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Evaluation of National Greenhouse Gas Removal Potential under a Changing Climate Using a Process-based Land Surface Model

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Abstract. Global warming and climate change caused by greenhouse gas emissions (GHG) will have multiple impacts on forest ecosystems. As the UK's currently planned contribution to global efforts to mitigating these impacts, the Climate Change Act has set a goal of net zero emissions of GHG by 2050. A core part of the strategy to meet this target is to use afforestation and forestry management to implement large-scale Greenhouse Gas Removal (GGR). These measures will need to be resilient to some level of climate change even if the international community successfully meets the goals of the Paris Agreement in limiting global warming. However, the effectiveness of afforestation as a GGR strategy is difficult to fully evaluate with standard empirical models due to a myriad of changing environmental conditions. Here we use the process-based land surface model, coupled to a model of large-scale forest demography (JULES-RED). We focus on a low climate change scenario, which would yield peak global warming close to 2°C. We project that widespread Sitka Forest afforestation could potentially sequester 15 $MtCO_2$ annually by 2080 assuming a plantation rate of 30,000 ha year^{-1} from 2025 to 2050. If the world fails to meet the goals of the Paris Agreement, UK woodlands will need to be resilient to more severe regional climate changes and the plantation locations will need be selected more precisely.

1 Introduction

The UK's Climate Change Act has set a goal of net zero emissions of greenhouse gas (GHG) by 2050, following the Paris Agreement to limit global warming to "well below 2°C" (UNFCCC, 2015). To meet this commitment, the Committee on Climate Change (CCC) notes that, alongside emission reductions via changes to energy use and generation, residual emissions from sectors such as aviation and agriculture necessitate large-scale direct Greenhouse Gas Removal (GGR) from the atmosphere (Committee on Climate Change, 2019). Land use, land use change and forestry (LULUCF) are central to GGR (IPCC, 2019) and the CCC recognises that "The UK's net-zero target will not be met without changes in how we use

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our land". The role of trees has become central to the UK's GGR strategy, as it combines the highest CO_2 removal potential with the lowest per tonne costs and greatest technology readiness level (The Royal Society and Royal Academy of Engineering, 2018).

The UK government currently has a target to plant 30,000 hectares of new woodlands every year from March 2025 onward, with most of this afforestation likely to be as managed coniferous plantations (House of Commons Environmental Audit Committee, 2023). However, the effectiveness of afforestation as a GGR strategy is difficult to fully evaluate with standard empirical models such as C-FLOW (Milne et al., 1998) and CARBINE (Forest Research, 2025), due to many interacting environmental factors affecting future forest growth under climate change (Argles et al., 2023), including warming, increases in atmospheric CO_2, and changes in rainfall, incoming solar radiation, humidity and windspeed.

Alternatively, process-based land surface models (LSMs) such as the Joint UK Land Environment Simulator (JULES) are widely used for environmental evaluation because of their more detailed representation of physical processes under climate change. LSMs simulate the processes that control carbon uptake and storage between the land surface and the atmosphere by calculating photosynthesis and respiration every 30 to 60 minutes. In addition, these models are increasingly utilising plant demography to increase the realism of forest dynamics (Argles et al., 2022). For the JULES model, this is in the form of the recently developed JULES-RED (Robust Ecosystem Demography) model (Argles et al., 2020). This model has previously been successfully evaluated against detailed observational data for a Sitka spruce site (Argles et al., 2023).

Climate projections continue to be uncertain, especially at the regional scale, because of both structural and parameter uncertainties within climate models. A better understanding of how forests will respond to the range of possible climate changes (especially on the warmer and drier end) is therefore needed to help inform decisions about planting strategies. Probabilistic projections provided for UK land account for both sources of uncertainty. These give a wide range of potential climate changes, ranging from summertime increase in temperature of 0.3 to 2.9 °C and from a 30% reduction to a 4% increase in rainfall during the summer (Lowe et al., 2018).

Here we evaluate the climate and CO_2 sensitivity of forest dynamics using JULES-RED by selecting 300 grid points across the UK, spanning a range of climate and soil types. We focus on trends of carbon accumulation, the meteorological drivers, and spatial patterns, as well as identifying the fertilizing effect of CO_2 as simulated by JULES. We identify the most relevant forcings (i.e. air temperature, annual mean precipitation, humidity, soil saturation), which affect the carbon accumulation (Baker et al., 2022) by using analysis of variance. We point out the places to plant which are likely to increase efficiency of GGR under climate change uncertainties based on a reliable evaluation of forest growth, therefore reduce the cost of meeting the net-zero target considerably.

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2 Methods and data

2.1 Model description

JULES was originally developed by the Met Office as a community land surface model (Best et al., 2011; Clark et al., 2011). It is part of the UK Unified Modelling framework, where it serves as the lower boundary condition for applications ranging from weather forecasting to climate projections (Clark et al., 2011). JULES simulates the fluxes between the land surface and the atmosphere, including carbon (Clark et al., 2011), water, energy, and momentum (Best et al., 2011). It has been used successfully for various applications such as weather forecasting, climate change prediction, hydrological assessment (Le Vine et al., 2016), and earth system modelling (Sellar et al., 2019).

In JULES, precipitation is intercepted by the plant canopy, then partitioned into surface flow and infiltration into the soil based on the Hortonian infiltration excess mechanism. Infiltration is assumed to be redistributed following the Darcy-Richards diffusion equation, which generates the subsurface flow at the lower boundaries as the gravity drainage. The soil parameters required by JULES (i.e. water retention parameters, van Genuchten parameters, hydraulic conductivity, dry thermal conductivity) are calculated using pedotransfer functions by obtaining soil properties such as texture and dry bulk density from the Harmonized World Soil Database version 1.21 (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012).

