

Uncertainty in Land Carbon Fluxes Simulated by CMIP6 Models from Treatments of Crop Distributions and Photosynthetic Pathways

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Abstract. A reliable representation of the diversity of vegetation in terrestrial ecosystems is needed for the accurate simulation of present and future biogeochemical cycling and global climate, particularly as climate change affects different vegetation types differently. We compare the distributions of crops and of C₃ versus C₄ photosynthetic pathways in both natural vegetation and crops across Earth System Models in the 6th Coupled Model Intercomparison Project (CMIP6). We find a large range in C₃ and C₄ crop, natural and total vegetation area, gross and net primary production (GPP) and carbon stock change in both natural vegetation and croplands across the models. Even though 10 of the 11 models used Land Use Harmonization (LUH2) crop areas as input data, modeled total crop area ranges from -28 to +10 % of a satellite-based estimate. The C₃ and C₄ crop areas were -56 to +15 % and -100 to +38 % of LUH2 for 2014, respectively. The C₄ fraction of total vegetation area in the models is 9-25 %, compared to 17 % in observation-based estimates compared to 20 ± 3 % in observation-based estimates for the year 2014. Total global GPP varies by a factor of two across the models, and the C₄ fraction of GPP ranges from 12 to 27 %. Simulated trends in the fraction of GPP by C₃ versus C₄ vegetation type (-20 to +29 %) would have changed global stable carbon isotopic discrimination by -0.35 to +0.11 ‰ over 1975-2005, not including changes in discrimination over time within C₃ and C₄ vegetation, indicating that modeled changes in the fraction of GPP by C₃ and C₄ vegetation type do not account for the +0.7 ‰ increase indicated by atmospheric data. Disparity in vegetation with these photosynthetic pathways in models types contributes to uncertainty in land carbon fluxes simulations and further constraints and improvements in models are needed.

1 Introduction

The terrestrial biosphere captures ~30 % of anthropogenically emitted CO₂ annually (Friedlingstein et al., 2025) reducing CO₂ accumulation in the atmosphere and the accompanying global warming. However, this CO₂ uptake may be sensitive to future climate change (Arora et al., 2020). Understanding the mechanisms contributing to the CO₂ uptake, including the role of

different types of vegetation and land use, is essential to understanding potential carbon-climate feedback and future changes to the terrestrial carbon cycle.

The implementation of ~~land cover use and~~ land use and land cover change (LUCC) and its impact on vegetation cover and dynamics are important components of terrestrial biosphere model development (Hu et al., 2021; Hurtt et al., 2020; Wang et al., 2022). LUCC is mainly driven by agriculture. The fraction of global land area used for agriculture increased from 14 % in 1850 to about 37 % in 2015 (Hurtt et al., 2020) and LUCC emitted about 118 PgC between 1850 and 2020 (Houghton & Castanho, 2023). In addition to CO₂ emissions, the biophysical effects of land conversion also drive global temperature rise due to changes in surface albedo (Arora & Boer, 2010; Houghton et al., 2012). The alteration of the land surface will continue to be significant in the future as, for example, it has been projected that 14 % of vegetation and 5 % of soil carbon stocks will be lost to cropland expansion globally over 2010-2050 in a “middle-of-the-road” scenario (Molotoks et al., 2018^a).

To represent plant diversity and function, most model developers use plant functional types (PFTs) that group vegetation by similar features such as growth form, ecological requirements, and photosynthetic pathways. This helps to account for the variation in adaptive mechanisms and ecological distribution of different plants (Haxeltine & Prentice, 1996; Hurtt et al., 2020; Wullschlegel et al., 2014). One important characteristic of plants is their use of either the C₃ or C₄ photosynthetic pathways. In C₃ plants the first product of the photosynthetic pathway is a three-carbon molecule called 3-phosphosphoglycerate (3-PGA), while in C₄ vegetation, it is a four-carbon molecule called oxaloacetate. C₃ and C₄ types also differ in their response to changes in soil moisture content, temperature, CO₂, and light (Luo et al., 2024). For more information about the anatomical/structural and physiological differences between vegetations with these photosynthetic pathways which drive their distinct climate and CO₂ concentration responses see Luo et al., 2024, Cortés et al., 2021; Smith & Boers, 2023, Polley et al., 1994, Farquhar et al 1989, Still et al 2003.

Under increasing temperature, especially increases above the thermal optimum threshold, productivity in C₃ vegetation is limited by an increase in photorespiration (Hermida-Carrera et al., 2016), which reduces photosynthetic efficiency in C₃ plants. In contrast, C₄ species overcome photorespiration through their CO₂ concentrating mechanism that increases the amount of CO₂ at the site of carboxylation (da Silva et al., 2020), leading to an abundance of C₄ species (natural grasses and crops such as maize) in hot areas in the tropics and sub-tropics (Luo et al., 2024). While rising temperature generally favours C₄ plants, rising atmospheric CO₂ concentration confers a physiological advantage upon C₃ species (Polley et al., 1994) due to a reduction in photorespiration and increase in water use efficiency. This CO₂ fertilization effect is responsible for the increasing presence of C₃ woody species in previously C₄ dominated grasslands (Luo et al., 2024). Shifts in C₃ and C₄ species composition and carbon fluxes across different regions are projected to continue in future due to changing temperature, water availability and increasing CO₂ concentration in the atmosphere (Cortés et al., 2021; Smith & Boers, 2023).

A change in the relative contributions of C₃ and C₄ vegetation to global productivity may contribute to a global trend in stable photosynthetic carbon isotope discrimination (Δ) because C₃ plants discriminate against carbon-13 more strongly than C₄ plants (Farquhar et al., 1989). Since atmospheric studies have indicated that Δ increased by 0.7 ‰ over 1975-2005 globally (Keeling et al 2017), and by 0.4 ‰ over 2000-2011 in the Northern Hemisphere (Peters et al 2018), understanding the effect

of changes in vegetation type on discrimination would help to quantify the environmental and physiological factors influencing plant function and resulting discrimination, including soil moisture content, vapour pressure deficit and stomatal conductance (Cornwell et al., 2018; Griffis et al., 2010).

Currently, the relative contribution, and its change over time, of C₃ vs C₄ vegetation to global terrestrial biosphere productivity and their ecological roles in climate change mitigation are not well-known. Using remote sensing products, physiological modeling and crop data, Still et al (2003) found that C₃ and C₄ area abundances are 87.4 and 18.8 million km² (17.7 % as C₄) and C₃ and C₄ gross primary production were 114.7 and 35.3 PgC yr⁻¹ (23 % as C₄), respectively, on average for the 1980s and 1990s. More recently, Luo et al (2024) used global observations of plant photosynthetic pathways, satellite remote sensing, and photosynthetic optimality theory to estimate a similar level of C₄ area coverage (17.5 %), but a lower fraction of gross primary productivity (19.4 %), compared to Still et al (2003). Luo et al (2024) showed that C₄ vegetation coverage decreased from 17.7 % to 17.1 % over 2001 to 2019 as natural C₄ grass cover declined in favor of C₃ vegetation, especially C₃ trees in tropical grasslands and savannas. In comparison, across the TRENDY ensemble of dynamic global vegetation models, there were large ranges of 7-23 % of vegetation area and 2-40 % of productivity from C₄ vegetation (Luo et al. 2024), showing a need for better constraints and understanding of C₃/C₄ vegetation competition and change over time.

Here we investigate the contribution of vegetation diversity representation to uncertainty in carbon flux simulation in Earth System Models. We evaluate the representation of C₃ and C₄ vegetation over 1850-2014 in 11 Earth System Models used in the 6th Coupled Model Intercomparison project (CMIP6). We assess the distribution, productivity and carbon content of C₃ and C₄ vegetation and compare with observation/satellite-based estimates where possible. We also explore the potential trend in global carbon isotope discrimination $\Delta^{13}\text{C}$ due to C₃ and C₄ vegetation changes simulated in the models.

2 Materials and Methods

2.1 CMIP6 Models Outputs and the LUH v2 Data

To analyze the CMIP6 models, we obtained the output for the following variables from the CMIP6-ESGF repository (<https://esgf-index1.ceda.ac.uk/projects/cmip6-ceda/>): fractions of C₃ and C₄ vegetation coverage (c3PftFrac and c4PftFrac), C₃ and C₄ crop fraction (cropFracC3 and cropFracC4), total crop fraction (cropFrac), gross primary production (gpp), ~~vegetation carbon content (cVeg), soil carbon content (cSoil)~~, grid cell area (areacella), and percentage of each grid cell covered by land (sftlf). The necessary output was available from 11 models (Table 1). Brief descriptions of the implementation of vegetation abundance in each of the 11 models are provided in the Supplementary resources (Materials and Methods S1).

Table 1. Summary of each model's definition of crop cover and our calculation of C₃ and C₄ crop cover. More detail is given in SM Materials and Methods.

Earth Model	System	<u>Resolution:</u> <u>Lat, Lon (°)</u>	Land Model	C ₃ Crop Fraction	C ₄ Crop Fraction	Definition of crop cover
ACCESS-ESM1.5		<u>1.25, 1.875</u>	CABLE	cropFracC3	Zero everywhere	LUH2 mapped onto PFTs
CanESM5		<u>2.813, 2.813</u>	CLASS-CTEM	cropFracC3	cropFracC4	LUH2 mapped onto PFTs
CESM2		<u>0.938, 1.25</u>	CLM5.0	cropFrac * c3PftFrac	cropFrac * c4PftFrac	LUH2 mapped onto PFTs
CESM2-WACCM		<u>0.938, 1.25</u>	CLM5.0	cropFrac * c3PftFrac	cropFrac * c4PftFrac	LUH2 mapped onto PFTs
CMCC-CM2-SR5		<u>0.938, 1.25</u>	CLM4.5	cropFracC3	Zero everywhere	LUH2 mapped onto PFTs
CMCC-ESM2		<u>0.938, 1.25</u>	CLM4.5	cropFracC3	Zero everywhere	LUH2 mapped onto PFTs
CNRM-CM6.1		<u>1.406, 1.406</u>	ISBA-CTRIP	cropFrac * c3PftFrac	cropFrac * c4PftFrac	ECOCLIMAP-II fixed
CNRM-ESM2.1		<u>1.406, 1.406</u>	ISBA-CTRIP	cropFrac * c3PftFrac	cropFrac * c4PftFrac	LUH2 mapped onto PFTs
MPI-ESM-1-2-HAM		<u>1.875, 1.875</u>	JSBACH	cropFracC3	cropFracC4	LUH2 mapped onto PFTs
MPI-ESM1-2-LR		<u>1.875, 1.875</u>	JSBACH	cropFracC3	cropFracC4	LUH2 mapped onto PFTs
UKESM1		<u>1.25, 1.875</u>	JULES-TRIFFID	cropFracC3	cropFracC4	LUH2 mapped onto PFTs with C ₃ /C ₄ competition from TRIFFID

100 To specify crop cover, ten of the eleven CMIP6 models use the Land Use Harmonization version 2 (LUH2) dataset (Hurtt et al 2017, Table 1) so we also analyze the LUH2 data directly here. LUH2 estimates the fractional area and transition of use of 12 categories at an annual and 0.25° by 0.25° spatiotemporal resolution, starting from the year 850 (Hurtt et al., 2020). Five of these categories are C₃ annual crops, C₃ perennial crops, C₃ nitrogen fixers crops, C₄ annual crops and C₄ perennial crops. We group these categories into C₃ crops and C₄ crops, and their sum as total crops.

105 The UKESM1 model uses the LUH2 crop cover data with some modifications including simulation of competition between C₃ and C₄ vegetation using the dynamic vegetation model TRIFFID (Top-down Representation of Interactive Foliage and Floral Including Dynamics, Sellar et al., 2019, Clark et al., 2011). Other models use the LUH2 data more directly, but differences can result from mapping the LUH2 data onto the model's PFTs, land cover and grid maps.

110 In CNRM-CM6.1, the crop cover is based on the ECOCLIMAP-II database (Voldoire et al., 2019). CNRM-CM6.1 adopts a vegetation cover map that is fixed to its present-day distribution, so that temporal changes in crop area are not included. The reasoning for using a fixed distribution is that the carbon cycle is not fully resolved in the model and there is uncertainty in impacts of land use and land cover change on carbon flux (Faroux et al., 2013; Voldoire et al., 2019).

2.2 Global Land Vegetation Cover, ~~and vegetation~~ Productivity, ~~and Carbon Content~~

We analysed changes in the vegetation cover (C₃, C₄ cropland and natural vegetation) for ~~all the~~ 11 CMIP6 models by calculating the gridded annual area fraction for C₃ and C₄ vegetation for each year 1850-2014, which we also separated into crops, natural and total vegetation. We also calculated gridded annual gross primary production (GPP), ~~vegetation and ecosystem carbon content~~ for C₃ and C₄ vegetation in crops, natural and total vegetation in each model. We combined gridded estimates into global totals.

We calculated annual maps of area fraction of C₃ crops (cropFracC3) and C₄ crops (cropFracC4). Most models included the cropFracC3 and cropFracC4 variables that could be used directly (Table 1). Some models had to be treated differently, due to the output provided. ACCESS-ESM1.5, CMCC-CM2-SR5 and CMCC-ESM2 ~~and the CMCC models~~ did not provide cropFracC4 and their cropFracC3 was equal to the total crop fraction (cropFrac), so we specified the fraction of C₄ crops to be zero everywhere. The CESM2 models did not provide cropFracC3 and cropFracC4 variables, but they did provide c3PftFrac or c4PftFrac (the fractions for total vegetation), so cropFracC3 and cropFracC4 were calculated by multiplying cropFrac by c3PftFrac or c4PftFrac. In CNRM-CM6-1 and CNRM-ESM2.1, the cropFracC3 and cropFracC4 variables were identical to the c3PftFrac and c4PftFrac variables, which appears to be an error in the output. So, in CNRM-CM6-1 and CNRM-ESM2.1 cropFracC3 and cropFracC4 were calculated by multiplying cropFrac by c3PftFrac or c4PftFrac. We also compared the total cropland area in all the models and the LUH2 dataset to a satellite-based estimate from Potapov et al (2022).

To calculate the fractions of natural C₃ and C₄ vegetation, we subtracted cropFracC3 and cropFracC4 from c3PftFrac or c4PftFrac (the total C₃ and C₄ vegetation fractions). Therefore, for each grid cell we had the fractional area of C₃ and C₄ crops and of C₃ and C₄ natural vegetation.

The GPP from C₃ or C₄ vegetation was not provided so we estimated these by multiplying total GPP with the area fractions. ~~We applied the same procedure to estimate vegetation carbon content and total ecosystem carbon content by vegetation type.~~ In Luo et al. (2024) it was found that the per unit area photosynthetic rate of C₄ grass was generally higher than for C₃ vegetation, ~~indicating so we thought these~~ ~~these~~ calculations may overestimate the proportion assigned to C₃ vegetation. ~~To ensure that this is not the case and that our approach produce reliable and robust result~~ Therefore, we conducted a reliability analysis to determine the similarity between the values and distribution of C₃ and C₄ crops obtained from $\text{cropFrac} \times \text{c3PftFrac}$ and $\text{cropFrac} \times \text{c4PftFrac}$ in the models (CESM2, CESM2-WACCM, CNRM-ESM2-1 and CNRM-CM6.1) and LUH2 values and distribution using kernel density estimate (KDE) (Silverman 1986, Chen 2017) and constructed spatial probability distribution plots using all land pixels for C₃, C₄ and total crops for the year 2014 (Chiang et al., 2021). We also visually compared the spatial distribution of these values to ~~the LUH2;~~ ~~and to UKESM1 and MPI-ESM-1-2-HAM,~~ two models that provided their C₃ and C₄ crops. ~~to ensure they are consistent.~~

2.3 Global Stable Carbon Isotopic Discrimination

To estimate how the simulated changes in C₃ and C₄ fractions of GPP influenced the global stable carbon isotopie discrimination, we estimated discrimination assuming fixed values for stable carbon isotope discrimination by C₃ and C₄ vegetation. This neglects any environmental or physiological effects on discrimination that may be simulated by the models to isolate the potential effect from changes in C₃ and C₄ fractions of GPP alone. The total annual global stable carbon isotopic discrimination (Δ_{tot}) was calculated by the following weighted average with GPP:

$$\Delta_{\text{tot}} = (\text{GPP}_{\text{C}_3} \Delta_{\text{C}_3} + \text{GPP}_{\text{C}_4} \Delta_{\text{C}_4}) / (\text{GPP}_{\text{C}_3} + \text{GPP}_{\text{C}_4}) \quad (1)$$

Here, GPP_{C_3} and GPP_{C_4} are the integrated GPP for all C₃ and C₄ vegetation each year, and Δ_{C_3} and Δ_{C_4} are the fixed stable carbon isotope discrimination for C₃ and C₄ respectively. We also calculated the global natural stable carbon isotopic discrimination (Δ_{nat}) using the natural C₃ and C₄ GPP for all the models using the same weighted average approach. To calculate the effect of crops on the global annual stable carbon isotopie discrimination (Δ_{crop}), we subtracted Δ_{nat} from Δ_{tot} .

