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LETTER

Potential strong contribution of future anthropogenic land-use and land-cover change to the terrestrial carbon cycle

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Abstract

Anthropogenic land-use and land cover changes (LULCC) affect global climate and global terrestrial carbon (C) cycle. However, relatively few studies have quantified the impacts of future LULCC on terrestrial carbon cycle. Here, using Earth system model simulations performed with and without future LULCC, under the RCP8.5 scenario, we find that in response to future LULCC, the carbon cycle is substantially weakened: browning, lower ecosystem C stocks, higher C loss by disturbances and higher C turnover rates are simulated. Projected global greening and land C storage are dampened, in all models, by 22% and 24% on average and projected C loss by disturbances enhanced by ~49% when LULCC are taken into account. By contrast, global net primary productivity is found to be only slightly affected by LULCC (robust +4% relative enhancement compared to all forcings, on average). LULCC is projected to be a predominant driver of future C changes in regions like South America and the southern part of Africa. LULCC even cause some regional reversals of projected increased C sinks and greening, particularly at the edges of the Amazon and African rainforests. Finally, in most carbon cycle responses, direct removal of C dominates over the indirect CO_2 fertilization due to LULCC. In consequence, projections of land C sequestration potential and Earth's greening could be substantially overestimated just because of not fully accounting for LULCC.

1. Introduction

Terrestrial soils and vegetation contribute to the global carbon cycle and climate mainly through biogeochemical emissions and uptake of greenhouse gases (CO_2, CH_4, N_2O, etc) and exchange of energy, water and momentum (i.e. biophysical effects) [1–3]. The productivity and carbon stocks of terrestrial ecosystems can be in turn affected by climate and human use. All other things equal, changes in terrestrial carbon storage are found to be positively correlated with changes in atmospheric CO_2 concentration and negatively to temperature changes (~1 PgC.ppm^{-1} and ~−80 PgC.K^{-1} as approximated sensitivities among the studies [4–7]).

Land-use and land cover changes (LULCC), like conversion of forests into crops or pastures, also affect ecosystem-climate-carbon cycle processes through changes in biophysical properties of the land-cover, changes in phenology and changes in biogeochemical emissions and uptake. Using bookkeeping, censuses, remote sensing or carbon/vegetation models, several studies quantified the contribution of past and present-day LULCC to carbon fluxes and global warming [e.g. 8–13]. Over the last 150 years, estimated cumulative LULCC emissions represent approximately one-third of total cumulative anthropogenic CO_2 emissions but only one-eighth over the recent period 1990–2010 [8, 10].

By contrast, relatively few studies have focused on future LULCC impacts on the carbon cycle, and in most cases (historical or future perspective) the emphasis was on net carbon uptake rather than on the underlying terrestrial carbon processes: photosynthesis, heterotrophic and autotrophic respiration, carbon turnover time, land cover productivity, phenology or even disturbances. Under present-day climate conditions, [14, 15] estimate that land-use reduced terrestrial NPP of potential natural vegetation at global scale by ~5%–10%. [16] found that under A2/B1/B2 future scenarios, based on LPJmL vegetation model simulations with climate forcings from four global climate models, land-use (from 1970–2100) contributes to modulate NPP by ~−5%/−1%/−3%, vegetation carbon by −47%/−19%/−27% and soil carbon by −7%/+1%/−2% compared to a baseline scenario, respectively. Moreover, while historical LULCC decreased soil carbon sequestration, meta-analysis reviews [17–19] found that deforestation would not necessarily lead to decreased soil carbon stocks: conversion of native forest to plantation or crops can imply reductions varying from −13% to −42% (~−2.1 kgC m^{-2}) while transformation of native forest to pasture or grassland tends to increase them by 8% up to 19% (+1.2 kgC m^{-2}).

In consequence, LULCC also alter the ecosystem carbon turnover time at global scale, in general reducing it by several years [16, 20–24]. By comparing the vegetation carbon turnover time of the actual vegetation and with that of a hypothetical vegetation state without land-use under current climate conditions, [24] find that land-use halved the biomass turnover time.

Robust estimates of the interplay between LULCC and terrestrial ecosystems state are of paramount importance to constrain the future projections in terrestrial carbon cycle and reduce their uncertainties. However, few studies have attributed and quantified the net impacts of LULCC on the terrestrial carbon cycle and all the above-mentioned underlying physical processes, *a fortiori* in a multi-Earth system model (ESM) framework or based on a common realistic and global LULCC scenario. Finally, future land-use and land-cover changes are not often explicitly taken into account in global coupled models and sometimes only included in terms of CO_2 emissions only [9, 25, 26]. Besides, biophysical effects can substantially modify future hydrological cycle and energy balance at the surface particularly in tropical deforested areas [27, 28], which can in turn modulate the future terrestrial carbon cycle.

Our study fills those gaps and explores new findings on terrestrial carbon cycle, making use of simulations with and without future LULCC (based on the RCP8.5 scenario) from five ESMs (i.e. General circulation models–GCMs—including interactive carbon cycle). We aim to analyze (i) the likely effects of LULCC on the global terrestrial carbon cycle (section 3.1) and (ii) the relative contribution of LULCC forcing in the projected changes at global (section 3.2) and regional scale (section 3.3). Furthermore, we not only attribute the *net* changes in carbon cycle in response to future LULCC, but we also disentangle the direct effect of LULCC without altering CO_2 emissions ('LULCC only') and the biogeochemical effect of the emissions induced by LULCC ('LULCC-emissions only').

