varied between 3 and 8%, 17–23% and 30–39% for the R10, R30 and R50 scenarios, respectively. The greatest reductions were predicted for winter crops. Predicted changes in GWP20 generally followed the same pattern.

In summary, reductions in fertiliser application rates under baseline climate generated lower GHG emissions, energy use and GWP20, but with a yield penalty, subdued biomass accumulation and elevated SOC loss. Some of these predicted changes demonstrated stronger soil type dependencies than others.

4.5. *Impacts of reductions in BAU fertiliser rates under future climate*

Estimated regression slopes between fertiliser rates and values of modelled various variables are shown in Table 4 which summarises the scenario results for changes in fertiliser application rates under future climate. Correlation analysis (c.f. Supplementary Table S2) for each unique combination of climate condition, soil type and crop type were, in the main, $R > 0.85$; i.e., the responses of the modelled variables exhibited significant linear relationships with the change in application rates. The only exception here was for the CH_4 emissions for SB, where

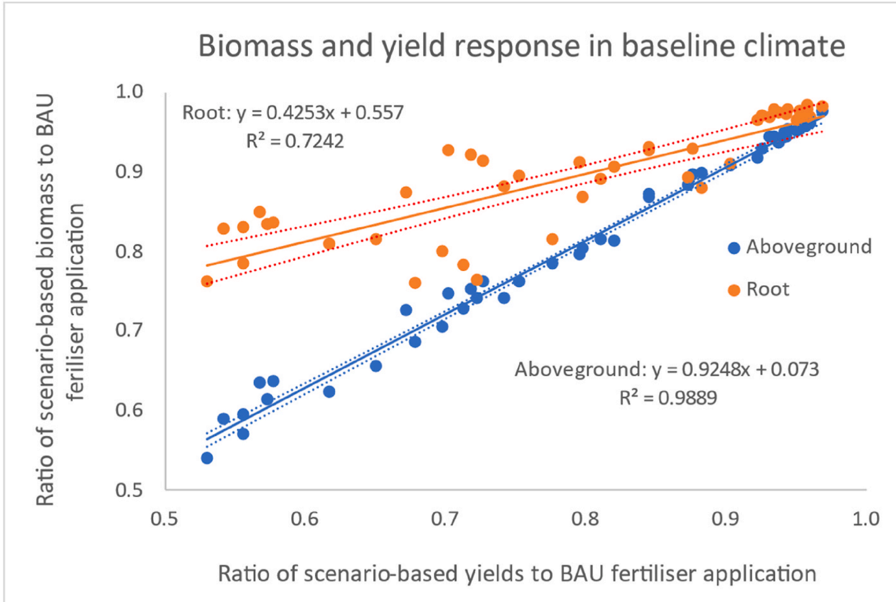

Fig. 5. Relationship between relative yield response and crop biomass under baseline climate.

weaker correlations (R < 0.7) were found.

The calculated regression slope values for the changes in the modelled responses for the fertiliser reduction scenarios (Table 4) suggested that variations between the different combinations of soil types and climate change scenarios were small for crop yields, aboveground biomass and root biomass. For crop yields, the estimated regression slope values were much higher (generally >3) for WW, SB and IG. Slopes of <2 were generated for MZ and WOSR. For aboveground biomass, the slopes were mostly between 2 and 3 except for MZ, which was characterised by much higher values (>6). In comparison, more variations in regression slopes were estimated for root biomass with values varying between <0.1 for WW and >1.2 for MZ.

The change of slopes for energy use were closely associated with the predicted changes in crop yield. Maize exhibited steeper slope values (>15) than the remaining crops (5–10). In the case of SOC, a general pattern was observed for all crops. Here, the smallest slopes were associated with the RCP4.5 climate scenario. Substantial differences were also exhibited for GWP20. The median values of slopes for all scenarios considered are lower for winter crops (16 for WOSR, 29 for WB, 35 for WW) and slightly higher for spring crops (43 for SB and 68 for MZ). These slopes show limited variation (<15%) among scenarios for each crop. More significant variations among scenarios were reported for IG with a range between 31% and 78%.