For the carbon fluxes, JULES calculates carbon pools and litter fluxes (soil carbon in decomposable plant material pool and resistant plant material pool) for wood, leaf, and root, using distinct parameters of Plant Functional Type (PFT) (e.g. broadleaf forest, needle-leaf forest, C3 grasses, C4 grasses, shrubs) and allometric and litter production rate equations (Clark et al., 2011). We select the needle-leaf evergreen tree PFT to represent Sitka spruce as the closest approximation, using growth curves and demography of Sitka spruce which were calibrated to the Harwood Forest site (Argles et al., 2023). The carbon and water fluxes are simulated at a half hourly timestep, with the vegetation dynamics (tree carbon, height, and LAI) being updated daily. Vegetation dynamics and forest demography was simulated with the coupled JULES-RED model that includes a simple implementation of forestry management and a new implementation of canopy closure (Argles et al., 2023). RED partitions the number density, n (kg C^{-1} m^{-2}), of each PFT into mass, m (kg C), size classes and updates the size-structure by using a Fokker-Planck continuity equation of plant growth, g (kg C yr^{-1}), and mortality, γ (yr^{-1}):

$$\frac{\partial n}{\partial t} - \frac{\partial}{\partial m}[ng] = -\gamma n \quad (1)$$

In JULES-RED, the carbon assimilate density (P) is the difference of estimated NPP (Π_{NPP}) and the local litterfall (Λ_{LLF}) multiplied by the fractional grid-box coverage (v)(Argles et al., 2020):

$$P = v(\Pi_{NPP} - \Lambda_{LLF}) \quad (2)$$

2.2 Vegetation and JULES-RED model calibration

In Argles, et al. (2023), JULES-RED was calibrated and evaluated against a mature Sitka spruce plantation at Harwood Forest. Harwood forest is classified as a stand of Yield Class 18, which representing the maximum average annual stem

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productivity. Planted in 1973, by 2018 the stand had 1348 trees ha^{-1}, biomass of 208 tonnes C ha^{-1}, height of 17.6 m, and LAI of 5.6. Assuming an initial standard number density of 2,500 trees ha^{-1} (Matthews et al., 2016), Sitka spruce allometry, recruitment and mortality rates were selected to minimise differences with the observations seen in 2018. The historical simulations were performed from 1973 to 2018 using the CHESS-met reanalysis observations (Robinson et al., 2020) with and without thinning and historical CO_2 concentrations (Fig. 1). Under the most realistic scenario (Thinned), JULES-RED had a number density of 1,279 trees ha^{-1}, biomass of 200 tonnes C ha^{-1}, height of 16 m, and LAI of 5.2 m^2 m^{-2} by 2018.

Additionally, the JULES-RED growth curve was compared against the 2018 UK Woodland Carbon Code (WCC) (Randle & Jenkins, 2011). Figure 1 shows how the stand biomass changes across the historical simulation and stand age for both JULES-RED and the WCC. With historically varying CO_2 concentrations, JULES-RED has a greater sequestration rate when compared to the WCC. As the WCC has no explicit representation of transient CO_2 this is to be expected. Fixing the CO_2 concentration to be the same level as 1973 demonstrates good agreement with the unthinned growth curve from the WCC.

Using the Argles, et al. (2023) evaluation as a basis, in this study, we utilise the parameterisation of JULES-RED to simulate vegetation dynamics across Great Britain. This assumes a low recruitment rate of $\alpha = 0.005$, a baseline mortality rate of $\gamma = 0.01$ yr^{-1}, a boundary mass of 0.1 kgC, and corresponding power-law allometric coefficients of $a_0 = 0.23$ m^2, $h_0 = 2.89$m, and $l_{\mathrm{bal},0} = 0.8$ m^2 m^{-2} for respective crown area, height and balanced LAI. The respective allometric exponents with respect to tree mass are: 0.5, 0.25, and 0.25 (Crown Area, Height, and LAI).

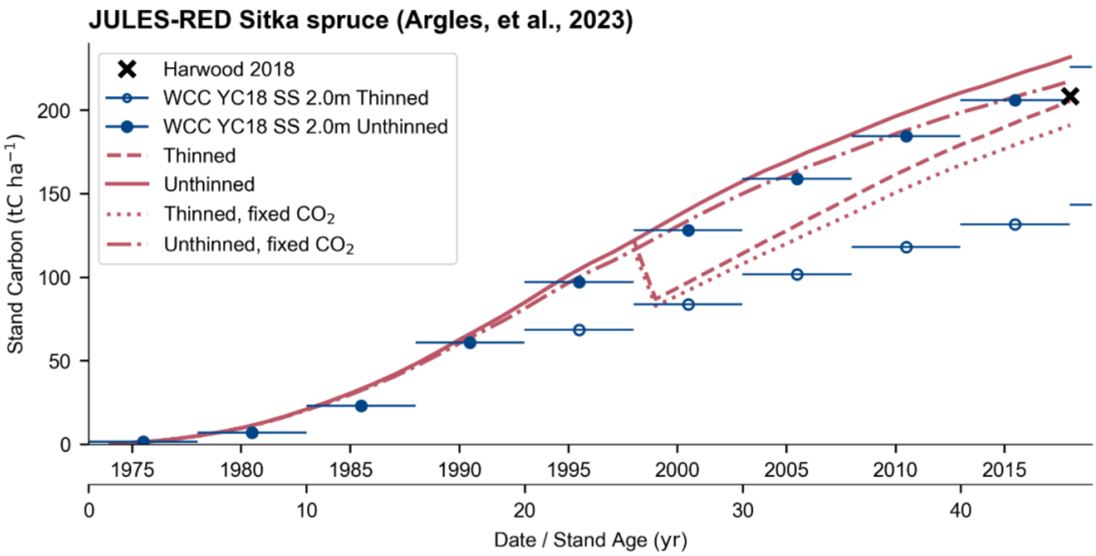

Figure 1: Adapted from Argles, et al., 2023. Historical simulations of stand carbon stock, comparing the growth curves of various historical JULES-RED (red lines) experiments, and the stand carbon for Sitka spruce for Yield Class (YC) 18 WCC look-up table (Randle & Jenkins, 2011). The black cross indicates the 2018 empirical estimate of carbon for Harwood Forest.

