



Predicted yield and soil organic carbon changes in agroforestry, woodland, grassland, and arable systems under climate change in a cool temperate Atlantic climate

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Abstract

The impact of a changing climate on crop and tree growth remains complex and uncertain. Whilst some areas may benefit from longer growing seasons and increased CO₂ levels, others face threats from more frequent extreme weather events. Models can play a pivotal role in predicting future agricultural and forestry scenarios as they can guide decision-making by investigating the interactions of crops, trees, and the environment. This study used the biophysical EcoYield-SAFE agroforestry model to account for the atmospheric CO₂ fertilization and calibrated the model using existing field measurements and weather data from 1989 to 2021 in a case study in Northern Ireland. The study then looked at two future climate scenarios based on the representative concentration pathways (RCP 4.5 and RCP 8.5) for 2020–2060 and 2060–2100. The predicted net impacts of future climate scenarios on grass and arable yields and tree growth were positive with increasing CO₂ fertilization, which more than offset a generally negative effect of increased temperature and drought stress. The predicted land equivalent ratio remained relatively constant for the baseline and future climate scenarios for silvopastoral and silvoarable agroforestry. Greater losses of soil organic carbon were predicted under arable (1.02–1.18 t C ha⁻¹ yr⁻¹) than grassland (0.43–0.55 t C ha⁻¹ yr⁻¹) systems, with relatively small differences between the baseline and climate scenarios. However, the predicted loss of soil organic carbon was reduced in the long-term by planting trees. The model was also used to examine the effect of different tree densities on the trade-offs between timber volume and understory crop yields. To our best knowledge this is the first study that has calibrated and validated a model that accounts for the effect of CO₂ fertilization and determined the effect of future climate scenarios on arable, grassland, woodland, silvopastoral, and silvoarable systems at the same site in Europe.

Keywords Biomass · Model · Crop · Resilience · Timber · Tree · Sequestration · RCP · RothC · Yield-SAFE

1 Introduction

The interactions between land use and climate change are complex. Agriculture and changes in land use are important sources of greenhouse gases (GHG), and changes in climate and carbon dioxide concentrations affect crop, grass, and tree growth. Globally, about 22% of GHG emissions are associated with agriculture, and land use and land-use change and forestry (LULUCF) (IPCC 2023). In the EU, for the period 2016–2018, agriculture and LULUCF were associated with an annual average net source of about 118 Mt CO₂e. This was derived from annual average agricultural emissions of about 386 Mt CO₂e (European Environment Agency 2024) and an annual average sink for LULUCF of 268 Mt CO₂e (European Commission 2018), even though LULUCF activities such as deforestation or conversion of

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organic soils to croplands can also emit GHG. Ostańska and Negre (2022) report that soils in the EU27 include about 34 Gt (0–20 cm) and 75 Gt (0–30 cm) of soil organic carbon. Hence, adopting regenerative practices such as cover crops, conservation tillage, peatland restoration, and agroforestry can aid in maintaining or enhancing these stocks. In the United Kingdom (UK) in 2019, agriculture emitted 46 Mt CO₂e and LULUCF was associated with an additional 6 Mt CO₂e, down from 18 Mt CO₂e in 1990 (BEIS 2021).

Agroforestry or ‘farming with trees’ is one method that farmers can use to mitigate against and adapt to the impact of climate change. The European Commission (2013) defines agroforestry as a land use system in which trees are grown in combination with agriculture on the same land. Silvopasture, the combination of trees with grazing animals, is the main agroforestry system in Europe, whilst silvoarable, the integration of trees with arable crops, is present on much smaller areas (den Herder et al. 2017; Rubio-Delgado et al. 2023).

A large and growing body of literature has investigated the benefits of integrating trees in agricultural land. These include agricultural outputs such as cereals and livestock, and outputs derived directly from the tree component such as fruit, nuts, timber, and wood fuel (Reed et al. 2017; Wiebe et al. 2022). There can also be enhanced ecosystem services from integrating trees into agricultural systems, such as carbon sequestration, regulation of runoff, and biodiversity enhancement (Giannitsopoulos et al., 2020; Torralba et al. 2016; Medinski et al. 2015).

Agroforestry systems can offer production benefits per unit area of land compared to growing trees on separate areas of land from pasture or crop production. This is because the trees and the crops or pasture can be complementary in terms of the capture of solar radiation and water (Cannell et al., 1996). For example, when establishing widely spaced trees, an interrow arable crop can make effective use of the solar radiation and water not intercepted by the trees (Burgess et al. 2005; Ivezic et al. 2021). Hence, the combined yields of timber and arable crops within an agroforestry system are typically greater than when trees and crops are grown separately. Trees can also moderate microclimatic extremes, providing more stable environmental conditions for understory species by reducing heat stress (Arenas-Coraliza et al. 2018).

Since pre-industrial times, land surface air temperatures have risen nearly twice as much as the global average temperature (land and ocean) (IPCC 2023). Additionally, increases in frequency and intensity of weather extremes are adversely impacting terrestrial ecosystems and the ecosystem services they provide (Seneviratne et al. 2021). A system that can absorb perturbations, bounce back, or adapt to change whilst still retaining the same functions can be defined as ‘resilient’ (Viñals et al. 2023). Combinations of trees and annual crops have been reported

to enhance agro-ecosystem resilience to extreme weather, contributing to soil and water conservation and improving carbon stocks and sequestration potential (Kay et al. 2019; Kumar et al. 2020).

Agroforestry can also have drawbacks. For instance, the complexity of agroforestry can create management challenges requiring farmers to possess knowledge of tree-crop interactions and ecological processes (Tranchina et al. 2024), and additional administrative burdens (Augère-Granier 2020). The combination of high initial tree establishment costs and delayed tree yields can also create cash-flow problems (Sollen-Norrlin et al. 2020). Competition between trees and crops for resources like water, light, and nutrients can result in reduced crop yields (Ivezic et al. 2021; Mantino et al. 2020).

Although there are a number of agroforestry biophysical simulation models of varying complexity, the application of these models to climate adaptation is lacking (Farrell et al. 2023). Zhao et al. (2017) in China and Webber et al. (2018) applying crop models on a spatial grid across Europe reported that the adverse impacts of warming and drought were counterbalanced by CO₂ fertilization for crops such as wheat and maize, which showed some regional yield increases. Xiao et al. (2018) also reported on the negative effect of warming temperature and decreasing rainfall on wheat yield, and the fertilising effect of increased CO₂ concentrations in the atmosphere, under both RCP 4.5 and RCP 8.5 at the beginning of the twenty-first century in China.

This study examines the effects of current and future climates on crop yields, timber volumes, and soil organic carbon. It does this by using and further developing the biophysical agroforestry Yield-SAFE model (van der Werf et al. 2007; Graves et al. 2007; Burgess et al. 2023) to create EcoYield-SAFE to compare the productivity of grassland, arable, woodland, and agroforestry systems at a Northern Ireland case study location. The model was then used to run virtual experiments to explore the effect of climate change, and the effect of different tree densities.

2 Method

The workflow consisted of (i) developing the EcoYield-SAFE model to account for increased CO₂ atmospheric contents, (ii) compiling the measured data from two experimental sites in Northern Ireland, (iii) preparing unbiased weather data and climate scenarios, (iv) using the data to calibrate the EcoYield-SAFE model, (v) modelling climate scenarios, and (vi) undertaking virtual experiments for adaptive agroforestry management.

2.1 EcoYield-SAFE model

The biophysical Yield-SAFE model was originally developed to predict the growth and yields of poplar silvoarable systems in England (van der Werf et al. 2007). The model works on a daily time step and describes the growth of trees and crops in response to temperature, the capture of solar radiation by tree, grass, or crop canopies, and the competition for water between trees, grass and/or crops (Palma et al. 2016). We followed the recommended procedure of calibrating the model for a monoculture tree system and a monoculture crop or grass system as described in Graves et al. (2007; 2010) before running it for the selected agroforestry systems.

For this paper, we used an enhanced version of Yield-SAFE called EcoYield-SAFE, which is available online (Burgess et al. 2025). The changes include modifications so that crop water use responds to the daily vapour pressure deficit, which is dependent on the temperature and wind speed which is modified by the trees (Palma et al. 2016). Soil carbon changes to a depth of 23 cm were modelled using the Rothamsted Research soil carbon model (RothC; Coleman and Jenkinson 2014) that had been incorporated into EcoYield-SAFE and tested in European case studies (Palma et al. 2018).

The predicted decomposition rate of soil organic fractions within the RothC model are dependent on the temperature, moisture, and soil cover, and feed into daily calculations for decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), and humified organic matter (HUM). There is also a small amount of inert organic matter (IOM), which is resistant to decomposition. Initially, the input plant material is estimated from the daily tree leaf fall, daily root litter stored and crop residues after harvest (including straw and roots) calculated by EcoYield-SAFE. Thirdly the livestock carrying capacity of the system is used to determine manure carbon inputs (Palma et al. 2016).