Statistical tests (Table 5) were undertaken to compare the estimated slope values for the three climate change scenarios against the corresponding values for the same soil type under baseline climate. Here, the null hypothesis was that the regression slope values for the scenarios are the same as those for the baseline period. The results suggested that there were no statistically significant differences for most response variables and most arable crops examined, except for changes in SOC, CH_4 emissions and GWP20. In the case of SOC, significant differences were confirmed for WW and WOSR under all scenarios. Statistically, significant differences were also observed for SB, WB and IG under the RCP4.5 scenario. For CH_4 emissions, significant differences were mostly predicted for winter crops. For GWP20, statistically significant changes were consistently confirmed for MZ in different soils under the RCP8.5 climate scenario, but only on Halstow soil for IG under the same climate scenario.

5. Discussion

The use of synthetic fertilisers is one of the key characteristics of modern and intensive farming. Through intertwined nitrogen and carbon cycling across multiple scales, the changes of fertilization rates are expected to have complex effects across different components of the atmosphere-plant-soil continuum.

5.1. Overall impacts from integrated modelling

The integrated modelling approach implemented in this study has enabled the scenario-based evaluation of multiple ecosystem services, including provisioning and regulating services as indicated by crop yields, biomass accumulation, GHG emissions, and SOC sequestration. The comprehensive assessment of multiple services with internally coherent mass and energy flow makes it possible to identify potential trade-offs and synergies.

The BAU fertiliser management practices are based on the survey of commercial farms which could be considered as the most suitable practices for the crops under current environmental conditions. So, it is not surprising that the reductions of fertiliser inputs have resulted in the linear reductions of crop yields and aboveground biomass (Maaz et al., 2021) instead of the classical yield plateau, and even reduction in yields associated with high fertiliser inputs (c.f., Dhakal and Lange, 2021). Simulated outputs for the projected climates under BAU management indicate a very modest increase in yield for most winter crops (<10%) and larger increases (12–55%) for spring crops. This is within the magnitude of predicted relative change reported elsewhere for the UK by Wilcox and Makowski (2014) wherein an average change of 6%, varying between −100 and 64%, was estimated. However, the predicted changes are significantly lower than those simulated for barley in UK by Yawson et al. (2016) wherein a 100% increase was forecast for southwest England. Turning to grass, no significant reduction in yield was predicted, which is consistent with the findings of Addy et al. (2022) which related to southeast England with a dry and warm climate.

Without the change of crop residue management practices, the SOC sequestration rates are decreasing because less plant materials are available to be incorporated into the soil (Xia et al., 2018). Indeed, nitrogen fertilisers are known to stimulate plant productivity e.g., an increase in gross ecosystem photosynthesis (Xia et al., 2009), leaf area index and shoot/root ratios (Cheng et al., 2009), when there is ample

Table 4
Estimated linear regression slopes between fertiliser application rate (kg ha^{-1}) and modelled annual response variables (kg). The maximum fertiliser rate for each crop is the corresponding BAU rate and the minimum fertiliser rate is 50% of the BAU rate. 4 paired samples were used to derive the slope values shown.