Δ_{C_3} and Δ_{C_4} were specified as the means of C₃ and C₄ plant leaf stable carbon isotopie discrimination observations from the database of 3987 species published by Cornwell et al. (2018), which are 20.7 ‰ for Δ_{C_3} and 6.3 ‰ for Δ_{C_4} (Fig. 1). The two peaks in the histogram are assumed to correspond to the highest count for the species with either the C₃ and C₄ photosynthetic pathways. A breakpoint of 12.5 ‰ was chosen for C₃ and C₄ based on the midpoint between the two peaks, such that. The discrimination values to the left of lower than 12.5 ‰ in the figure are taken to correspond to the values of stable carbon isotope discrimination in vegetation with the C₄ photosynthetic pathway while values to its right higher than 12.5 ‰ correspond to stable carbon isotope discrimination in vegetation with the C₃ photosynthetic pathway. The and then the means of these two distributions were calculated and used to specify the fixed C₃ and C₄ discrimination: 20.7 ‰ for Δ_{C_3} and 6.3 ‰ for Δ_{C_4} for the analysis. from the two distributions.

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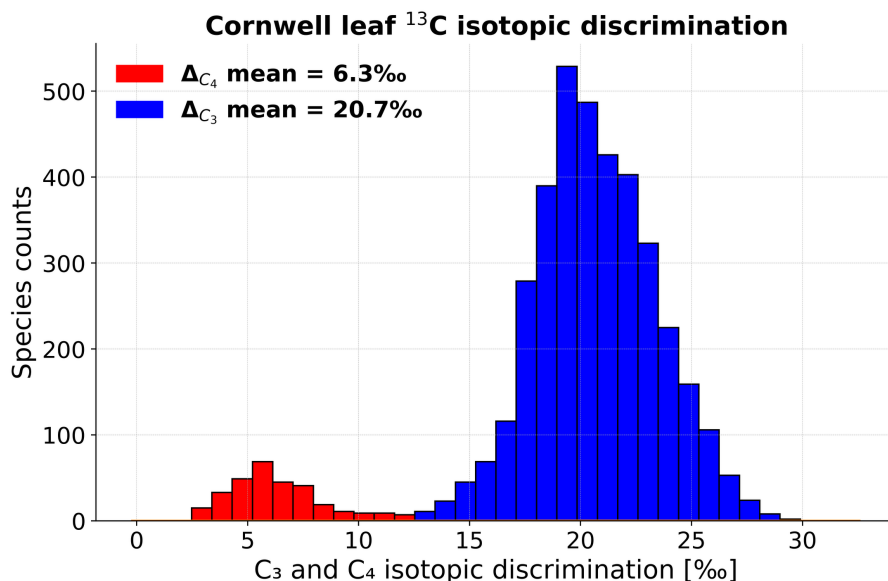


Figure 1: Stable carbon isotopie discrimination in leaves from the database published by Cornwell et al (2018).

3 Result

3.1 Crops Abundance Spatial Distribution and its Change between 1970 and 2014 Over Time

Based on the LUH2 dataset averaged over 1970-2014, the highest C₃ crop abundance is in agricultural regions in central North America, southwest Europe, southeast and south Asia, Sub-Saharan Africa, southeast South America and southern Australia (Figures 2 and 3) (Hurt et al., 2020). The fractional crop area is between 60 and 100 % in these regions. For C₄ crops, the highest abundance is in the Great Plains in North America, Sub-Saharan Africa, southwest Asia and southeast Asia (Fig. 2). The models that do not use LUH2 data directly, UKESM1 (which used LUH2 indirectly) and CNRM-CM6-1, show differences with LUH2 (Figures 2 and 3). UKESM1 underestimates C₃ crops in Sub-Saharan and central Africa and in southeast Asia, particularly in India, which is likely due to ~~decreased precipitation~~ ~~lack of precipitation~~ in UKESM1 in these areas since the vegetation cover is coupled to its simulated climate component (Sellar et al 2019) and UKESM1 underestimates precipitation in India. UKESM1 estimates more C₄ crop coverage than LUH2, particularly in Asia (Figure 2 and 3 and Table S1). Crop coverage in UKESM1 is about 10 % lower than LUH2 between the equator and 30°N (Fig. 3). CNRM-CM6-1 has less C₄ crop cover in Europe and Africa, but more in North and South America, compared to LUH2 (Figures 2 and 3). For models using LUH2 directly ~~In general, there was still disagreement of the models with the LUH2 crop coverage, which could be due to a number of reasons such as preprocessing of the LUH2 vegetation classes into the plant functional types (PFTs) and remapping of the LUH2 data into the spatial resolution needed for each model, and the treatment of its crops functional types (CFTs) and bare-grounds classes (Table S1). For the models where we calculated C₃ and C₄ crop cover by multiplying cropFrac by C3PftFrac and C4PftFrac, CESM2, CESM2-WACCM, CNRM-ESM2-1 and CNRM-CM6.1, we found that the kernel density estimate (KDE) and visual comparison of the values of C₃ and C₄ crops distribution for show they are consistent with~~ within the range of values for UKESM1, MPI-ESM-1-2-HAM and LUH2 in terms of magnitude, range and spatial distribution as shown by the spatial distribution, and the overlap area in the percentage cover vs density plots. For example, the overlap area between LUH2 and CESM2 in C₃ and C₄ crop cover is 0.68 and 0.70 respectively which is close enough to that between LUH2 and MPI-ESM-1-2-HAM that is 0.74 and 0.50 respectively (Figure 3, S7 – S13).

The models incorporating LUH2 have similar patterns in C₃ and C₄ crop; however, the total area of crops in these models differed from LUH2 by -19 to +3 % and from satellite-based estimate by -28 to +10 % (Fig. 4, Table S1) from Potapov et al (2022) study that analysed the change in global cropland area in the first two decades of the twenty-first century using satellite and sample data that estimate crop cover at ~10.9 and ~11.42 million km² respectively between 2003 and 2006. CanESM5 was the most consistent with LUH2. Inconsistencies among the models that use the LUH2 dataset may be due to how the data were pre-processed before incorporation into the model, due to grid spacing or due to differences in the model PFTs compared to LUH2 categories, particularly as some models did not include C₄ crops. Also, since the variables cropFracC₃ and cropFracC₄ were not available for all models, our calculations of the crop fractions may have contributed to the discrepancies. The magnitude of area abundance for C₃ and C₄ crop and natural vegetation for the years 1970 and 2014 are provided in the supplementary materials (Table S2).

Between 1970 and 2014, there were decreases in crop coverage in North America, Europe, Southern Africa, Chile, Japan and New Zealand but increases in South and Southeast Asia, Africa and South America (Figure 3b and S1). The largest increases of 10 % or more were concentrated around the eastern region of south America, especially in Brazil, the southern fringes of the Sahara Desert (sub-Saharan Africa) and southeast Africa. The largest decreases of more than 20 % were across the corn-belt of the United States and in southwest and central Europe. Changes in crop area in UKESM1 were consistent with LUH2 except in the low latitudes of the Northern Hemisphere, where increases in C₃ crops in Africa and Asia were underestimated, compared to LUH2 (Figure 3b and S1).

~~Also, the kernel density estimate (KDE) and visual comparison of the values of C₃ and C₄ crops distribution for CESM2, CESM2-WACCM, CNRM-ESM2-1 and CNRM-CM6.1 show they are consistent with values for UKESM1, MPI-ESM-1-2-HAM and LUH2 in terms of magnitude, range and spatial distribution (Figure 3, S7—S13).~~

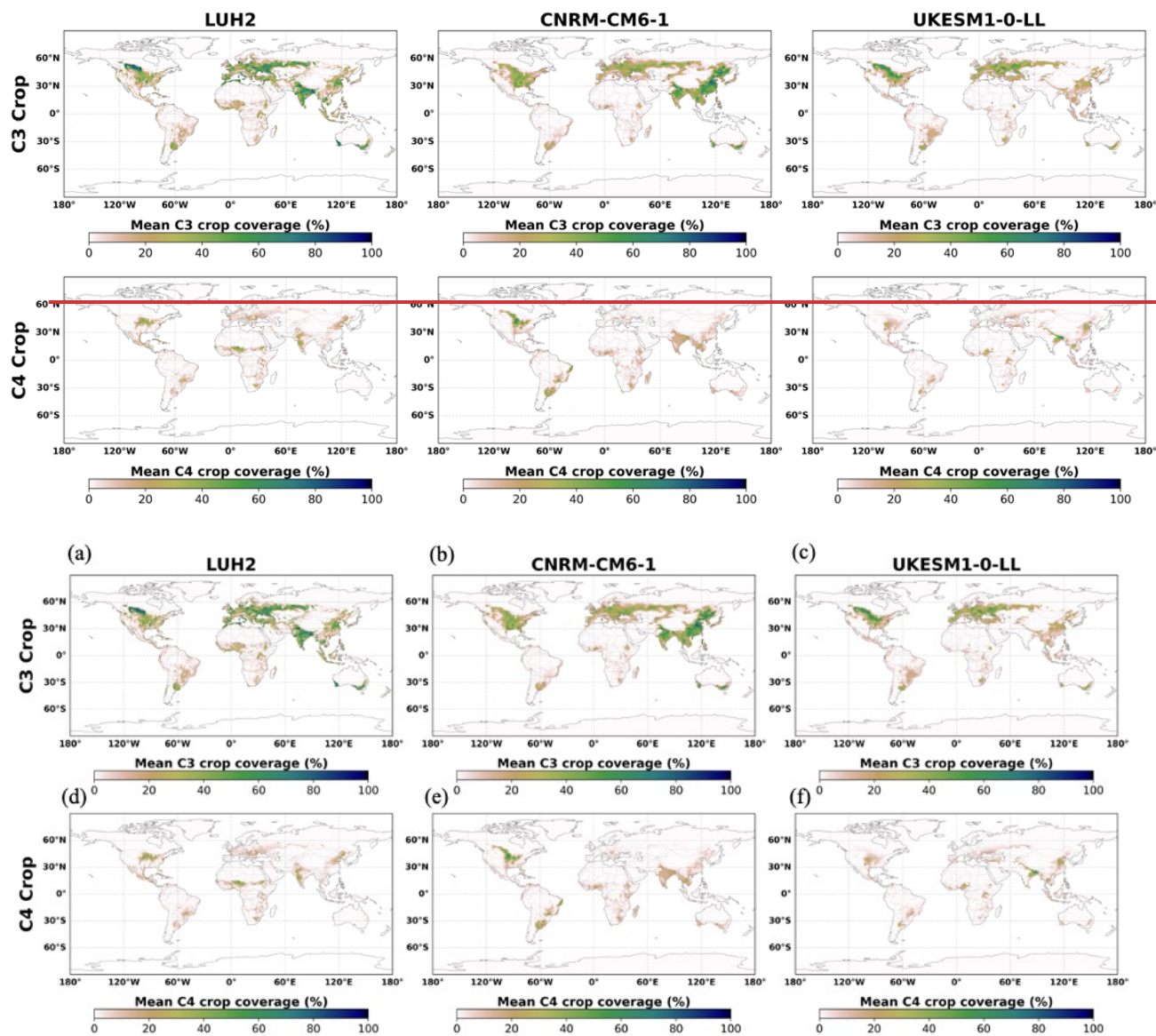


Figure 2: Mean percentage of Earth surface covered by crops between 1970 and 2014 for C₃ and C₄ in LUH2, CNRM-CM6.1 and UKESM1-0-LL. Other models not shown use the LUH2 crop variables directly for their crop coverage and change.

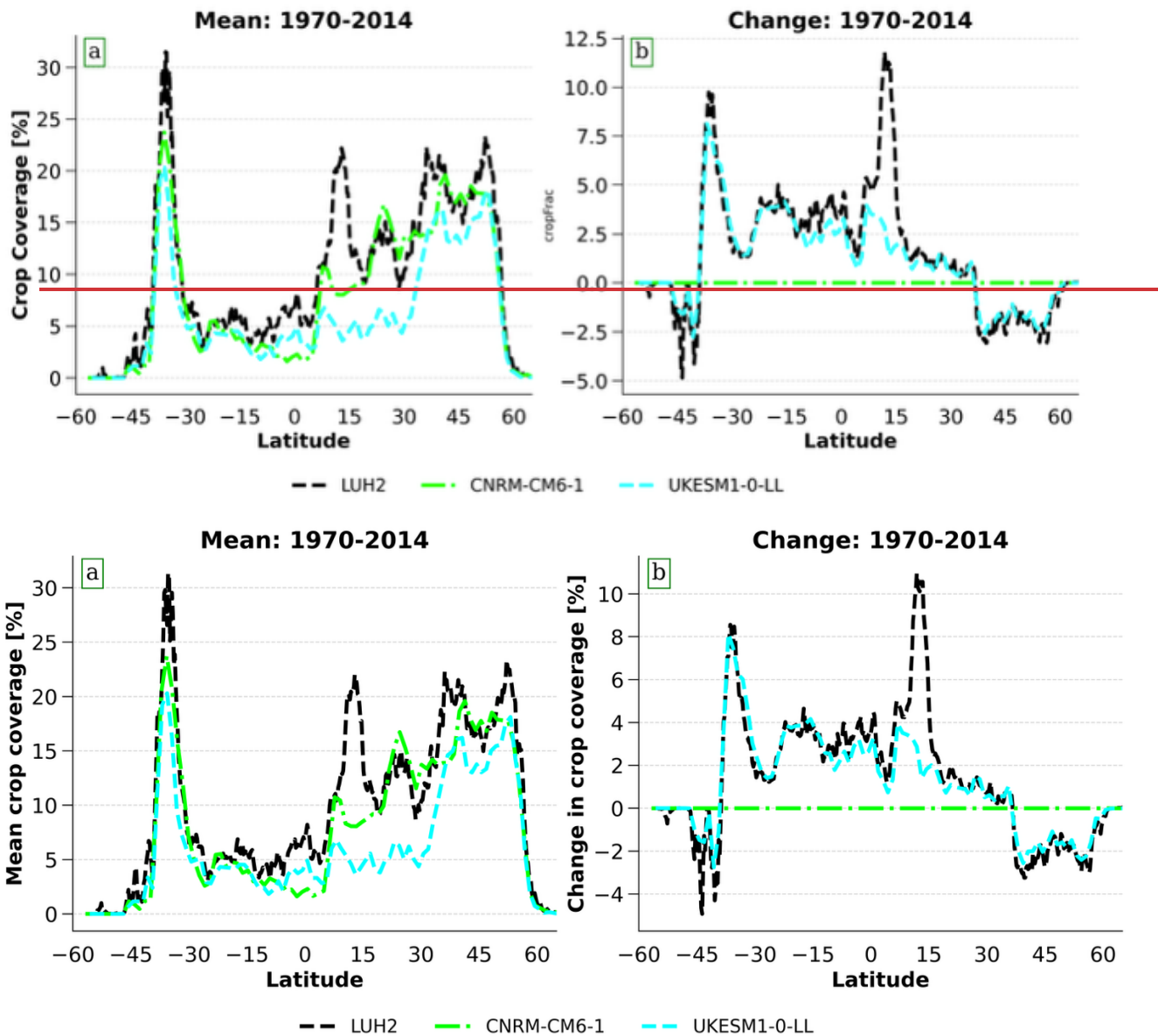


Figure 3: Mean and change in crop coverage averaged over latitude between 1970 and 2014. (a) Mean crop coverage (b) change in crop coverage.

3.2 Global Temporal Trends in Vegetation Coverage

The models incorporating LUH2 have similar patterns in C_3 and C_4 crop coverage over 1970–2014; however, the total area of crops in these models differed from LUH2 by –19 to +3 % (Fig. 4, Table S1). CanESM5 was the most consistent with LUH2. Inconsistencies among the models that use the LUH2 dataset may be due to how the data were pre-processed before

incorporation into the model, due to grid spacing or due to differences in the model PFTs compared to LUH2 categories, particularly as some models did not include C4 crops. Also, since the variables cropFracC3 and cropFracC4 were not available for all models, our calculations of the crop fractions may have produced discrepancies. The magnitude of area abundance for C3 and C4 crop and natural vegetation for the years 1970 and 2014 are provided in the supplementary materials (Table S2).

There is a strong positive trend in the area of croplands from 1850 until 2014 (Fig. 4a). Total crop area rose by 200 % in LUH2 and models using LUH2 data. Crop area in UKESM1 was lower than LUH2 but increased in greater proportion, from 3 to 10 million km² (217 %). In CNRM-CM6 total crop area was fixed at ~14 million km², similar to LUH2 in the 1990s.

While representing a smaller fraction of total crop area (10-45%) (Fig. 4a and g), the area of C4 crops increased in greater proportion (>300 %) than C3 crops (160 %) in the LUH2 data (Fig. 4). Historically, in the CESM2 models, C3 crop area is lower and C4 crop area is higher than in LUH2, despite the model using LUH2 data, although this may be affected by our calculation from the variables provided (Table 1). In UKESM1, C3 crop area was much smaller than LUH2 while its C4 crop area was larger (Fig. 4). UKESM1 C3 crop area peaked between the 1980s and 90s before declining slightly in the 2000s, in contrast to LUH2 where it continued to increase after 2010. UKESM1 C4 crop area rose through 2014, when it was about 42 % higher than LUH2. CNRM-CM6-1 had a fixed C4 crop fraction of 24 %, slightly higher than the C4 crop fraction in LUH2 in the 1990s. ACCESS-ESM1-5, CMCC-ESM2 and CMCC-CM2-SR5 do not have C4 crops so their total crop area is equivalent to the C3 crop area.