2.2 Incorporating the effect of CO₂ fertilization

To determine the effect of climate change on tree and crop yields, EcoYield-SAFE included the effect of increases in atmospheric carbon dioxide (CO₂) on the radiation use efficiency of the trees, grass, and crops. This was included by applying a multiplier to the radiation use efficiency as the atmospheric carbon dioxide concentration increased from 360 ppm (multiplier 1) to 720 ppm (multiplier 1.25), up to a maximum 28% benefit at a CO₂ concentration of 800 ppm (Supplementary material—Fig. S1; Prooter et al., 2022; Jägermeyr et al. 2021; Wolf 2012; Rodriguez et al. 1999).

2.3 Site description and agroforestry experiments

The study sites providing the experimental data are located at the Agri-Food and Biosciences Institute (AFBI) research centre (54° 23' 53.1" N 6° 36' 41.6" W) in Loughgall, County Armagh, Northern Ireland, UK, at an altitude of 30 m above sea level. Daily weather observations taken at the sites between 2003 and 2015 indicated that the mean annual temperature at the site was 8.5 °C and the mean annual rainfall was 810 mm. In 1989, a silvopastoral experiment was established comprising three plots planted at a spacing of 5 m × 5 m (400 stems ha⁻¹), three woodland (2500 stems ha⁻¹; 2 m × 2 m) plots planted with ash trees (*Fraxinus excelsior* L.), and three permanent grassland plots dominated by ryegrass (Fornara et al. 2018; Table 1, Fig. 1A). All silvopastoral and grassland plots received an annual fertiliser application of between 120 and 150 kg N ha⁻¹. Sheep grazing typically occurred in the pasture and silvopastoral system from April to October each year with a stocking rate of 12 ewes per hectare (1.2 livestock units; Fornara et al. 2018). The soil at this site is classified as brown earth on red limestone till with clay contents between 30 and 45% (Cruickshank 1997; Fornara et al. 2018), and analyses between 1990 and 1999 indicated a pH of 6.4 to 6.7 for all plots. Thinning regimes resulted in an ash density in silvopasture of 265, 170, and 128 trees ha⁻¹ in 2004, 2009, and 2023, respectively, whilst the woodland system was thinned and pruned in 2009 and 2021 to create a residual density of 1100 and 708 trees ha⁻¹ respectively (Table 1).

Ten years later in 1999, a silvoarable system was established with four poplar hybrids on a different grassland field approximately 200 m from the silvopastoral site (Fig. 1B). The four poplar (*Populus*) clones were initially Beaupré,

Table 1 Initial planted tree densities, thinning year and resulting tree densities in 2023 for the pasture, arable, silvopasture and silvoarable agroforestry, and woodland systems at Loughgall, Northern Ireland (Arable and poplar plantation yields were obtained from literature).

System	Initial tree density (trees ha ⁻¹)	Thinning year	Resulting density (trees ha ⁻¹)
Pasture	0		0
Silvopasture (SP)	400	2004	265
		2009	170
		2023	128
Woodland (WD)	2500	2009	1100
		2021	708
Arable	0		0
Silvoarable	142	-	142
Poplar plantation	900	-	900

Fig. 1 Ash silvopastoral (**A**) and poplar silvoarable (**B**) experiments at Loughgall in Northern Ireland (Photos taken by Rodrigo Olave in 2010 (**A**) and 2005 (**B**)).



Boelare, Hoogvorst, and Hassendans. However, due to poor establishment Boelare and Hassendans were substituted in 2000 with Trichobel and Gibecq hybrids. The poplars were planted as unrooted sets 5 m apart within rows and 14 m row spacings to give a 12 m crop alley (a density of 142 stems ha^{-1} ; Table 1). The soil has been classified as a brown earth on red limestone till, with pH ranging from 5.7 to 6.2 within the site. The silvoarable experiment was set as a randomised block design in four blocks with a split-split block treatment structure. An annual crop of spring barley (Riviera) was planted in the alleys for the first 10 years until 2009 and was then followed by a pasture mix of ryegrass and red and white clover. Two forms of mulching within the rows were adopted, continuous polythene and 1.5 m square mulch mats with intercrop rows sown with grass/clover. In 2013, as part of a study on tree crop interactions on alley coppice (Lunny 2017), a willow crop was established for a 4-year cycle as an understorey crop and since then the land has been cultivated as a permanent grassland sward. In the UK, the growth of poplar stands is described by provisional yield tables described by Christie (1994) (see Section 2.4.2).

2.4 Data preparation

2.4.1 Weather data

The EcoYield-SAFE model requires daily weather data. The modelling of the yields in the baseline period was a two-stage process. Firstly, the model was calibrated using data from planting (1989 or 1999) to 2021 (Supplementary material—Table S1). Secondly the yields over a 40-year period were determined using predicted weather data for the first 40 years after planting.

The weather for the calibration period to 2021 was firstly based on on-site weather data collected from AFBI for the period 2003–2015 (Supplementary material—Table S2). However, where there were gaps in the data, the weather station records were supplemented with data from the E-OBS Europe-wide gridded observational dataset (Cornes et al.

2018). Temperature, relative humidity, wind speed, rainfall, and radiation data were taken from E-OBS, which is available on a 0.1° resolution (equivalent to a grid cell size of approximately $7 \text{ km} \times 11 \text{ km}$ at the study site), and evaporation data from ERA5 (2.5° resolution), the fifth-generation global atmospheric reanalysis of European Centre for Medium-Range Weather Forecasts (ECMWF), covering the period from January 1950 to present (Hersbach et al., 2020).

Day-to-day weather for the period from 2021 to 2029 were taken from the Regional Atmospheric Climate Model (RACMO) developed by the Koninklijk Nederlands Meteorologisch Instituut (van Meijgaard et al. 2008, 2012). RACMO performs favourably with other regional climate models that contribute to the European Coordinated Regional Downscaling Experiment (EURO-CORDEX; Jacob et al. 2014; Vautard et al. 2021). The required daily data were accessed using CliPick, a webtool designed to facilitate the selection of climate change data for applications in forestry and agriculture (Palma 2017). Both global and regional climate models are typically associated with systematic biases, largely due to limitations imposed by the models' spatial resolution. When using climate model output at the local scale, it is prudent to apply a statistical correction of systematic model bias (Maraun and Widmann 2018). Here, quantile mapping, a well-established correction method (Cannon 2015), was used to account for bias in the RACMO data with the complete observational dataset (i.e. station observations supplemented by E-OBS/ERA5) taken as a reference.

2.4.2 Soil, grass, crop, and tree data

The following assumptions were made to run EcoYield-SAFE. The initial organic matter content of the soil in 1989 was assumed to be 8.2% at 0–10 cm and 5.4% at 10–20 cm, giving an average of 6.8% for the treatments related to the silvopastoral system (Fornara et al. 2018), and 5.0% (0–20 cm) for those related to the silvoarable system. For this study, a common soil bulk density of 1.02 g cm^{-3} was

assumed for the pasture, silvopasture and ash woodland systems, whilst a bulk density of 1.33 g cm^{-3} was assumed for the treatments related to the silvoarable experiment (Fornara et al. 2018; Supplementary material—Table S7). It was also assumed that the sheep returned $1.17 \text{ kg C ha}^{-1} \text{ day}^{-1}$ based on an excremental rate of $21.6 \text{ kg ha}^{-1} \text{ day}^{-1}$ ($18 \text{ kg ha}^{-1} \text{ day}^{-1}$ for 1.2 livestock units) and a fractional organic carbon content in the excrement of 0.054 (Nennich et al. 2005).

Data on grass yields (assumed to be harvested at the end of each year) and tree yields in the grass monoculture, silvopastoral system, and ash woodland control were obtained directly from measurements taken in the experimental site. Tree and crop yields in the silvoarable system were also sourced from the AFBI Loughgall site. However, because there was no dense stand of poplar at the experimental site, data on the growth of unthinned poplar at a density of $3 \text{ m} \times 3 \text{ m}$ ($1093 \text{ trees ha}^{-1}$) were derived from yield-class tables provided by Christie (1994). Because the yield-class table assumes some tree mortality, a constant tree density of 900 trees per hectare was assumed in the model. Yield estimates for monoculture crops of spring-planted barley of $5.3\text{--}5.9 \text{ t ha}^{-1}$ were derived from Mercer (2006) and Irish Farmers Journal (2021).