Crop type[a]	Soil type[b]	Climate Scenario	Yield	Root biomass	Above-ground mass	Nitrous oxide emissions	Methane emissions	Energy use	SOC sequestration rate	GWP20
WW	D	Baseline	3.55	0.08	2.17	0.0052	0.0037	7.25	2.1	33.5
	D	RCP2.6	3.89	0.09	2.34	0.0036	0.0064	7.31	1.4	35.1
	D	RCP4.5	3.96	0.09	2.33	0.0033	0.0046	7.32	0.4	35.3
	D	RCP8.5	4.10	0.10	2.52	0.0042	0.0062	7.34	1.3	39.8
	H1	Baseline	3.37	0.08	2.10	0.0031	0.0048	7.22	2.1	32.7
	H1	RCP2.6	3.82	0.09	2.34	0.0022	0.0075	7.29	1.5	32.1
	H1	RCP4.5	3.74	0.09	2.25	0.0020	0.0063	7.28	0.4	37.5
	H1	RCP8.5	3.90	0.10	2.42	0.0027	0.0068	7.31	1.3	36.7
	H2	Baseline	3.76	0.07	2.26	0.0011	0.0053	7.29	2.2	33.1
	H2	RCP2.6	4.11	0.09	2.47	0.0011	0.0078	7.35	1.5	34.7
	H2	RCP4.5	4.25	0.09	2.46	0.0010	0.0071	7.37	0.4	34.7
	H2	RCP8.5	4.41	0.10	2.66	0.0009	0.0092	7.40	1.4	37.6
SB	D	Baseline	3.35	0.11	2.28	0.0128	0.0031	5.39	1.5	37.6
	D	RCP2.6	3.61	0.11	2.35	0.0098	−0.0088	5.46	1.0	40.9
	D	RCP4.5	3.85	0.11	2.45	0.0092	−0.0028	5.53	0.3	41.1
	D	RCP8.5	4.35	0.13	2.92	0.0113	0.0062	5.68	1.1	45.1
	H1	Baseline	3.96	0.12	2.74	0.0085	0.0008	5.57	1.9	42.6
	H1	RCP2.6	4.60	0.13	3.06	0.0082	−0.0012	5.76	1.4	48.6
	H1	RCP4.5	4.79	0.12	3.08	0.0082	0.0032	5.81	0.4	45.4
	H1	RCP8.5	5.06	0.14	3.39	0.0101	0.0023	5.89	1.4	51.8
	H2	Baseline	3.82	0.13	2.67	0.0044	0.0021	5.53	1.8	40.1
	H2	RCP2.6	4.40	0.14	2.96	0.0037	−0.0058	5.70	1.3	43.4
	H2	RCP4.5	4.55	0.13	2.91	0.0026	0.0075	5.74	0.4	41.3
	H2	RCP8.5	4.70	0.15	3.11	0.0039	0.0048	5.79	1.2	47.6
WB	D	Baseline	1.85	0.20	1.75	0.0113	0.0038	9.06	1.2	28.0
	D	RCP2.6	2.26	0.23	2.09	0.0063	0.0060	9.86	0.8	28.1
	D	RCP4.5	2.21	0.21	2.04	0.0070	0.0059	9.90	0.2	29.7
	D	RCP8.5	2.55	0.24	2.37	0.0084	0.0065	10.22	0.8	32.4
	H1	Baseline	2.24	0.21	2.04	0.0054	0.0042	8.84	1.4	28.2
	H1	RCP2.6	2.75	0.25	2.48	0.0043	0.0062	9.59	1.0	30.7
	H1	RCP4.5	2.65	0.23	2.39	0.0043	0.0059	9.46	0.3	28.3
	H1	RCP8.5	2.87	0.25	2.61	0.0047	0.0057	9.62	0.9	30.2
	H2	Baseline	2.28	0.23	2.02	0.0014	0.0051	9.19	1.4	26.0
	H2	RCP2.6	2.87	0.27	2.47	0.0013	0.0084	10.38	1.0	30.8
	H2	RCP4.5	2.72	0.25	2.35	0.0010	0.0089	10.29	0.3	29.2
	H2	RCP8.5	3.10	0.29	2.68	0.0008	0.0090	10.35	0.9	30.7
WOSR	D	Baseline	1.30	0.69	2.73	0.0013	0.0003	7.81	2.3	16.5
	D	RCP2.6	1.26	0.77	2.86	0.0012	0.0011	7.80	1.2	16.9
	D	RCP4.5	1.22	0.71	2.68	0.0012	0.0013	7.79	0.4	16.3
	D	RCP8.5	1.32	0.81	3.10	0.0012	0.0009	7.82	1.1	16.5
	H1	Baseline	1.18	0.66	2.36	0.0009	0.0004	7.77	3.1	13.8
	H1	RCP2.6	1.12	0.76	2.39	0.0011	0.0008	7.76	0.7	14.1
	H1	RCP4.5	1.14	0.71	2.27	0.0012	0.0012	7.76	−0.2	14.1
	H1	RCP8.5	1.15	0.79	2.42	0.0012	0.0006	7.77	0.5	14.0
	H2	Baseline	1.33	0.75	2.71	0.0016	0.0009	7.82	2.4	15.1
	H2	RCP2.6	1.28	0.88	2.78	0.0005	0.0017	7.80	1.0	16.0
	H2	RCP4.5	1.21	0.81	2.51	0.0017	0.0017	7.79	0.1	15.9
	H2	RCP8.5	1.31	0.88	2.74	0.0012	0.0015	7.81	0.8	15.4
MZ	D	Baseline	1.20	1.22	9.35	0.0061	0.0092	19.64	4.8	69.4
	D	RCP2.6	1.81	1.58	9.52	0.0048	0.0143	20.65	2.7	75.8
	D	RCP4.5	1.76	1.61	9.36	0.0047	0.0131	20.37	0.7	74.4
	D	RCP8.5	1.78	1.58	10.32	0.0050	0.0120	21.66	2.5	83.7
	H1	Baseline	0.99	1.22	6.81	0.0040	0.0073	16.05	4.2	56.8
	H1	RCP2.6	1.75	1.65	8.31	0.0032	0.0125	19.00	2.7	69.4
	H1	RCP4.5	1.53	1.52	7.71	0.0033	0.0117	17.93	0.6	61.7
	H1	RCP8.5	1.73	1.64	8.80	0.0040	0.0117	19.60	2.4	70.4
	H2	Baseline	0.90	1.34	6.66	0.0014	0.0087	15.74	4.3	49.1
	H2	RCP2.6	1.60	1.70	7.60	0.0012	0.0144	17.88	2.3	66.6
	H2	RCP4.5	1.36	1.52	6.74	0.0012	0.0114	16.43	0.4	52.9
	H2	RCP8.5	1.41	1.53	7.48	0.0024	0.0122	17.48	1.8	61.9
IG	D	Baseline	3.03			0.0383	0.0418	7.66	2.1	57.3
	D	RCP2.6	3.44			0.0324	0.0386	7.66	1.7	51.9
	D	RCP4.5	3.11			0.0296	0.0921	7.66	1.3	61.9
	D	RCP8.5	3.52			0.0324	0.1635	7.66	1.6	54.3
	H1	Baseline	2.67			0.0405	−0.0228	7.66	1.8	30.6
	H1	RCP2.6	3.08			0.0305	0.1464	7.66	1.5	47.2
	H1	RCP4.5	2.87			0.0307	0.0231	7.66	1.3	40.5
	H1	RCP8.5	3.00			0.0329	0.0749	7.66	1.3	43.7
	H2	Baseline	2.85			0.0067	0.1804	7.66	1.9	33.1
	H2	RCP2.6	3.13			0.0075	0.2276	7.66	1.5	57.9
	H2	RCP4.5	3.18			0.0068	0.2626	7.66	1.3	59.6
	H2	RCP8.5	3.55			0.0088	0.3698	7.66	1.6	78.4