The area of natural vegetation decreases in all models from 1850 until 1940-70, when four models (CNRM-ESM2-1, UKESM1-2, and the MPI-ESM-1-2-HAM and MPI-ESM1-2-LR MPI models) start increasing while the others continue decreasing. Natural vegetation is similarly dominated by C3, with 9-23 % of natural vegetation as C4 in 2014, and most of the decline in natural vegetation area is in C3 vegetation. The trend in natural C4 vegetation area is inconsistent across the models. In CanESM5 and ACCESS-ESM1-5, the natural C4 vegetation area decreased over 1850-2014, while for MPI-ESM-1-2-HAM and MPI-ESM1-2-LR the MPI-ESM models the natural C4 vegetation area increased especially from 1990. For the CESM2, and CMCC-ESM2 and CMCC-CM2-SR5 CMCC models, the natural C4 vegetation area was constant until the early 2000s before falling slightly. The UKESM1 estimate of the area of natural C4 vegetation for 2000-14 compares well with Luo et al (2024)'s estimate of the area of natural C4 vegetation for 2000-14, UKESM1 is quite consistent, while other models simulate up to 15 % larger and up to 63 % smaller areas (Fig. 4h).

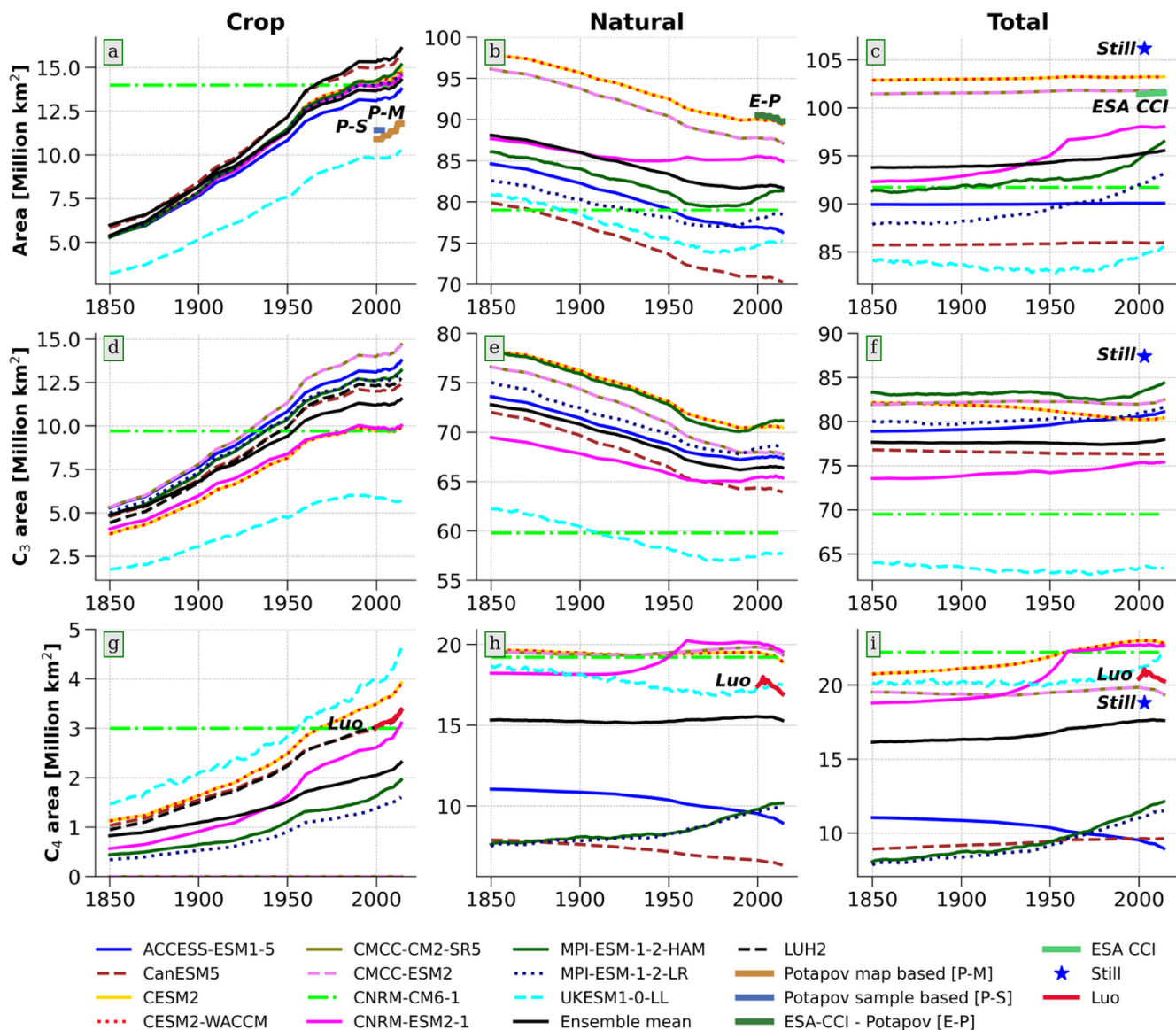


Figure 4: Global temporal trends in vegetation area from 1850 to 2014 in CMIP6 models. Trend of the area covered by (a) total crop, (b) total natural vegetation (c) total global vegetation, (d) C₃ crops, (e) C₃ natural vegetation, (f) total C₃ vegetation, (g) C₄ crop, (h) C₄ natural vegetation and (i) total C₄ vegetation. All models except CNRM-CM6-1 used LUH2 data to inform their crop coverage. ACCESS-ESM1-5, CMCC-ESM2 and CMCC-CM2-SR5 do not have C₄ crops.

For the total vegetation area, four models have distinct positive trends from the late 1960s through to 2014 (CNRM-ESM2.1, UKESM1, MPI-ESM1-2-HAM and MPI-ESM1-2-LR and the MPI models) (Fig. 4c), driven mostly by an increase in C₄ natural vegetation (Fig. 4h). In the other models the increase in crop area is balanced by the decreased in area covered by natural vegetation. The estimated total vegetated area from the European Space Agency Climate Change Initiative (ESA-CCI) for 2000-2014 is matched by the CMCC-ESM2 and CMCC-CM2-SR5-CMCC models, while the CESM2 models simulate

265 larger vegetated areas and all other models simulate smaller vegetated areas. The ESA CCI data shows a small increase that may be caused by the replacement of bare ground by natural grasses (Fig. S5).

3.3 Global Trends in Gross Primary Production

270 While all the models simulate an increase in GPP, the magnitude and contribution by vegetation types (in this context: crop/natural and C₃/C₄) differ (Figure 5). The models disagree on the magnitude of total global GPP, ranging from 80 PgC yr⁻¹ in CNRM-ESM2.1 to 150 PgC yr⁻¹ in MPI-ESM-1-2-HAM and MPI-ESM1-2-LR (-20 to +29 %) in 2014 (Gier et al., 2024; Arora et al., 2020) (Fig 5c). The total GPP for all the models increased steadily until the 1960s and then grew sharply for the rest of the historical period (Fig. 5c).

275 The increase in GPP in crops is linked to the cropland expansion~~area increase~~, while the GPP change in natural vegetation is decoupled from the change in area (Figure S9 and S10). In Fig. 4a total crop area increased by 200 % compared to Figure 4 b, in which natural vegetation decreased by 7 % on average. Comparing this change in area to change in GPP in Fig 5a and 5b, total crop GPP increased by 209 % on average. However, for CNRM-CM6.1 with a temporally fixed vegetation cover, the increase in total crop GPP is only 18 %. For natural vegetation, even though there is a mean 7 % decrease in total natural vegetation cover, we see there is an ~18 % increase in GPP on average. In CNRM-CM6-1 with a fixed vegetation cover, the trend of C₃, C₄ and total crop GPP is not as strong compared to other models especially before the 1970 (Fig. 5a, d and g).
280 They increased by 32 %, 27 %, and 18 % for C₃, C₄ and total crop GPP, respectively, compared to the ensemble mean increase of 195 %), 251 % and 209 % respectively (Fig. 5a, d and g). ~~The increasing GPP trend in natural vegetation is likely dominated by the CO₂ fertilization effect in C₃ vegetation. The models disagree on the magnitude of total global GPP, ranging from 80 PgC yr⁻¹ in CNRM-ESM2.1 to 150 PgC yr⁻¹ in MPI-ESM-1-2-HAM and MPI-ESM1-2-LR MPI-ESM (-20 to +29 %) in 2014 (Gier et al., 2024; Arora et al., 2020) (Fig 56c).~~

285 For GPP in natural vegetation, there are large ranges of 54 - 100 PgC/yr⁻¹ simulated for C₃ vegetation and 9-23 PgC/yr⁻¹ simulated for C₄ vegetation across the models before 1970 (Fig. 5e and h). Despite the decrease in natural C₃ vegetation area before 1970, the C₃ GPP trend is generally either weakly negative or unchanging until the 1970 (Fig. 5e). Then all models increase steadily over 1970-2014. In natural C₄ vegetation, there is generally an increase in GPP since 1850, but the increase is not at the same rate in all the models. It is weaker in ACCESS-ESM1-5, CanESM5 and UKESM1 (Fig. 5h). Three models
290 show a decrease in natural C₄ GPP over 2000-14 (ACCESS-ESM1-5 and the CESM2 models).

The proportion of total GPP by C₄ vegetation in the models is 12-27 % (Fig. 5i and S7), compared to 23 % in Still et al. (2003) and 20 ± 3 -19% in Luo et al (2024). Compared to other model simulations, the range was 2-40 % in TRENDY models (Luo et al. 2024), and 18-27 % in previous modelling studies (Farquhar & Lloyd, 1993; Fung et al., 1997).

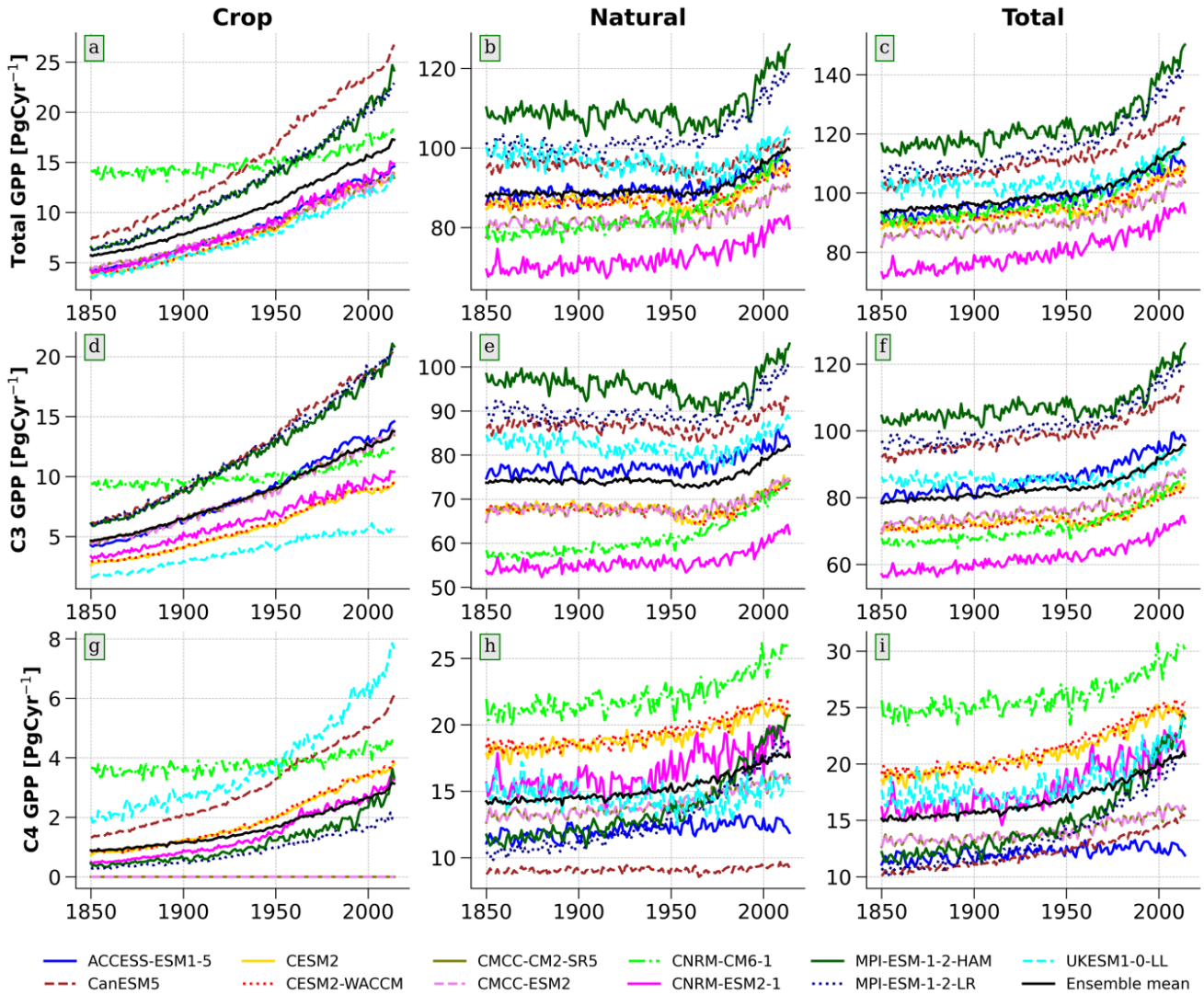
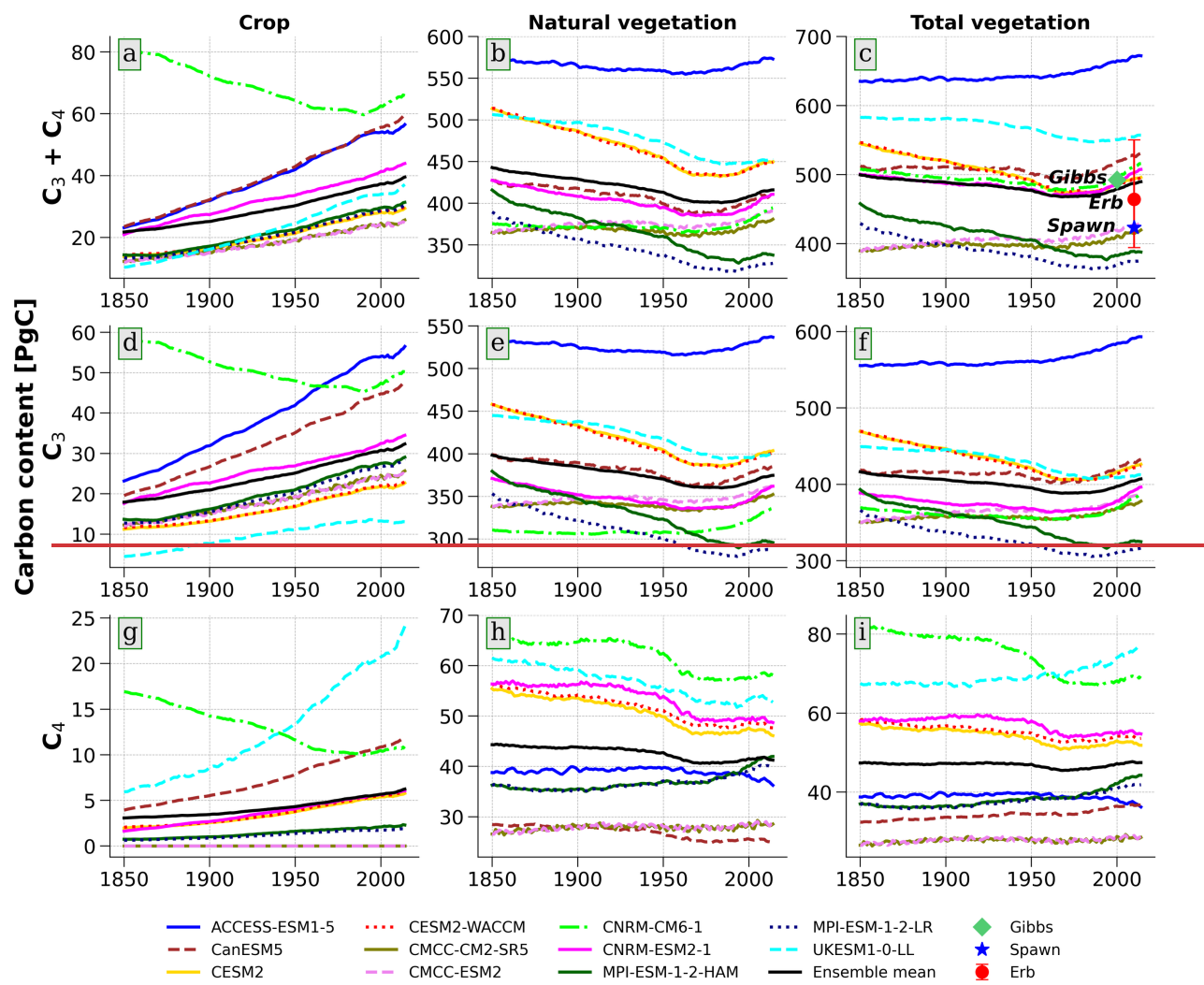


Figure 5: Temporal trend in gross primary production (GPP) between 1850 and 2014. Trend of GPP of (a) total crop, (b) total natural vegetation (c) total global vegetation, (d) C₃ crops, (e) C₃ natural vegetation, (f) total C₃ vegetation, (g) C₄ crop, (h) C₄ natural vegetation and (i) total C₄ vegetation.

3.4 Trends in Global Vegetation and Land Carbon Stock

The vegetation carbon stock (C_{veg}) in crops increased consistently in 10 of the 11 models, at least doubling in magnitude for the historical period. This increase was generally less than the increase in area (Fig. 4a) and GPP (Fig. 5a). In CNRM-CM6-1 that used fixed vegetation cover, the C_{veg} in crops decreased until the late 1990s before increasing slightly for the rest of the period. The magnitude of vegetation carbon content in crops ranged widely, from 26 PgC in CMCC-ESM2 to 66 PgC in CNRM-CM6-1 in 2014 (Fig. 6a).

