Agronomy for Sustainable Development (2025) 45:26
https://doi.org/10.1007/s13593-025-01020-7

RESEARCH ARTICLE

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

Michail L. Giannitsopoulos[1] · Paul J. Burgess[1] · Anil R. Graves[1] · Rodrigo J. Olave[2] · Jonathan M. Eden[3] · Felix Herzog[4]

Accepted: 27 March 2025

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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2e. This was derived from annual average agricultural emissions of about 386 Mt CO_2e (European Environment Agency 2024) and an annual average sink for LULUCF of 268 Mt CO_2e (European Commission 2018), even though LULUCF activities such as deforestation or conversion of

✉ Paul J. Burgess
p.burgess@cranfield.ac.uk

1 Faculty of Engineering and Applied Sciences, Cranfield University, Cranfield MK43 0AL, UK

2 Agri-Food and Biosciences Institute, 18a Newforge Lane, Belfast BT9 5PX, UK

3 Centre for Agroecology, Water and Resilience, Coventry University, Coventry CV8 3LG, UK

4 Agroscope, Department of Agroecology and Environment, 8046 Zurich, Switzerland

Published online: 13 May 2025

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 CO_2e and LULUCF was associated with an additional 6 Mt CO_2e, down from 18 Mt CO_2e 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-Corraliza 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 cashflow 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 CO_2 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 CO_2 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 CO_2 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 CO_2 fertilization

To determine the effect of climate change on tree and crop yields, EcoYield-SAFE included the effect of increases in atmospheric carbon dioxide (CO_2) 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 CO_2 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

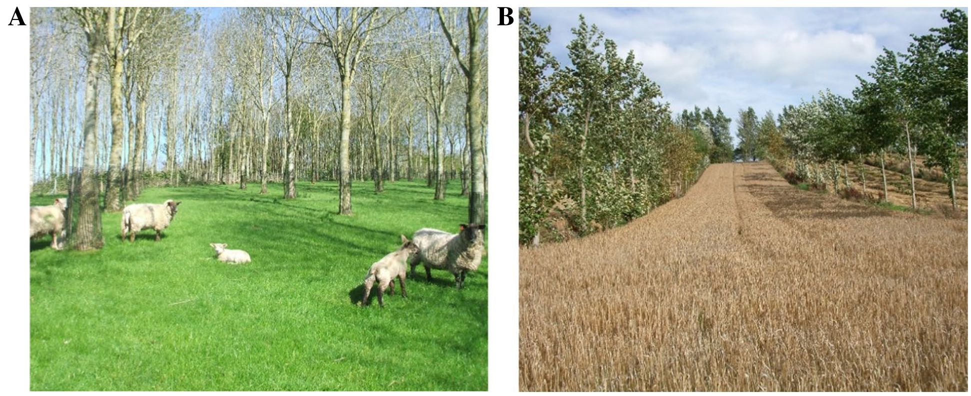

Fig. 1 Ash silvopastoral (**A**) and poplar silvoarable (**B**) experiments at Loughgall in Northern Ireland (Photos taken by Rodrigo Olave in 2010 (**A**) and 2005 (**B**)).

Boelare, Hoogvorst, and Hassendans. However, due to poor establishment Boelare and Hassadans 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 km × 11 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 kg C ha^{-1} day^{-1} based on an excremental rate of 21.6 kg ha^{-1} day^{-1} (18 kg ha^{-1} 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 m × 3 m (1093 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 5.3–5.9 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, $Ytree_{AF}$ and $Ycrop_{AF}$ are the tree and crop yields per hectare of the agroforestry system, and $Ytree_{\mathrm{Mono}}$ and $Ycrop_{\mathrm{Mono}}$ 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).

$$LER = \frac{Ycrop_{AF}}{Ycrop_{Mono}} + \frac{Ytree_{AF}}{Ytree_{Mono}} \quad (1)$$

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 0.2–0.5 MJ m^{-2} 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 CO_2 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 m^3 ha^{-1} in year 15 was similar to the modelled value of 98 m^3 ha^{-1} (Supplementary material—Fig. S2; RMSE: 6.7 m^3 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 m^3 ha^{-1} was close to the modelled value of 45 m^3 ha^{-1} (Supplementary material—Fig. S2; RMSE: 13.7 m^3 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 m^3 ha^{-1} with EcoYield-SAFE was similar to the yield of 260 m^3 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 m^3 ha^{-1}; $n = 4$). In the silvoarable system, the measured timber volume reached 163 m^3 ha^{-1} (as averaged across the four cultivars) at 22 years, compared to a modelled value of 169 m^3 ha^{-1} (Supplementary material—Table S9; RMSE: 10.2 m^3 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 CO_2 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 m^3 ha^{-1} to 458–514 m^3 ha^{-1} (Table 3; Fig. 2D).

Within the silvopastoral system, the predicted timber after 40 years increased from 272 m^3 ha^{-1} to 302–366 m^3 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 (t ha^{-1} yr^{-1}) and timber yield (m^3 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 6.4–7.3 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 m^3 ha^{-1} to 429–473 m^3 ha^{-1} (Table 4; Fig. 3D). Within the silvoarable system, the predicted harvested timber after 40 years increased from 297 m^3 ha^{-1} to 298–324 m^3 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 4.2–5.6 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 t ha^{-1} 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 t C ha^{-1} 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 t C ha^{-1} 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 t C ha^{-1} 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 t C ha^{-1} yr^{-1}, and the silvoarable system was predicted to result in an intermediate loss of 0.29 t C ha^{-1} 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).