2. Methods

2.1. Models and experiments

The Land-Use and Climate, Identification of Robust Impacts (LUCID) is a major international intercomparison exercise that aims to investigate the robust impacts of LULCC using as many climate models as possible forced with a common LULCC scenario (www.lucidproject.org.au/).

Analyzing the future impacts of LULCC, several modeling groups from the 5th Phase of the Coupled Model Intercomparison Project (CMIP5) performed ESM simulations without anthropogenic land-use changes from 2006–2100. We use outputs from all the five state-of-the-art CMIP5 models used in LUCID-CMIP5 (CanESM2, HadGEM2-ES, IPSL-CM5A-LR, MPI-ESM-LR and MIROC-ESM) on the last 30 years period of each experiment (2071–2100). Several different ESM experiments are explored here as detailed in table 1.

RCP8.5 simulations are the CMIP5 runs with all forcings including the future anthropogenic land-use and land-cover change forcing based on the business-as-usual RCP8.5 scenario (see table 1). This scenario includes spatially explicit future LULCC characterized by an expansion of croplands and pastures driven by the food demands of an increasing population and corresponds to a radiative forcing of more than 8.5 W.m^{-2} in 2100 [29] (CO_2 atmospheric concentration ~936 ppm in 2100). L2A85 simulations are the same runs as RCP8.5 but without the anthropogenic land-use and land-cover change forcing (after year 2005), with atmospheric CO_2 concentration prescribed from the RCP8.5 scenario (table 1).

The difference between RCP8.5 and L2A85 simulations (i.e. RCP8.5–L2A85) corresponds thus to the sole *biophysical* effects of future anthropogenic land-use and land cover changes ('LULCC only', i.e. without changes in CO_2 atmospheric concentration). L1A85 (respectively, L1B85) is a similar simulation to RCP8.5 but without future anthropogenic land-use and land cover changes and prescribed (resp., interactively simulated) atmospheric CO_2 concentration. Thus, L1A85–L1B85 corresponds to the sole *biogeochemical* effects corresponding to the changes in atmospheric CO_2 in response to future anthropogenic land-use and land cover changes ('LULCC-emissions only', i.e. without LULCC). The 'net' effects, including feedbacks between biophysical

Table 1. Description of simulations used from CMIP5 and LUCID-CMIP5 following the RCP8.5 scenario.

CMIP5 simulations	Atmospheric CO_2 concentration	LULCC
Historical	Prescribed from historical scenario	Transient changes from 1850–2005
rcp85	Prescribed from RCP8.5 scenario	Transient changes from 2006–2100
esmrcp85	Interactive (emissions-driven with atmospheric CO_2 concentration determined by model)[a]	As in rcp85
L1A85	Prescribed (concentration-driven) from esmrcp85	Fixed to year 2005
L1B85	Interactive (emissions-driven atmospheric CO_2 concentration from RCP8.5 scenario)	Fixed to year 2005
L2A85	As in rcp85	Fixed to year 2005
rcp85–L2A85	(1) Biophysical effects: 'LULCC only' (same CO_2 but different LULCC)	
L1A85–L1B85[b,c]	(2) Biogeochemical effects: 'LULCC-emissions only' (same LULCC but different CO_2)	
esmrcp85–L1B85	(3) Net effects of LULCC	
(3) minus [(1)+(2)]	(4) Synergistic effects: non-linear feedbacks between biophysical and biogeochemical effects of LULCC	

[a] The CO_2 concentration results among other factors from prescribed anthropogenic CO_2 emissions and land-use and land-cover changes. As the predicted CO_2 concentration also depends on the climate simulated by the models, the esmrcp85 simulations allow for carbon-climate feedbacks.

[b] CanESM2 model does not provide L1A85 simulations, so for this model, the effects of 'LULCC-emissions only' are reasonably approximated by (esmrcp85–L1B85)–(rcp85–L2A85).

[c] HadGEM2-ES model does not provide L1A85 nor L1B85 simulations, so for this model, the effects of 'LULCC-emissions only' cannot be calculated and the net effects correspond to the effects of 'LULCC only'.

and biogeochemical effects, correspond to the difference between esmrcp85 and L1B85, while the difference between net effects and the sum of 'LULCC only' and 'LULCC-emissions only' yields the 'synergistic effects' (table 1). Supplementary table S1 available at stacks.iop.org/ERL/13/064023/mmedia details the main characteristics of the five LUCID-CMIP5 models including number of PFTs representation of dynamical vegetation, fire modules and horizontal resolution.

Historical simulations (HIST, *historical* according to CMIP5 abbreviation) are also used and averaged over the 1976–2005 period. For HadGEM2-ES model, it is not possible to calculate biogeochemical effects due to LULCC (absence of L1A85 and L1B85 simulations, see table 1). We can however infer from the smallest cumulative net land-use emissions simulated by this model (~25 PgC from 2006–2100 under RCP8.5 [30]) that those effects are overall negligible *vs.* 'LULCC only' effects.