305 In natural vegetation, most models simulated a negative trend in C_{veg} until the late 1970s before reversing the trend and increasing sharply for the remainder of the historical period (Fig. 8b). In two models, natural C_{veg} was relatively constant until the 1970s (CNRM-CM6-1 and CMCC-ESM2). Again, the models do not agree on the magnitude of natural C_{veg} , which ranges from 328 PgC in MPI-ESM1-2-LR to 573 PgC in ACCESS-ESM1.5 with a mean of 415.04 PgC in 2014 (Fig. 6b).



310 **Figure 6: Temporal Trend in global vegetation carbon content between 1850 and 2014.** Absolute values of carbon content in (a) crops, (b) natural vegetation and (c) total vegetation. Carbon accumulation since 1850 in (d) crop, (e) natural vegetation and (f) total vegetation. Gibbs and Ruesch (2008) above and below ground vegetation carbon stock estimate of 492.3 PgC is based on a map created using the International Panel on Climate Change (IPCC) Good Practice Guidance for reporting national greenhouse gas inventories, to serve as a benchmark to guide policies aimed at reducing carbon emissions from land use change and also enhance simulation of carbon stock in ESMs. Spawn et al (2020) estimate the above and below ground global terrestrial vegetation biomass at 423.3 PgC by merging different landcover-specific global maps generated from remote sensing products into one global vegetation carbon stock map at 300m spatial resolution for the year 2010. Erb et al (2018) estimated that the actual mean global carbon stock is 450 (range of 380 to 536 PgC) by analysing the impact of vegetated land cover conversion and land management on the global carbon state of the biosphere ecosystems.

320 **3.5 Global Trends in Stable Carbon Isotope Discrimination**

The models disagree on the magnitude and trend of Δ_{tot} , Δ_{nat} and Δ_{crop} (Fig. ~~67~~), for our calculation of discrimination based only on the fraction of GPP from C₃ and C₄ vegetation, neglecting any physiological or environmental effects (Equation 1). As a result of the 12-27 % range in C₄ fraction of total GPP, the global total stable carbon discrimination ranges from 16.9 to 19.5 ‰ (Table S2) in 2014 across the models, compared to 16.5 ‰ in Still et al. (2003). Models simulate no change (CESM2 models), slightly increasing Δ_{tot} (ACCESS-ESM1.5 and CNRM-CM6.1) or decreasing Δ_{tot} (all other models). The strongest decreases in Δ_{tot} were in MPI-ESM-1-2-HAM and MPI-ESM1-2-LR ~~the MPI models~~ which had the strongest increases in C₄ vegetation area (Fig. ~~67~~). Compared to the strong positive trend in global stable carbon isotope discrimination trend derived by Keeling et al (2017) from atmospheric $\delta^{13}\text{C}$ data, the effect of vegetation change in the models was much smaller or had the opposite sign (Fig. ~~67~~).

330 The models also disagree on the sign and magnitude of the trends in change in Δ_{nat} (~~-0.83~~17 to ~~0.14~~9.42 ‰) and Δ_{crop} (~~-0.57~~ to ~~0.233~~ ‰, Table S2). Among models with decreasing Δ_{tot} , the trend is primarily driven by growth in productivity of C₄ natural vegetation affecting Δ_{nat} in MPI-ESM-1-2-HAM and MPI-ESM1-2-LR ~~the MPI models~~ but by growth in productivity of C₄ crops affecting Δ_{crop} in UKESM1 and CanESM5 models (Fig 6).

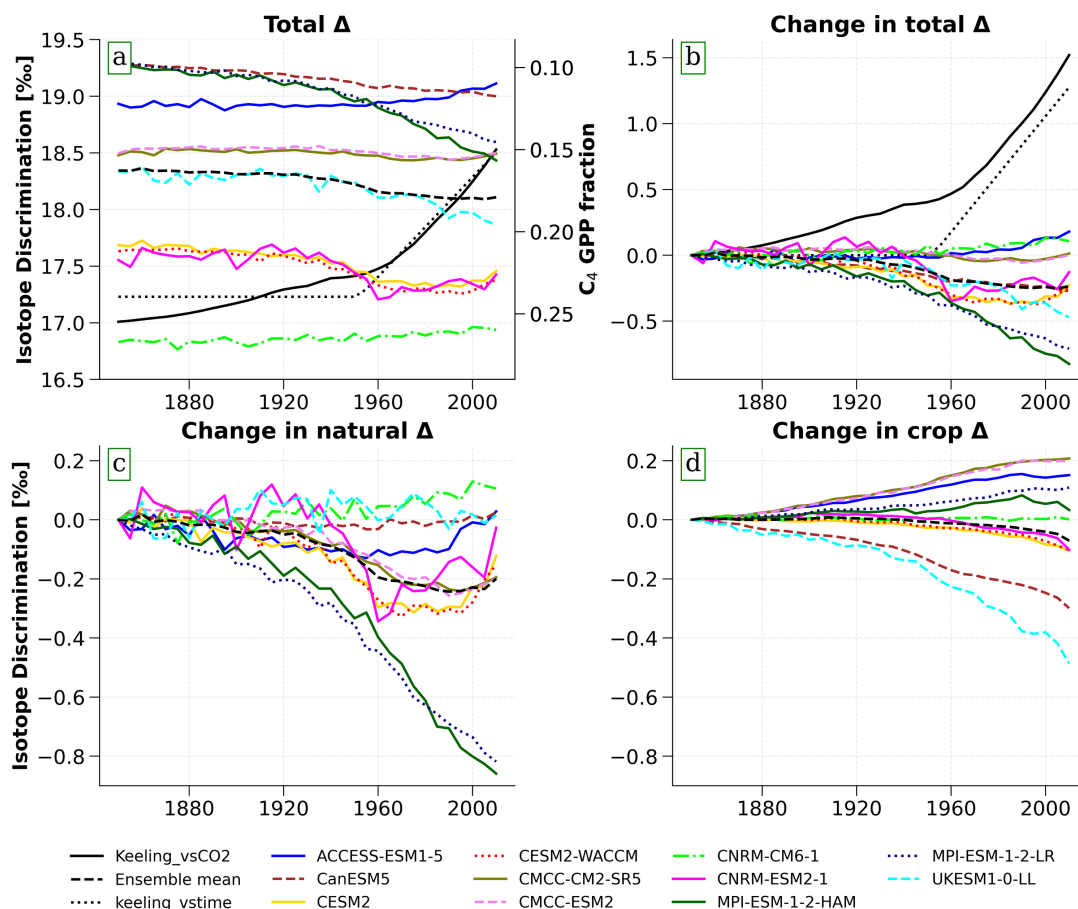


Figure 76: Trend of global stable carbon isotope discrimination between 1850 and 2014. 10-year average stable carbon isotope discrimination of (a) total vegetation (Δ_{tot}), (b) difference in Δ_{tot} from 1850, (c) component of difference due to natural vegetation (Δ_{nat}) and (d) due to crops (Δ_{crop}).

4 Discussion

By examining the components of global vegetation area, and GPP and carbon stocks by vegetation types, we find that CMIP6 models span a large range for nearly all variables. Some models showed stronger gains in GPP and carbon stocks in natural C_3 vegetation, while for others the strongest gains were in either crop or natural C_4 vegetation. Therefore, better quantification of vegetation types and more consistency in models would improve future carbon modelling. For example, total vegetated areas in some models that are much lower than the ESA-CCI estimate (Harper et al., 2023) and total C_4 vegetated areas in some models that are much lower than the Luo et al. (2024) estimate can probably be ruled out. Additionally, Zhao et al (2025) show that the uncertainty in the terrestrial biosphere GPP simulation in models depends strongly on the area of each PFTs and this dependence enabled them to reduce the spread in land carbon estimates by $\sim 75\%$. They also found that changes in PFTs distribution is responsible for $56 \pm 21\%$ climate-induced variability in dynamic global vegetation models (DGVMs) GPP.

However, this spread across models in many cases reflects the lack of observational constraints and may also be linked to the discrepancies in the natural vegetation composition in the context of our study.

Even though nearly ~~all of all~~ the models use LUH2 for input data, their crop area and particularly its attribution to C₃ and C₄ vegetation are not consistent. While most models underestimated total crop area compared to LUH2 (Fig. 4a), another satellite data-based cropland map (Potapov et al., 2022) estimates lower crop areas that overlaps some of the CMIP6 models' crop areas. ~~Therefore, the spread in crop area in the models may be consistent with the uncertainty in actual crop area. A~~
Therefore, the spread in crop area in the models may be consistent with the uncertainty in their input crop area data. A limitation of some current models is that they do not include C₄ crops, thus carbon fluxes associated with C₄ crops cannot be simulated in those models. In future, the total crop area is likely to increase (Molotoks et al., 2018; O'Neill et al., 2016) so that agriculture will become an even stronger influence on carbon fluxes.

~~While increasing crop area leads to increased GPP in crops, this does not translate to an increase in total vegetation biomass carbon stocks in vegetation because the expansion of croplands leads to reduction of forested land and CO₂ emissions (Gasser et al., 2020; Lam et al., 2021; Luo et al., 2024).~~ The range in global GPP was even larger than the range in vegetated area across the models, both for total (GPP: -23 to +37 % vs area: -11 to +8 %, compared to the model mean) and for C₃ (GPP: -24 to +32 vs area: -19 to +8 %) vegetation types. In C₄ natural vegetation, there was also disagreement over the sign of the trend in GPP, with some models showing increases in GPP in grid cells dominated by C₄ (>75 %, Fig. S6; a-d), and others showing decreases. These inconsistencies indicate that models' parametrizations, simulated climate and other factors (Campbell et al., 2017; Hou et al., 2022; Lavergne et al., 2022; Zscheischler et al., 2014) are at least as important as vegetation area for GPP simulation. Therefore, achieving consistency in area for vegetation types is not sufficient and improved understanding and representation of C₃ and C₄ GPP in models is needed.

~~West et al (2010) estimated that the replacement of a unit of natural vegetated land by crop will lead to the loss of double the amount of CO₂ uptake in croplands (-12 million kg km⁻² vs. +6.3 million kg km⁻²). As such, in some models the accumulation of carbon in crop vegetation did not outweigh the loss in natural vegetation over 1850-2014 and there was a net loss of carbon. In other models there was a net loss followed by a net gain in recent decades, due to strong gains in carbon in natural vegetation (Fig. 6). Observation-based estimates also disagree on the carbon stock changes in vegetation, with Bar-On et al. (2025) finding little to no change in vegetation carbon stocks over 1992-2019 while (Pan et al., 2011; 2024) found significant gains.~~

~~The range in global GPP was even larger than the range in vegetated area across the models, both for total (GPP: -23 to +37 % vs area: -11 to +8 %, compared to the model mean) and for C₃ (GPP: -24 to +32 vs area: -19 to +8 %) vegetation types. In C₄ natural vegetation, there was also disagreement over the trend in GPP, with some models showing increases in GPP in grid cells dominated by C₄ (>75 %, Fig. S6; a-d), and others showing decreases. These inconsistencies indicate that models' parametrizations, simulated climate and other factors (Campbell et al., 2017; Hou et al., 2022; Lavergne et al., 2022; Zscheischler et al., 2014) are at least as important as vegetation area for GPP simulation. Therefore, achieving consistency in area for vegetation types is not sufficient and improved understanding and representation of C₃ and C₄ GPP in models is needed.~~

The range in total area fraction of C₄ vegetation of 10-26 % in the CMIP6 models spans the observation-based estimates of 17.1-17.7 % (Still et al. 2003; Luo et al. 2024) and has a similar range as the dynamic global vegetation models in the TRENDY project (7-23 %; Luo et al. 2024). Since the observation-based estimates are quite consistent, model simulations of carbon fluxes can likely be improved by detailed comparison and specification of C₄ vegetation cover in particular PFTs in models to improve their correspondence to observational estimates.

The trends in C₃ vs C₄ contributions to GPP simulated by CMIP6 models produced differing trends in stable carbon isotopic discrimination, when only C₃ and C₄ fractions of GPP are used to calculate discrimination trends (Eq. 1, Fig. 7). The simulated changes in C₃ and C₄ fractions of GPP did not produce strong increasing trends as found by analysis of atmospheric δ¹³C data (Keeling et al. 2017; Peters et al. 2018). Since the effect of changing C₃ and C₄ fractions of GPP ~~vegetation change~~ on stable carbon isotopic discrimination varied widely across the CMIP6 models, it is still uncertain how much vegetation changes they could add to or oppose changes in stable carbon isotopic discrimination caused by environmental or physiological effects. Nevertheless, Lavergne et al (2026) found that accounting for the changes in C₃ and C₄ vegetation abundance improves the modelled trends in atmospheric carbon isotope composition compared to data. In particular, since the GPP trend in the models (11 to 18 %, Fig. S8) is weaker than the CO₂ fertilization effect over the 20th century based on carbonyl sulphide data (+30 %; Campbell et al. 2017), there may have been a more positive C₃ vegetation-driven trend in stable carbon isotopic discrimination in reality than in the models. Since the CMIP6 models did not provide output for GPP ~~and carbon stocks~~ for C₃ and C₄ vegetation or for crops and natural vegetation, we had to scale total GPP ~~and carbon stocks~~ by the area fractions of each vegetation type for grid cells with mixed vegetation. This calculation may not represent the models' actual attribution precisely, since ~~C₃ vegetation typically has higher carbon density and~~ C₄ vegetation can have higher GPP relative to area (Luo et al. 2024) in grid cells with a mosaic of C₃ and C₄. However, the extra resources needed in the C₄ photosynthetic pathway (Ehleringer et al., 1978) to concentrate CO₂ may make the difference between C₃ and C₄ CO₂ uptake minimal, especially if they co-occur relatively equally in such grid cells. Incorporating more detailed vegetation information from the models would improve the accuracy of the calculations and analysis based on TRENDY models could be a good place to start.

6-Discussion Conclusion

We analysed changes in vegetation with C₃ and C₄ photosynthetic pathways for natural vegetation and crops in 11 CMIP6 models over the historical period of 1850 to 2014. Except for one model that used a fixed vegetation distribution, the models include the expansion of agriculture using LUH2 data. Still, there is a significant variation in the fraction of area and GPP allocated to crops in these models, and the UKESM1 model strongly underestimated crops in Asia and Africa, likely due to biases in simulated climate. The C₄ fraction of vegetated area has remained relatively constant in the models, though there is a large range in simulated C₄ area fraction of 910- to 26 % ~~43 million km²~~ in 2014 while observation based estimates are quite consistent at 17.1 - 17.7 % from 1980s to 1990s and between 2001 and 2019 (Luo et al. 2024; Still et al. 2003). Overall, we found that the total vegetation area in most models is not changing, but the global vegetation composition is changing in favour

415 of crops. ~~Expansion of crops has negative implications for the carbon sink capacity of the terrestrial biosphere.~~ Whereas all the models agree that C₃ vegetation GPP and total global GPP ~~is-are~~ increasing, the magnitude of the increase spans a large range. In C₄ vegetation, the models disagree on the magnitude of GPP but also the sign of its trend, especially in natural vegetation, implying that the understanding of and model parametrizations for the simulation of C₄ GPP need improvement. The strong positive trends in UKESM1 C₄ crop and MPI-ESM-1-2-HAM and MPI-ESM1-2-LR ~~MPIs~~ C₄ natural vegetation
420 area clearly drives the decline of their global stable carbon isotopic discrimination trend, an effect which is not as pronounced in other models' vegetation categories. ~~However,~~ due to the large uncertainty in vegetation area abundance and GPP, it will be difficult to ~~accurately~~ determine if this effect of how consistent change in vegetation area abundance and GPP on global stable carbon isotopic discrimination trend is consistent across all the models. this influence is on global isotopic discrimination trend. ~~The mean of vegetation carbon contents in the model generally agrees with observation-based estimates.~~ We have shown
425 in this study that carbon flux simulation in current ESMs includes uncertainties in different components ~~C₃ and C₄ photosynthetic pathways in crops and natural vegetation;~~ reducing these uncertainties will require more observational constraints and more robust and realistic model representations.

Appendices

Appendix A contains the supplementary material.

430 Code Availability

The code (Jupyter notebooks) used for the analysis of the CMIP6 models data and for the data visualization can be found in the following Github repository: https://github.com/jovwemuvwose/CMIP6_Model_Analysis_Project_2025 and Zenodo at: <https://zenodo.org/records/16883407>

Data Availability

435 The CMIP6 models data used in the are available at the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (Phase 6) website: <https://esgf-node.ipsl.upmc.fr/projects/cmip6-ipsi/>. The leaf carbon isotope data by Cornwell et al (2018) are available at <https://onlinelibrary.wiley.com/doi/10.1111/geb.12764>. For the ESA CCI, LUH2, Still, Potapov and Luo data used in Figure 4, see Harper et al (2023), Hurtt et al (2020), Still et al (2003), Potapov et al (2022) and Luo et al (2024) respectively. ~~For Gibbs, Spawn and Erb data used in the Figure 6 above see Gibbs and Ruesch (2008), Spawn et al (2020), Erb et al (2018) respectively and Graven et al (2024) for all these three data in in one file at~~
440 ~~<https://www.science.org/doi/10.1126/science.adl4443>.~~ For the Keeling_vsCO₂, Keeling_vstime used in Figure 7 see Keeling

et al 2017. And for the GCB data used in Figure S4 see Friedlingstein et al (2025). The processed data used for the figures can be made available by the authors on request.