Timber volumes were calculated from field measurements of tree height and diameter at breast height, and it was assumed that carbon formed 50% of the biomass. A land equivalent ratio (LER) was calculated to determine whether it was agronomically more efficient to combine two or more crops on the same area of land, compared to production in monocultures (Eq. 1). In the equation, $Y_{tree_{AF}}$ and $Y_{crop_{AF}}$ are the tree and crop yields per hectare of the agroforestry system, and $Y_{tree_{Mono}}$ and $Y_{crop_{Mono}}$ are the tree and crop yields in the monoculture systems. The parameters used and assumptions made in EcoYield-SAFE for crops, trees, and soil are provided in Supplementary material (Table S4; Table S5; Table S6).

$$LER = \frac{Y_{crop_{AF}}}{Y_{crop_{Mono}}} + \frac{Y_{tree_{AF}}}{Y_{tree_{Mono}}} \quad (1)$$

2.5 Future climate scenarios

Global and regional climate models are frequently used to generate climate projections under different scenarios of future greenhouse gas emissions. These scenarios are defined by the representative concentration pathways (RCPs) (Moss et al. 2010), which specify concentrations of greenhouse gases that will lead to a given increase in total radiative forcing by 2100, relative to pre-industrial levels. Four pathways have been defined by the Intergovernmental Panel on Climate Change (IPCC), RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5, that cover a range of global temperature change

through the remainder of the century (van Vuuren et al. 2011). For example, the RCP 4.5 pathway represents 4.5 W m^{-2} of extra warming by 2100. The RCPs map directly to the Shared Socioeconomic Pathways (SSPs) used in the IPCC 6th Assessment Report (IPCC 2023).

For this study, the effect of climate change on tree, crop, and agroforestry yields were examined using day-to-day weather simulated by RACMO under the ‘intermediate’ RCP 4.5 scenario and the ‘high’ RCP 8.5 emissions scenario. Assuming a tree rotation of 40 years, the scenarios were split into two periods of 2020–2060 and 2060–2100. In addition to the changes in climate, we included estimates of the changes in atmospheric CO_2 up to 2100 for both RCP 4.5 and RCP 8.5 scenarios, using data presented by Meinshausen et al. (2020). The value of CO_2 was estimated to reach 603 ppm in 2100 in the RCP 4.5 scenario, and 1142 ppm in 2100 in the RCP 8.5 scenario (Supplementary material—Fig. S4). As mentioned in Section 2.2 however, a cut-off point of 800 ppm was assumed in EcoYield-SAFE for the carbon dioxide fertilization effect on plants.

The general effect of the climate change scenarios was to increase maximum air temperatures by between 1.2 and 2.8 °C and minimum air temperatures by between 1.2 and 3.0 °C (Table 2). The change in annual rainfall was predicted to range from a decrease of 16 mm to an increase of 84 mm. It was predicted that the mean level of solar radiation would decrease by $0.2\text{--}0.5 \text{ MJ m}^{-2} \text{ d}^{-1}$, but higher temperatures were predicted to increase mean daily evaporation rates. A detailed summary is provided in Supplementary material—Table S8. Mean atmospheric CO_2 concentration was assumed to be 340 ppm for the period 1960–2000, rising to a mean of 574 ppm and 879 ppm in RCP 4.5 and RCP 8.5, respectively, for 2060–2100 (Table 2).

2.6 Virtual experiments

Within the high radiative forcing climate scenario RCP 8.5 and for the period 2060–2100, a key objective was to examine whether decreasing or increasing the original tree densities (Table 1) had an effect on crop yields of the silvoarable and silvopastoral experiments. The range of tree densities tested were 0, 50, 142, 300, 400, and 600 trees per hectare. The thinning regime for the silvopastoral tree density simulations was assumed to be in the same proportions as for the original case study thinnings (Supplementary material—Table S3).

3 Results

The results first cover the calibration of the EcoYield-SAFE model for the crop, grass, and tree yields using the baseline weather data. Following calibration of the model, the model

Table 2 Mean annual rainfall, maximum and minimum temperatures, daily evaporation and solar radiation (simulated by RACMO), and projected CO₂ concentration (Meinshausen et al. 2020) for the 1960–

2000 historic period and for 2020–2060 and 2060–2100 under RCP 4.5 and RCP 8.5.

	Historic	RCP 4.5		RCP 8.5	
	(1960–2000)	(2020–2060)	(2060–2100)	(2020–2060)	(2060–2100)
Annual rainfall (mm)	861	845	930	891	945
Mean maximum temperature (°C)	13.0	14.2	14.6	14.2	15.8
Mean minimum temperature (°C)	5.1	6.3	6.8	6.6	8.0
Daily evaporation (mm)	1.49	1.57	1.58	1.57	1.58
Solar radiation (MJ m ⁻² d ⁻¹)	9.3	9.2	9.1	9.0	8.8
Carbon dioxide concentration (ppm)	340	480	574	515	879

was then used to determine the effect of future climate scenarios and tree densities on crop, grass, and tree growth and changes in soil organic carbon.

3.1 Calibration of the pasture, silvopastoral, and woodland systems

The mean modelled monoculture pasture yield with EcoYield-SAFE of 9.1 t DM ha⁻¹ was similar to the measured pasture yields of 9.3 t DM ha⁻¹ in 1995, 1998 and 2000 (RMSE: 1.7 t ha⁻¹). In the woodland with a tree density of 2500 trees ha⁻¹, the measured timber yield of 104 m³ ha⁻¹ in year 15 was similar to the modelled value of 98 m³ ha⁻¹ (Supplementary material—Fig. S2; RMSE: 6.7 m³ ha⁻¹; $n = 11$). In the silvopastoral system at a tree density of 400 trees ha⁻¹, the measured timber volume in year 18 of 43 m³ ha⁻¹ was close to the modelled value of 45 m³ ha⁻¹ (Supplementary material—Fig. S2; RMSE: 13.7 m³ ha⁻¹; $n = 15$). The mean measured grass yield in 1995, 1998, and 2000 was 6.6 t DM ha⁻¹ whilst the model predicted a mean yield of 7.3 t DM ha⁻¹ for the same years (RMSE: 2.0 t ha⁻¹). As the trees matured, grass yields were predicted to decline starting with a dry matter yield of 10.2 t ha⁻¹ in the first year and decreasing to about 1.5 t ha⁻¹ after 30 years (Supplementary material—Fig. S5).

3.2 Calibration of the arable, poplar plantation and silvoarable systems

The mean monoculture spring barley yield predicted by EcoYield-SAFE (5.8 t ha⁻¹) was similar to the mean spring barley yield reported for Northern Ireland (5.3–5.9 t ha⁻¹; Mercer 2006; Irish Farmers Journal 2021). For the poplar woodland system, the modelled timber yield of 233 m³ ha⁻¹ with EcoYield-SAFE was similar to the yield of 260 m³ ha⁻¹ in year 20 described in yield profiles of poplar with a yield class of 6 as described by Christie (1994) (Supplementary material—Fig. S3; RMSE: 27 m³ ha⁻¹; $n = 4$). In the silvoarable system, the measured timber volume reached 163 m³ ha⁻¹

(as averaged across the four cultivars) at 22 years, compared to a modelled value of 169 m³ ha⁻¹ (Supplementary material—Table S9; RMSE: 10.2 m³ ha⁻¹; $n = 5$). With the silvoarable system, the modelled spring barley yield of 6.3 t ha⁻¹ in year 1 was higher than the measured value of 3.9 t ha⁻¹. However, the modelled value of 4.8 t ha⁻¹ was similar to the measured value of 4.3 t ha⁻¹ in year 3. With time, and as trees developed, the modelled grass yields in the silvoarable system were predicted to decline from 4.8 t ha⁻¹ in year 11 to 2.5 t ha⁻¹ in year 20 (Supplementary material—Fig. S6).

3.3 Effect of climate change on yields of pasture, woodland, and silvopastoral system

The calibrated model was then used to determine the effect of climate change. In the monoculture grassland plots, EcoYield-SAFE predicted that climate change and the increase in CO₂ would result in higher grass yields in future years, with the mean grass yield increasing from 9.6 t ha⁻¹ to 11.0–12.7 t ha⁻¹ (Table 3; Fig. 2A). The model also predicted that the total timber volume from the woodland system at 40 years would increase from 429 m³ ha⁻¹ to 458–514 m³ ha⁻¹ (Table 3; Fig. 2D).

Within the silvopastoral system, the predicted timber after 40 years increased from 272 m³ ha⁻¹ to 302–366 m³ ha⁻¹, with the increase due to the assumed fertilization effect of the carbon dioxide (Table 3; Fig. 2C). Within the silvopastoral system, there was also a predicted increase in the mean understorey grass yield from 4.2 t ha⁻¹ to 4.6–5.0 t ha⁻¹. Hence, the net effect was that the predicted increase in timber growth was greater than the increase in grass growth as demonstrated by the declining proportion of the land equivalent ratio derived from the grass component (Table 3).

3.4 Effect of climate change on yields of arable, poplar plantation and silvoarable system

For the treatments related to the silvoarable system, the EcoYield-SAFE model predicted that climate change and the

Table 3 Predicted average annual grass yield ($\text{t ha}^{-1} \text{ yr}^{-1}$) and timber yield ($\text{m}^3 \text{ ha}^{-1}$) in the monoculture systems and within the silvopastoral system for the baseline period and in two time steps of 40 years each (with and without the carbon dioxide fertilization effect), and

the predicted land equivalent ratio. Silvopasture grass yields are per hectare of agroforestry system (Graphical illustration of the effect of CO_2 on grass and timber yields is presented in Supplementary material—Fig. S7).