In general, all figures present ensemble-mean results i.e. averaged results among the 5 LUCID-CMIP5 models interpolated on a common medium resolution grid of MIROC-ESM (2.8° × 2.8°, see supplementary table S1). When all 5 ESM simulate the same anomaly sign for spatial averages in response to LULCC, the signal is called 'robust'. Supplementary figure S1 shows the tree fraction changes between RCP8.5 and historical simulation (from 2006–2100) averaged over the 5 LUCID-CMIP5 models. Future changes in tree cover are about 4 million km^2 by 2100 (i.e. ~1/10th> of global tree cover [31]). A strong tropical deforestation signal (up to −20% change in some regions) robustly dominates while at mid- and high-latitudes, given the representation or not of dynamical vegetation (see supplementary table S1), some forest expansion signal takes place (HadGEM2-ES, MPI-ESM-LR and MIROC-ESM) or not (CanESM2 and IPSL-CM5A-LR). Note that the LULCC scenario implemented here do not include simulation of specific land-use as the irrigation, fertilizers, urbanization or other land management. Harmonization and implementation of future LULCC scenario into the five CMIP5 models are fully detailed in [29] and [30].

2.2. Carbon cycle variables

For the analysis of the changes in carbon cycle, we investigate seven key variables: net primary productivity (*npp*, CMIP5 abbreviation), leaf area index (*lai*), total ecosystem carbon stocks (C_{TOT}, sum of soil *cSoil* and vegetation carbon *cVeg*), ecosystem carbon residence time (τ, defined as the ratio between C_{TOT} and gross primary productivity *gpp*, similar to the definition of [22]), heterotrophic respiration (r_H), autotrophic respiration (r_A) and carbon loss due to disturbances (e.g. fires) (L_d, defined as the difference between net ecosystem production NEP and net biome production NBP).

3. Results and Discussion

3.1. Weakened terrestrial carbon cycle in response to future LULCC

The biophysical (left column), biogeochemical (middle column) and net effects (right column) of LULCC on each carbon cycle variable (row) at global scale are presented in figure 1. Global changes in NPP in response to future LULCC are simulated: −1.1, +6.6 and +9.8 gC m^{-2} yr^{-1} on average, respectively i.e. −0.2, +1.0 and +1.5 PgC yr^{-1} for 'LULCC only', 'LULCC emissions only' and net effects of LULCC. However, models simulate a large spatial variability of net NPP responses: strong NPP decreases are simulated in South African region (up to −100 gC m^{-2} yr^{-1}) enhanced by biogeochemical effects of LULCC as well as in Eastern South America and Sahelian regions.