[a] WW = winter wheat; SB = spring barley; WB = winter barley; WOSR = winter oilseed rape; MZ = maize and IG = improved grass.
[b] D = Denbigh; H1 = Hallsworth; H2 = Halstow.

supply of water to the ecosystem (Harpole et al., 2007). The interplay between fertiliser management and SOC has also been reviewed by Han et al. (2016). The reduction of fertiliser application rates, however, does result in reduced direct emissions of N_2O and energy consumption related CO_2 emissions. This expected reduction was also reported by Zhang et al. (2022a) when different rates of nitrogen application were simulated on the Loess plateau in China. The modelled increase in CH_4 emissions for IG further demonstrates the trade-off between increased SOC rates and GHG emissions if organic manures are introduced to replace inorganic fertilisers. For arable crops, no FYM application was considered because it is still not a widely adopted nutrient management practice (Fertiliser Usage, 2022). It is, nevertheless, recognized that its use could be higher for some crops in specific regions where arable farms are located near intensive livestock farms.

5.2. Assessment of modelled outputs under BAU settings

Based on published values for 2017 to 2021 (National Statistics, 2022), the estimated average yields in southwest England for WW, SB, WB, WOSR were 7.8, 5.5,6.8 and 3.1 t ha^{-1}, respectively. On this basis, the simulated yields from SPACSYS in Table 1 were deemed to be acceptable. Likewise, the SPACSYS predicted MZ and IG yields were also deemed acceptable on the basis of conversations with farmers in the study area.

Turning to N_2O emissions, the division of the emission rates by the corresponding fertiliser application rates yielded emission factors in the range of 0.2–0.8%, which are very close to the reported values for small grain crops (Smith et al., 1998) and within the range reported for grassland (Clayton et al., 1997).