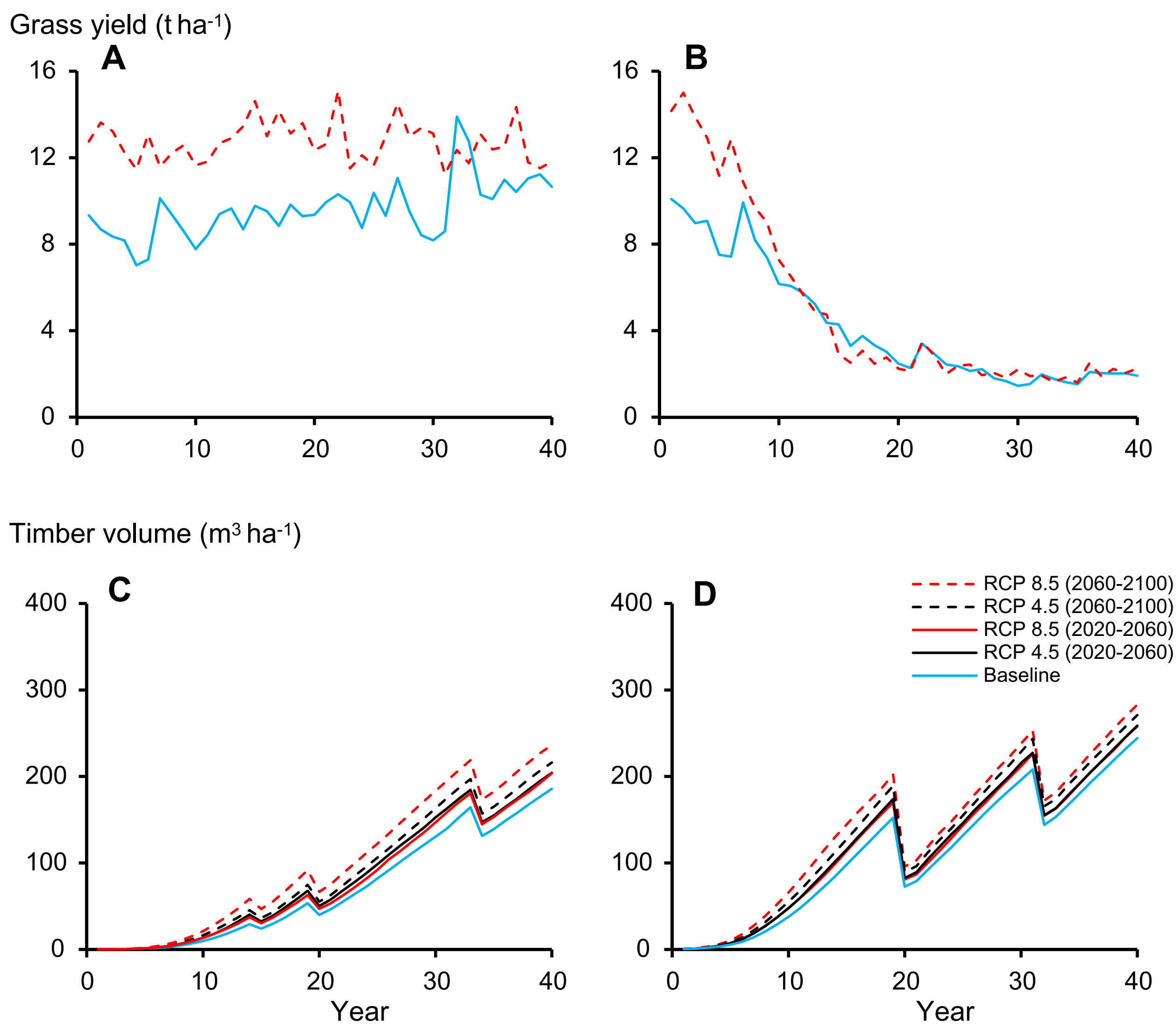

Fig. 2 Predicted grass yields in **A** the monoculture grassland and **B** ash silvopastoral system, and timber volume in the **C** ash silvopastoral and **D** ash woodland systems for the baseline and RCP 4.5 and RCP 8.5 scenarios in 2020–2060 and 2060–2010. All values are per hectare of system.

Table 4 Predicted average annual crop yield (t ha^{-1} yr^{-1}) and timber yield (m^3 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 CO_2 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

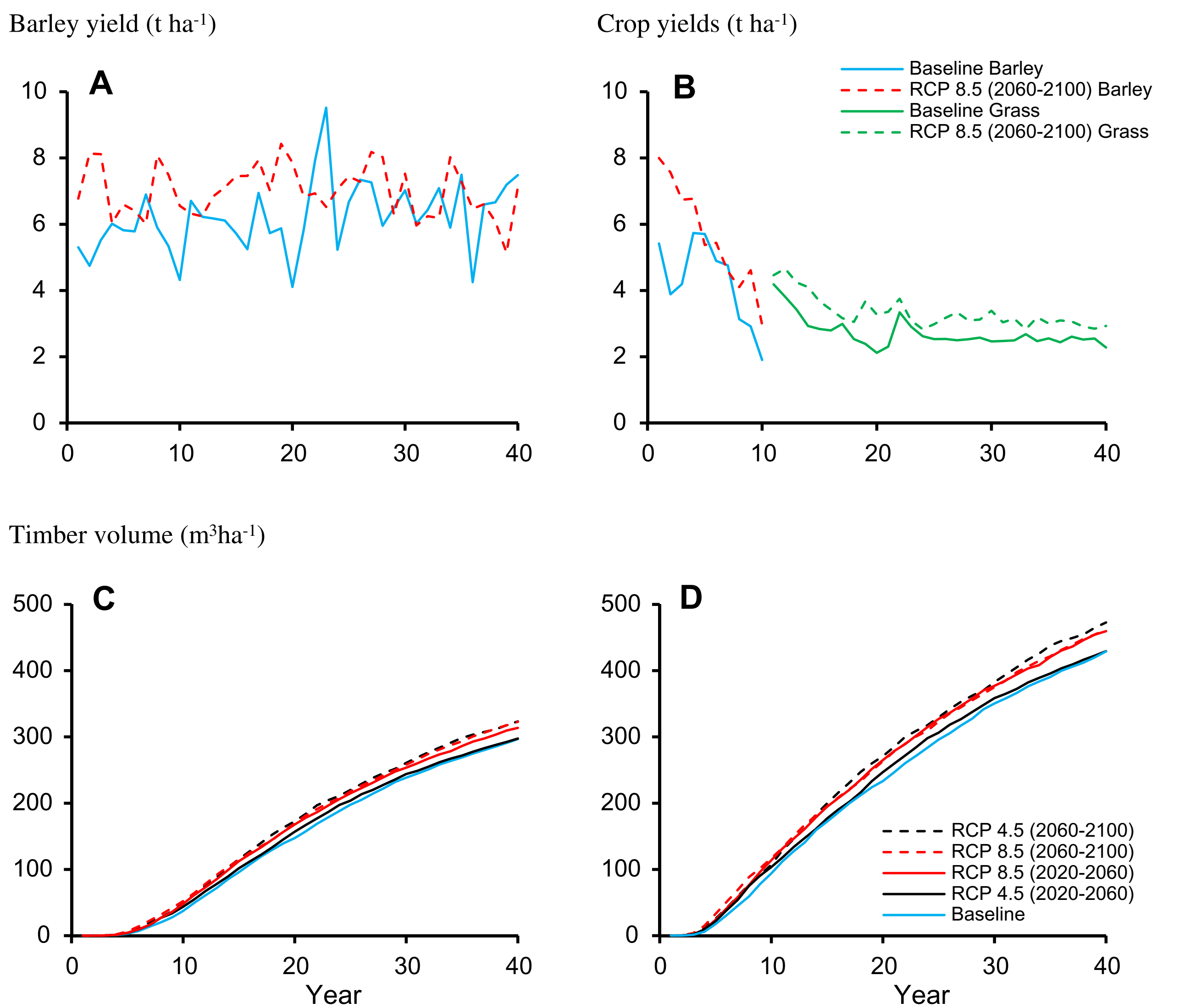

Fig. 3 Predicted **A** barley yields in the monoculture arable system; **B** predicted barley (year 1–10) and then grassland yield in the poplar silvoarable system, and predicted timber volume in the **C** poplar silvoarable system and **D** the poplar plantation for the baseline and RCP 4.5 and RCP 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) (t C ha^{-1} 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