Authors contribution

445 JO and HG conceptualize the overarching research and CIP contributed to broadening it; JO prepared and created the published work, specifically data analysis and visualization and writing of the initial draft of the manuscript. HG and CIP reviewed and edited the manuscript.

Competing interests

The authors declare that they have no competing interest.

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Supporting Information for

Uncertainty in Land Carbon Fluxes Simulated by CMIP6 Models from Inconsistent Treatments of Crop Distributions and Photosynthetic Pathways

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Supplementary:**Material and Method S1 - Description of implementation of vegetation cover in CMIP6 models****S1.1 ACCESS-ESM1.5**

In the Australian Community Climate and Earth System Simulator Earth System Model version 1.5 (ACCESS-ESM1.5) land surface and biogeochemical processes are simulated using the Community Atmosphere Biosphere Land Exchange (CABLE) (Kowalczyk et al., 2013) model and a modified Carnegie–Ames–Stanford Approach (CASA) carbon (C) cycle model which incorporates nitrogen (N) and phosphorus (P) cycles (CASA-CNP module) (Ziehn et al., 2020). The area abundance of crops for the historical period is based on the LUH2 dataset (Hurtt et al., 2020). The 12 land-use types in the LUH2 dataset are mapped into 9 plant functional types (PFTs) in CABLE including C₃ grass, C₃ crops and C₄ crops. The rest of the PFTs (evergreen needleleaf forest, evergreen broadleaf forest, deciduous needleleaf forest, deciduous broadleaf forest, shrub and tundra) are not specified as either C₃ or C₄ but most of them would be C₃ vegetation since it is the most prevalent of these two photosynthetic pathways in the given PFTs. However, even though a C₄ crop PFT was specified in the model description (Ziehn et al., 2020), the variable cropFracC₄ was not provided in the CMIP6 archive. The values for cropFracC₃ and for the total crop fraction (cropFrac) were identical, so we specified the fraction of C₄ crops to be zero everywhere.

S1.2 CanESM5

The land component of the Canadian Earth System Model version 5 (CanESM5) is comprised of the Canadian Land Surface Scheme (CLASS) and the Canadian Terrestrial Ecosystem Model (CTEM) making up the CLASS-CTEM modelling framework. CLASS simulates the physical and CTEM simulates the biogeochemical land surface processes. Energy and water balances and land surface physical processes are calculated in CLASS using four vegetation categories: needleleaf trees, broadleaf trees, grasses and crops. Each of these is divided into sub-categories: needleleaf trees into evergreen and deciduous, broadleaf trees into three categories; cold deciduous, drought deciduous, and evergreen, crops into C₃ and C₄ types, and grasses into C₃ and C₄ types to form 9 PFTs (Swart et al., 2019). The increase in the area abundance of crops s for the historical period is based on the LUH2 dataset (Hurtt et al., 2020).

S1.3 CESM2, CESM2-WACCM, CMCC-CM2-SR5 and CMCC-ESM2-HAM

The Community Earth System Model Version 2 (CESM2) and Whole Atmosphere Community Climate Model (WACCM) are developed by teams of individuals from the National Centre for Atmospheric Research (NCAR), and other research institutions and universities. The major difference between CESM2 and CESM2-WACCM is the vertical extent of their atmospheric configuration. In CESM2-WACCM the simulated properties extend up to 130-140 km in the upper atmosphere with 70 vertical levels (Gettelman et al., 2019) whereas CESM2 has only 32 vertical levels and a model top of 40 km, without a prognostic scheme for ozone and other stratospheric entities (Danabasoglu et al., 2020).

CESM2 and CESM2-WACCM use the Community Land Model Version 5 (CLM5) for the simulation of terrestrial biogeochemical cycles including interactions with the soil-plant-atmospheric continuum, anthropogenic land use change and vegetation coverage (Danabasoglu et al., 2020; Lawrence et al., 2019). CLM5 computes land unit weights through two methods: dataset input or prognostic representation. In the prognostic representation, the land surface heterogeneity is represented in several land units which are divided into columns and the columns are divided into patches. The land units are vegetated land, lake, urban, glacier, and cropland. The vegetated land unit is divided into patches of 14 plant or crop functional type (P/CFTs) which are (N = needleleaf; B = broadleaf; E = evergreen; D = deciduous; T = tree; S = shrub): NET temperate, NET boreal, NDT boreal, BET tropical, BET temperate, BDT tropical, BDT temperate, BDT boreal, BES temperate, BDS temperate, BDS boreal, C₃ Arctic grass, C₃ grass and C₄ grass. Crops are categorised into C₃ unmanaged rainfed crop, C₃ unmanaged irrigated crop, managed rainfed unirrigated crops and managed irrigated crops. Apart from the last three PFTs, it is not explicitly stated which of the other PFTs uses the C₃ or C₄ photosynthetic pathways. However, their output variables provided include the percentage area coverage of all C₃ and C₄ vegetation. The CLM uses its Land Use Data Tool to translate the LUH2 dataset transitions and information into its P/CFTs distribution and management (Hurtt et al., 2020; Lawrence et al., 2019). The

CESM2 models did not provide cropFracC3 and cropFracC4 variables, but they did provide c3PftFrac or c4PftFrac (the fractions for total vegetation), so cropFracC3 and cropFracC4 were calculated by multiplying cropFrac by c3PftFrac or c4PftFrac.

The Euro-Mediterranean Centre on Climate Change (CMCC) Foundation model simulates biogeochemical cycles and land use change with the Community Land Model version 4.5 (CLM4.5) (Lovato et al., 2022), which is an earlier version of the model used in CESM2 and CESM2-WACCM. The land use implementation is similar to CESM2, which implies they used the LUH2 dataset as well (Lawrence et al., 2019). However, unlike CESM2, the CMCC models do provide cropFracC3, although not cropFracC4. Their cropFracC3 was equal to the total crop fraction (cropFrac), so we specified the fraction of C₄ crops to be zero everywhere

S1.4 CNRM-CM6.1 and CNRM-ESM2.1

CNRM-CM6.1 is the sixth generation of the fully coupled atmosphere-ocean general circulation model jointly developed by Centre National de Recherches Météorologiques (CNRM) and Cerfacs. Its land surface is simulated with the Interaction Soil-Biosphere-Atmosphere-CNRM TRIP (ISBA-CTRIP) coupled system (Decharme et al., 2019). Its vegetation cover is based on the ECOCLIMAP-II database in which each land cover type is portioned into fractions of 4 main surface types or tiles (nature, water bodies, sea, urban areas). The nature tile is further divided into bare soil, bare rock or one of ten PFTs. CNRM-CM6-1 adopts a fixed vegetation cover map from ECOCLIMAP-II (Faroux et al., 2013; Voldoire et al., 2019). It does not incorporate LUH2 datasets.

CNRM-ESM2.1 and CNRM-CM6.1 share the same code, physical parameterization and grid resolution but vegetation coverage in CNRM-ESM2.1 is dynamic, incorporating the LUH2 crop coverage dataset. In CNRM-CM6-1 and CNRM-ESM2.1, the cropFracC3 and cropFracC4 variables were identical to the c3PftFrac and c4PftFrac variables, which appears to be an error in the output. So, in CNRM-CM6-1 and CNRM-ESM2.1 cropFracC3 and cropFracC4 were calculated by multiplying cropFrac by c3PftFrac or c4PftFrac.

S1.5 MPI-ESM1.2

The Max Planck Institute Earth System Model version 1.2 (MPI-ESM1.2) uses the land surface scheme JSBACH which focuses on the competition between two vegetation types: graminoids (grass-like) and woody species (trees and shrubs). These two broad categories are further divided into different PFTs. To integrate the LUH2 dataset into their JSBACH simulation, they aggregated the four LUH2 natural vegetation and grasslands states into the natural vegetation type, the five LUH2 crop variables into crops, the LUH2 pasture and urban into pasture. These three broad types: natural vegetation, crops and pastures are then proportionally adjusted to sum up to one (Mauritsen et al., 2019). JSBACH dynamic vegetation component DYNVEG has 8 PFTs, 6 of which are woody (tropical evergreen trees, tropical deciduous trees, extratropical evergreen trees, extratropical deciduous trees, raingreen shrubs, deciduous shrubs) and 2 of which are grass- (C₃ grasses and C₄ grasses). In the model, prevalent climate conditions determine the extent of the presence or absence of vegetation in hot and cold regions (Reick et al., 2013).

S1.6 UKESM1-0-LL

The UK Earth System Model version 1 (UKESM1) (Mulcahy et al., 2023; Sellar et al., 2019) uses a physical core built on a prior model, HadGEM3-GC3.1 (Kuhlbrodt et al., 2018; Williams et al., 2018). It simulates the terrestrial ecosystem biogeochemistry and land surface dynamics using the Joint UK Land Environment Simulator (JULES) (Clark et al., 2011; Littleton et al., 2020) which is built on the Top-down Representation of Interactive Foliage and Flora Including Dynamics (TRIFFID) which uses the LUH2 crop cover data with some modifications including simulation of competition between C₃ and C₄ (Cox et al., 2001). ~~It uses, and the~~ Rothamsted carbon model soil carbon scheme (RothC) (Falloon et al., 1998). TRIFFID is a dynamic vegetation model that divides the earth surface into five components: vegetated land, urban and lake surface types, bare soil, and land covered permanently by ice. The vegetated component is divided into five PFTs : broadleaf trees, needleleaf trees, C₃ (temperate) grasses, C₄ (tropical) grasses and shrubs. These are assumed to sufficiently represent the phenotypic and genotypic variations needed to capture biophysical and biogeochemical roles of vegetation in earth system models (Sellar et al., 2019, Clark et al., 2011).

Table S1. Global land area in each category in LUH2 and in CMIP6 models for 1970 and 2014.

	Area Abundance (Million km ²)			
	C3 crop	C4 Crop	C3 Natural	C4 Natural
LUH2 1970 (2014)	11.59 (12.75)	2.68 (3.34)		
Luo (2014)		(3.32)		(17.02)
Ensemble mean 1970 (2014)	10.71 (11.55)	1.81 (2.31)	66.76 (66.41)	15.33 (15.29)
ACCESS-ESM1-5 1970 (2014)	12.41 (13.76)	0.00 (0.00)	67.66 (67.35)	9.97 (8.95)
CanESM5 1970 (2014)	11.43 (12.41)	2.68 (3.30)	64.96 (63.92)	6.88 (6.33)
CESM2 1970 (2014)	9.42 (9.94)	3.04 (3.92)	71.34 (70.48)	19.44 (18.91)
CESM2-WACCM 1970 (2014)	9.42 (9.94)	3.04 (3.92)	71.34 (70.48)	19.44 (18.91)
CMCC-CM2-SR5 1970 (2014)	13.21 (14.68)	0.00 (0.00)	68.99 (67.79)	19.63 (19.35)
CMCC-ESM2 1970 (2014)	13.21 (14.68)	0.00 (0.00)	68.99 (67.79)	19.63 (19.35)
CNRM-CM6.1 Fixed	9.71 (9.71)	3.00 (3.00)	59.82 (59.82)	19.22 (19.22)
CNRM-ESM2.1 1970 (2014)	9.48 (10.03)	2.26 (3.10)	65.01 (65.37)	20.09 (19.56)
MPI-ESM1.2-HAM 1970 (2014)	11.89 (13.19)	1.35 (1.96)	70.72 (71.18)	8.75 (10.18)
MPI-ESM1-2-LR 1970 (2014)	11.96 (13.03)	1.14 (1.60)	68.33 (68.59)	8.79 (9.91)
UKESM1-LL 1970 (2014)	5.68 (5.65)	3.36 (4.62)	57.12 (57.76)	16.84 (17.47)

Table S2. Ranges of simulated terrestrial biosphere carbon flux variables for 2014 simulated by CMIP6 models from 1850 to 2014.. $\div$ GPP is Gross Primary Production; C_{veg} is vegetation carbon content; dC_{veg}/dt is vegetation carbon accumulation; C_{land} is land carbon content; dC_{land}/dt is land carbon accumulation .

Variable	Area (Million km ²)	GPP (PgCyr ⁻¹)	Discrimination (‰)	Discrimination change (‰)
Total	95 [85, 105]	116 [93, 150]	18.12 [16.98, 19.15]	-0.23 [-0.68, 0.20]
Total Natural	82 [71, 90]	100 [80, 126]	18.15 [17, 19.42]	-0.17 [-0.80, 0.22]
Total Crop	14 [10, 15.4]	17 [13, 26]	-0.06 [-0.7, 0.33]	-0.07 [-0.50, 0.20]
C ₃ total	78 [63, 84]	96 [73, 126]		
C ₃ Natural	66 [57, 71]	82 [62, 105]		
C ₃ crop	12 [6, 15]	14 [6, 21]		
C ₄ total	18 [9, 13]	21 [12, 30]		
C ₄ Natural	15 [6, 19]	18 [15, 26]		
C ₄ crop	2 [0, 4.6]	3 [0, 8]		

Table S2 biosphere carbon accumulation.

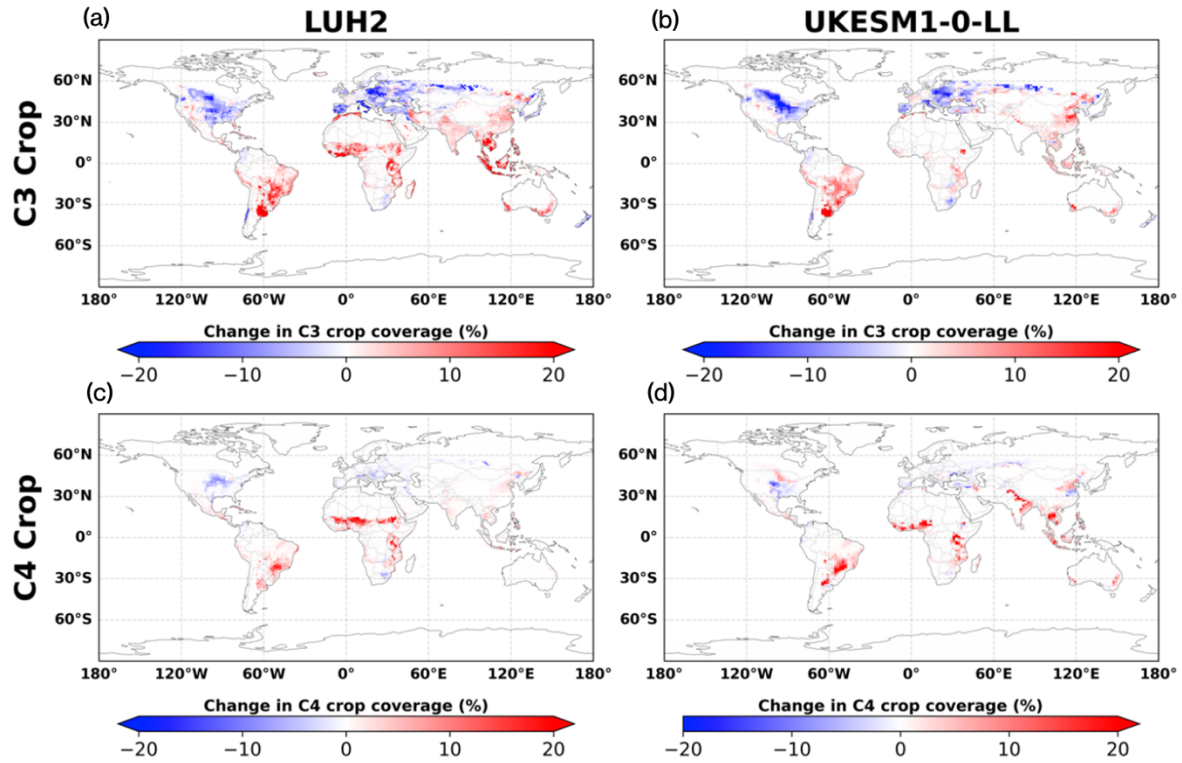


Figure S1. Percentage change in crop abundance between 1970 and 2014. For C₃ and C₄ in LUH2 (a) and (c) and UKESM1-0-LL (b) and (d). All the other models not shown use the LUH2 crop variables for their crop coverage and change. CNRM-CM6-1 is not shown here because it has fixed crop coverage.