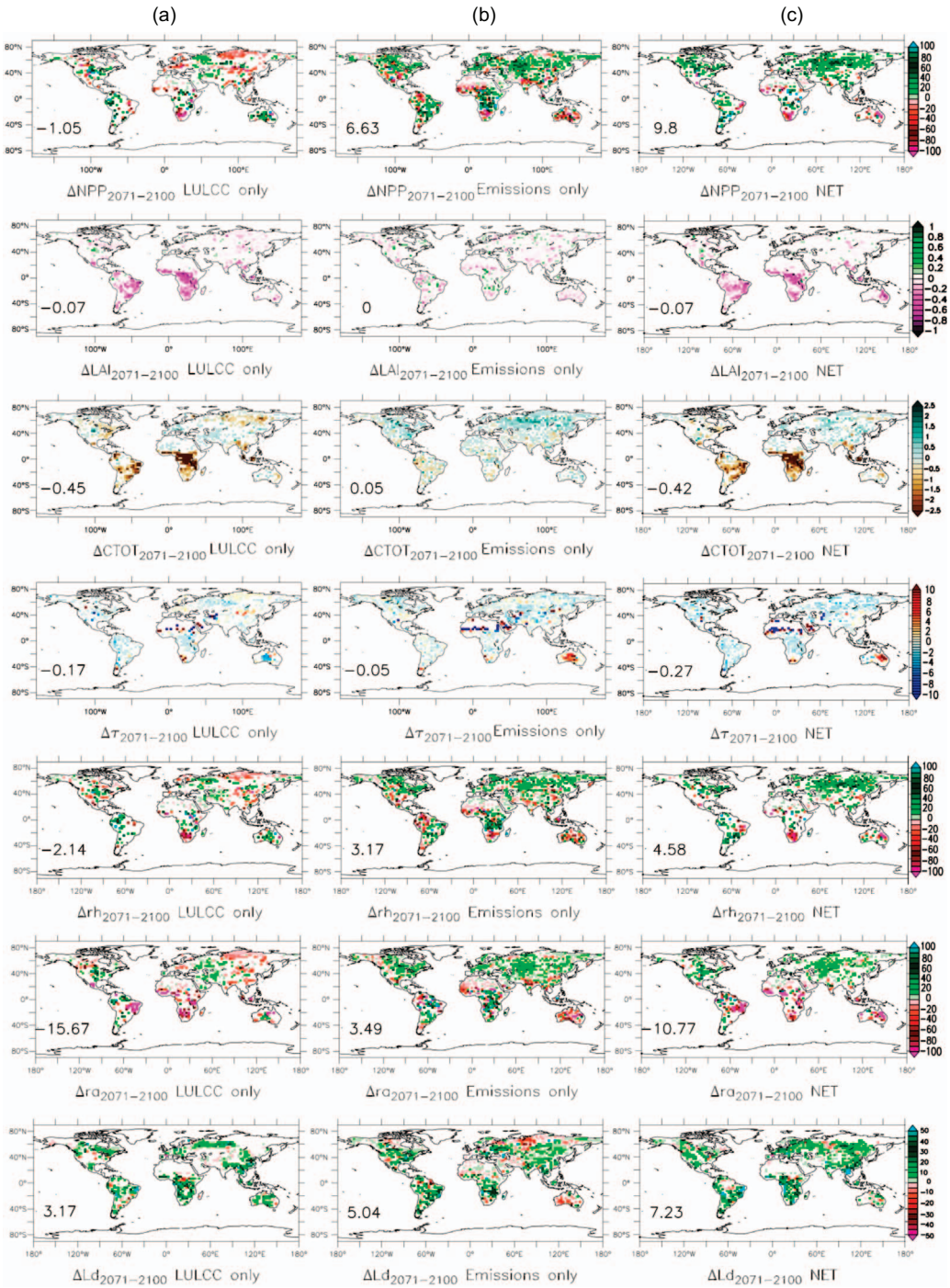

Figure 1. Spatial patterns of changes in carbon cycle variables in response to (*a*) LULCC only, (*b*) LULCC-emissions only and (*c*) sum of both (net effects of LULCC) averaged on 2071–2100 period. Units are for NPP, r_H, r_A and L_d: gC yr^{-1} m^{-2}, LAI: non-dimensional, C_{TOT}: kgC m^{-2} and τ: years. Global continental averaged values are indicated in the bottom left corner of each panel (for τ, the ratio between global continental averages of C_{TOT} and of GPP is calculated). Only gridpoints where four out of five LUCID-CMIP5 models simulate the anomaly sign are shown (white blank otherwise).

By contrast, Eurasia, large parts of South America, tropical Africa and Canada display increases in NPP. A disagreement in the sign of model NPP response occurs above several tropical deforested areas (blank areas in figure 1), particularly due to 'LULCC only' effects, while biogeochemical effects via CO_2 fertilization tend to slightly boost vegetation productivity. LAI is decreased in response to future LULCC by 0.07 on average, predominantly affected by direct LULCC effects of tropical deforestation in South America, Africa, Eastern Australia and Indonesia up to −0.6. Biogeochemical effects of LULCC cause no significant change on LAI at global scale. Changes in C_{TOT} maps mirror the changes in LAI: although some slight increases in C_{TOT} due to CO_2 fertilization, particularly in boreal latitudes (+0.05 kgC m^{-2} on global average or ∼7.5 GtC globally), direct land-cover changes strongly decrease the content in carbon of

the vegetation and soils (-0.45 kgC m^{-2} on global average or ~67 GtC globally). In response to future LULCC, we also find that soil carbon reductions are on average five times less important than vegetation carbon (not shown). Overall, the net effects of LULCC result in reduced ecosystem carbon content, particularly pronounced in Eastern South America, Africa and Indonesia. Global negative impacts of climate change on land carbon storage and foliage density, particularly in the Tropics [7, 32], are thus aggravated by LULCC.

Ecosystem carbon residence time τ at global scale is found to decrease both in response to 'LULCC only' (-0.17 yrs) and to 'LULCC-emissions only' (-0.05 yrs) causing a global net decrease of ~-0.27 yrs (see figure 1 for τ). Large changes are simulated at regional level, particularly in deserts and semi-arid areas (e.g. Central Australia, Sahara) because of very low GPP on average which makes τ being very sensitive to any small modulation of C_{TOT} or GPP in response to global LULCC. Plant respirations (r_A) are substantially weakened globally in response to LULCC (-10.8 gC m^{-2} yr^{-1} i.e. -1.6 PgC yr^{-1}), particularly due to LULCC-only effects (-15.7 gC m^{-2} yr^{-2} i.e. -2.3 PgC yr^{-1}), and to the conversion of landscape in the Tropics: Eastern South America and Tropical Africa being the most affected regions. Dead organic matter by decomposition (r_H) results in small positive net changes (+4.6 gC m^{-2} yr^{-1}) due to LULCC-only (-2.1 gC m^{-2} yr^{-1} on average) and LULCC-biogeochemical effects (+3.2 gC m^{-2} yr^{-1}).

The net carbon loss due to terrestrial disturbances (L_d) is enhanced under LULCC (+7.2 gC m^{-2} yr^{-1}) where both LULCC-only effects (+3.2 gC m^{-2} yr^{-1}) and biogeochemical effects of LULCC (+5.0 gC m^{-2} yr^{-1}) play a significant positive role, particularly marked above deforested areas of Tropical Africa, South America and to some lesser extent in Eurasia. Aside from direct biomass removal induced by LULCC, land carbon sequestration potential is expected to decrease due to increased decomposition rates (r_H) and disturbances (L_d) but only very weakly influenced by changes in gross primary productivity (-0.97 gC m^{-2} yr^{-1}, not shown). Besides, depleted total carbon stocks (C_{TOT}) explain the increases in carbon turnover rates, while enhancement in global NPP (i.e. GPP-r_A) is fully due to decrease in plant respiration (r_A).