The simulated SOC rates reaffirmed the widely held view that continuous arable cropping, without organic manure inputs, will result in the loss of SOC, whereas IG with the incorporation of FYM, has the potential to increase SOC sequestration. Furthermore, these effects are clearly dependent on soil texture, which is a key input to the RothC model.

5.3. Effects of site-specific environmental conditions

With site-specific combinations of plant varieties and soil types, the simulations for the designed scenarios have highlighted diverse responses at farm scale. Different plant species have specific phenology, morphological characteristics and thermal and nutritional requirements (Martin et al., 1976) as well as adaptation strategies for water and heat stress (Yamori et al., 2014; Acevedo et al., 2020). Climate change scenarios are known to have seasonal patterns and affect some periods more than others (Met Office, 2019). Some species will be affected more than others as illustrated by the simulated contrasting responses among WOSR, spring crops and winter crops with BAU fertiliser management under future climate conditions. Climate-resilient crops have already been adopted to increase drought tolerance and improve water use efficiency (Acevedo et al., 2020).

In the case of soil types, their spatial patterns were mapped along with the descriptions of soil structures, textures and associated chemical and biological attributes. These properties have significant impacts on the response of individual plants to field management, including fertiliser application rates as they determine the intrinsic nutrient stocks available under abiotic stress and connectivity to the wider environment (Gałczyńska et al., 2018). For instance, compared with more coarse soil, clay-enriched soil tends to have higher SOC, slower water release (Lal, 2020) and weaker linkages with the atmosphere and groundwater. All these properties resulted in soil texture based thermal and hydrological environments which could explain the wide variability of responses shown on different soil types (Bonetti et al., 2017). These effects were also highlighted by Huang et al. (2021) in their study of soil-dependent yield responses of multiple crops to climate conditions in the USA and a recent meta-data analysis by Shang et al. (2021). While plant development and accumulation of dry mass for generating farm income will only be active during the respective growth seasons, processes related to regulating services are operating throughout the year. The non-growth periods, mostly in the winter, are also the time when significant changes in rainfall patterns are predicted for the study area. This could be the main reason why more significant and variable impacts have been predicted for the regulating services, such as emissions to air and SOC sequestration rates. It has been shown that the magnitudes and directions of changes under uncertain future climate and any mitigation efforts, e.g., reduction of fertiliser inputs, are going to be dependent on the local environmental setting and current management practices (Feng et al., 2016). Therefore, more site-specific and comprehensive assessments are required to understand the effects of any mitigation strategy on the farming industry and ecosystem services at larger scale.

5.4. Effects of climate change on functional response

To examine the potential impacts of proposed fertiliser management strategies under future climate, the emphasis herein was on the change of functional response to fertiliser inputs relative to BAU under baseline climate conditions, as there are known inherent variabilities associated with the different combinations of site conditions (e.g., soil types), crop types and existing management practices. There are indications that the relationships between fertiliser rates and multiple responses modelled in the baseline conditions will be worse, i.e., more changes are expected from the same fertiliser input changes, but these signals are statistically not significant for most crop-soil combinations (Table 5). While significant changes were confirmed for CH_4, its relative contributions to overall GWP20 have to be taken into account. For most arable crops included here, the CH_4 derived GHG emission is <5% and only SB has a slightly higher (up to 20%) contribution. The predicted change of SOC rate seems to be climate scenario specific as significant changes from RCP4.5 seem to be quite different from the other scenarios. This is attributed to the distinctive soil moisture regimes from the specific combinations of temperature and rainfall conditions in the future climate scenario.

5.5. Contribution of off-farm activities

While it is not a full life cycle assessment, this study does include key off-farm and off-field activities for the calculation of GWP20 related to crop production, including embedded emissions from fertiliser production and transport and post-harvest on-farm operations. The simulated results suggest that GHG emissions from energy use for these activities are significant sources for all arable crops. The relative contribution to the total estimated annual equivalent CO_2 emissions varies between 3 and 50% under the BAU scenario. For IG, the lower fertiliser inputs and extra CH_4 emissions from FYM application results in a lower relative contribution at <5%. For arable crops, the corresponding contributions are ~14% for SB, 20% for WW and WB, 30% for WW and 48% for WOSR, respectively. The increased contribution from pre- and post-production processes have also been highlighted by other researchers (e.g., Tubiello et al., 2022). These results indicate that a cross-sector approach is needed for the reduction of agricultural related GHG emissions on arable land, including lowering the embedded emissions associated with the fertiliser industry and adoption of environmentally friendly land management practices by the farming industry, such as minimum tillage (Tyagi et al., 2022).