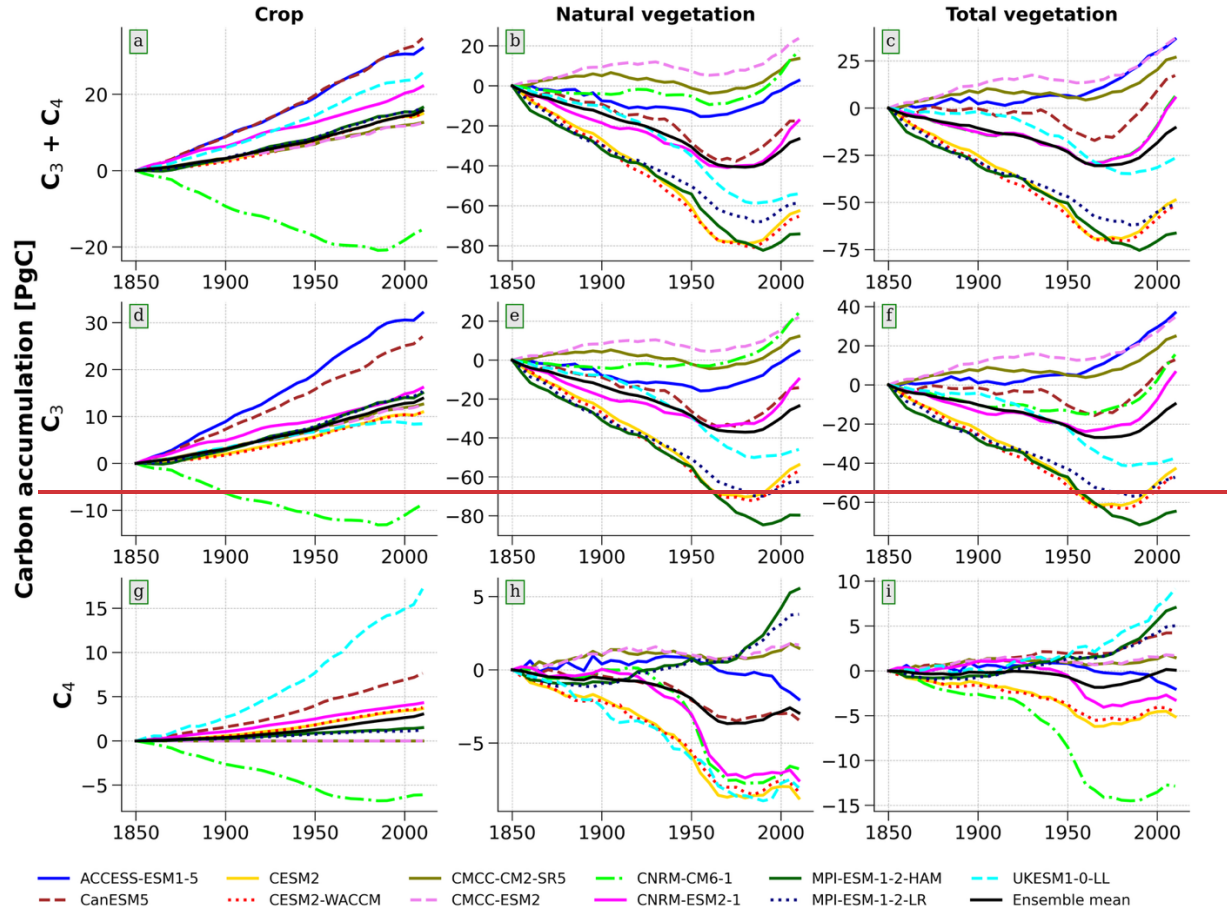


Figure S2—Temporal trend in gGlobal vegetation carbon accumulation between 1850 and 2014. Values of carbon accumulation in (a) croplands, (b) natural vegetation and (c) total vegetation. (d) C_3 -crop, (e) natural C_3 vegetation, (f) total C_3 vegetation, (g) C_4 -crops, (h) natural C_4 vegetation and (i) total C_4 vegetation

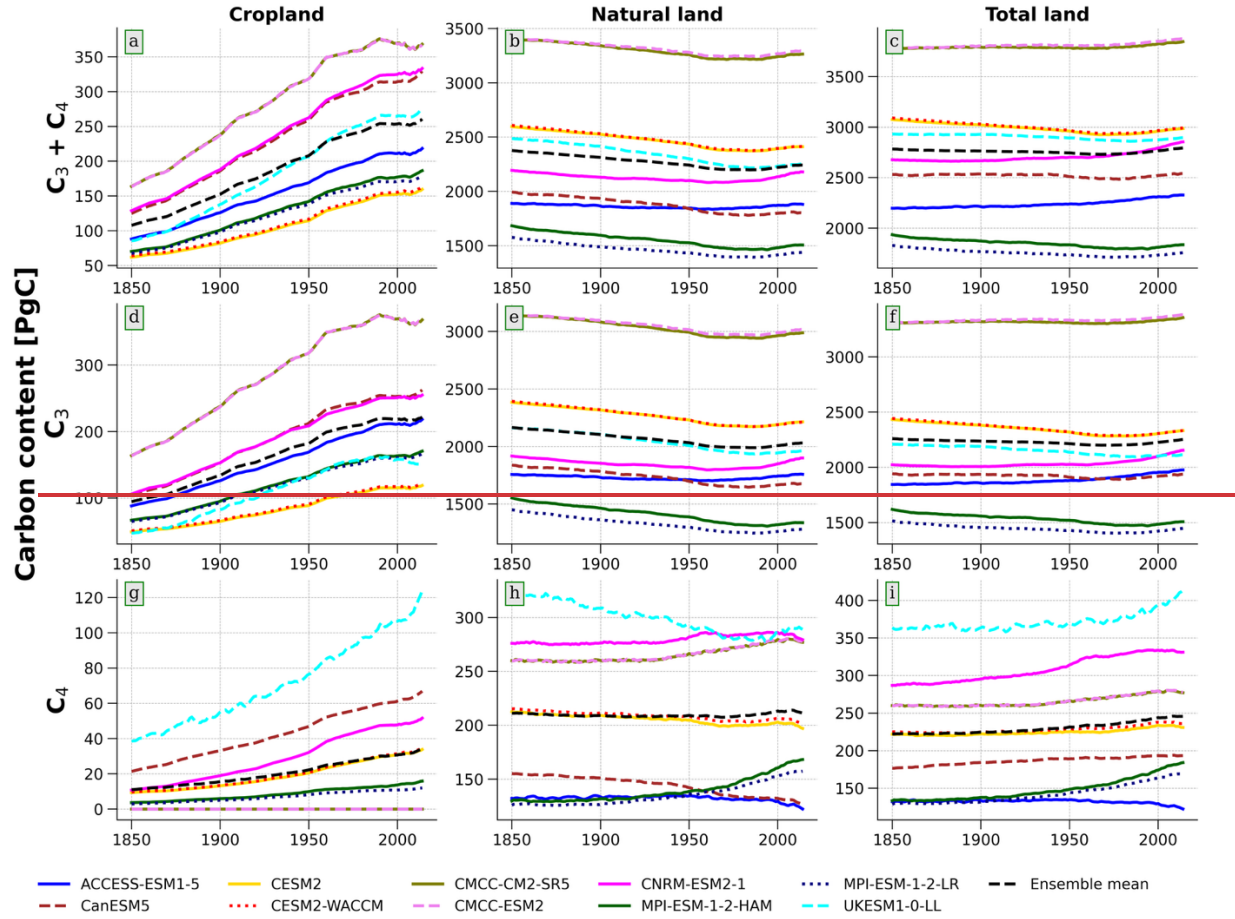


Figure S3—Temporal trend in gGlobal land carbon content between 1850 and 2014. Absolute values of carbon content in (a) croplands, (b) natural vegetated land (c) total vegetated land, (d) C_3 croplands, (e) natural C_3 vegetated land, (f) total C_3 vegetated land, (g) C_4 croplands, (h) natural C_4 vegetated land and (i) total C_4 vegetated lands.

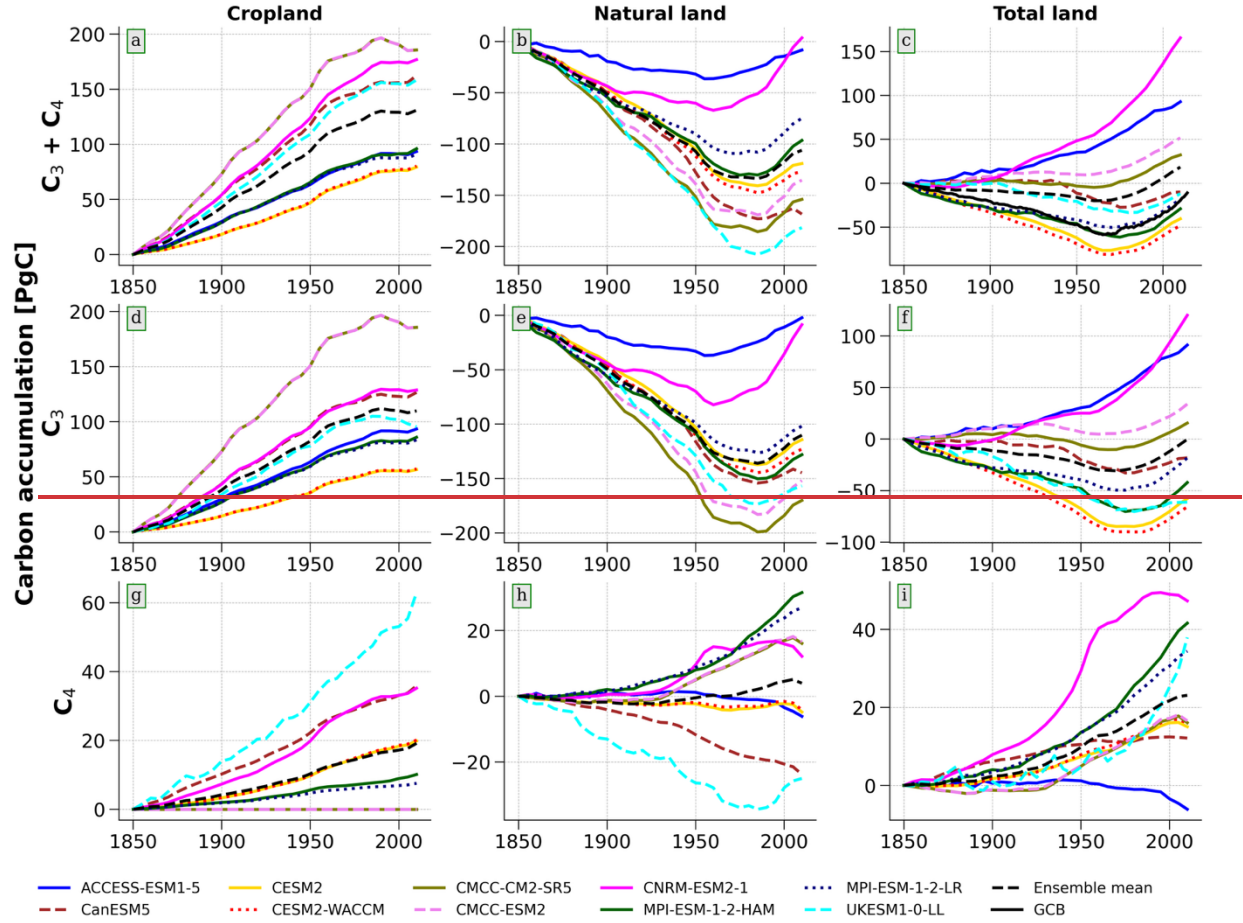


Figure S4—Temporal trend in gGlobal land carbon accumulation between 1850 and 2014. Absolute values of carbon content in (a) croplands, (b) natural vegetated land (c) total vegetated land, (d) C_3 croplands, (e) natural C_3 vegetated land, (f) total C_3 vegetated land, (g) C_4 croplands, (h) natural C_4 vegetated land and (i) total C_4 vegetated lands. Estimated global land carbon accumulation from the Global Carbon Budget

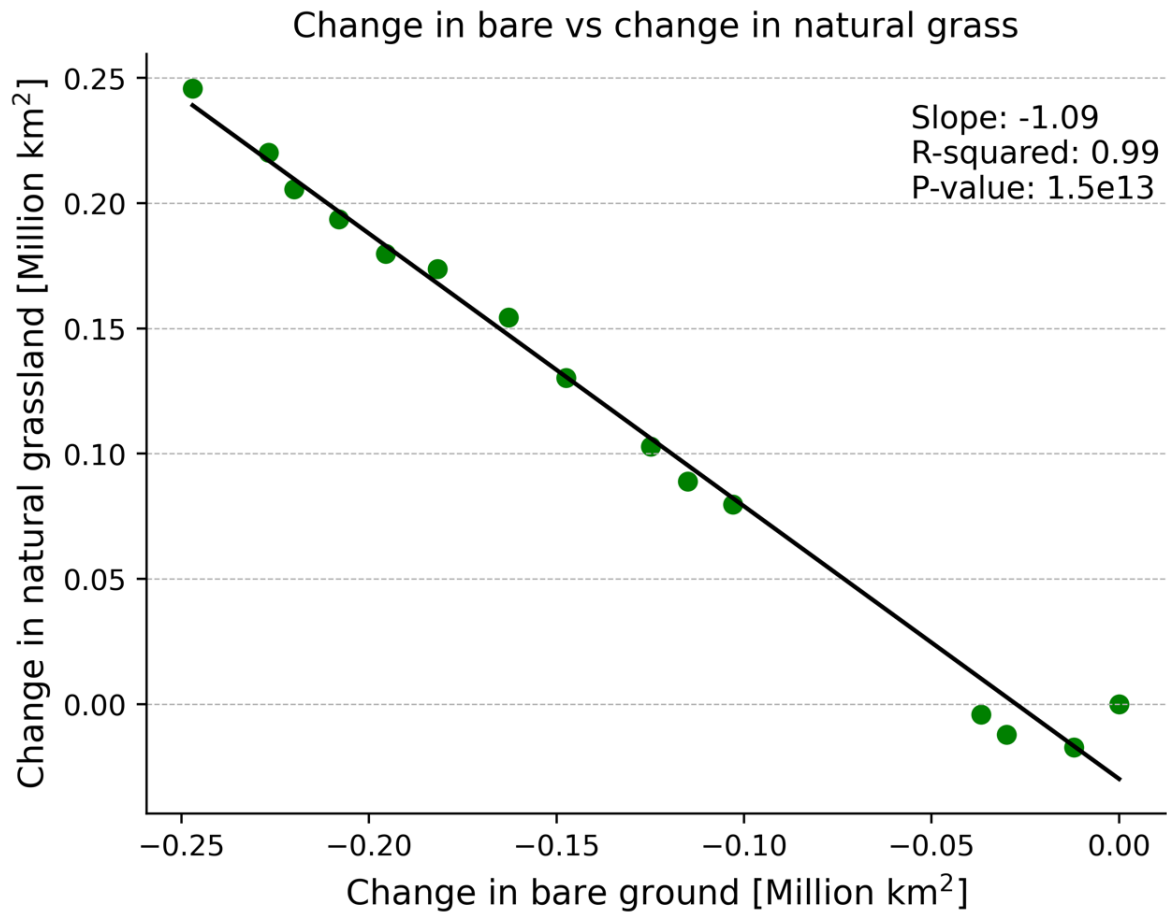


Figure S25 – Relationship between the change in bare ground and natural grass in the ESA CCI land cover dataset between 2000 and 2014. The change is calculated as the difference between the values of the variables in 2000 and 2014.

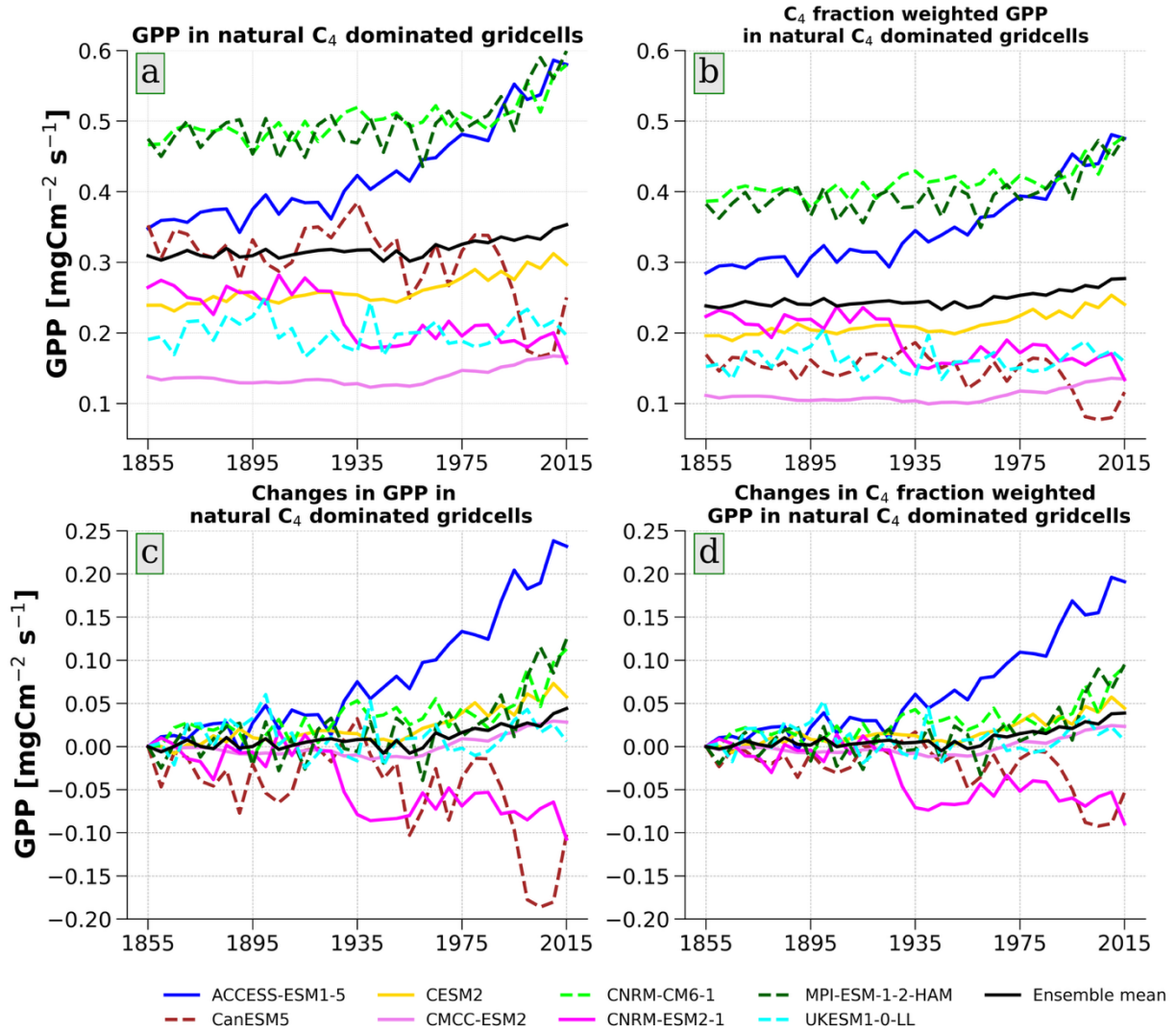


Figure S36 - Temporal trend of GPP in natural C₄ dominated grid cells between 1850 and 2014. Here natural C₄ $\Rightarrow$ 75% except in CanESM5 where there are no grid cells with natural C₄ $\Rightarrow$ 75% and as such a threshold of natural C₄ $\Rightarrow$ 45.5% is used instead. (a) GPP in natural C₄ dominated grid cells, (b) GPP in natural C₄ dominated grid cells weighted by the natural C₄ vegetation fraction, (c) Changes in the GPP in natural C₄ dominated grid cells, (d) changes in the GPP in natural C₄ dominated grid cells weighted by the natural C₄ vegetation fraction.