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2.3 The soil and meteorological data

In this study, we focus on a subset of 300 x 1km^2 points across Great Britain to allow analysis of potential forest demography and the associated carbon storage in newly planted Sitka spruce forests. These 300 sites were chosen to span the different climate of GB (Alpine, Sub-alpine, Cool-moist, Warm-moist, Warm-dry) and the most dominant soil classifications (Cambisol, Histosols, Gleysol, and Luvisol). The soil data is obtained from the Harmonized World Soil Database version 1.21 (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012).

The meteorological data required for JULES, i.e. precipitation, downward shortwave and longwave radiation, temperature, specific humidity, wind speed, and surface pressure, are extracted from the CHESS-SCAPE dataset (Robinson et al., 2022), which is available on daily, 1 km^2 resolution for England, Scotland, and Wales from January 1980 to 2080. We simulate the forest growth from 2024 onwards following the lowest emissions scenario currently available for regional climate projections in the UK (RCP2.6), which results in global warming of approximately 2°C by the end of the 21st Century relative to 1850-1900 (IPCC, 2013).

The CHESS-SCAPE dataset contains different ensemble members (EM) representing the climate model uncertainty of temperature and precipitation change in the UKCP18 ensemble (Robinson et al., 2022). Here, we selected RCP2.6_EM15 as our baseline scenario as it has a small increase in annual temperature (1°C) and has very little change in annual precipitation. This could be considered to represent a minimum level of regional climate change to which the UK will need to adapt, based on available climate projections in a suitable form for driving JULES. As future regional climate changes to a particular global emissions scenario remains uncertain, we also used the climate projected in the scenario RCP2.6_EM06, which represents a middle range of annual and seasonal warming and the largest decrease in June-July-August precipitation compared to other available members (-16%). This ensemble member represents the greatest warming in the southeast and drying in the higher elevation areas of western England and Wales, which can be considered as a more severe example of a regional climate scenario for the UK consistent with approximately 2°C global warming.

Since vegetation generally also responds directly changes in atmospheric CO_2 via increased photosynthesis and decreased transpiration – hereafter referred to as "CO_2 fertilization" - and 2°C global warming could occur at a range of levels of atmospheric CO_2 concentration (Betts & McNeall, 2018), we further evaluated the sensitivity of our results to this uncertainty by conducting further simulations with the same projected climate change but different trajectories of atmospheric CO_2 concentrations (Fig. 2):

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1) Fixed: a fixed CO_2 concentration of 422 ppm, which is the level at the start of 2024. Combining this with the 2°C global warming scenario could represent a world in which the future climate change is driven by increases in other greenhouse gas such as methane, rather than increases in CO_2.
2) RCP2.6: CO_2 emissions start declining by 2020 and reach net zero in the second half of the 21st Century, resulting in atmospheric CO_2 concentrations peaking at 443 ppm around 2052 and declining to 422 ppm in 2100.
3) RCP6.0: CO_2 concentrations projected to rise throughout the 21st century. Combining this with the 2°C global warming scenarios could represent a world in which changes in other climate forcings such as non-CO_2 greenhouses gases or aerosols act to limit warming even as CO2 concentrations rose, and/or a world in which climate sensitivity is much smaller than in the UKCP18 climate projections.

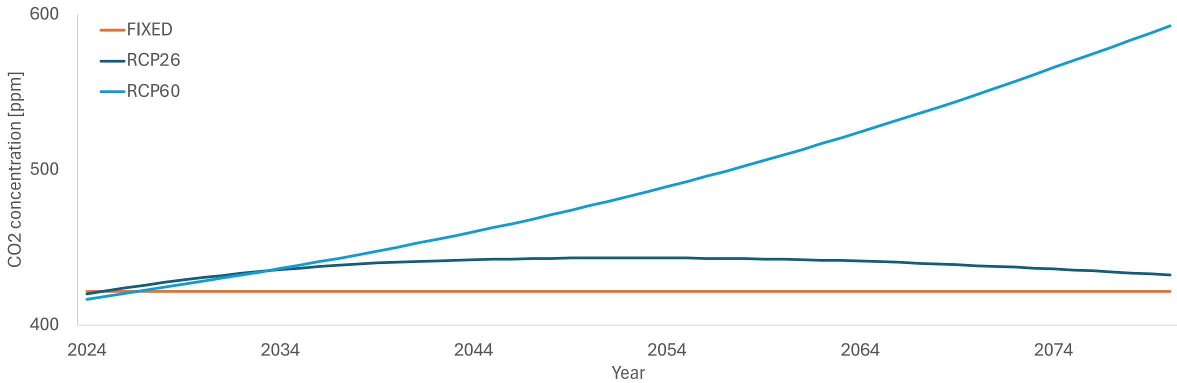

Figure 2: The prescribed CO2 concentrations in the atmosphere from 2024 to 2080, as used to assess the impact of CO2 fertilization independently of climate change.

2.4 Estimating the carbon fluxes in 2050 and 2080

Under the fixed CO_2 concentrations, we evaluated the sensitivity of vegetation growth to meteorological driving variables (i.e. annual temperature, annual precipitation, mean specific humidity, mean shortwave incoming radiation), soil hydraulic properties (i.e. hydraulic conductivity, total available water), and topographic variable (i.e. slope). We assessed the simulated vegetation carbon in 2050 and 2080, then classified the top 16 percentile values as 'high vegetation growth', the 50 percentile values as 'mid vegetation growth', and the 84 percentile values as 'low vegetation growth.

Following the target to plant 30,000 hectares of new woodlands every year from March 2025 to 2050, the total plantation covers 750,000-hectare forest area in the year 2080 (at forest age of 42.5 years in average). Here we use the average value of forest age 55 and forest age 30 to estimate the average carbon stock of forest age 42.5. The total carbon flux under EM15 and EM06 are estimated by using the 16/84 percentile of the modelling values:

$$Carbon\ stock\ \left(\frac{MtCO_2}{year}\right) = 750000\ ha \times \frac{Carbon_{2055} + Carbon_{2080}}{2}\ \frac{kgC}{m^2} \div 55\ years \quad (3)$$

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3 Results

3.1 Climate projection

For growing trees, we are most interested in growing season climate with the climate model uncertainty of temperature and precipitation changes. Here we summarised the changes in the CHESS-SCAPE RCP2.6 ensemble members for the period 2060-2079 compared to 1981-2000. The summer temperature increase from the probabilistic projections is 0.5°C-2.6°C, while the summer precipitation decreases from 0-26% (Lowe et al., 2018). The patterns of change for the period 2060-2079 compared to 1981-2000 are similar across ensemble members (Fig. 3). Generally, the highest levels of warming occur in the southeast with lower levels in the north and west.