3.2. Global relative contribution of future LULCC

Under the RCP8.5 scenario, particularly due to the effect of increased CO_2 fertilization and global warming induced by greenhouses gases emissions, terrestrial carbon cycle is found to be enhanced on average as reported by previous studies, despite a large inter-model uncertainty [9, 16, 26, 33]. When looking at the trends over the 21st century (supplementary figure S2), the multimodel-mean projects more productive terrestrial ecosystems (NPP is boosted by 236 gC m^{-2} yr^{-1} i.e. 35.2 Pg yr^{-1}) with denser foliage density (LAI is increased by 0.22), more carbon content in soils and vegetation (C_{TOT} is increased by 1.33 kg m^{-2} on average i.e. 198 GtC global total) in parallel with stronger decomposition rates and plant respiration (projected changes in r_H and r_A are +192 and +210 gC m^{-2} yr^{-1}, respectively: +28.7 and 31.3 PgC yr^{-1}). The five ESM projections used in our study are consistent with previous literature estimates: Wieder *et al* [34] find similar projected patterns of NPP and total carbon stocks with 11 CMIP5 GCM including carbon cycle, while, Friend *et al* [35] using seven DGVMs simulate on average increases in NPP, carbon stocks and vegetation carbon residence time comparable in magnitude to the changes presented in our analysis (supplementary figure S3). Ecosystem carbon residence time is projected to decrease by ~3.7 years by the end of the century under RCP8.5 scenario (supplementary figure S3), which can be explained by ESMs simulating a greater relative increase in gross primary productivity (here GPP) with respect to the increase in ecosystem carbon stocks (C_{TOT}). Moreover, LUCID-CMIP5 models project enhanced disturbance-related carbon losses (L_d is enhanced by 16 gC m^{-2} yr^{-1}), which is coherent with projected increases in fire carbon emissions by ESM in CMIP5 [36].

When future LULCC impacts on the terrestrial carbon cycle changes are compared *versus* projected impacts (i.e. with all forcings, supplementary figure S2), the relative carbon cycle response becomes more prominent (see global relative contribution of LULCC and relative changes in figure 2 and supplementary figure S3, respectively). Figure 2 displays for each carbon cycle variable (*x*-axis), each model (symbols) and for the ensemble-mean (bars), the relative contribution of LULCC, disentangled in 'LULCC only' effects (e.g. blue bars), 'LULCC-emissions only' (red bars) and net effects (black bars; synergistic effects being indicated by grey hatching, see table 1). While global LAI and C_{TOT} are simulated to increase at the end of the 21st century (supplementary figure S2), net effects of future LULCC contribute to reduce those projected changes by 22% and 24% respectively (blacks bars for those variables in figure 2). This negative contribution is found robust as every LUCID-CMIP5 model simulates it with relative contributions for LAI varying from -10% (HadGEM2-ES) to -45% (MIROC-ESM) and for C_{TOT} varying from -9% (HadGEM2-ES) to -65% (MIROC-ESM). The future contribution of LULCC to the projected changes of greening and carbon storage are thus much more important than the current contribution estimates: for instance, in a multi-dynamic global vegetation model (DGVM) framework, Zhu *et al* [37] find a positive relative contribution of present-day LULCC to the Earth's greening (increased LAI) compared to all forcings lesser than 5% *vs.* -22% in our study for future LULCC under RCP8.5. Besides, we found smaller contributions of LULCC to projected changes in global C_{TOT} (-24%) compared to [16] and [38] who simulate