Scenario	Time step	CO_2 effect	Grass yield (40 years)	Woodland standing+ harvested timber (at year 40)	Silvopastoral		Predicted land equivalent ratio (grass + tree)
					Grass yield (40 years)	Standing + harvested timber (at year 40)	
Baseline	1989–2029	No	9.2	418	4.1	263	$0.45 + 0.63 = 1.08$
		Yes	9.6	429	4.2	272	$0.44 + 0.63 = 1.08$
RCP 4.5	2020–2060	No	9.5	422	4.3	269	$0.46 + 0.64 = 1.09$
		Yes	11.2	462	4.7	307	$0.42 + 0.66 = 1.08$
	2060–2100	No	8.9	413	4.2	259	$0.47 + 0.63 = 1.10$
		Yes	12.0	489	4.9	327	$0.41 + 0.67 = 1.08$
RCP 8.5	2020–2060	No	8.9	406	4.2	254	$0.48 + 0.62 = 1.10$
		Yes	11.0	458	4.6	302	$0.43 + 0.66 = 1.08$
	2060–2100	No	7.7	397	3.9	249	$0.51 + 0.63 = 1.14$
		Yes	12.7	514	5.0	366	$0.39 + 0.71 = 1.11$

increase in CO_2 would result in higher yields in a monoculture arable system, with the mean arable yield increasing from 6.2 t ha^{-1} to $6.4\text{--}7.3 \text{ t ha}^{-1}$ (Table 4; Fig. 3A). The model also predicted that the total timber volume from the poplar plantation at year 40 would increase from $429 \text{ m}^3 \text{ ha}^{-1}$ to $429\text{--}473 \text{ m}^3 \text{ ha}^{-1}$ (Table 4; Fig. 3D). Within the silvoarable system, the predicted harvested timber after 40 years increased from $297 \text{ m}^3 \text{ ha}^{-1}$ to $298\text{--}324 \text{ m}^3 \text{ ha}^{-1}$ (Table 4; Fig. 3C).

There was also a predicted increase in the alley crop arable yield from 4.3 t ha^{-1} to $4.2\text{--}5.6 \text{ t ha}^{-1}$ with the largest increase observed in 2060–2100. If the land equivalent ratio is calculated on the basis of the crop (barley) and tree yields only, then the silvoarable system resulted in a land equivalent ratio of less than 1.0 (Table 4). If the grass yield was also included, then a higher LER would have been derived (Supplementary material—Table S11).

3.5 Predicted effect of land use and climate change on soil organic carbon

The EcoYield-SAFE model predicted a mean net decrease in the soil organic carbon (0–23 cm) across 40 years of $0.48 \text{ t ha}^{-1} \text{ yr}^{-1}$ within the monoculture grass system under the baseline climate (Table 5, Fig. 4A).

In contrast to the grassland system, the baseline soil organic carbon storage in the woodland system was predicted to decline in the initial years but then increase from year 11 to 40 after tree planting, with a mean increase of $0.85 \text{ t C ha}^{-1} \text{ yr}^{-1}$ over the 40 years (Table 5; Fig. 4C). The soil organic carbon in the silvopastoral system was predicted to show an intermediate effect with a decrease predicted in the initial 13 years, a stable period until year 20, and an increase from year 20 to year 40 (Fig. 4B).

In general, the four future climate scenarios resulted in similar changes and temporal profiles in the predicted soil organic carbon content as the baseline system. The greatest increases in soil organic carbon (or smallest decreases) occurred within the RCP4.5 2020–2060 scenario, and the smallest increases or greatest decreases occurred in the RCP 8.5 2060–2100 scenario (Table 5; Fig. 4).

In the systems related to the silvoarable experiment, the EcoYield-SAFE model predicted an average annual decline in the soil organic carbon in the barley only system of $1.02 \text{ t C ha}^{-1} \text{ yr}^{-1}$ over 40 years in the baseline climate. A monoculture system (without trees) of barley followed by grass was predicted to result in a decline of $0.51 \text{ t C ha}^{-1} \text{ yr}^{-1}$ (Table 6) and similar to that observed for the monoculture grass system (Table 5). The poplar system predicted an increase in soil organic carbon of $0.19 \text{ t C ha}^{-1} \text{ yr}^{-1}$, and the silvoarable system was predicted to result in an intermediate loss of $0.29 \text{ t C ha}^{-1} \text{ yr}^{-1}$.

There was a distinct temporal pattern to the loss of soil organic carbon. For the arable and the silvoarable system, the soil organic carbon tended to decline when there was a barley crop, before stabilising when grass was established (Fig. 5A, B). In the poplar plantation, although the soil organic carbon declined for the first 10 years, it was predicted to increase from year 10 to 40 after tree planting (Fig. 5C). Again, the predicted effects of climate on the soil organic carbon were broadly similar for the four future climate scenarios. However, the lowest increase or greatest decrease in soil organic carbon occurred in the RCP 8.5 (2060–2100) scenario (Fig. 5).

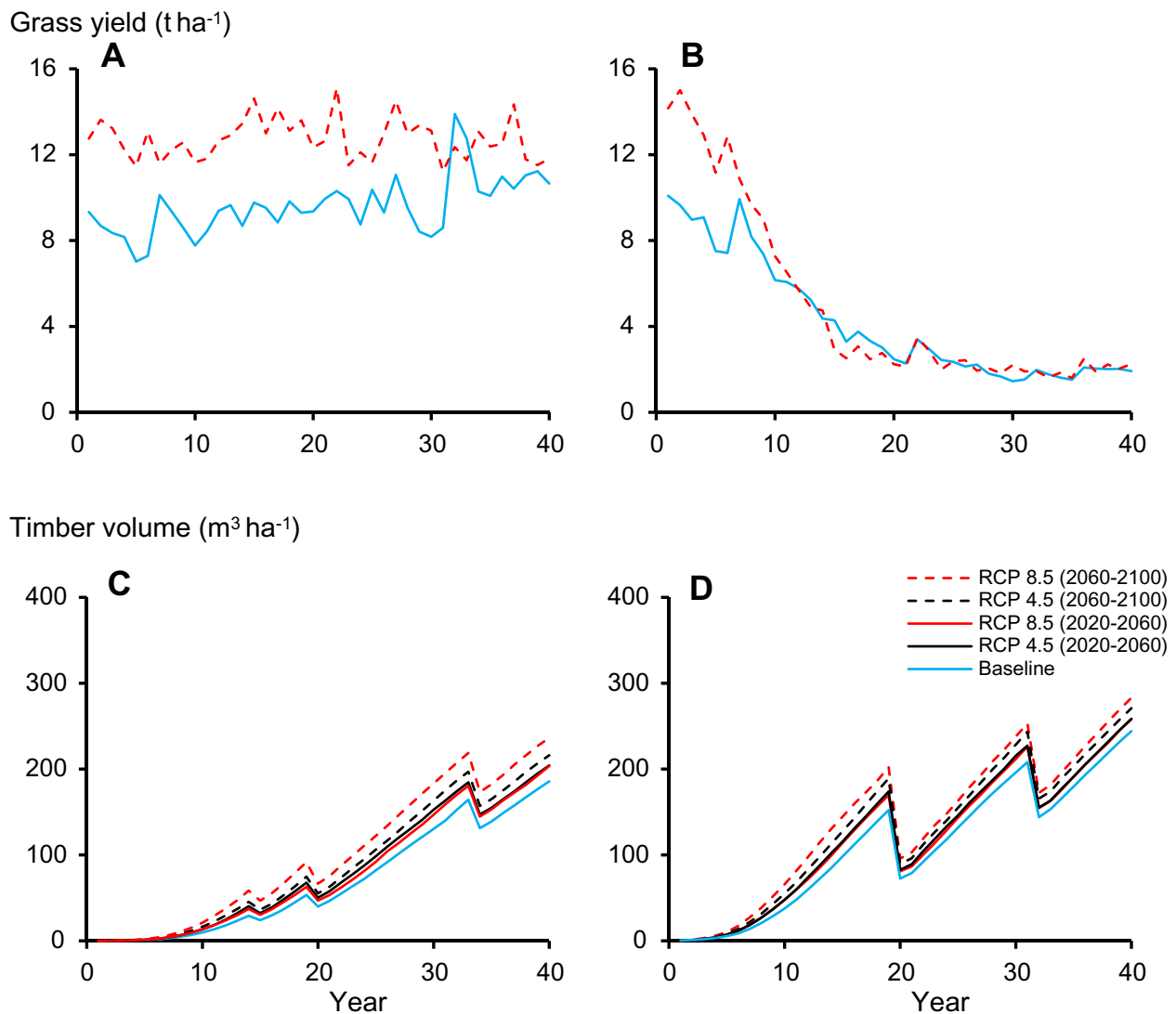


Fig. 2 Predicted grass yields in **A** the monoculture grassland and **B** ash silvopastoral system, and timber volume in the **C** ash silvopastoral and **D** ash woodland systems for the baseline and RCP 4.5 and RCP 8.5 scenarios in 2020–2060 and 2060–2100. All values are per hectare of system.