Here, we selected EM15 and EM06 to represent two possible climate patterns. Table 1 summarised the range of the mean values of the meteorological variables across 300 selected sites. EM15 is relatively cooler, with average increase in winter precipitation and a relatively large decrease in summer precipitation. This could be considered to represent a minimum level of regional climate change to which the UK will need to adapt, based on available data. By contrast, EM06 is the driest member with a moderate decrease in annual precipitation, including an average increase in winter precipitation but a large decrease in summer precipitation. This ensemble member features the most warming in the southeast and drying in the higher elevation areas of western England and Wales.

Table 1. Mean of meteorological variables across 300 sites under EM15 and EM06

	EM15	EM06
Temperature (°C)	2.7 – 11.4	3.7 – 12.3
Annual precipitation (mm)	598 – 4072	536 – 4351
Specific humidity (g/kg)	4.48 – 7.27	4.73 – 7.59
Shortwave radiation (W m-2)	78 – 127	77 – 128

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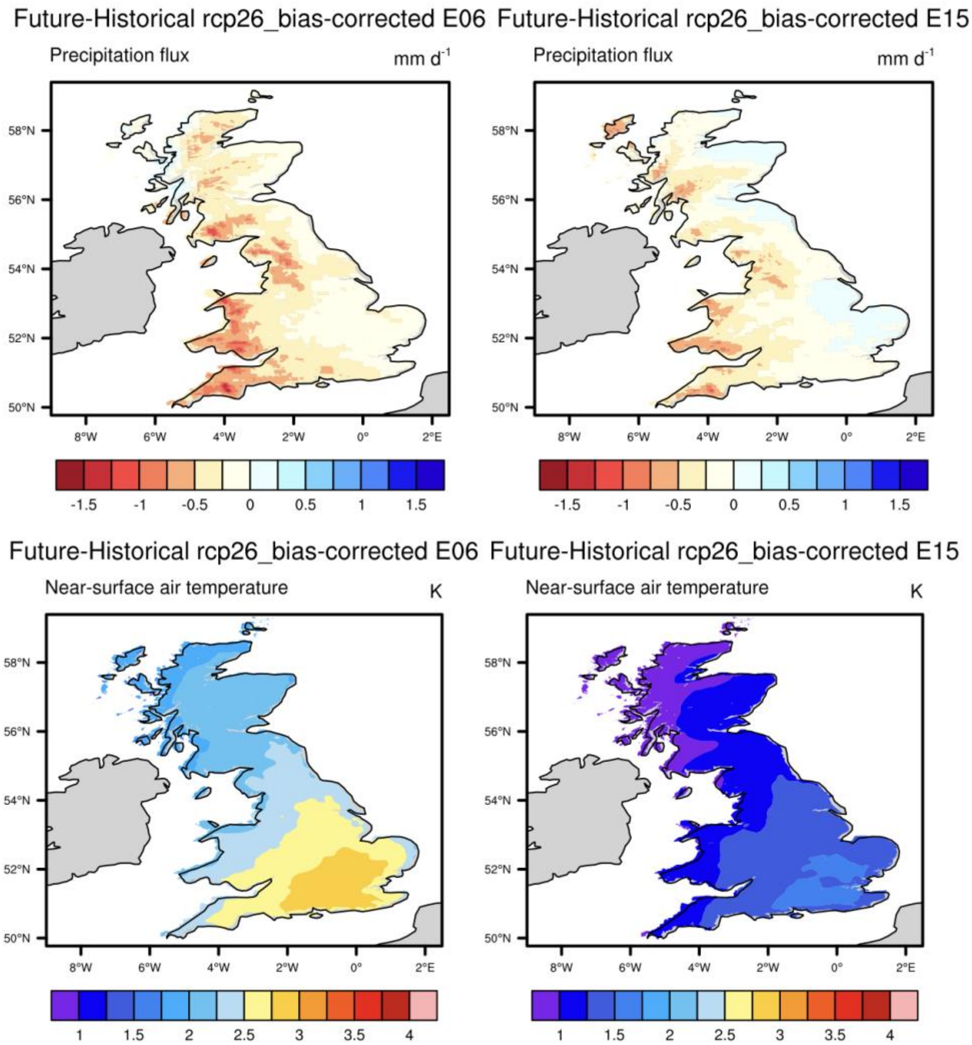

Figure 3: The changes of temperature and precipitation for the period 2060-2079 compared to 1981-2000 in EM06 and EM15.

3.2 The temporal and spatial distribution of the modelling carbon fluxes

We simulated forest dynamics from 2025 to 2080 (at forest age of 55 years) with projection EM15 and EM06, then evaluated the time series of the carbon fluxes across the 300 sites (Fig 4). For both scenarios, a steady increase of vegetation carbon is found until 2070, followed by a slight decrease over the next 10 years. Negative outliers for the vegetation carbon are found during the modelling period, this indicates that vegetation growth is hinder under certain meteorological and land surface conditions.

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Negative soil carbon is found from the start of the plantation, where it becomes positive around 2070. The litterfall has steadily accumulated from 2040 to 2080. Overall, we can see a steady increase of carbon fluxes after the initial plantation. Table 2 shows the range and mean values of the simulated carbon fluxes in 2080. We found that the vegetation carbon, net soil carbon, litterfall, and the total carbon fluxes are generally higher under EM15 than the values under EM06.