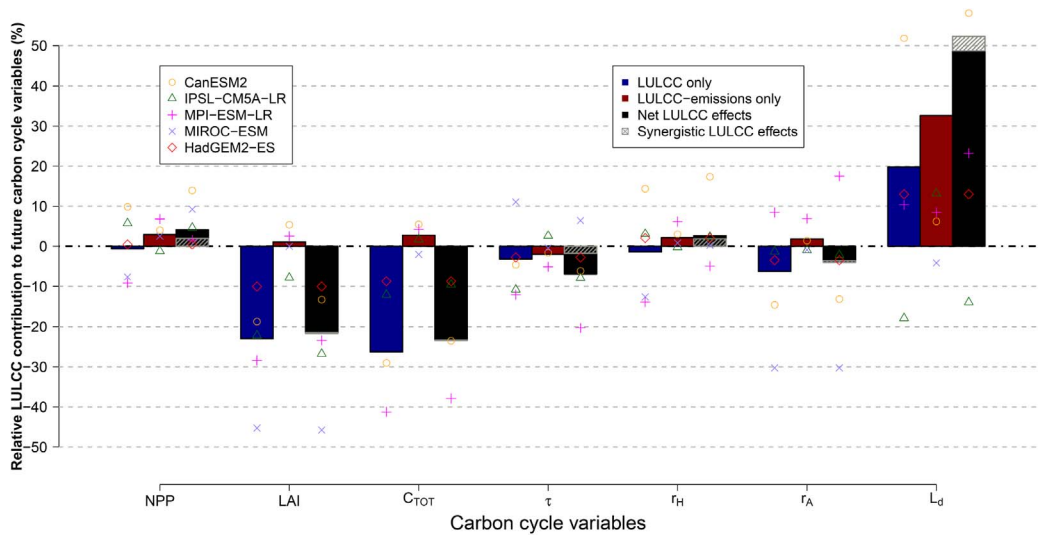

Figure 2. Relative contribution of future LULCC effects to global changes of carbon cycle variables. Blue, red and black bars (*Y*-Axis) correspond to the percentage contribution of 'LULCC only', 'LULCC-emissions only' and 'net effects of LULCC', respectively, relative to future projections with all other forcings (|RCP8.5–HIST| or |RCP8.5–HIST|+|net effects of LULCC| depending whether LULCC effects have the same sign or not, respectively) for each of the seven carbon cycle variables (*x*-Axis). Averaged period for future projections and future impacts of LULCC is 2071–2100. Grey hatching corresponds to the synergistic effects between 'LULCC only' and 'LULCC-emissions only' simulated changes i.e. the difference between net effects and the sum of 'LULCC only' and "LULCC-emissions only (see table 1). Each symbol represents the individual model contribution.

very large LULCC relative contribution of −183% and −97%, respectively (when changes in total carbon stocks due to future LULCC are compared to projected changes under A2 scenario, most similar to RCP8.5 scenario used here).

This effect is even more pronounced for L_d where net effects of LULCC are found to enhance the projected changes by +49% on average. The other carbon cycle variables are relatively less affected by LULCC: projected increases in NPP are robustly enhanced by 4%, projected increases in r_A are dampened by 4% while projected decrease in carbon residence times τ are enhanced by 7% (figure 2 for τ). The global relative contributions calculated on 2071–2100 period tend to remain stable on time as depicted by the transitional values calculated on 2011–2040 and 2041–2070 periods (supplementary figure S4).

As suggested by [39], we find that synergy between biophysical and biogeochemical effects on carbon cycle variables are in general low (in most cases, < 2% additional relative contribution) but relatively non-negligible, particularly for NPP (see synergistic LULCC effects in figure 2). When such synergistic effects are accounted for, spatial variability of net impacts of LULCC on NPP (figure 1) is reduced by 25% (in terms of standard deviation), attenuating negative impacts in Tropics and enhancing positive ones in mid- and high-latitudes.

We also find a strong model disagreement and an overall small relative contribution of LULCC-only induced changes in NPP and r_H. HadGEM2-ES, IPSL-CM5A-LR and CanESM2 simulate global increase in NPP and r_H due to future LULCC while MIROC-ESM and MPI-ESM-LR simulate global decrease. However, even if the LULCC-only effects on NPP are largely uncertain (symbols around blue bar for NPP, figure 2) in agreement with a recent multi-DGVM study [40], positive synergistic effects (with biogeochemical effects of LULCC, grey hatching and red bars for NPP) make all 5 ESM agree on a net NPP enhancement in response to future LULCC ([1%–13%] relative contribution range among models, see symbols around black bar for NPP in figure 2), which corresponds to an opposite sensitivity compared with previous modelling studies [14–16]. In other means, ESM simulate that in a slightly warmer climate with more CO_2, NPP is slightly more enhanced by LULCC.

The effects of LULCC on NPP and respirations can be attributed to several complex competing mechanisms differently simulated by ESM and across regions: plant functional trait (PFT) classification and parametrization of key plant properties [41], temperature and precipitation changes induced by PFT changes [28], climate and stomatal conductance changes induced by CO_2 increase [42], as well as non-linear interactions between them highlighted in our study. For instance, global NPP tends to be negatively related to temperature but positively with precipitation [4, 43–46] and CO_2 [46–48] while LULCC impact on climate and stomatal conductance is regional-, PFT transitions- and model-dependent. That being said, the increases in NPP, r_H and r_A caused by the combination of climate change and CO_2 fertilization in response to fossil fuel emissions outweigh the changes caused by LULCC, which are even smaller here than the ones simulated by [16]. Except for L_d, we also find that biogeochemical effects of LULCC (red bars) have a very limited contribution (< 3%, in general