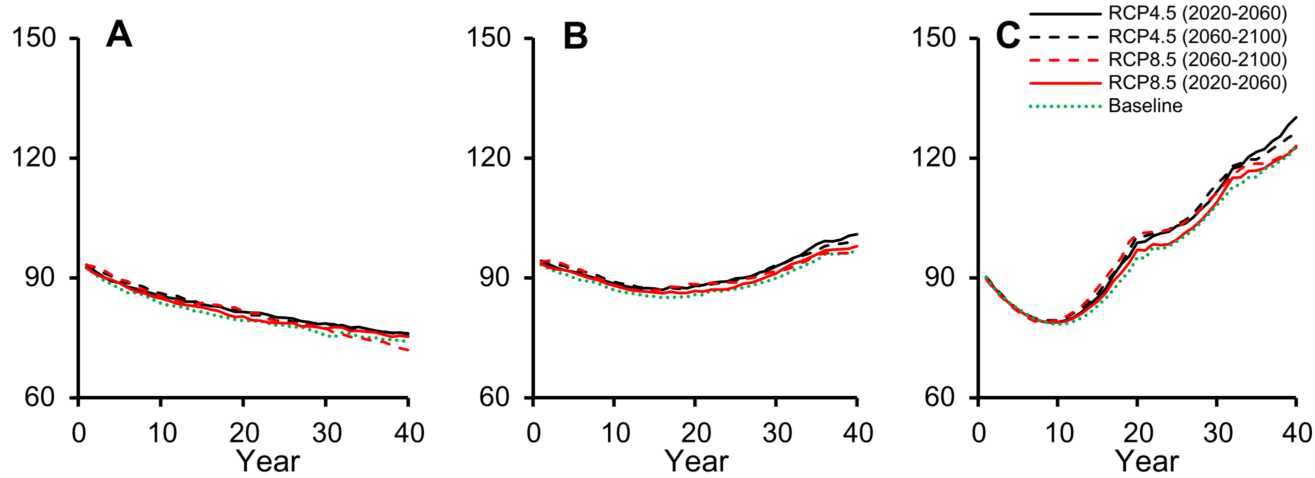

Fig. 4 Soil organic carbon (0–23 cm) as simulated for the baseline and RCP 4.5 and RCP 8.5 scenarios across 40 years in the **A** grass system, **B** ash silvopastoral system, and **C** ash woodland system (assuming the same bulk density of 1.02 Mg m^{-3}).

Table 6 Predicted effect of climate change and carbon dioxide fertilization on the mean annual *change* in soil organic carbon (t C ha^{-1} 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 m^3 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 m^3 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).

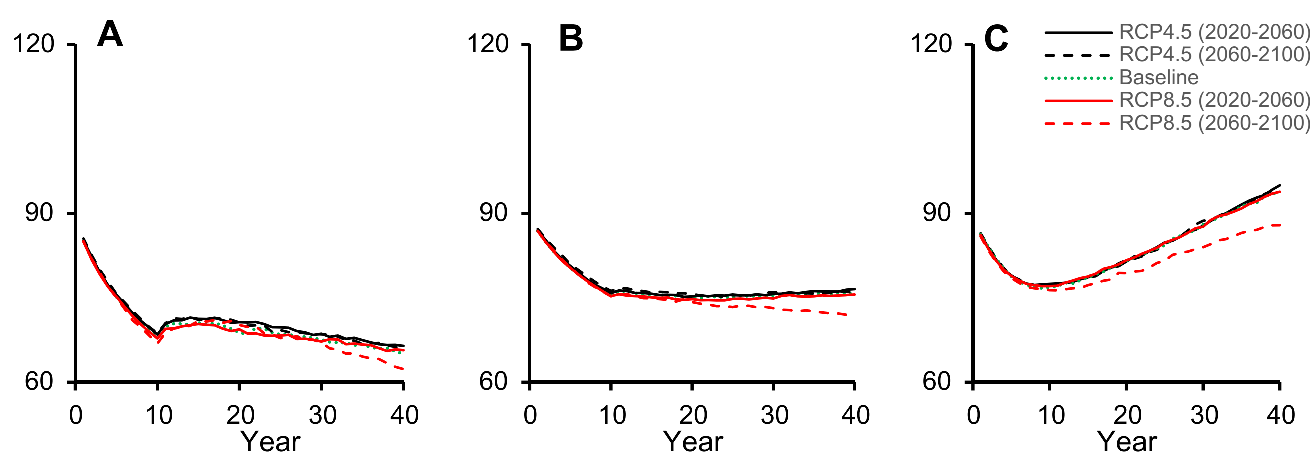

Fig. 5 Soil organic carbon (0–23 cm) as simulated for the baseline and RCP 4.5 and RCP 8.5 scenarios across 40 years in the **A** arable (10 years arable + 30 years grassland), **B** poplar silvoarable system, and **C** poplar plantation system.