Table 4 Predicted average annual crop yield (t ha⁻¹ yr⁻¹) and timber yield (m³ ha⁻¹) in the monoculture systems and within the silvoarable system with the carbon dioxide fertilization effect, and the predicted

land equivalent ratio (silvoarable crop yield is per hectare of agroforestry system). Graphical illustration of the effect of CO₂ on crop and timber yields is presented in Supplementary material—Fig. S8.

Scenario	Time step	Barley only yield (40 years)	Poplar only yield (at year 40)	Silvoarable poplar (at year 40)	Silvo-arable crop (10 years)	LER (crop+tree)
Baseline	1999–2039	6.2	429	297	4.3	0.17 + 0.69 = 0.86
RCP 4.5	2020–2060	6.6	429	298	4.8	0.18 + 0.69 = 0.87
	2060–2100	7.3	473	324	5.6	0.19 + 0.68 = 0.88
RCP 8.5	2020–2060	6.4	459	314	4.2	0.16 + 0.68 = 0.85
	2060–2100	7.0	462	323	5.6	0.20 + 0.69 = 0.90

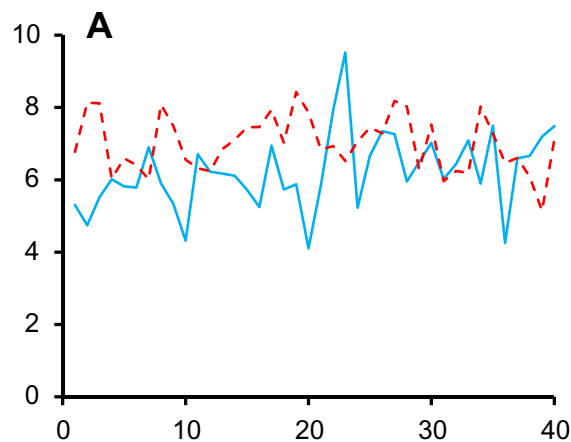
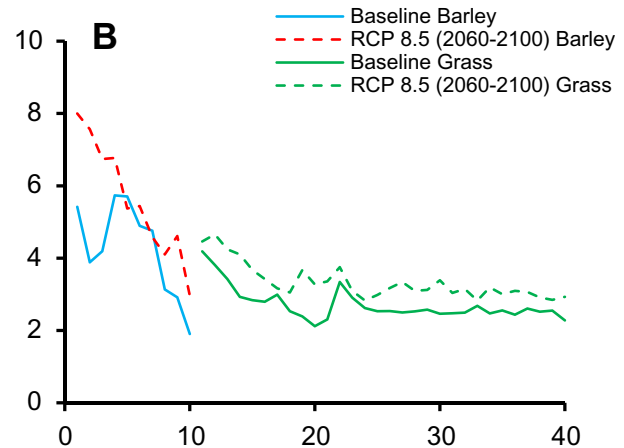
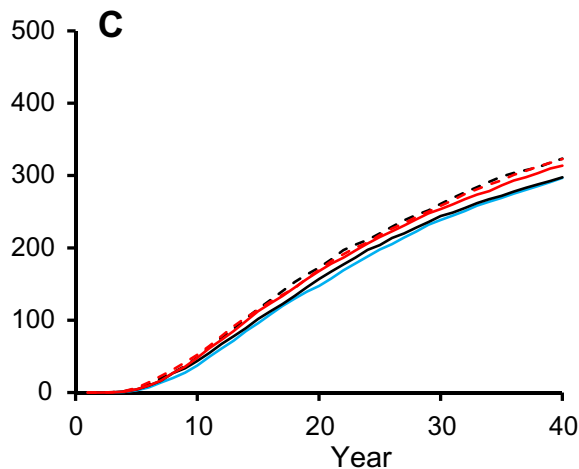
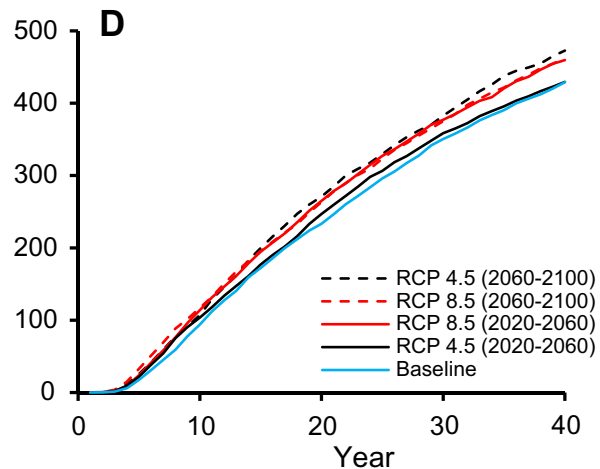
Barley yield (t ha^{-1})Crop yields (t ha^{-1})Timber volume (m^3ha^{-1})

Fig. 3 Predicted **A** barley yields in the monoculture arable system; **B** predicted barley (year 1–10) and then grassland yield in the poplar silvoarable system, and predicted timber volume in the **C** poplar sil-

voarable system and **D** the poplar plantation for the baseline and RCP 4.5 and RCP 8.5 scenarios for 2020–2060 and 2060–2100. All values are per hectare of system.

Table 5 Predicted effect of climate change and carbon dioxide fertilization on the mean annual *change* in soil organic carbon (0–23 cm) ($\text{t C ha}^{-1} \text{ yr}^{-1}$) in the grass, woodland and silvopastoral systems (assuming the same bulk density of 1.02 Mg m^{-3}).

Scenario	Time step	Grass	Woodland	Silvopasture
Baseline	1989–2029	– 0.48	0.85	0.09
RCP 4.5	2020–2060	– 0.43	1.03	0.18
	2060–2100	– 0.46	0.92	0.12
RCP 8.5	2020–2060	– 0.44	0.85	0.11
	2060–2100	– 0.55	0.84	0.05

3.6 Virtual experiments with tree densities

The final set of results relate to the effect of different tree densities with the RCP 8.5 scenario for 2060–2100. Within the silvopastoral experiments, the greatest grass yield was predicted with no trees (Fig. 6A), and the greatest timber volumes per hectare were predicted with high tree densities (Fig. 6C). When trees were integrated with the grass, whilst the initial grass yields were similar to the monoculture grass, grass yields were predicted to decline as the trees grew in

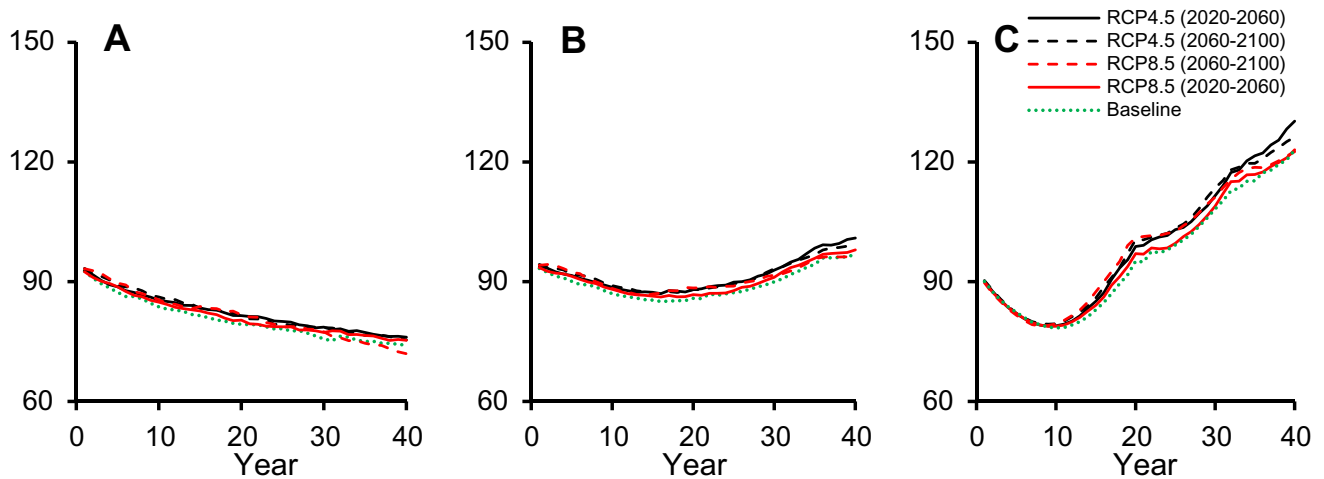


Fig. 4 Soil organic carbon (0–23 cm) as simulated for the baseline and RCP 4.5 and RCP 8.5 scenarios across 40 years in the **A** grass system, **B** ash silvopastoral system, and **C** ash woodland system (assuming the same bulk density of 1.02 Mg m^{-3}).