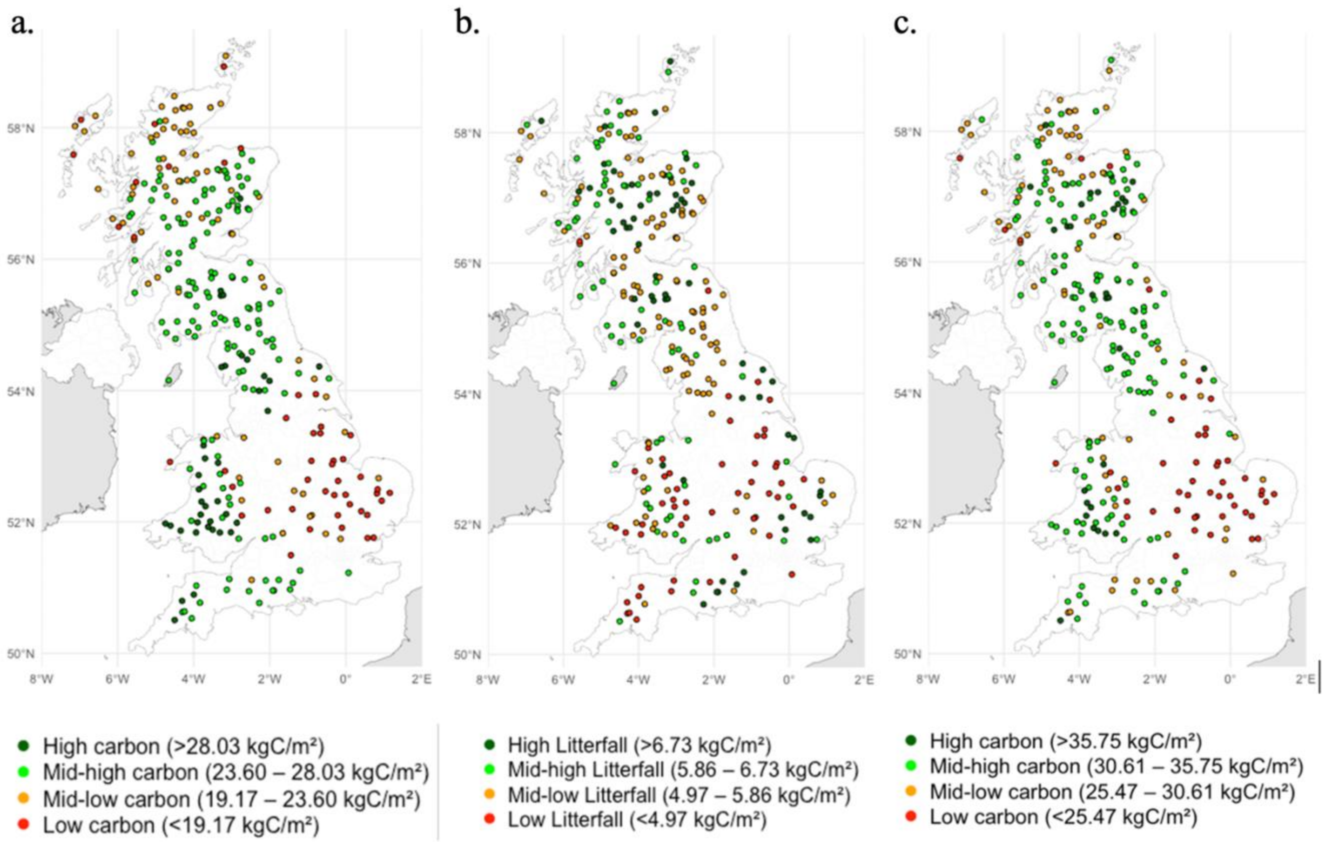

Figure 4: Time series of a. vegetation carbon, b. net soil carbon, c. litterfall, and d. total carbon fluxes from 2025 to 2080 under climate projections EM15 and EM06.

Table 2. The range and mean values of simulated carbon fluxes at 2080 (kg C m^{-2})

	EM15	EM06
Vegetation carbon	9.5 - 32.3 (23.6)	4.1 - 31.2 (20.2)
Net soil carbon	-2.1 - +5.7 (+0.9)	-2.6 - +5.8 (+0.5)
Litterfall	4.3 - 8.4 (6.1)	3.8 - 8.2 (5.9)
Total carbon	13.9 - 41.7 (30.6)	7.0 - 38.5 (26.6)

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We further map the spatial distribution of vegetation carbon, litterfall, and total carbon fluxes under EM15 by 2080 (Fig. 5). In which, vegetation carbon accumulation more than 28.03 kg C m^{-2} is identified as high carbon sequestration (16 percentile), whereas values lower than 19.17 kg C m^{-2} are marked as low carbon potential (84 percentile) alongside the classification mid-high and mid-low partitioned by the mean value 23.6 kg C m^{-2}. We found most of the points with low and mid-low growth potential are distributed in the north Scotland and the south-east England. Plantation in South Scotland and North England has mid-high growth potential. Further, we identify most of the points in Wales and south-west England are the most suitable location for Sitka Spruce plantation with high growth potential. For the litterfall, we classified values over 6.7 kg C m^{-2} as high litterfall (16 percentile), whereas values lower than 5 kg C m^{-2} as low litterfall (84 percentile). Mid-high and mid-low partitioned by the mean value of litterfall 5.86 kg C m^{-2}. We find most of sites in Scotland have high litterfall, while sites in South England and Wales have lower litterfall. For the total carbon fluxes, high values are more than 35.75 kg C m^{-2}, which is mostly distributed over south Scotland and Wales. Mid-high values more than 30.61 kg C m^{-2} are found in South Scotland, North England, southwest England, and Wales. Most of sites classified as low to mid-low values (less than 30.61 kg C m^{-2}) are in North Scotland and southeast England.