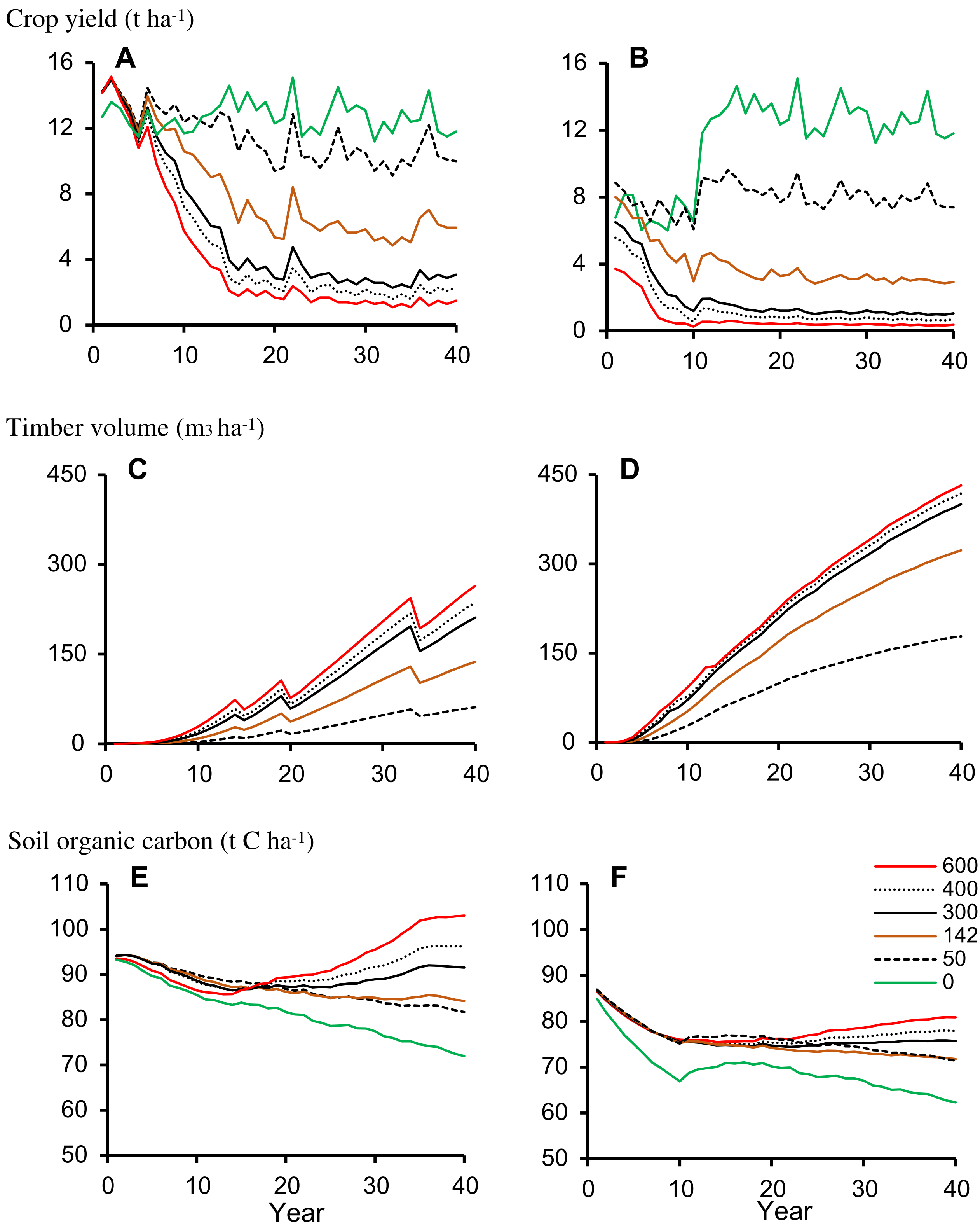

Fig. 6 Predicted effect of six tree densities ranging from 0 to 600 trees ha^{-1} on **A**) the understorey grass yields in the ash silvopasture system and on **B**) the understory crop (barley and grass) yields in the poplar silvoarable system, the standing timber volume per hectare **C**) in the ash 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 to m^3 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 m^3 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 m^3 ha^{-1}, compared to 429 m^3 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 CO_2 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 CO_2, 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 C ha^{-1} yr^{-1} (Table 6). Although the timber volumes of the ash and the poplar were similar after 40 years (429 m^3 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 understory 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; Ivezic 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 CO_2 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 CO_2 fertilization was included by adding a simple algorithm in EcoYield-SAFE. However, the mechanisms linking atmospheric CO_2 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 CO_2 impacts on plant growth was conservative (up to 28% benefit for up to 800 ppm of CO_2) 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 CO_2 fertilization can continue over long time periods (Norby et al. 2010). As discussed, low nutrient availability can constrain the proportional growth stimulation of elevated CO_2 (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 CO_2 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 CO_2 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.

Acknowledgements ERA5 is made available by the Copernicus Climate Change Service (C3S) at European Centre for Medium-Range Weather Forecasts (ECMWF).

Authors' contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by all authors. The first draft of the manuscript was written by MLG, and all authors reviewed and edited subsequent versions of the manuscript. All authors read and approved the final manuscript.

Funding We acknowledge the support of EU Horizon 2020 AGROMIX project under grant agreement 862993 and the DEFRA Nature for Climate Fund (NCF) England Tree Planting Programme (ETTP) Expanding Agroforestry project. We also thank AFBI (Agri-Food and Biosciences Institute) and DAERA (Department of Agriculture, Environment and Rural Affairs) in establishing and maintaining the silvopastoral and silvoarable experiments at Loughgall.

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.

References

Aiba SI, Kitayama K (2020) Light and nutrient limitations for tree growth on young versus old soils in a Bornean tropical montane forest. J Plant Res 133(5):665–679. https://doi.org/10.1007/s10265-020-01217-9

Ainsworth EA, Long SP (2020) 30 years of free-air carbon dioxide enrichment (FACE): what have we learned about future crop productivity and its potential for adaptation? Glob Change Biol 27(1):27–49. https://doi.org/10.1111/gcb.15375

ALRahahleh L, Kilpeläinen A, Ikonen VP, Strandman H, Asikainen A, Venäläinen A, Kaurola J, Kangas J, Peltola H, (2018) Effects of using certain tree species in forest regeneration on volume growth, timber yield, and carbon stock of boreal forests in Finland under different CMIP5 projections. Eur J for Res 137:573–591. https://doi.org/10.1007/s10342-018-1126-z

Arenas-Corraliza MG, López-Díaz ML, Moreno G (2018) Winter cereal production in a Mediterranean silvoarable walnut system in the face of climate change. Agric Ecosyst Environ 264:111–118. https://doi.org/10.1016/j.agee.2018.05.024

Ashwood F, Watts K, Park K, Fuentes-Montemayor E, Benham S, Vanguelova EI (2019) Woodland restoration on agricultural land: long-term impacts on soil quality. Restor Ecol. https://doi.org/10.1111/rec.13003Citat

Augère-Granier ML (2020) Agroforestry in the European Union. Briefing. European Parliamentary Research Service (EPRS), PE 651.982. https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/651982/EPRS_BRI(2020)651982_EN.pdf [Accessed on 12 March 2023]

Bednar-Friedl B, Biesbroek R, Schmidt DN, Alexander P, Børsheim KY, Carnicer J, Georgopoulou E, Haasnoot M., Le Cozannet G, Lionello P, Lipka O, Möllmann C, Muccione V, Mustonen T, Piepenburg D, Whitmarsh L (2022) Europe. In: Climate change 2022: impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)].

Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927. https://doi.org/10.1017/9781009325844.015
BEIS (Department for Business, Energy and Industrial Strategy) (2021) Final UK greenhouse gas emissions national statistics: 1990 to 2019. https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-to-2019 [Accessed on 10 March 2023]
Broadmeadow MSJ, Jackson SB (2000) Growth responses of *Quercus petraea, Fraxinus excelsior* and *Pinus sylvestris* to elevated carbon dioxide, ozone and water supply. New Phytol 146:437–451. https://doi.org/10.1046/j.1469-8137.2000.00665.x
Broadmeadow MSJ, Ray D, Samuel CJA (2005) Climate change and the future for broadleaved tree species in Britain, Forestry 78:2, May, 145-161. https://doi.org/10.1093/forestry/cpi014
Burgess PJ, Incoll LD, Corry DT, Beaton A, Hart BJ (2005) Poplar growth and crop yields within a silvoarable agroforestry system at three lowland sites in England. Agroforest Syst 63:157–169. https://doi.org/10.1007/s10457-004-7169-9
Burgess PJ, Graves AR, Wiltshire K, Giannitsopoulos M, Metselaar K, Stappers R, Keesman K, Palma J, van der Werf W (2023) Description of the biophysical Yield-SAFE model as implemented in Microsoft Excel. Cranfield, Bedfordshire, UK, Cranfield University. p 22. https://dspace.lib.cranfield.ac.uk/handle/1826/22344. Accessed 30 Apr 2024
Burgess PJ, Graves AR, Giannitsopoulos ML, Upson M, Palma JHN (2025). EcoYield-SAFE v 2 model in Excel. Cranfield, Bedfordshire, UK; Cranfield University. 1 March 2025. https://doi.org/10.57996/cran.ceres-2735
Cannell MGR, Van Noordwijk M (1996) Ong CK (1996) The central agroforestry hypothesis: the trees must acquire resources that the crop would not otherwise acquire. Agroforest Syst 34:27–31. https://doi.org/10.1007/BF00129630
Cannon AJ, Sobie SR, Murdock TQ (2015) Bias correction of simulated precipitation by quantile mapping: How well do methods preserve relative changes in quantiles and extremes? J Climate 28:6938–6959. https://doi.org/10.1175/JCLI-D-14-00754.1
Christie JM (1994) Provisional yield tables for poplar in Britain. Forestry Commission. Technical Paper 6. https://cdn.forestresearch.gov.uk/1994/09/fctp006.pdf [Accessed on 27 January 2023]
Coleman K, Jenkinson D (2014) RothC - a model for the turnover of carbon in soil - model description and users guide. Rothamsted Research, Harpenden, UK. https://doi.org/10.1007/978-3-642-61094-3_17[Accessedon30April2024]
European Commission (2018) Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU. http://data.europa.eu/eli/reg/2018/841/2023-05-11 [Accessed on 10 March 2023]
Cornes R, van der Schrier G, van den Besselaar EJM, Jones P (2018) An ensemble version of the E-OBS temperature and precipitation datasets, J Geophys Res Atmos 123. https://doi.org/10.1029/2017JD028200
Cruickshank JG (1997) Soil and environment: Northern Ireland Agricultural and Environment Science Division, DANI and the Agricultural Environmental Science Department, The Queen's University Belfast. p. 77
Das S, Richards BK, Hanley KL, Krounbi L, Walter MF, Walter MT, Steenhuis TS, Lehmann J (2019) Lower mineralizability of soil carbon with higher legacy soil moisture. Soil Biol Biochem 130:94–104. https://doi.org/10.1016/j.soilbio.2018.12.006
den Herder M, Moreno G, Mosquera-Losada RM, Palma JHN, Sidiropoulou A, Santiago Freijanes JJS, Crous-Duran J, Paulo JA, Tomé M, Pantera A, Papanastasis VP, Mantzanas K, Pachana P, Papadopoulos A, Plieninger T, Burgess PJ (2017) Current extent and stratification of agroforestry in the European Union. Agric Ecosyst Environ 241:121–132. https://doi.org/10.1016/j.agee.2017.03.005
Deryng D, Elliott J, Folberth C, Müller C, Pugh TAM, Boote KJ, Conway D, Ruane AC, Gerten D, Jones JW, Khabarov N, Olin S, Schaphoff S, Schmid E, Yang H, Rosenzweig C (2016) Regional disparities in the beneficial effects of rising CO_2 concentrations on crop water productivity. Nat Clim Change 6:786–790. https://doi.org/10.1038/nclimate2995
Ehret M, Graß R, Wachendorf M (2015) The effect of shade and shade material on white clover/perennial ryegrass mixtures for temperate agroforestry systems. Agroforest Syst 89:557–570. https://doi.org/10.1007/s10457-015-9791-0
Department of Agriculture, Environment and Rural Affairs (DAERA) (2022) Future agricultural policy for Northern Ireland, grants and funding https://www.daera-ni.gov.uk/news/future-agricultural-policy-northern-ireland#skip-link [Accessed on 10 March 2023]
Department of Agriculture, environment and Rural Affairs (DAERA) (2023) Future Agricultural Policy Decisions for Northern Ireland. https://www.daera-ni.gov.uk/sites/default/files/publications/daera/Future%20Agricultural%20Policy%20Decisions%20for%20Northern%20Ireland%20%28Final%29%20%28002%29.pdf [Accessed on 10 March 2023]
Edo M, Entling MH, Rösch V (2024) Agroforestry supports high bird diversity in European farmland. Agron Sustain Dev 44:1. https://doi.org/10.1007/s13593-023-00936-2
European Environment Agency (2024) Greenhouse gas emissions from agriculture in Europe. https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-agriculture [Accessed on 10 March 2023]
Falloon P, Jones CD, Ades M, Paul K (2011) Direct soil moisture controls of future global soil carbon changes: an important source of uncertainty. Global Biogeochem Cycles 25:GB3010. https://doi.org/10.1029/2010GB003938
Farrell AD, Derying D, Neufeldt H (2023) Modelling adaptation and transformative adaptation in cropping systems: recent advances and future directions. Current Opinion in Environmental Sustainability, 61, 101265, ISSN 1877-3435. https://doi.org/10.1016/j.cosust.2023.101265
Favero A, Sohngen B, Parker Hamilton W (2022) Climate change and timber in Latin America: Will the forestry sector flourish under climate change? For Policy Econ 135:102657. https://doi.org/10.1016/j.forpol.2021.102657
Fornara DA, Olave R, Burgess P, Delmer A, Upson M, McAdam J (2018) Land use change and soil carbon pools: evidence from a long-term silvopastoral experiment. Agroforest Syst 92:1035–1046. https://doi.org/10.1007/s10457-017-0124-3
Giannitsopoulos M, Graves AR, Burgess PJ, Crous-Duran J, Moreno G, Herzog F, Palma JHN, Kay S, García de Jalón S (2020) Whole system valuation of arable, agroforestry and treeonlysystems at three case study sites in Europe. J Clean Prod 269:122283. https://doi.org/10.1016/j.jclepro.2020.122283
Graves AR, Burgess PJ, Palma JHN, Herzog F, Moreno G, Bertomeu M, Dupraz C, Liagre F, Keesman K, van der Werf W, Koeffeman de Nooy A, van den Briel JP (2007) Development and application of bio-economic modelling to compare silvoarable, arable and forestry systems in three European countries. Ecol Eng 29:434–449. https://doi.org/10.1016/j.ecoleng.2006.09.018
Graves AR, Burgess PJ, Palma J, Keesman K, van der Werf W, Dupraz C, van Keulen H, Herzog F, Mayus M (2010) Implementation and calibration of the parameter-sparse Yield-SAFE model to predict production and land equivalent ratio in mixed tree and crop systems under two contrasting production situations in Europe. Ecol Model 221:1744–1756. https://doi.org/10.1016/j.ecolmodel.2010.03.008

Hausfather Z, Peters GP (2020) Emissions - the 'business as usual' story is misleading. Nature 577:618–620. https://doi.org/10.1038/d41586-020-00177-3

Hersbach H, Bell B, Berrisford P, Hirahara S, Horányi A, Muñoz-Sabater J, Nicolas J, Peubey C, Radu R, Schepers D, Simmons A, Soci C, Abdalla S, Abellan X, Balsamo G, Bechtold P, Biavati G, Bidlot J, Bonavita M, De Chiara G, Dahlgren P, Dee D, Diamantakis M, Dragani R, Flemming J, Forbes R, Fuentes M, Geer A, Haimberger L, Healy S, Hogan RJ, Hólm E, Janisková M, Keeley S, Laloyaux P, Lopez P, Lupu C, Radnoti G, de Rosnay P, Rozum I, Vamborg F, Villaume S, Thépaut J-N (2020) The ERA5 global reanalysis. Q J R Meteorol Soc 146:1999–2049. https://doi.org/10.1002/qj.3803