Table 6 Predicted effect of climate change and carbon dioxide fertilization on the mean annual *change* in soil organic carbon ($\text{t C ha}^{-1} \text{ yr}^{-1}$) in the monocrop barley, monoculture barley followed by grass, poplar plantation, and silvoarable systems (Spring barley was present in the field in the initial 10 years, followed by 30 years of grass).

Scenario	Time step	Barley only	Arable	Poplar plantation	Silvoarable
Baseline	1999–2039	– 1.02	– 0.51	0.19	– 0.29
RCP 4.5	2020–2060	– 1.02	– 0.48	0.22	– 0.27
	2060–2100	– 1.07	– 0.50	0.20	– 0.29
RCP 8.5	2020–2060	– 1.05	– 0.50	0.20	– 0.29
	2060–2100	– 1.18	– 0.58	0.05	– 0.39

size and captured more resources (Fig. 6A). For example, reducing the initial silvopastoral tree density of 400 to 300 trees ha^{-1} enhanced the mean annual grass yield over 40 years by 15% (or 0.7 t ha^{-1} ; Fig. 6A), but reduced the total timber volume by $25 \text{ m}^3 \text{ ha}^{-1}$ (Fig. 6C). Although timber volume per hectare declined with the reduced tree density, the predicted timber volume per tree was predicted to be $0.35 \text{ m}^3 \text{ tree}^{-1}$ greater in year 40 after planting (Supplementary material—Fig. S9a). With 50 trees per hectare, the predicted mean annual grass yield across 40 years (11.5 t ha^{-1}) was predicted to be approximately 90% of the mean annual grass yield (12.7 t ha^{-1}) with no trees (Fig. 6A).

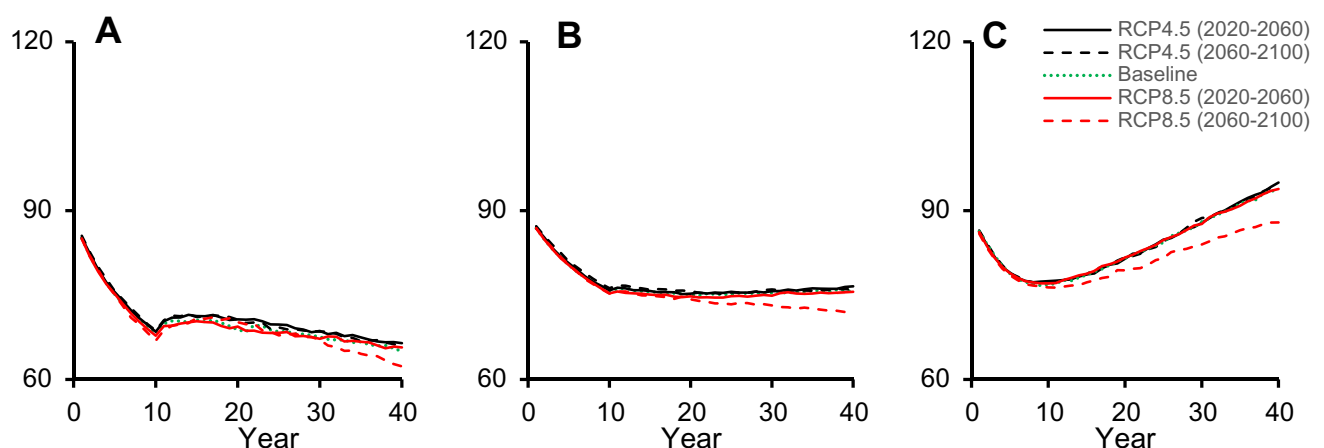


Fig. 5 Soil organic carbon (0–23 cm) as simulated for the baseline and RCP 4.5 and RCP 8.5 scenarios across 40 years in the **A** arable (10 years arable + 30 years grassland), **B** poplar silvoarable system, and **C** poplar plantation system.

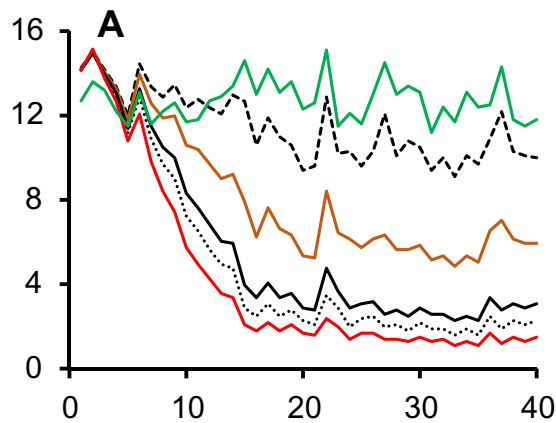
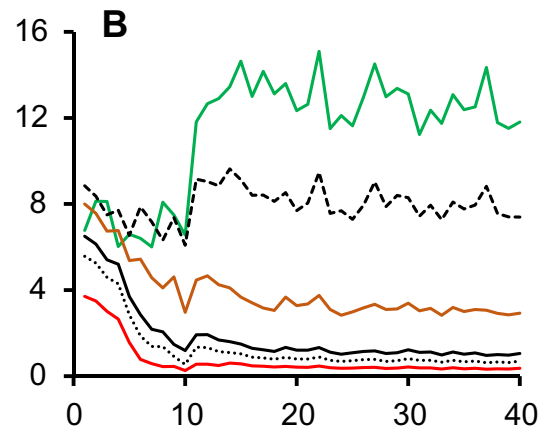
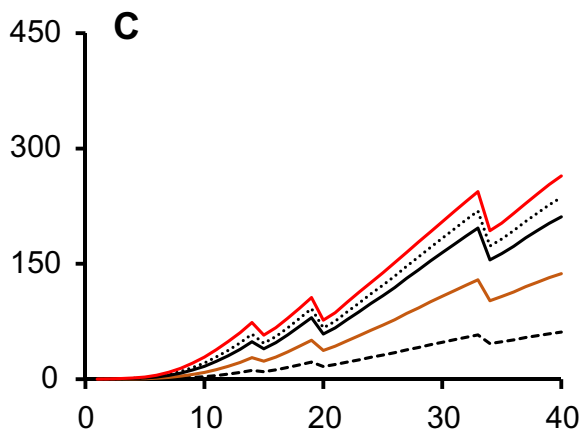
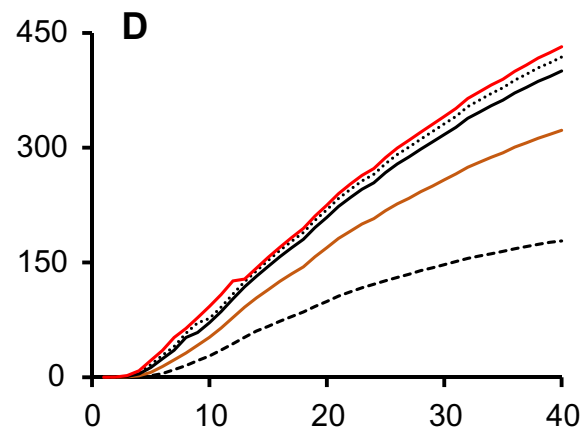
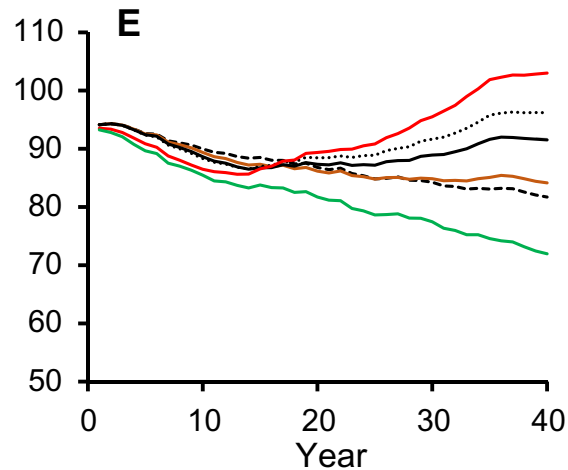
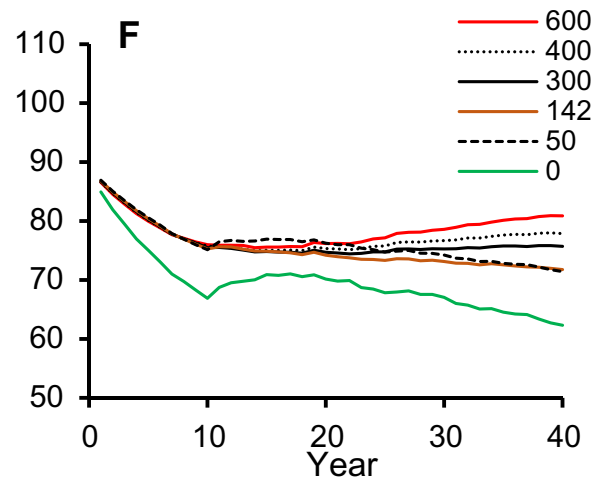
Crop yield (t ha^{-1})Timber volume ($\text{m}^3 \text{ha}^{-1}$)Soil organic carbon (t C ha^{-1})

Fig. 6 Predicted effect of six tree densities ranging from 0 to 600 trees ha^{-1} on **A**) the understorey grass yields in the ash silvopasture system and on **B**) the understorey crop (barley and grass) yields in the poplar silvoarable system, the standing timber volume per hectare **C**) in the ash silvopasture and **D**) in the poplar silvoarable system, and

soil organic carbon (SOC) in the **E**) ash silvopasture (assumed that only 15% of grass is left after harvest) and **F**) poplar silvoarable system, as simulated for the late RCP 8.5 scenario across 40 years (2060 - 2100). Graphs A and B illustrate the values per hectare of agroforestry system.