Table 5
P values for comparisons between regression slopes for the baseline and future climates.

Crop type*	Soil type**	Climate scenario	Yield	Root biomass	Above-ground mass	Nitrous oxide emissions	Methane emissions	Energy use	SOC sequestration rate	GWP20
WW	D	RCP2.6	0.40	0.19	0.44	0.13	0.01	0.40	0.01	0.67
		RCP4.5	0.31	0.18	0.46	0.08	0.03	0.31	0.00	0.65
		RCP8.5	0.26	0.06	0.20	0.31	0.00	0.26	0.01	0.24
	H1	RCP2.6	0.20	0.15	0.20	0.47	0.05	0.20	0.01	0.83
		RCP4.5	0.25	0.38	0.39	0.33	0.12	0.25	0.00	0.12
		RCP8.5	0.18	0.13	0.14	0.72	0.10	0.18	0.00	0.29
	H2	RCP2.6	0.44	0.32	0.37	0.88	0.04	0.44	0.01	0.78
		RCP4.5	0.25	0.33	0.32	0.91	0.07	0.25	0.00	0.81
		RCP8.5	0.20	0.10	0.13	0.53	0.01	0.20	0.01	0.45
SB	D	RCP2.6	0.79	0.55	0.90	0.18	0.38	0.80	0.15	0.75
		RCP4.5	0.65	0.41	0.80	0.12	0.52	0.67	0.01	0.75
		RCP8.5	0.40	0.18	0.40	0.60	0.46	0.43	0.28	0.48
	H1	RCP2.6	0.63	0.61	0.72	0.87	0.92	0.65	0.33	0.67
		RCP4.5	0.53	0.93	0.69	0.85	0.87	0.55	0.02	0.83
		RCP8.5	0.42	0.31	0.47	0.43	0.64	0.45	0.31	0.50
	H2	RCP2.6	0.62	0.73	0.70	0.53	0.77	0.64	0.28	0.84
		RCP4.5	0.55	0.97	0.75	0.13	0.54	0.57	0.01	0.94
		RCP8.5	0.47	0.44	0.56	0.52	0.54	0.50	0.18	0.62
WB	D	RCP2.6	0.34	0.30	0.43	0.56	0.00	0.65	0.09	0.97
		RCP4.5	0.38	0.66	0.48	0.62	0.00	0.57	0.00	0.53
		RCP8.5	0.14	0.15	0.18	0.74	0.00	0.38	0.07	0.11
	H1	RCP2.6	0.19	0.11	0.25	0.11	0.05	0.65	0.08	0.42
		RCP4.5	0.33	0.35	0.40	0.12	0.08	0.67	0.00	0.99
		RCP8.5	0.16	0.14	0.19	0.37	0.05	0.59	0.05	0.58
	H2	RCP2.6	0.27	0.14	0.40	0.76	0.00	0.82	0.14	0.39
		RCP4.5	0.39	0.48	0.53	0.39	0.00	0.83	0.00	0.54
		RCP8.5	0.16	0.08	0.25	0.20	0.00	0.82	0.08	0.34
WOSR	D	RCP2.6	0.86	0.31	0.65	0.49	0.01	0.86	0.01	0.58
		RCP4.5	0.65	0.80	0.88	0.24	0.00	0.56	0.00	0.65
		RCP8.5	0.92	0.18	0.22	0.49	0.00	0.90	0.01	0.99
	H1	RCP2.6	0.23	0.19	0.72	0.29	0.03	0.66	0.01	0.33
		RCP4.5	0.51	0.53	0.40	0.08	0.01	0.80	0.00	0.45
		RCP8.5	0.52	0.13	0.51	0.04	0.03	0.85	0.01	0.36
	H2	RCP2.6	0.38	0.18	0.38	0.01	0.00	0.71	0.00	0.13
		RCP4.5	0.09	0.46	0.08	0.66	0.01	0.45	0.00	0.17
		RCP8.5	0.74	0.17	0.71	0.11	0.02	0.90	0.00	0.47
MZ	D	RCP2.6	0.15	0.51	0.78	0.99	0.95	0.25	0.91	0.14
		RCP4.5	0.20	0.45	0.99	0.98	0.97	0.46	0.83	0.16
		RCP8.5	0.23	0.52	0.22	0.99	0.97	0.09	0.91	0.01
	H1	RCP2.6	0.06	0.38	0.03	0.99	0.94	0.01	0.92	0.01
		RCP4.5	0.18	0.48	0.23	0.99	0.97	0.07	0.82	0.15
		RCP8.5	0.12	0.45	0.05	1.00	0.96	0.02	0.92	0.01
	H2	RCP2.6	0.05	0.46	0.08	0.99	0.95	0.02	0.90	0.01
		RCP4.5	0.16	0.68	0.88	1.00	0.98	0.22	0.78	0.35
		RCP8.5	0.09	0.63	0.13	0.99	0.98	0.03	0.86	0.02
IG	D	RCP2.6	0.12			0.03	0.96	1.00	0.05	0.65
		RCP4.5	0.85			0.02	0.37	1.00	0.04	0.57
		RCP8.5	0.16			0.06	0.09	1.00	0.04	0.73
	H1	RCP2.6	0.04			0.01	0.16	1.00	0.05	0.17
		RCP4.5	0.09			0.02	0.44	1.00	0.00	0.39
		RCP8.5	0.03			0.01	0.23	1.00	0.01	0.30
	H2	RCP2.6	0.08			0.48	0.79	1.00	0.02	0.37
		RCP4.5	0.04			0.81	0.47	1.00	0.01	0.05
		RCP8.5	0.01			0.09	0.06	1.00	0.08	0.01