Honfy V, Pödör Z, Keserű Z, Rásó J, Ábri T, Borovics A (2023) The effect of tree spacing on yields of alley cropping systems - a case study from Hungary. Plants (Basel) 12(3):595. https://doi.org/10.3390/plants12030595

IPCC (2019) Summary for Policymakers. In: Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [Shukla PR, Skea J, Calvo Buendia E, Masson-Delmotte V, Pörtner H-O, Roberts DC, Zhai P, Slade R, Connors S, van Diemen R, Ferrat M, Haughey E, Luz S, Neogi S, Pathak M, Petzold J, Portugal Pereira J, Vyas P, Huntley E, Kissick K, Belkacemi M, Malley J, (eds.)]. https://doi.org/10.1017/9781009157988.001 [Accessed on 20 May 2024]

IPCC (2023) Sections. In: Climate Change (2023). Synthesis Report. Contribution of working groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Lee H, Romero J (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115. https://doi.org/10.59327/IPCC/AR6-9789291691647 [Accessed on 20 May 2024]

Irwin R, Short I, Mohammadrezaei M, Ní Dhubháin Á (2023) Increasing tree cover on Irish dairy and drystock farms: the main attitudes, inlfuencial bodies and barriers that affect agroforestry uptake. Environ Sci Policy 146:76–89. https://doi.org/10.1016/j.envsci.2023.03.022

Isaac ME, Borden KA (2019) Nutrient acquisition strategies in agroforestry systems. Plant Soil 444:1–19. https://doi.org/10.1007/s11104-019-04232-5

Ivezic V, Yu Y, van der Werf W (2021) Crop yields in European agroforestry systems: A meta-analysis. Front Sustain Food Syst 5:606631. https://doi.org/10.3389/fsufs.2021.606631

Jacob D, Petersen J, Eggert B, Alias A, Christensen OB, Bouwer LM, Braun A, Colette A, Déqué M, Georgievski G, Georgopoulou E, Gobiet A, Menut L, Nikulin G, Haensler A, Hempelmann N, Jones C, Keuler K, Kovats S, Kröner N, Kotlarski S, Kriegsmann A, Martin E, van Meijgaard E, Moseley C, Pfeifer S, Preuschmann S, Radermacher C, Radtke K, Rechid D, Rounsevell M, Samuelsson P, Somot S, Soussana JF, Teichmann C, Valentini R, Vautard R, Weber B, You P (2014) EURO-CORDEX: New high-resolution climate change projections for European impact research. Reg Environ Change 14(2):563–578. https://doi.org/10.1007/s10113-013-0499-2

Jägermeyr J, Müller C, Ruane AC, Elliott J, Balkovic J, Castillo O, Faye B, Foster I, Folberth C, Franke JA, Fuchs K, Guarin JR, Heinke J, Hoogenboom G, Iizumi T, Jain AK, Kelly D, Khabarov N, Lange S, Lin TS, Liu W, Mialyk O, Minoli S, Moyer EJ, Okada M, Phillips M, Porter C, Rabin SS, Scheer C, Schneider JM, Schyns JF, Skalsky R, Smerald A, Stella T, Stephens H, Webber H, Zabel F, Rosenzweig C (2021) Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. Nat Food 2:873–885. https://doi.org/10.1038/s43016-021-00400-y

Jonard M, Nicolas M, Coomes DA, Caignet I, Saenger A, Ponette Q (2017) Forest soils in France are sequestering substantial amounts of carbon. Sci Total Environ 574:616–628. https://doi.org/10.1016/j.scitotenv.2016.09.028

Kay S, Rega C, Moreno G, den Herder M, Palma JHN, Borek R, Crous-Duran J, Freese D, Giannitsopoulos M, Graves A, Jäge M, Lamersdorf N, Memedemin D, Mosquera-Losada R, Pantera A, Paracchini ML, Paris P, Roces-Díaz JV, Rolo V, Rosati A, Sandor M, Smith J, Szerencsits E, Varga A, Viaud V, Wawer R, Burgess PJ, Herzog F (2019) Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe. Land Use Pol 83:581–593. https://doi.org/10.1016/j.landusepol.2019.02.025

Kellomäki S, Strandman H, Heinonen T, Asikainen A, Venäläinen A, Peltola H (2018) Temporal and spatial change in diameter growth of boreal Scots pine, Norway spruce, and birch under recent-generation (CMIP5) global climate model projections for the 21st century. Forests 9:118. https://doi.org/10.3390/f9030118

Klein H, Gauss M, Tsyro S, Nyíri Á (2022) Transboundary air pollution by sulphur, nitrogen, ozone and particulate matter in 2020. The United Kingdom. Norwegian Meteorological Institute. https://emep.int/publ/reports/2022/Country_Reports/report_GB.pdf

Kumar A, Singh V, Shabnam S, Oraon PR (2020) Carbon emission, sequestration, credit and economics of wheat under poplar based agroforestry system. Carbon Manag 11(6):673–679. https://doi.org/10.1080/17583004.2020.1840875

Li S, Waring BG, Powers JS, Medvigy D (2024) Tropical dry forest response to nutrient fertilization: A model validation and sensitivity analysis. Biogeosc 21:455–471. https://doi.org/10.5194/bg-2022-243

Lunny R (2017) Tree-crop interactions in alley coppice - A Novel Land Use System. Unpublished PhD thesis. Queen's University Belfast. UK

Mantino A, Volpi I, Micci M, Pecchioni G, Bosco S, Dragoni F, Mele M, Ragaglini G (2020) Effect of tree presence and soil characteristics on soybean yield and quality in an innovative alley-cropping system. Agronomy 10:52. https://doi.org/10.3390/agronomy10010052

Maraun D, Widmann M (2018) Statistical downscaling and bias correction for climate research. Cambridge University Press, Cambridge,978110758878, doi: 10.1017/9781107588783

Medinski TV, Freese D, Bohm C (2015) Soil CO_2 flux in an alley-cropping system composed of black locust and poplar trees, Germany. Agroforest Syst 89:267–277. https://doi.org/10.1007/s10457-014-9764-8

Meinshausen M, Nicholls ZRJ, Lewis J, Gidden MJ, Vogel E, Freund M, Beyerle U, Gessner C, Nauels A, Bauer N, Canadell JG, Daniel JS, John A, Krummel PB, Luderer G, Meinshausen N, Montzka SA, Rayner PJ, Reimann S, Smith SJ, van den Berg M, Velders GLM, Vollmer MK, Wang RHJ (2020) The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. Geosci Model Dev 13:3571–3605. https://doi.org/10.5194/gmd-13-3571-2020

Mercer PC (2006) Growing organic cereals in Northern Ireland - disease and weed problems. In: Atkinson C, Ball B, Davies, DHK, Rees R, Russell G, Stockdale EA, Watson CA, Walker R, Younie D (Eds.) Aspects of applied biology 79, what will organic farming deliver? COR 2006, Association of Applied Biologists, pp. 229-232. https://orgprints.org/id/eprint/10234/ [Accessed on 20 May 2024]

Morison JIL, Lawlor DW (1999) Interactions between increasing CO2 concentration and temperature on plant growth. Plant, Cell and Environment 22:659–682. https://doi.org/10.1046/j.1365-3040.1999.00443.x

Moss RH, Edmonds J, Hibbard K, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JFB, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomson AM, Weyant JP, Wilbanks TJ (2010) The next generation of scenarios for climate change research and assessment. Nature 463:747–756. https://doi.org/10.1038/nature08823

Nennich TD, Harrison JH, VanWieringen LM, Meyer D, Heinrichs AJ, Weiss WP, St-Pierre NR, Kincaid RL, Davidson DL, Block E (2005) Prediction of manure and nutrient excretion from dairy cattle, J Dairy Sci 88:3721-3733, ISSN 0022-0302. https://doi.org/10.3168/jds.S0022-0302(05)73058-7.