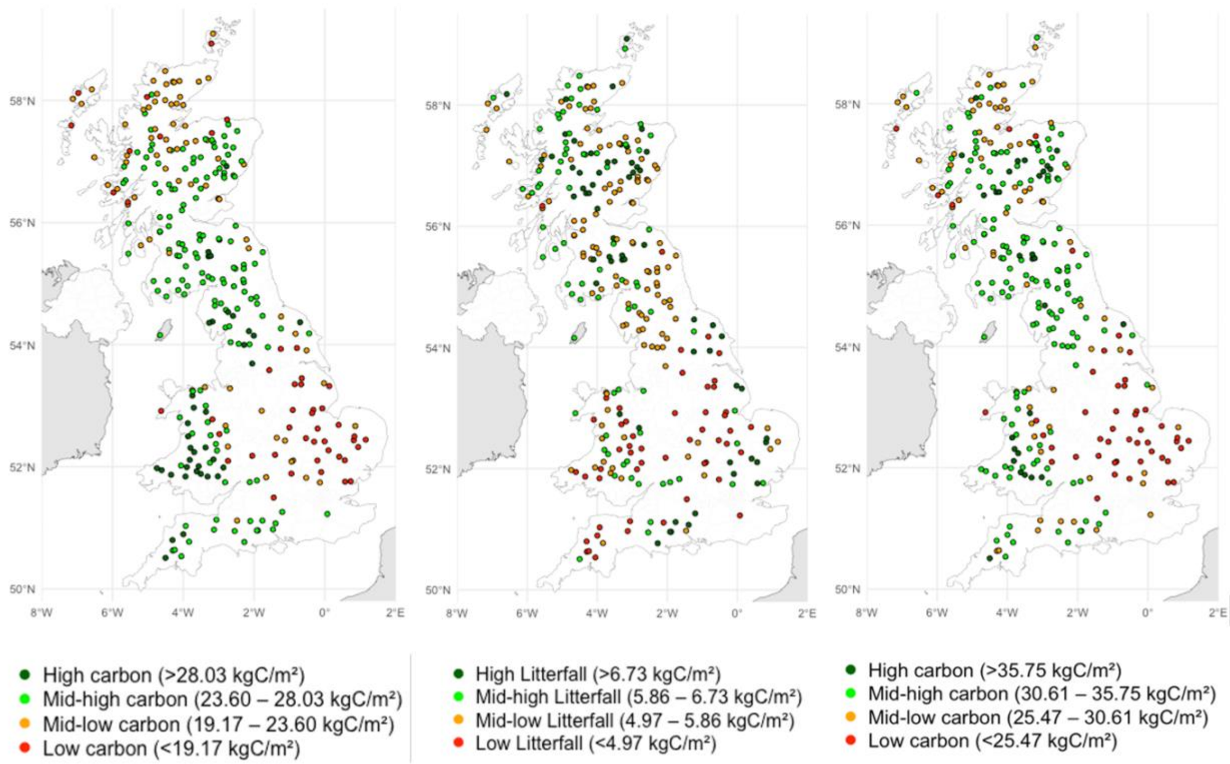

Figure 5: The projected level (EM15) of a. vegetation carbon, b. litterfall, and c. total carbon fluxes in 2080 on the UK map.

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3.3 Carbon fluxes under different atmospheric CO2

We evaluated the effects of carbon fertilisation by changing the CO_2 concentration between 1) fixed at 422 ppm on the year of 2024 level; 2) RCP2.6; and 3) RCP6.0 concentrations. Figure 6 shows the time series of the simulating carbon flux. On average, vegetation carbon increased by 2.2% in 2080 when the scenario is switched from fixed concentrations to RCP2.6 concentrations. When RCP6.0 concentration is selected, the average vegetation carbon is 10.6% higher in 2080 compared to the value under fixed concentrations. By means, negative soil carbon is found following the initial plantation, where it become positive around 2070. The mean value has slightly increased under RCP2.6 (+0.03 kg C m^{-2}) and RCP6.0 (+0.12 kg C m^{-2}), compared to the fixed CO2 scenario. The litterfall in the end of simulation has slightly increased by 0.02 kg C m^{-2} with RCP2.6 and 0.09 kg C m^{-2} with RCP 6.0, compared to the fixed CO_2 scenario. Overall, we can see the total carbon flux has increased with high CO_2 concentration, mainly due to the increase in vegetation carbon.