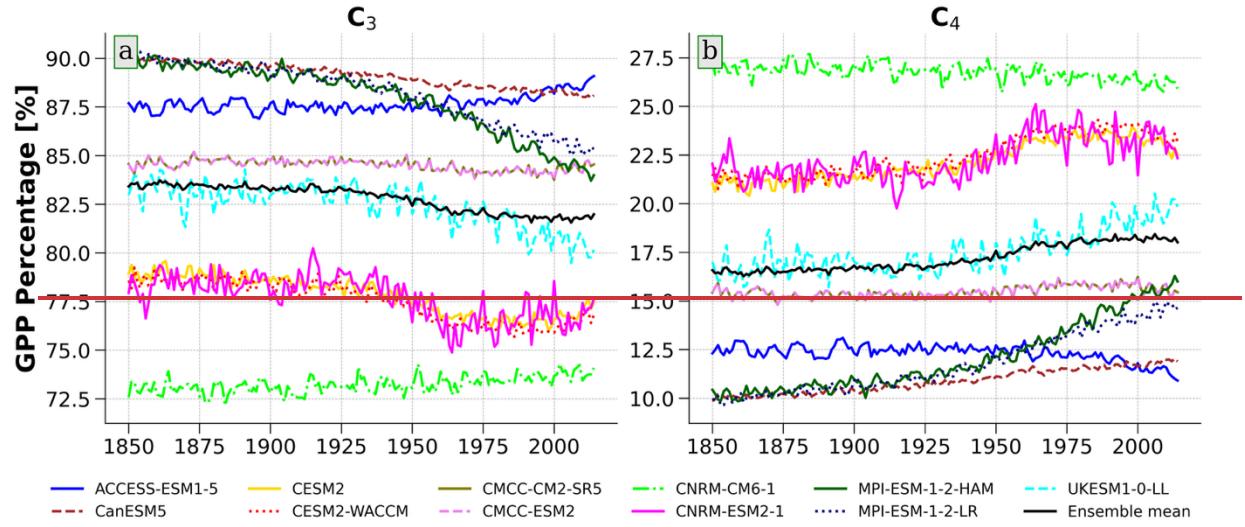


Figure S7— Temporal trend of C_3 and C_4 GPP percentage in CMIP6 models between 1850 and 2014. The model means show a decreasing C_3 and an increasing C_4 contribution to the total GPP.

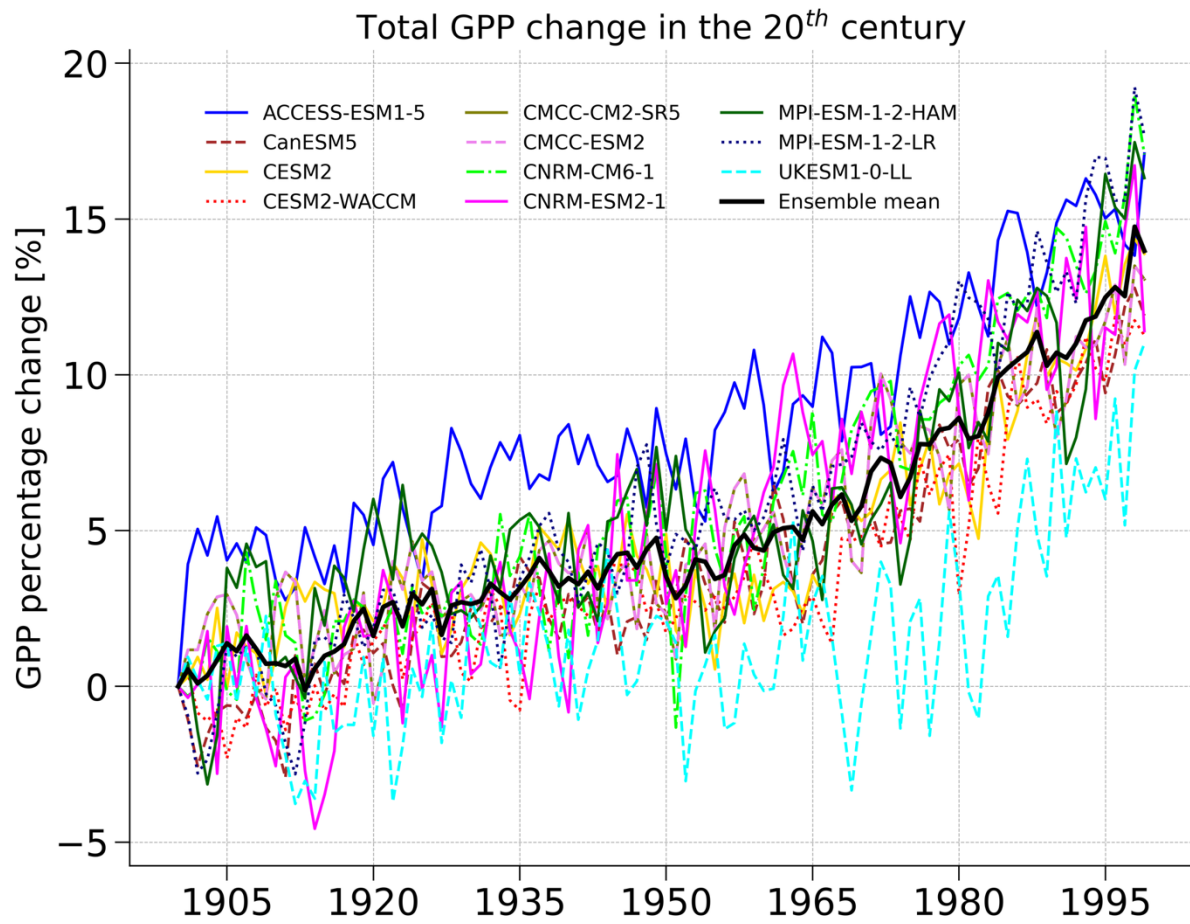


Figure S48— CMIP6 models percentage change in total GPP between 1900 and 2000. The value of the percentage change in the GPP is weak (11 to 17%) compared to 30% observed in other studies in the 20th century.

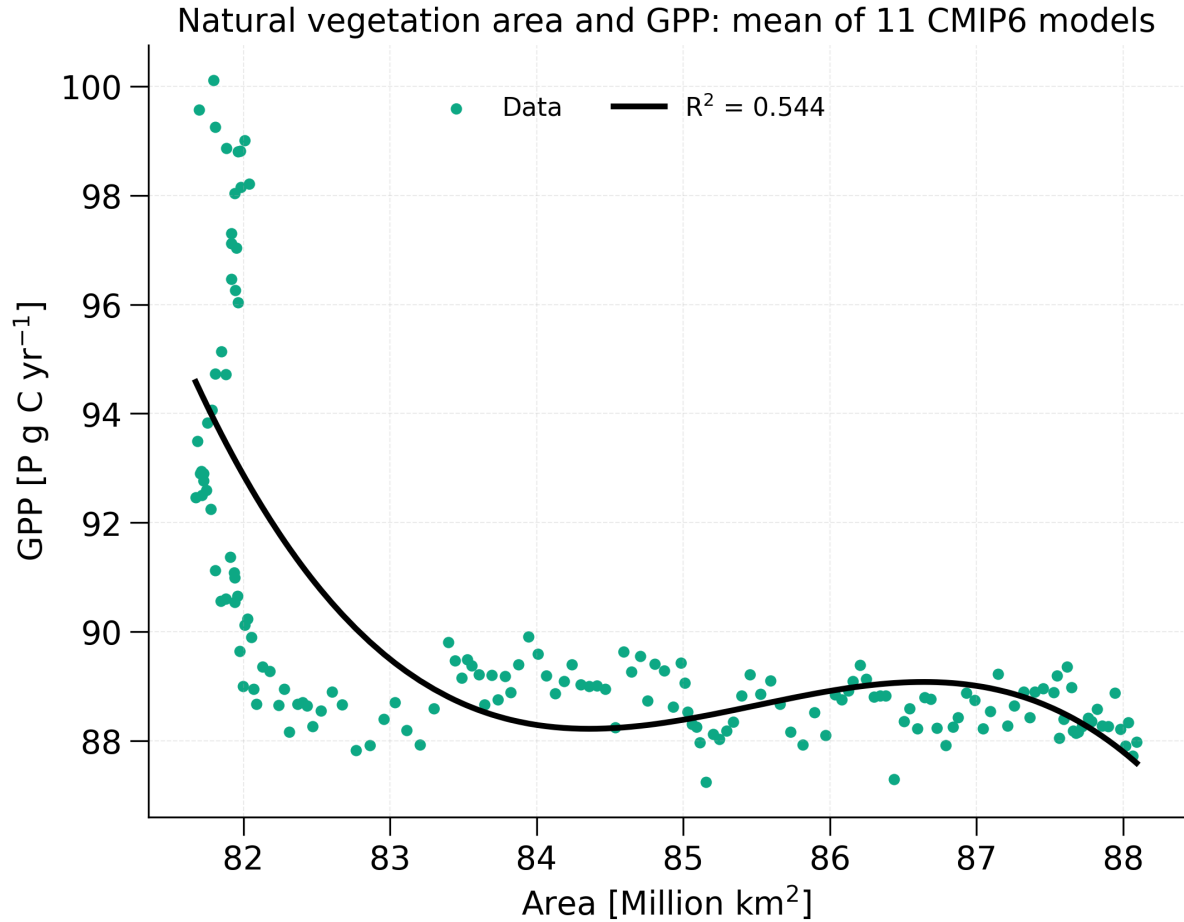


Figure S59— Relationship between GPP and area for natural vegetation for the mean of the 11 CMIP6 models. The line is fitted with a cubic polynomial and $R^2 = 0.544$. It shows GPP is decreasing with increasing area which is contrary to what is theoretically expected which is a decrease in GPP with decreasing area, hence our assumption that the change in GPP in natural vegetation may be decoupled from the change in its area.

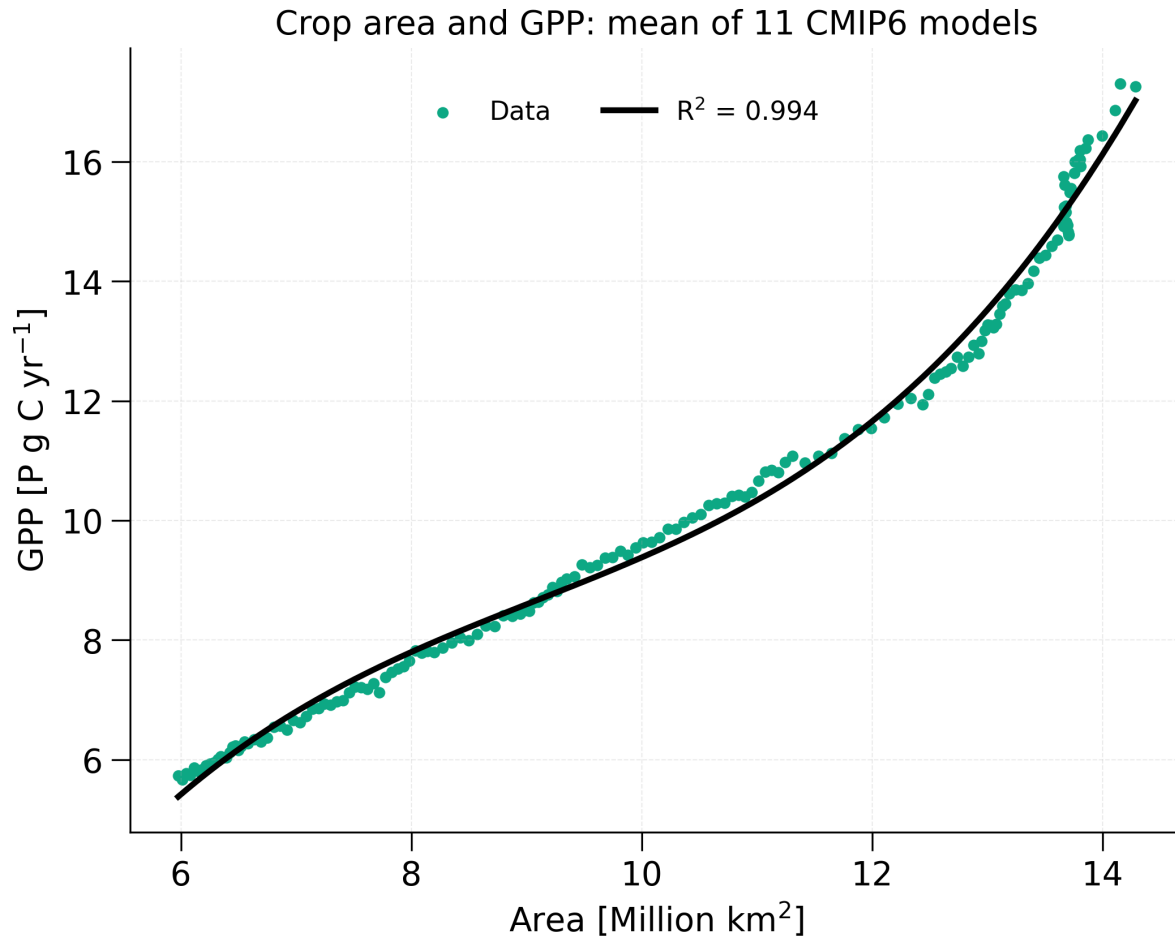


Figure S610— Relationship between GPP and area for cropland for the mean of the 11 CMIP6 models. The line is fitted with a cubic polynomial and $R^2 = 0.994$. The GPP increased with the increasing area.

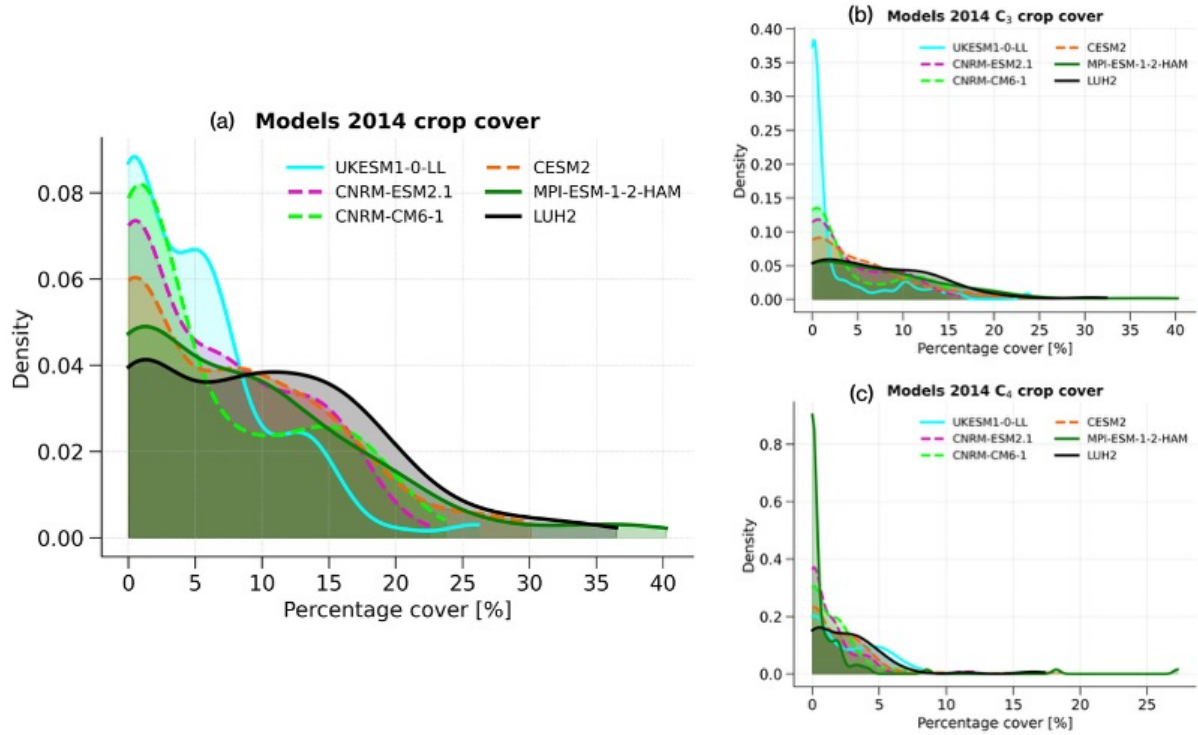


Figure S744 – Distribution density plot for CMIP6 models and LUH2 crop cover for 2014. Total crop (a), C₃ crop (b), and C₄ crop (c). The two models which have outliers for C₃ and C₄ crops are UKESM1 and MPI-ESM-1-2-HAM. The values we obtained by multiplying the total crop cover and the total C₃ and C₄ fraction to get the values of C₃ and C₄ crops for CESM2, CNRM-CM6.1 and CNRM-ESM2.1 are within the range of the other models and they are comparable to the values of the LUH2 values and the other models.