Norby RJ, Warren JM, Iversen CM, Medlyn BE, McMurtrie RE (2010) CO_2 enhancement of forest productivity constrained by limited nitrogen availability. PNAS 107:19368–19373. https://doi.org/10.1073/pnas.1006463107

Ostańska K, Negre F (2022) Agricultural potential in carbon sequestration. AT A GLANCE. Policy Department for Structural and Cohesion Policies. Directorate-General for Internal Policies of the Union. PE 699.656. https://www.europarl.europa.eu/RegData/etudes/ATAG/2022/699656/IPOL_ATA(2022)699656_EN.pdf [Accessed on 20 June 2023]

Palma JHN (2017) CliPick - Climate change web picker. A tool bridging daily climate needs in process-based modelling in forestry and agriculture, For Syst 26(1), eRC01, 4 pages. https://doi.org/10.5424/fs/2017261-10251

Palma JHN, Graves AR, Crous-Duran J, Upson M, Paulo JA, Oliveira TS, Silvestre Garcia de Jalón S, Burgess PJ (2016) Yield-SAFE Model Improvements. Milestone Report 29 (6.4) for EU FP7 Research Project: AGFORWARD 613520. (5 July 2016). 30 pp. https://agforward.eu/documents/MS29_Yield-SAFE_Improvements.pdf

Palma JHN, Crous-Duran J, Graves AR, Garcia de Jalon S, Upson M, Oliveira TS, Paulo JA, Ferreiro-Domínguez N, Moreno G, Burgess PJ (2018) Integrating belowground carbon dynamics into Yield-SAFE, a parameter sparse agroforestry model. Agroforest Syst 92:1047–1057. https://doi.org/10.1007/s10457-017-0123-4

Pardon P, Reubens B, Reheul D, Mertens J, De Frenne P, Coussement T, Janssens R, Verheyen K (2017) Trees increase soil organic carbon and nutrient availability in temperate agroforestry systems. Agric Ecosyst Environ 247:98–111. https://doi.org/10.1016/j.agee.2017.06.018

Pardon P, Reubens B, Reheul D, Mertens J, Verheyen K, De Frenne P, De Smet G, Van Waes C, Reheul D (2018) Effects of temperate agroforestry on yield and quality of different arable intercrops. Agric Syst 166:135–151. https://doi.org/10.1016/j.agsy.2018.08.008

Piao S, Sitch S, Ciais P, Friedlingstein P, Peylin P, Wang X, Ahlström A, Anav A, Canadell JG, Cong N, Huntingford C, Jung M, Levis S, Levy PE, Li J, Lin X, Lomas MR, Lu M, Luo Y, Ma Y, Myneni RB, Poulter B, Sun ZZ, Wang T, Viovy N, Zaehle S, Zeng N (2013) Evaluation of terrestrial carbon cycle models for their response to climate variability and to CO_2 trends. Glob Change Biol 19:2117–2132. https://doi.org/10.1111/gcb.12187

Poorter H, Pérez-Soba M (2001) The growth response of plants to elevated CO_2 under non-optimal environmental conditions. Oecologia 129:1–20. https://doi.org/10.1007/s004420100736

Poorter H, Knopf O, Wright IJ, Temme AA, Hogewoning SW, Graf A, Cernusak LA, Pons TL (2022) A meta-analysis of responses of C3 plants to atmospheric CO_2: dose–response curves for 85 traits ranging from the molecular to the whole-plant level. New Phytol 233:1560–1596. https://doi.org/10.1111/nph.17802

Rantakari M, Lehtonen A, Linkosalo T, Tuomi M, Tamminen P, Heikkinen J, Sievänen R (2012) The Yasso07 soil carbon model–testing against repeated soil carbon inventory. For Ecol Manag 286:137–147. https://doi.org/10.1016/j.foreco.2012.08.041

Reed J, van Vianen J, Foli S, Clendenning J, Yang K, MacDonald M, Petrokofsky G, Padoch C, Sunderland T (2017) Trees for life: the ecosystem service contribution of trees to food production and livelihoods in the tropics. For Policy Econ 84:62–71. https://doi.org/10.1016/j.forpol.2017.01.012

European Commission (2013) Regulation (EU) No 1305/2013 of the European Parliament and of the Council of 17 December 2013 on support for rural development by the European Agricultural Fund for Rural Development (EAFRD) and repealing Council Regulation (EC) No 1698/2005. https://faolex.fao.org/docs/pdf/eur129734.pdf [Accessed on 10 March 2023]

Rennenberg H, Schmidt S (2010) Perennial lifestyle—an adaptation to nutrient limitation? Tree Physiol 30(9):1047–1049. https://doi.org/10.1093/treephys/tpq076

Rodriguez D, Van Oijen M, Schapendonk AHMC (1999) LINGRA-CC: A sink-source model to simulate the impact of climate change and management on grassland productivity. New Phytol 144, 359–368. http://www.jstor.org/stable/2588780

Rowe EC, Sawicka K, Tomlinson S, Levy P, Banin LF, Martín Hernandez C & Fitch A (2021) Trends Report 2021: Trends in critical load and critical level exceedances in the UK. Reportto Defra under Contract AQ0849, UKCEH project 07617. https://uk-air.defra.gov.uk/library/reports?report_id=1020

Rubio-Delgado J, Schnabel S, Burgess PJ, Burbi S (2023) Reduced grazing and changes in the area of agroforestry in Europe. Front Environ Sci 11:1258697. https://doi.org/10.3389/fenvs.2023.1258697

Schwalm CR, Glendon S, Duffy PB (2020) Reply to Hausfather and Peters: RCP 8.5 is neither problematic nor misleading. PNAS. 10;117(45):27793-27794. https://doi.org/10.1073/pnas.2018008117

Seneviratne SI, Zhang X, Adnan M, Badi W, Dereczynski C, Di Luca A, Ghosh S, Iskandar I, Kossin J, Lewis S, Otto F, Pinto I, Satoh M, Vicente-Serrano SM, Wehner M, Zhou B (2021) Weather and climate extreme events in a changing climate. In Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte VP, Zhai A, Pirani SL, Connors C, Péan S, Berger N, Caud Y, Chen L, Goldfarb MI, Gomis M, Huang K, Leitzell E, Lonnoy JBR, Matthews TK, Maycock T, Waterfield O, Yelekçi R Yu, Zhou B (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1513–1766. https://doi.org/10.1017/9781009157896.013