In the silvoarable experiment, the highest crop yields were derived with no trees (Fig. 6B) and the greatest timber volume per hectare was derived from the highest tree density (Fig. 6D). Increasing the tree density from 50 to 142 trees ha⁻¹ led to similar understorey crop yields in the first 4–5 years, but the mean annual crop yield across 40 years decreased by 4.0 t ha⁻¹ (Fig. 6B), and the predicted poplar timber volume in the final year increased from 178 to 322 m³ ha⁻¹. In a similar way, increasing the tree density from 142 to 300 stems ha⁻¹ reduced the mean annual crop yield by 2.0 t ha⁻¹ and increased timber volume by 78 m³ ha⁻¹ at year 40 (Fig. 6B, D).

For RCP 8.5 (2060–2100), the land equivalent ratio (including crops, trees, and grass) of 1.14 for the silvoarable system at 50 trees ha⁻¹ (Supplementary material—Table S12) was similar to the value of 1.10 for the same system at a density of 142 trees ha⁻¹ (Supplementary material—Table S11). Although the effect was marginal, the land equivalent ratios for the late RCP 8.5 (1.10–1.14) at these two tree densities was greater than those predicted for the baseline climate (1.07–1.08) and those (1.04–1.09) for the two RCP4.5 and the RCP 8.5 (2020–2060) scenarios (Supplementary material—Table S11; Table S12).

In the silvopasture system, at a tree density of 400 trees ha⁻¹, the model predicted a decrease in soil organic carbon in the first 15 years after planting, followed by an increase in the next 25 years (Fig. 6E). Reducing the density from 400 to 142 trees ha⁻¹ led to a smaller reduction in soil organic carbon in the first 10 years, but soil organic carbon continued to steadily decline. These responses are based on an assumption that 85% of the grass was removed at each harvest and only 15% was left on the soil surface. Hence, SOC gradually declined in the no-tree scenario (Fig. 6E, F). However, if 50% of the grass was left on the soil surface, the soil organic content would generally be stable across a range of tree densities, and if 100% of the grass was left, then the soil organic content was predicted to increase in the long-term (Supplementary material—Fig. S10). In the latter case, it appears that integrating 50 trees into pasture, would gradually and consistently increase soil organic carbon for the entire 40-year period (RCP 8.5: 2060–2100). Integrating more trees would initially draw down some of soil organic carbon, stabilise around after year 20 and increase in the last 10–15 years (Supplementary material—Fig. S10).

By contrast within the silvoarable-related treatments, although there were differences in the soil organic carbon between systems with and without trees, the difference between the different tree densities was relatively small. In both the silvopastoral and silvoarable systems, moving from no trees to 50 trees ha⁻¹ increased the predicted soil organic carbon by 9.7 and 9.1 t C ha⁻¹ respectively at year 40 (Fig. 6E, F).

4 Discussion

4.1 Climate change and food and fibre production

The EcoYield-SAFE model predicted that climate change and carbon dioxide fertilization would increase woodland ash timber production by 20% in the RCP 8.5 (2060–2100) to 514 m³ ha⁻¹, compared to 429 m³ ha⁻¹ in the baseline scenario. This is broadly similar to an increase of 21–29% in net primary productivity predicted for forests in Germany in the RCP 8.5 scenario by Sperlich et al. (2020). In Latin America and under the same scenario, forest productivity was also predicted to increase (10%) by 2100 (Favero et al. 2022). Tree growth in cool regions is likely to benefit from warmer and longer growing seasons (Kellomäki et al. 2018). For example, AlRahahleh et al. (2018) in Finland, estimated higher forest growth under future climates in a model that included the effect of carbon dioxide concentrations. Likewise, in Tennessee in the United States, Norby et al. (2010) showed that elevated CO₂ experiments, resulted in significant enhancements (24%) of tree net primary productivity during the initial 6 years; however, from year 7 onwards, the enhancement reduced to 9% due to soil nitrogen limitations. A similar observation was reported by Broadmeadow and Jackson (2000) in a factorial experiment on one year old tree seedlings in Britain, where elevated CO₂, increased growth of Scots pine (*Pinus sylvestris* L.), oak (*Quercus petraea* (Matt.) Liebl) and ash (*Fraxinus excelsior* L.) by 20% in year one. However, a longer-term lack of nitrogen meant that there was no enhanced growth in year three for a nitrogen demanding species like ash. Summer temperature extremes can also result in severe drought-induced mortality, as reported in Southern England, for native tree species on some soils (Broadmeadow et al. 2005).

We note that the Yield-SAFE models do not account for nitrogen limitations and these effects cannot therefore be modelled (van der Werf et al. 2007). Like most models, our analysis does not account for the effect of changes in temperature on pests and diseases. For example, van Niekerk et al. (2022) indicated that wood-degrading organisms are likely to become more active in Europe due to climate change. Warmer temperatures are anticipated to enhance the decay capacity of fungi and to expand the range of some wood-degrading termite species.

4.2 Agroforestry and food and fibre production

The EcoYield-SAFE model predicted that the silvopastoral system would result in declines in grass yields relative to a grass monoculture and declines in timber yields relative to a woodland system (Table 3). This is consistent with Ehret et al. (2015) who reported reductions of 70% in grass species

herbage production when shade reached 80% in a 2-year artificial shade experiment in Lower Saxony, Germany. The decline in grass yields in the silvopastoral system, say after year 8 or 9, when compared to the pasture system is due to competition by the trees for light and water (Supplementary material—Fig. S5). This reduction in grass yields will also reduce the density of livestock that can be supported below the trees. However, the trees can provide other benefits such as moderating high temperatures in summer, resulting in fewer stress days for livestock, and this can support animal productivity and welfare (Palma et al. 2016).

The analysis revealed that the predicted land equivalent ratio (LER) would range from 1.08 to 1.11 for grass and ash timber (Table 3), meaning that monocultures require 8–11% more land than the silvopastoral system to obtain the same relative yields. By contrast, the land equivalent ratios for the silvoarable system in terms of only arable crop and poplar timber production were below one (Table 4), meaning that the agroforestry system was less productive than the two monoculture systems. This is because the understorey of the Loughgall silvoarable system comprised 10-years of spring barley followed by grass, and the grass yield was not considered. If the grass yield was also included, then the LER would range from 1.04 to 1.10 (Supplementary material—Table S11). Seserman et al. (2018) in Saxony in Germany also reported an LER lower than 1 for a cereal-poplar agroforestry system. In such analyses, the choice of the default forestry system can also be critical. For example, a silvoarable system may have an LER of 1.22–1.45 if the default tree system is widely spaced (Graves et al. 2007), but less than 1.12 (Graves et al. 2010) if the default tree system is densely spaced.

4.3 Changes in soil carbon

The study showed that the model predicted declines in soil carbon in the arable, silvoarable and pasture systems, and increases in the silvopastoral and two woodland systems. Xu et al. (2011) also using RothC predicted a decline in soil organic carbon (SOC) on grassland in Ireland of between 2 and 6% in future climates compared to a baseline. The reductions in soil organic carbon in the grassland system were partly a result of an assumed low rate of return of biomass to the soil surface.

The EcoYield-SAFE model predicted soil organic carbon increases for the silvopasture system ranging from 0.18 t C ha⁻¹ yr⁻¹ for RCP 4.5 (2020–2060) to 0.05 t C ha⁻¹ yr⁻¹ for RCP 8.5 (2060–2100). These values are similar to reported increases in SOC in forest soils of 0.12 t C ha⁻¹ yr⁻¹ in Finland and 0.35 t C ha⁻¹ yr⁻¹ in France (Rantakari et al. 2012; Jonard et al. 2017). In previous research, Upson et al.