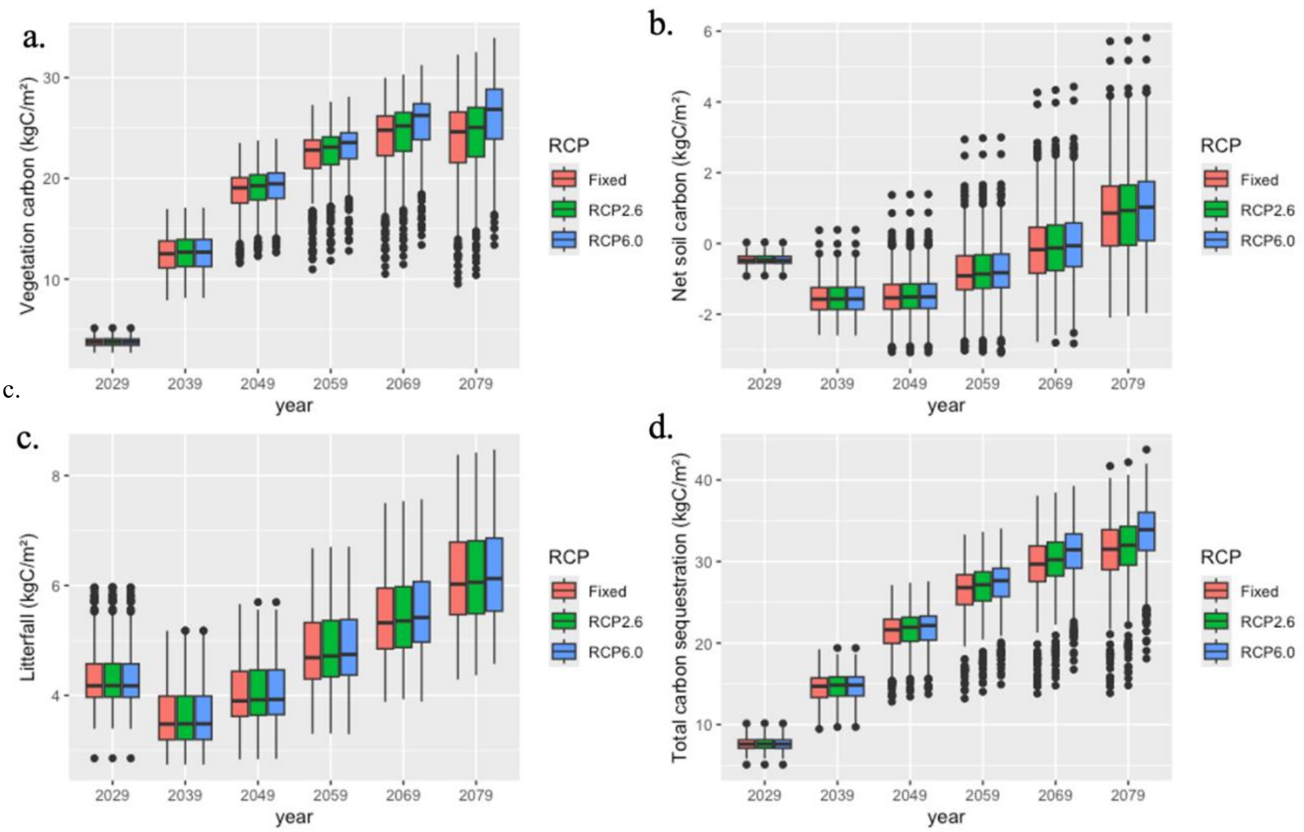

Figure 6: Time series of a. vegetation carbon, b. net soil carbon, c. litterfall, and d. total carbon fluxes from 2025 to 2080 under 1) fixed CO2 at 442 ppm, 2) RCP2.6 CO2, and 3 RCP6.0 CO2 under the project level RCP2.6_EM15.

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3.4 Effects on carbon fluxes of the driving factors

We evaluated the linear regression between the driving factors and the carbon flux with the simulating results (Table 2). We find solar radiation, air temperature, specific humidity, annual precipitation, slope, available soil water content, and CO_2 concentration are statistically significant (R^2=0.56) for vegetation carbon. For the litterfall, available soil water content, air temperature, and annual precipitation are statistically significant. We plot the scatter plot of solar radiation and the vegetation carbon (Fig. 7). We find two types of decreasing trend of the vegetation carbon with lower solar radiation. For the points follow the steep slope, we found that these sites are characterised by higher mean temperature (>11°C), higher specific humidity, and lower annual precipitation (< 800 mm year $^{-1}$). The rest of sites follow the flat slope. Whilst the short-wave radiation has a slightly gentle effect on the change of vegetation carbon for those sites with less precipitation, lower temperature.

Table 3. Linear regression between the driving factors and the vegetation carbon and Litterfall

	Vegetation Carbon (R^2=0.56)		*Litterfall (R^2=0.57)*	
Variables	*Coefficients*	*t Stat*	*Coefficients*	*t Stat*
Intercept	-42.838	-10.805	12.580	18.070
Air temperature (°C)	-5.557	-13.961*	-0.291	-4.158*
Annual precipitation (mm)	0.002	7.926*	0.000	4.764*
Specific humidity	10703.088	8.764*	81.274	0.379
Solar radiation (Wm^{-2})	0.279	20.489*	0.002	0.770
Slope (degree)	-0.201	-6.951*	-0.006	-1.121
Available soil water content	4.205	2.083*	-11.388	-32.126*
CO2 concentration (ppm)	0.040	11.314*	0.001	2.347*

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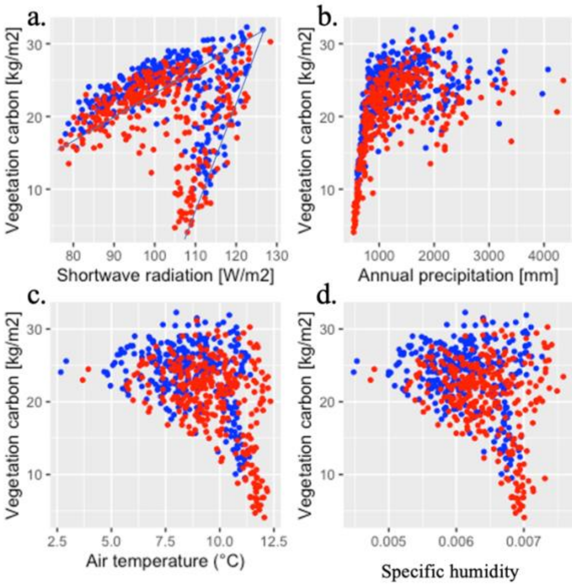

Figure 7: Scatter plot between carbon vegetation and a) shortwave radiation, b) annual precipitation, c) mean temperature, d) specific humidity. Blue: EM15, Red: EM06.

4 Discussions

4.1 Carbon removal potentials from planting Sitka Spruce in GB

We simulated the growth of Sitka Spruce from 2025 to 2080 (at forest age of 55 years) for 300 grid points represent the different climate and the most dominated soil classifications in United Kingdom. Following the target to plant 30,000 hectares of new woodlands every year from March 2025 to 2050, we summarise the carbon fluxes of the 16/84 percentile in 2050 and 2080 in Table 4. On EM15 scenario, the average carbon flux in 2050 ranges between 9.05 $MtCO_2$/year to 12.22 $MtCO_2$/year. In 2080, the value ranges between 11.39 $MtCO_2$/year to 15.14 MtCO2/year. On the drier and warmer EM06 scenario, the average carbon flux ranges between 7.33 $MtCO_2$/year to 11.46 MtCO2/year in 2050, and 8.82 $MtCO_2$/year to 14.08 $MtCO_2$/year in 2080.

In 2080, we found the vegetation carbon in the 84-percentile site has considerably reduced (9.2 $MtCO_2$/year to 6.1 $MtCO_2$/year). This is a 25%-37% difference in carbon uptake from the high to low end represented in these simulations. Once the Sitka Spruce is planted on proper locations, the amount of carbon sequestration could satisfy the Government's 2050 NetZero target of 12 $MtCO_2$ per annum (Climate Change Committee, 2020).