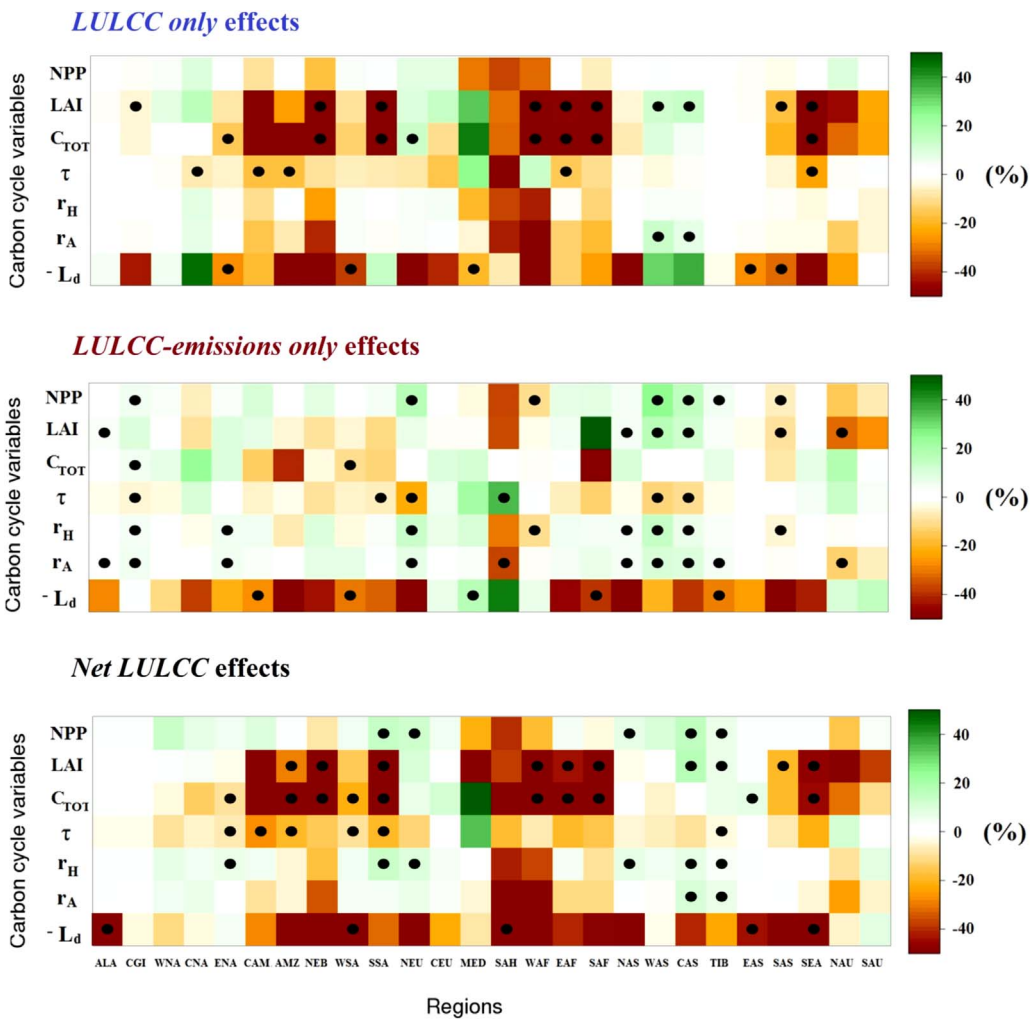

Figure 3. Regional relative contribution of effects of future LULCC to changes in carbon cycle variables (in %) in 26 IPCC regions. Top, middle and bottom mosaics represent the percentage contribution of 'LULCC only', 'LULCC-emissions only' and 'net effect of LULCC', respectively, relative to future projections with all other forcings as calculated in figure 2 but for each of the 26 IPCC regions. For inter-model robustness, a black dot is added when all the 5 LUCID-CMIP5 models simulate the same anomaly sign. Note that to remain consistent with weakened terrestrial carbon cycle depicted in red, carbon loss due to disturbances (L_d) is indicated via $-L_d$.

positive) on terrestrial carbon cycle. This result confirms that overall the biogeochemical effects of LULCC on future atmospheric CO_2 concentrations are relatively small in comparison to fossil fuel emissions (~4% relative contribution on average among models here) [38, 49]. Finally, biogeochemical effects on terrestrial carbon cycle simulated here by ESM could even be overestimated as those models do not fully represent ecophysiological mechanisms in response to temperature increase, such as changes in nutrient availability, permafrost dynamics, soil moisture, phenology, microbial decomposition and species distribution [47, 48, 50]. Key biogeochemical processes as for instance Carbon-Nitrogen interactions (not implemented in the ESMS here) would also affect the carbon cycle response to climate variations induced by CO_2 increase [51].

3.3. Regional relative contribution of future LULCC

Figure 3 shows the relative contribution of LULCC on the projected changes in the seven carbon cycle variables (Y-Axis) in each of the 26 IPCC regions (*x*-Axis, see domains in supplementary figure S5). In the great majority of the regions and variables (except L_d), the direct LULCC effects (upper panel) dominate over the slight CO_2 fertilization effect provoked by LULCC-biogeochemical impacts (middle panel). Black dots in figure 3 highlight inter-model robustness, when every LUCID-CMIP5 model simulates the same response sign for a given region and variable. Regions whose carbon cycle is most adversely affected by net LULCC effects (lower panel) are South America (in particular, Amazon AMZ, North East Brasil NEB, West Coast and South-Eastern parts of South America WSA and SSA, see supplementary figure S5 for geographical domains and names), Africa (WAF, SAF, EAF) and Southeast Asia (SEA), regions with most intense deforestation under RCP8.5 (see supplementary figure S1). Most negatively impacted variables are LAI, C_{TOT} and L_d (figure 3 lower panel). In NEB, SAH, WAF, EAF, SAF and SEA regions, LULCC contribute to dampen by more than 40% the

corresponding regional projected changes of the three variables LAI, C_{TOT} and L_d. In those regions, 'LULCC-only' effects explain the net contribution but, in South America, small warming and further drying due to biogeochemical effects ('LULCC-emissions only') tend to aggravate the browning and the decreasing capacity of land carbon sequestration (figure 3 middle panel for above-mentioned regions). To a lesser extent, τ is also robustly reduced by 7% (ENA), 27% (CAM), 19% (AMZ), 10% (WSA), 20% (SSA) and 3% (Western Asia, WAS) compared to regional projected changes.