* WW = winter wheat; SB = spring barley; WB = winter barley; WOSR = winter oilseed rape; MZ = maize and IG = improved grass.
**D = Denbigh; H1 = Hallsworth; H2 = Halstow.

5.6. Limitations

The main objective of the paper was to examine the interactions among biophysical environments, crop types and fertiliser application rates in a changing climate. Inevitably, the study has some limitations. It was not designed to be a climate impact assessment with full uncertainty analysis. It is recognized that a single realization of different climate scenarios cannot represent the full uncertainty ranges associated with the projected future climates. The work herein has also not taken into account the impacts of any biotic stresses, e.g., pests and diseases, which will be confounding factors for crop production (c.f. Donatelli et al., 2017) and associated farm incomes. With this preliminary exploratory study, only GWP20 was assessed. Other GHG emission indicators, such as GWP* (Cain et al., 2019) could be calculated to evaluate both short- and long-term effects of GHG emissions, and GWP intensity incorporating energy and the nutritional attributes of different crops could be estimated for inter-crop comparisons.

6. Conclusion

Modelled responses were found to be dependent on crop species and soil types and climate change scenario, especially in the case of the supporting and regulating services which are affected more by the significant changes projected for the non-growing season and which involve more biological processes, such as carbon cycling. Various chain reactions and trade-offs were identified by the modelling, e.g., the reduction of crop yield and biomass accumulation leads to less fresh carbon input to soils and accordingly, lower SOC rates; the increased SOC rates on IG associated with the addition of FYM increased CH_4 emissions. While the relationships among fertiliser application rates and most ecosystem services were predicted to be maintained under future climate conditions, some significant changes could occur for SOC. This is especially the case for winter crops under the RCP4.5 scenario. High uncertainties attached to the climate change scenarios themselves make the quantification of any effects of any fertiliser reductions for the future much more challenging. More explicit consideration of uncertainties associated with different climate change scenarios is required to confirm the potential changes reported herein. Further studies are required to consider the financial impacts of any yield loss on farm finances and margins and to explore feasible alternatives to inorganic fertilisers which do not elevate GHG emissions and result in negative impacts on other ecosystem services expected from agroecosystems.

Credit author statement

Yusheng Zhang: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. Adrian Collins: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. Asma Jebari: Data curation, Formal analysis, Methodology, Software, Writing – original draft, Writing – review & editing. Lianhai Wu: Conceptualization, Data curation, Investigation, Methodology, Software, Writing – original draft.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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