(2016) measured a decline in soil organic carbon during the first 14 years of growth when trees were planted in grassland. The inclusion of the RothC within EcoYield-SAFE provides an explanation for this in that whilst soil organic carbon declines after the first 15 years from tree planting, it may then recover (Supplementary material—Table S10; Fig. 4B). Such an analysis illustrates the potential strength of using a biophysical model to account for temporal changes. Ashwood et al. (2019) in a study focused on woodlands in the UK also found that, whereas the levels of soil carbon under pasture and young woodland were similar, the soil carbon content in the woodlands increased with time. Pardon et al. (2017) also highlighted the potential of middle-aged to mature tree rows to increase soil organic carbon stocks in the agricultural crops of agroforestry systems.

With the EcoYield-SAFE model, the predicted increase in the soil organic carbon of the ash woodland system of 0.84–1.03 t C ha⁻¹ yr⁻¹ (Table 5) was substantially greater than in the poplar plantation system of 0.05–0.22 t C ha⁻¹ yr⁻¹ (Table 6). Although the timber volumes of the ash and the poplar were similar after 40 years (429 m³ ha⁻¹), ash wood has a higher density than poplar wood, and hence the biomass accumulation of the ash woodland was greater and led to a greater cycling of biomass carbon to the soil.

The model predicted that the RCP 4.5 2020–2060 and 2060–2100 and RCP 8.5 2020–2060 climate scenarios would marginally increase soil organic carbon in the ash woodland (Table 5) and the poplar plantation (Table 6), compared to the baseline. This can be explained by the greater biomass production and recycling within these agroforestry systems.

As temperatures increase, retaining soil organic carbon becomes more difficult, and hence there is potentially a greater role for trees to help maintain or increase soil organic carbon. It has been reported that soil organic carbon decomposition rates may be lower in agroforestry systems than in arable and grassland systems due to the maintenance of high levels of moisture, reduced soil evaporation and cooler soil temperatures (Falloon et al. 2011; Das et al. 2019). Within the RothC module in EcoYield-SAFE, we predicted greater soil organic carbon decomposition rates in the grass monocrop than under the silvopasture for the RCP 8.5 2060–2100 scenario (Supplementary material—Table S13). Likewise, in the poplar plantation, under RCP 8.5, predicted soil organic carbon decomposition rates were lower in 2020–2060, than in RCP 8.5 2060–2100 causing the lowest soil organic carbon increase in the latter (Table 5; Supplementary material—Table S13). Furthermore, maintaining higher levels of soil organic matter can also be useful to increase climate resilience as soils with high organic contents can also maintain higher water contents, reducing the impact of prolonged droughts (IPCC 2019).

4.4 Management interventions

One advantage of developing and using calibrated models is that it is possible to investigate management interventions that could affect tree growth, grass and crop yields, and soil carbon levels. For example, within the models, we included the effect of regular tree pruning to create high-value knot-free timber. This in turn will affect the value of the timber and the solar radiation reaching the understorey grass and arable crops. It would also be possible to use the model developed to examine the effect of different pruning regimes on tree growth and grass and crop yields alongside different initial tree densities and thinning regimes.

The choice of initial tree density is an important choice when planting agroforestry systems, and it can be affected by whether the priority is tree growth or the crop (Isaac and Borden 2019). Low tree densities result in greater solar radiation availability for the understorey crop when compared to high densities. As tree density increases, competition for resources like light, water, and nutrients can result in a substantial decrease in crop yields (Pardon et al. 2018; Ivezić et al. 2021; Honfy et al. 2023). In our simulations, the understorey yield decreased substantially when tree density increased from 50 to 400 trees ha⁻¹, beyond which yield losses were relatively small (Fig. 6A, B). Timber volumes per hectare at 400 trees ha⁻¹, on the other hand, were 385% and 235% of that at 50 trees ha⁻¹ for the silvopasture (Fig. 6C) and silvoarable (Fig. 6D) systems respectively after 40 years. Depending on the objectives of the manager, the selected tree density can be modified. For example, the biodiversity benefits of including trees on a farm may be achievable at relatively low tree densities (Edo et al., 2024).

4.5 Implications for policy

The current modelling study in Northern Ireland illustrates that agroforestry can make more efficient use of light and water than separate crop and tree monocultures in the current relatively cool and wet climate. There is also a prediction that the relative benefit of agroforestry will be maintained under future climate scenarios and with elevated CO₂ concentrations. In Northern Ireland, programs such as the Environmental Farming Scheme (EFS) can support land managers to carry out environmentally beneficial farming practices on agricultural land (DAERA 2023). The 'Farming for Carbon' measure supports low carbon emission practices and the 'Farming with Nature' package supports habitat creation and species diversity (DAERA 2022). In addition to such economic incentives, the increased uptake of agroforestry is also dependent on demonstration and promotion through influential organisations and farmer-led and local community events involving co-design and co-creation (Irwin et al. 2023).

4.6 Limitations of the study—future research

In this study, the effect of CO₂ fertilization was included by adding a simple algorithm in EcoYield-SAFE. However, the mechanisms linking atmospheric CO₂ fertilization to biomass accumulation and evapotranspiration are still not well understood (Morison and Lawlor 1999; Deryng et al. 2016; Sperlich et al. 2020). Hence, our approach to modelling elevated CO₂ impacts on plant growth was conservative (up to 28% benefit for up to 800 ppm of CO₂) compared to other studies (Poorter et al. 2022; Ainsworth and Long 2020) that went beyond the thresholds used in this study. There is also a question as to whether short-term enhancement of growth from CO₂ fertilization can continue over long time periods (Norby et al. 2010). As discussed, low nutrient availability can constrain the proportional growth stimulation of elevated CO₂ (Poorter and Soba 2001; Piao et al. 2013; Li et al. 2024), and this is not accounted for in EcoYield-SAFE. Nevertheless, atmospheric deposition of nitrogen in Northern Ireland can range between 11 and 20 kg N ha⁻¹ (Rowe et al., 2021; Klein et al., 2022), and the default nitrogen status of lowland agricultural land is often high (Aiba and Kitayama 2020). Even so, others report that nitrogen and phosphorus can be limiting factors for tree growth even on relatively nutrient-rich soils (Rennenberg and Schmidt 2010). In addition to the above, this study has also assumed that there are no growth limitations due to the potential higher risk of pests or diseases associated with a changing climate.

With respect to the climate model and RCP emissions scenarios chosen, it is important to note the following points. RACMO was chosen for this analysis based on (i) its strong performance in simulating the meteorological variables required by EcoYield-SAFE and (ii) the ease of its accessibility via the CliPick web portal, which facilitated its application for further study. We note that each model has inherent errors and biases and the use of multiple models is encouraged in studies seeking to assess differences between climate scenarios. Future work could use the next generation of EURO-CORDEX regional climate, simulations for which are currently in progress. Additionally, we note that, whilst the appropriateness of RCP 8.5 as the most likely scenario for the future has been questioned (Hausfather and Peters 2020), RCP 8.5 has been shown to be a closer match to historical (2005–2020) and anticipated future CO₂ emissions than alternative RCPs (Schwalm et al. 2020).

5 Conclusions

To our knowledge, this is the first study to validate a biophysical model for arable, grassland, woodland, silvopastoral, and silvoarable systems at the same site in Europe

and to use the calibrated model to predict the effect of the IPCC's Representative Concentration Pathways (RCP 4.5 and RCP 8.5 for 2020–2060 and 2060–2100) on yield and soil carbon for those contrasting land-use systems. This combination of modelling alongside the use of calibration data from long-term experimental sites created a powerful combination to investigate the effects of future climate scenarios. The capacity to model daily changes in soil organic carbon over long time periods provided additional insight on the changes taking place in soil organic carbon when trees are planted on grassland and cropland. Although integrating trees on cropland and grassland resulted in higher soil organic carbon at 40 years, these positive effects only became apparent once the trees had been established for at least 10 years. Prior to that, soil organic carbon decreased. Virtual experiments with models can provide guidance on how farming systems, including agroforestry, can be designed to adapt to future climate change. The land equivalent ratio of the studied agroforestry systems is relatively resilient to a changing climate, as an increased capacity by one of the components to capture light and water resources is offset by a decline in the resources available to the other component. However, the virtual tree density experiments showed how individual system components and benefits (soil organic carbon) varied between tree densities over time. This provides insight for those tasked with selecting and designing agroforestry systems. For example, within the silvopastoral system, the effect of integrating 50 trees per hectare, compared to no trees, on grass yields appeared to be relatively low and the silvopasture results showed that soil organic carbon could decrease to begin with although these could also later recover and increase. The study also highlights the importance of including the atmospheric CO₂ fertilization effect on plant growth when predicting tree, crop, water, and soil responses to climate change. Within each system, management interventions such as thinning and pruning can also moderate the climate impacts on yield.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s13593-025-01020-7>.

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Data availability The datasets generated or analysed and the model used during the current study are available in Cranfield University repository <https://doi.org/10.57996/cran.ceres-2735>.

Declarations

Competing interests The authors declare no competing interests.

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