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Table 4. The 16/84 percentile estimated carbon removal by the newly planted forest in 2080 (MtCO2 per annual)

	EM15	EM06
Vegetation carbon	9.17 – 12.31	6.90 – 11.64
Net soil carbon	-0.50 - +0.45	-0.72 – +0.25
Litterfall	2.24 - 3.05	2.21 – 2.87
Total carbon fluxes	11.39 – 15.14	8.82 – 14.08

4.2 Major factors affecting the carbon fluxes

Planting in locations with the potential for high vegetation growth is vital to reach the UK's carbon sequestration target. We evaluated implications of the climate uncertainty by simulating the vegetation growth using RCP26_EM06, which projects a moderate decrease in annual precipitation and middle range of annual and seasonal warming over the modelling period (Robinson et al., 2020). From the results as shown in Table 3 and Figure 7, we also find that short wave radiation is the major driver to vegetation growth (Waring, 2000). Further, we find that insufficient precipitation (< 900 - 1000 mm/year) considerably hinders the vegetation growth (Jarvis & Mullins, 1987), especially for the sites with insufficient moisture (Cameron, 2015). These regions with relatively lower precipitation are prone to climate change (e.g. southeast England), as we find the vegetation growth have considerably decreased with the dropped down precipitation.

In addition, we simulated the vegetation growth under three levels of CO_2 concentrations still with the RCP2.6 to assess the impact of CO_2 fertilization independently of climate change. Increasing CO_2 concentration has positive effects on the vegetation growth (Boisvenue & Running, 2006; Kimball et al., 1993). In our simulation, rising the CO_2 concentrations from a constant value of 422 ppm to values that rise to 593 ppm increases vegetation carbon by 10-40% depending on the site. We found that higher increases occur at sites with sufficient shortwave radiation and higher temperature. Obviously, the changes predicted using JULES-RED are in good agreement with previous research on the impacts of specific environmental factors, which provides reasonable estimation for the future vegetation growth.

We map the spatial distribution of vegetation carbon stored by 2080, then find that Wales and south-west England has higher growth potential for Sitka Spruce growth. These regions have the highest shortwave radiation in the UK with sufficient precipitation. Sites with lower growth potential are distributed in the north Scotland and the south-east England. Lower shortwave radiation is observed in these north Scotland sites, whereas the precipitation is generally sufficient. For the sites in the south-east England, solar radiation is high in the UK, whereas vegetation growth is limited by insufficient precipitation.

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4.3 Limitations of the study and future research priorities.

Here we only investigated a very low climate change scenario. This therefore represents minimum levels of regional climate change for which woodland creation in the UK will need to be resilient. Under the climate uncertain, the locations should be selected more precise as the dropdown of precipitation could limit the vegetation growth. We have not considered higher scenarios of global warming and the associated more severe levels of regional climate change in the UK. If the world fails to meet the goals of the Paris Agreement, UK woodlands will need to be resilient to more severe regional climate changes. Further, effects of disturbances such as fire and windthrow (Taylor, 1990), which may also post challenges due to climate change. In this case the planted trees are not harvested over the simulation period, which kind of management strategy could increase the carbon sequestration further. Lastly, our model is currently limited to one commonly planted tree type, Sitka Spruce (Argles et al., 2023). The model is capable to represent this type of vegetation growth based on physically based assumptions, we plan to extend the model for other common plantation types.

5 Conclusions

We evaluate the potential carbon accumulation from 2025 to 2080 under a scenario with low climate change in which the goal of the Paris Agreement to limit warming to 2°C is achieved. As it is the scenario with the smallest climate changes (RCP2.6_EM15), we present an interesting case study where government is considering where to plant new Sitka Spruce Forest. We found that sufficient solar radiation is the main driver for a good growth condition of Sitka Spruce. In which, most of our sites marked as good plantation conditions were in the southwest part of Great Britain, which is consistent with the radiation condition. Although solar radiation is also high in southeast England, low precipitation alongside with other environmental factors may hinder the forest growth. For Scotland, we found the northern area are generally insufficient in solar radiation, which led to lower forest growth except some sites with extremely high precipitations. The south-Scotland are identified as mid-high to high vegetation growth in general.

We then simulate the vegetation growth using ensemble RCP2.6_EM06 to evaluate the potential effects under a serve climate change condition. This therefore represents minimum levels of regional climate change for which woodland creation in the UK will need to be resilient. We found the drop down of annual precipitation in some sites (e.g. southeast England) to a level below a threshold for sufficient vegetation growth could considerably decrease the carbon accumulation. We have not considered higher scenarios of global warming and the associated more severe levels of regional climate change in the UK. If the world fails to meet the goals of the Paris Agreement, UK woodlands will need to be resilient to more severe regional climate changes and the plantation locations will need be selected more precisely.

We further evaluate the impact of CO_2 fertilization independently of climate change under the baseline scenario RCP_EM15. We found the average vegetation carbon in 2080 could increase by 41% considering the CO_2 physiological effects solely, when a 1.37 times higher CO_2 concentration is selected. We show that JULES-RED is a useful modelling tool for predicting this type of vegetation growth and carbon accumulation values as both climate and atmospheric CO_2 levels change are highly consistent with the previous research reports based on these physically based assumptions.

Our results demonstrate the capability for calculating tree based GGR of one commonly planted tree type, Sitka Spruce, and these results are a reliable reference for land use management strategy. With the baseline scenario RCP2.6_EM15, we found that the potential annual removal of 15 $MtCO_2$ is sufficient to meet the Government's 2050 NetZero target by 2080 following the new woodlands plantation strategy once the plantation sites are selected properly. For a more comprehensive estimation for multiple tree types, we plan to extend the model for other common plantations.

Author contributions

HKC, ABH, RAB, and PMC led the writing and development of the manuscript. HKC, APKA, EWL, and MCDR developed the model and performed the simulations. All the authors contributed to the development of ideas and the reflection process.

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