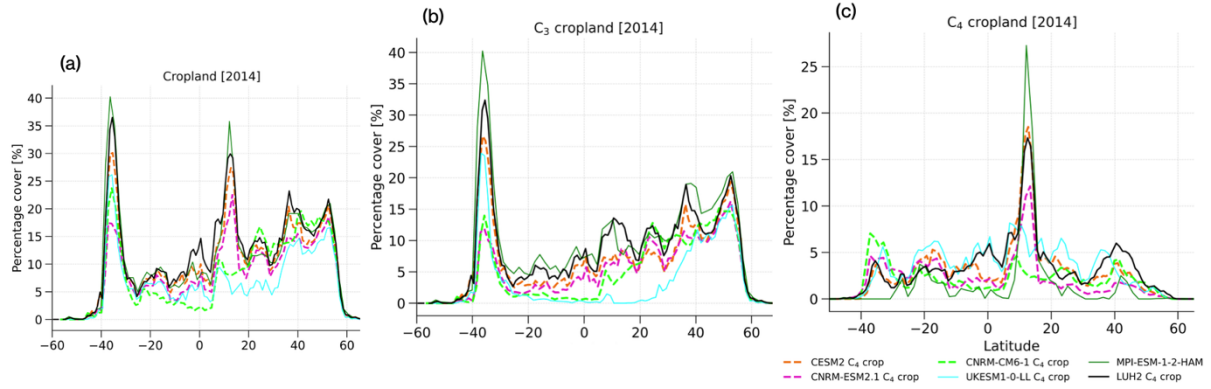


Figure S812— Plot of the spatial variation in cropland area in CMIP6 models and LUH2 for 2014. Total cropland (a), C₃ crop (b), and C₄ cropland (c). The spatial variation of C₃ and C₄ crops obtained by multiplying the total crop cover and the total C₃ and C₄ fraction in CESM2, CNRM-CM6.1 and CNRM-ESM2.1 is consistent with the range of those of the other models and the LUH2 datasets.

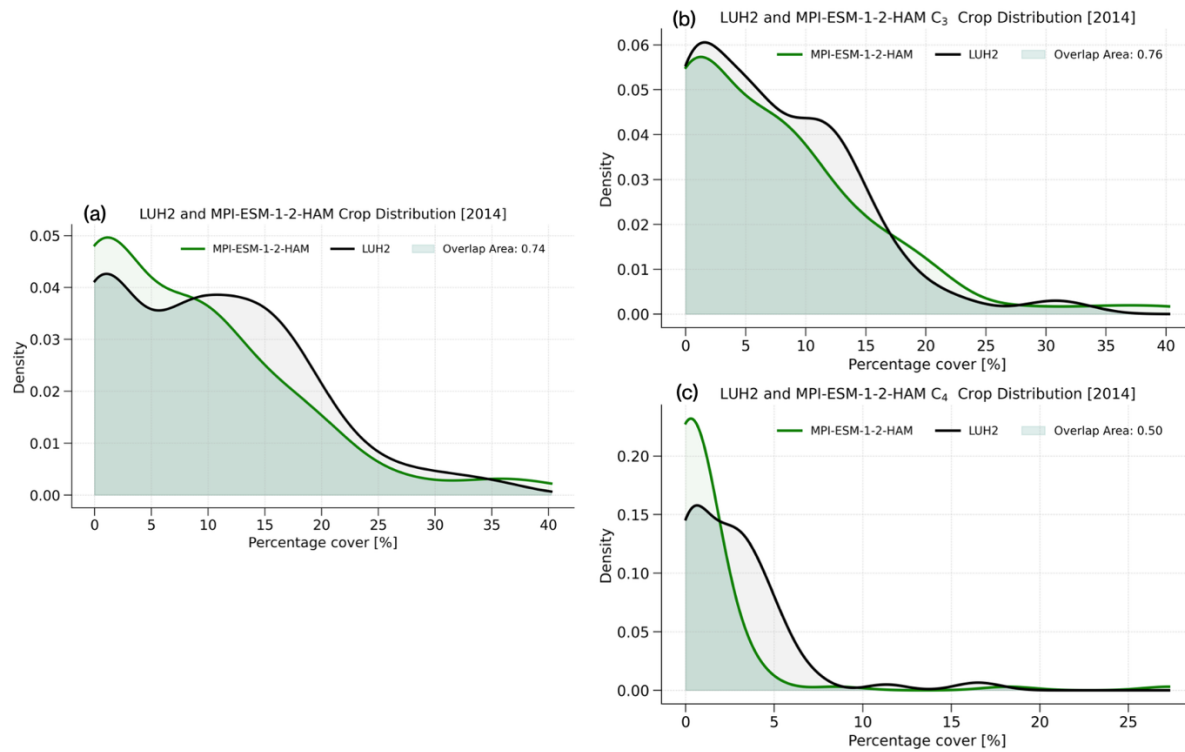


Figure S213 – Kernel density plot of the spatial distribution of crop in and MPI-ESM-1-2-H and LUH2 for 2014. Total cropland (a), C₃ crop (b), and C₄ cropland (c). The overlap area is 74, 76 and 50 % for total, C₃ and C₄ crops between the model and LUH2.

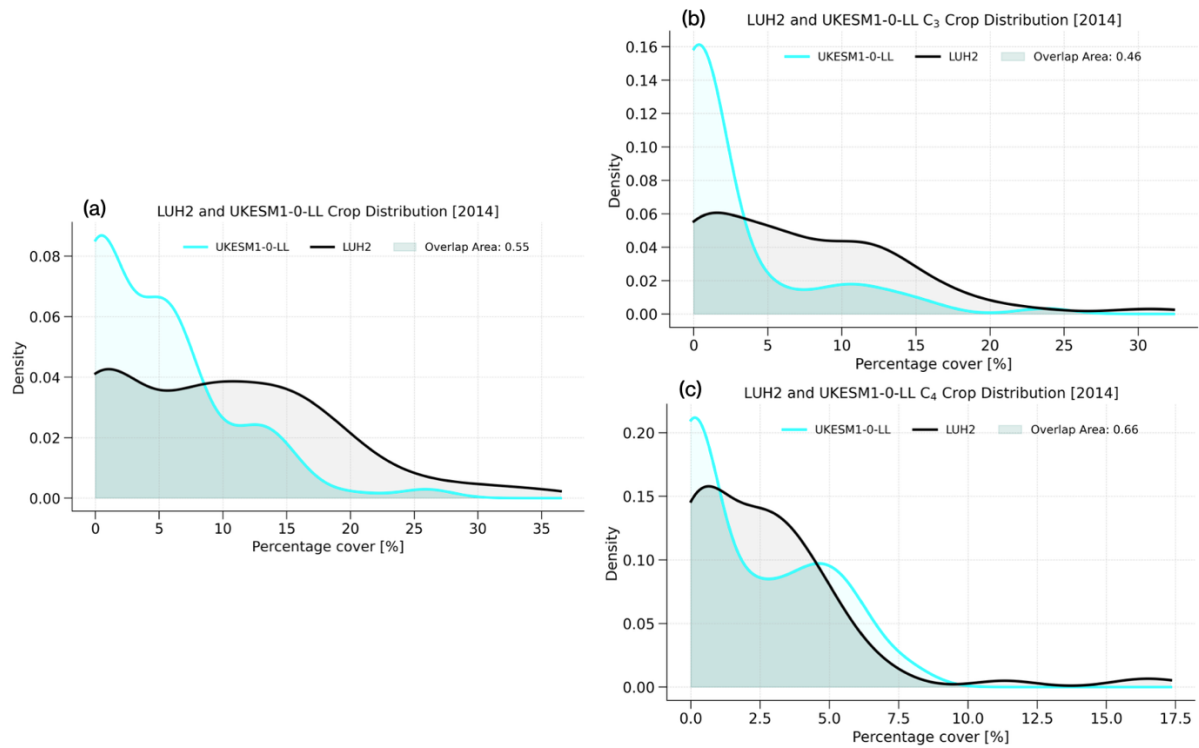


Figure S1014— Kernel density plot of the spatial distribution of crop in and UKESM1 and LUH2 for 2014. Total cropland (a), C₃ crop (b), and C₄ cropland (c). The overlap area is 55, 46 and 66 % for total, C₃ and C₄ crops between the model and LUH2.

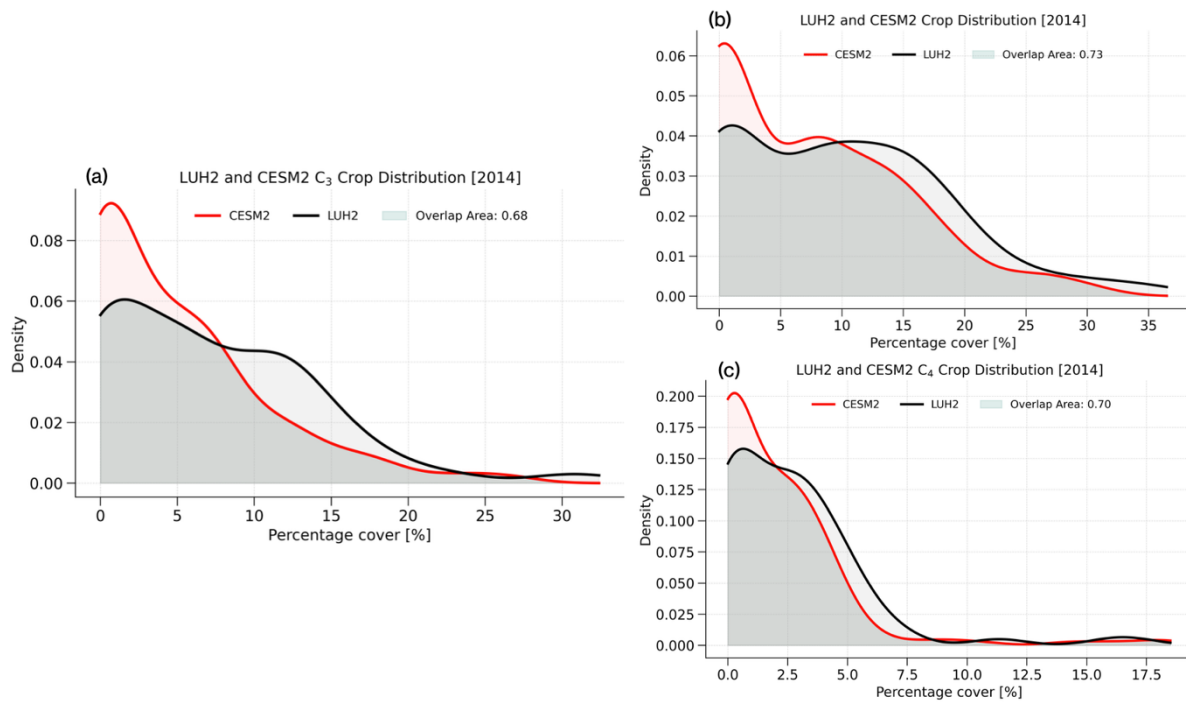


Figure S1145 – Kernel density plot of the spatial distribution of crop in CESM2 and LUH2 for 2014. Total cropland (a), C₃ crop (b), and C₄ cropland (c). The overlap area is 68, 73 and 70 % for total, C₃ and C₄ crops between the model and LUH2.

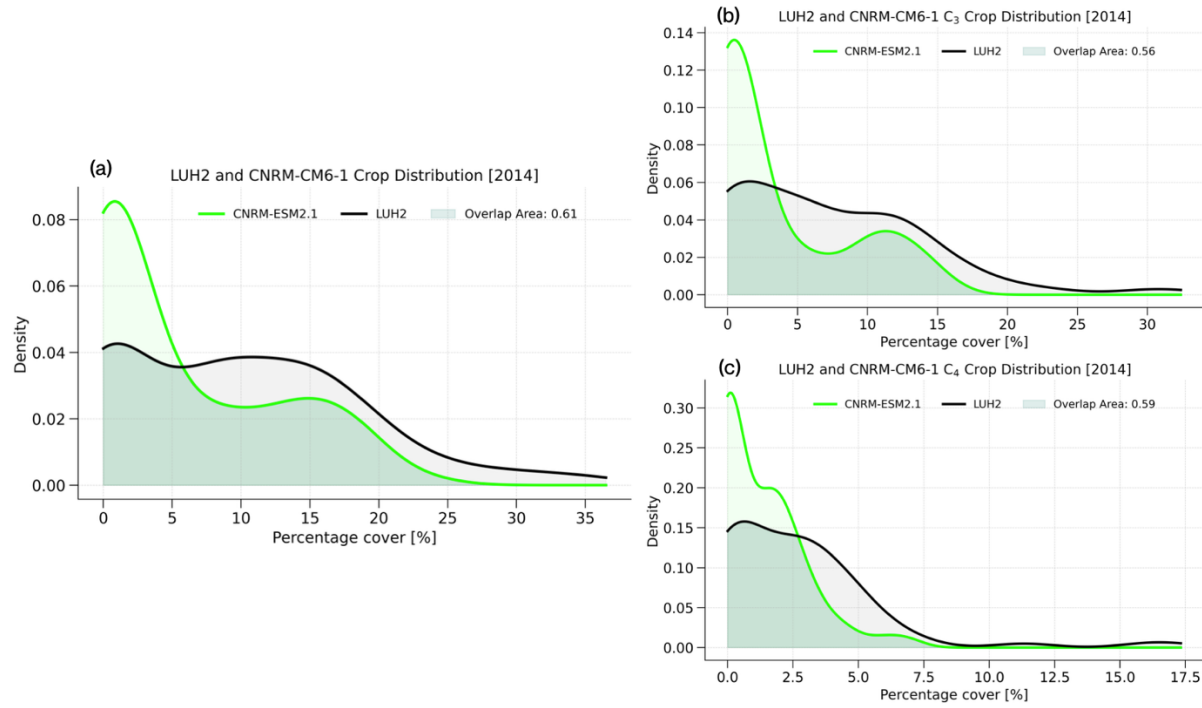


Figure S1246 – Kernel density plot of the spatial distribution of crop in and CNRM-CM6.1 and LUH2 for 2014. Total cropland (a), C₃ crop (b), and C₄ cropland (c). The overlap area is 61, 56 and 59 % for total, C₃ and C₄ crops between the model and LUH2.

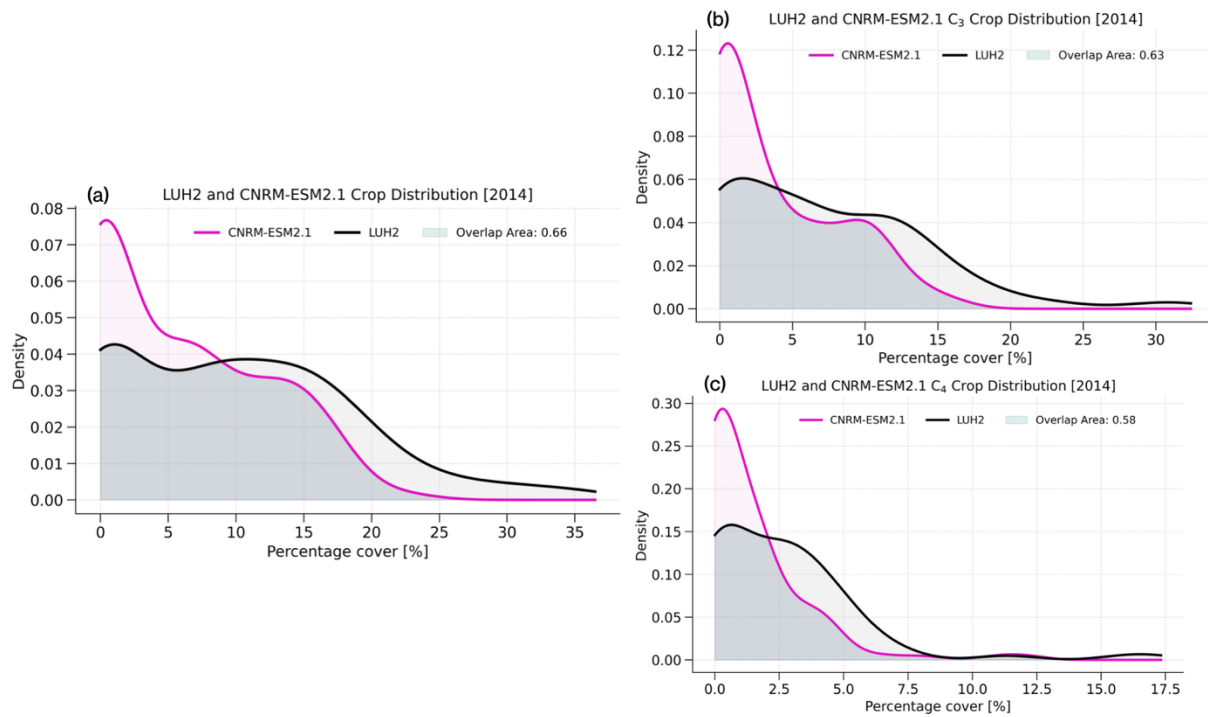


Figure S1347— Kernel density plot of the spatial distribution of crop in and CNRM-ESM2.1 and LUH2 for 2014. Total cropland (a), C₃ crop (b), and C₄ cropland (c). The overlap area is 66, 63 and 58 % for total, C₃ and C₄ crops between the model and LUH2.