Seserman DM, Veste M, Freese D, Swieter A, Langhof M (2018) Benefits of agroforestry systems for land equivalent ratio – case studies in Brandenburg and lower Saxoy, Germany. 4th European Agroforestry Conference: Agroforestry as Sustainable Land Use; Conference Proceedings, Nijmegen, Netherlands. https://core.ac.uk/download/pdf/250590018.pdf

Sollen-Norrlin M, Ghaley BB, Rintoul NLJ (2020) Agroforestry benefits and challenges for adoption in Europe and beyond. Sustainability-Basel 12(17):7001. https://doi.org/10.3390/su12177001

Sperlich D, Nadal-Sala D, Gracia C, Kreuzwieser J, Hanewinkel M, Yousefpour R (2020) Gains or losses in forest productivity under climate change? The uncertainty of CO_2 fertilization and climate effects. Climate 8(12):141. https://doi.org/10.3390/cli8120141

Torralba M, Fagerholm N, Burgess PJ, Moreno G, Plieninger T (2016) Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis, Agric Ecosyst Environ 230. ISSN 150–161:0167–8809. https://doi.org/10.1016/j.agee.2016.06.002

Tranchina M, Reubens B, Frey M, Mele M, Mantino A (2024) What challenges impede the adoption of agroforestry practices? A global perspective through a systematic literature review. Agroforest Syst 98:1817–1837. https://doi.org/10.1007/s10457-024-00993-w

Upson MA, Burgess PJ, Morison JIL (2016) Soil carbon changes after establishing woodland and agroforestry trees in a grazed pasture. Geoderma 283:10–20. https://doi.org/10.1016/j.geoderma.2016.07.002

van der Werf W, Keesman K, Burgess PJ, Graves AR, Pilbeam D, Incoll LD, Metselaar K, Mayus M, Stappers R, van Keulen H, Palma J, Dupraz C (2007) Yield-SAFE: a parameter-sparse, process-based dynamic model for predicting resource capture, growth, and production in agroforestry systems. Ecol Eng 29:419–433. https://doi.org/10.1016/j.ecoleng.2006.09.017

van Meijgaard E, Van Ulft LH, Van de Berg WJ, Bosveld FC, Van den Hurk BJJM, Lenderink G, Siebesma AP (2008) The KNMI regional atmospheric climate model RACMO, version 2.1 (p. 43). De Bilt, The Netherlands: KNMI. https://cdn.knmi.nl/knmi/pdf/bibliotheek/knmipubTR/TR302.pdf [Accessed on 20 May 2024]

van Meijgaard E, Van Ulft LH, Lenderink G, De Roode SR, Wipfler EL, Boers R, van Timmermans RMA (2012) Refinement and application of a regional atmospheric model for climate scenario calculations of Western Europe (No. KVR 054/12). KVR. https://edepot.wur.nl/312258. Accessed 20 May 2024

van Niekerk P, Marais B, Brischke C, Borges L, Kutnik M, Niklewski J, Ansard D, Humar M, Cragg S. Militz H (2022) Mapping the biotic degradation hazard of wood in Europe – biophysical background, engineering applications, and climate change-induced prospects. Holzforschung, Vol. 76 (Issue 2), pp. 188-210. https://doi.org/10.1515/hf-2021-0169

van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque JF, Masui T, Meinshausen M, Nakicenovic N, Smith SJ, Rose SK (2011) The representative concentration pathways: an overview. Clim Change 109:5–31. https://doi.org/10.1007/s10584-011-0148-z

Vautard R, Kadygrov N, Iles C, Boberg F, Buonomo E, Bülow,K, Coppola E, Corre L, van Meijgaard E, Nogherotto R, Sandstad M, Schwingshackl C, Somot S, Aalbers E, Christensen OB, Ciarlo JM, Demory ME, Giorgi F, Jacob D, Jones RG, Keuler K, Kjellström E, Lenderink G, Levavasseur G, Nikulin G, Sillmann J, Solidoro C, Sørland SL, Steger C, Teichmann C, Warrach-Sagi K, Wulfmeyer V (2021) Evaluation of the large EURO-CORDEX regional climate model ensemble. J Geophys Res Atmos 126, e2019JD032344. https://doi.org/10.1029/2019JD032344

Viñals E, Maneja R, Rufí-Salís M, Martía M, Puy N (2023) Reviewing social-ecological resilience for agroforestry systems under climate change conditions. Sci Total Environ 869:161763. https://doi.org/10.1016/j.scitotenv.2023.161763

Webber H, Ewert F, Olesen JE, Müller C, Fronzek S, Ruane AC, Bourgault M, Martre P, Ababaei B, Bindi M, Ferrise R, Finger R, Fodor N, Gabaldón-Leal C, Gaiser T, Jabloun M, Kersebaum KC, Lizaso JI, Lorite IJ, Manceau J, Moriondo M, Nendel C, Rodríguez A, Ruiz-Ramos M, Semenov MA, Siebert A, Stella T, Stratonovitch P, Wallach TG, D, (2018) Diverging importance of drought stress for maize and winter wheat in Europe. Nat Commun 9(1):4249. https://doi.org/10.1038/s41467-018-06525-2

Wiebe PC, Zhunusova E, Lippe M, Ferrer Velasco R, Günter S (2022) What is the contribution of forest-related income to rural livelihood strategies in the Philippines' remaining forested landscapes? For Policy Econ 135:102658. https://doi.org/10.1016/j.forpol.2021.102658

Wolf J, (2012) Users Guide for LINGRA-N: Simple generic model for simulation of crop growth under potential, water limited and nitrogen limited conditions. Available online: https://models.pps.wur.nl/lingra-n-grassland-model-potential-waterlimited-and-n-limited-conditions-fortran [Accessed on 25 March 2024]

Xiao D, Bai H, Liu DL (2018) Impact of future climate change on wheat production: a simulated case for China's wheat system. Sustainability-Basel 10(4):1277. https://doi.org/10.3390/su10041277

Xu X, Liu W, Kiely G (2011) Modeling the change in soil organic carbon of grassland in response to climate change: effects of measured versus modelled carbon pools for initializing the Rothamsted Carbon model. Agric Ecosyst Environ 140(3–4):372–381. https://doi.org/10.1016/j.agee.2010.12.018

Zhao C, Piao S, Wang X, Lobell DB, Huang Y, Huang M, Yao Y, Bassu S, Ciais P, Durand JL, Elliott J, Ewert F, Janssens IA, Li T, Lin E, Liu Q, Martre P, Müller C, Peng S, Peñuelas J, Ruane AC, Wallach D, Wang T, Wu D, Liu Z, Zhu Y, Zhu Z, Asseng S (2017) Temperature increase reduces global yields of major crops in four independent estimates. PNAS 114(35):9326–9331. https://doi.org/10.1073/pnas.1701762114