Enhanced productivity and heterotrophic respirations are also simulated in regions like SSA, NEU (Northern Europe), TIB (Tibetan Plateau), NAS (Northern Asia) and CAS (Central Asia). For instance, in CAS and TIB region, robust positive contribution of NPP (17% and 7%, respectively), LAI (27% and 5%), r_A (10% and 4%) and r_H (16% and 6%) are simulated. Those are regions where conversions of landscape are very low (supplementary figure S1), where projected LAI changes and LAI changes due to LULCC are both slightly positive (supplementary figure S2 and figure 3) and where the global biogeochemical effects mostly due to tropical deforestation tend to fertilize remote areas with CO_2.

There is a generalized model disagreement on the sign of change in NPP, r_H and r_A in response to 'LULCC-only' (upper panel) in almost every region. However, in response to LULCC, a majority of models simulates increase in mid- and high-latitudes and an overall decrease in some tropical areas (figure 3), that hides a large spatial variability (see also figure 1). At the gridcell level, we find that models simulate a net decrease in NPP and r_H with strong tropical deforestation greater than 10% change in tree fraction (~ -4gC m^{-2} yr^{-1}/%; see supplementary figure S6, red curves) but in mid- and high-latitudes decrease in tree cover are associated with higher NPP (supplementary figure S6, orange and blue curves). Furthermore, r_H is negatively affected by tropical deforestation (-3.5 gC m^{-2} yr^{-1}/%) by a factor 3 compared to r_A (-1.2 gC m^{-2} yr^{-1}/%).

By contrast, LAI and components of C_{TOT}, *cSoil* and *cVeg*, are gradually decreased by deforestation: on average, carbon in soils is decreased by -0.03 kgC m^{-2}/% while carbon in vegetation is decreased by -0.15 kgC m^{-2}/% due to direct tropical deforestation effect (five times more than *cSoil*).

At regional level, figure 4 shows stronger effects due to LULCC than a weakened terrestrial carbon cycle. If under RCP8.5 scenario, models do not simulate a global 'projected terrestrial carbon reversal' (i.e. global changes in total carbon stocks in response to LULCC fully dampen their projected changes until 2071–2100 period), as discussed by [52] and [53] with DGVMs, we find however strong evidence of regional terrestrial carbon reversal mainly located in tropical regions (see figure 4(*a*) below, ratio of changes in carbon stocks due to LULCC vs. changes in carbon stocks due to all forcings except LULCC).

About 19% of land gridpoints between 25°S and 10°N are subject to a projected terrestrial carbon reversal, particularly located around deforested edges of Amazon and African rainforests. Similar results are found for a 'projected terrestrial greening reversal' (i.e. changes in LAI in response to LULCC fully dampen projected greenings): at global scale, there is not such evidence while at regional level, a portion of deforested areas (~18% of land gridpoints between 25°S and 10°N) show a reversal in greening towards browning when LULCC is accounted for (figure 4(*b*)). Those reversals evidence the regional overwhelming impact of LULCC that dominate projected carbon cycle changes over all other forcings (greenhouse gases, aerosols and others).

In consequence, our regionalized results prove that LULCC play an extremely important role in the South American and African terrestrial carbon cycle, which makes stopping deforestation in those regions a paramount mitigation measure that could lead to even more benefits than previously thought.

4. Conclusion

The contributions of future LULCC to the projections of global and regional terrestrial carbon cycle (2071–2100) are now assessed in a multi-model framework of five different ESMs and under a common realistic LULCC scenario (RCP8.5), distinguishing the direct impacts of carbon removal and the indirect CO_2 emissions induced by those LULCC.

The terrestrial biosphere currently absorbs large amounts of carbon dioxide (CO_2) from the atmosphere, partially compensating CO_2 emissions from fossil fuel combustion and LULCC and tempering anthropogenic climate change. If land carbon uptake is projected to increase under future greenhouse gases scenarios, mainly driven by the positive effects of CO_2 fertilization of photosynthesis [5, 42], although large uncertainties [9, 33, 54, 55], our results show that the ability of the terrestrial biosphere to sequester carbon from the atmosphere is substantially dampened by future LULCC.

We find that in response to future LULCC, the terrestrial carbon cycle is robustly weakened: browning, lower ecosystem carbon stocks, higher carbon loss by disturbances and higher turnover rates are simulated. At the end of the 21st century, projected global greening and land carbon storage are dampened, in all models, by ~20%–25% on average and projected carbon loss by disturbances enhanced by ~50% when LULCC are taken into account. By contrast, global NPP is found to be robustly but very slightly enhanced by LULCC (~+4% relative contribution on average) compared to effects of greenhouse gases. LULCC are found to be a predominant driver of future C changes

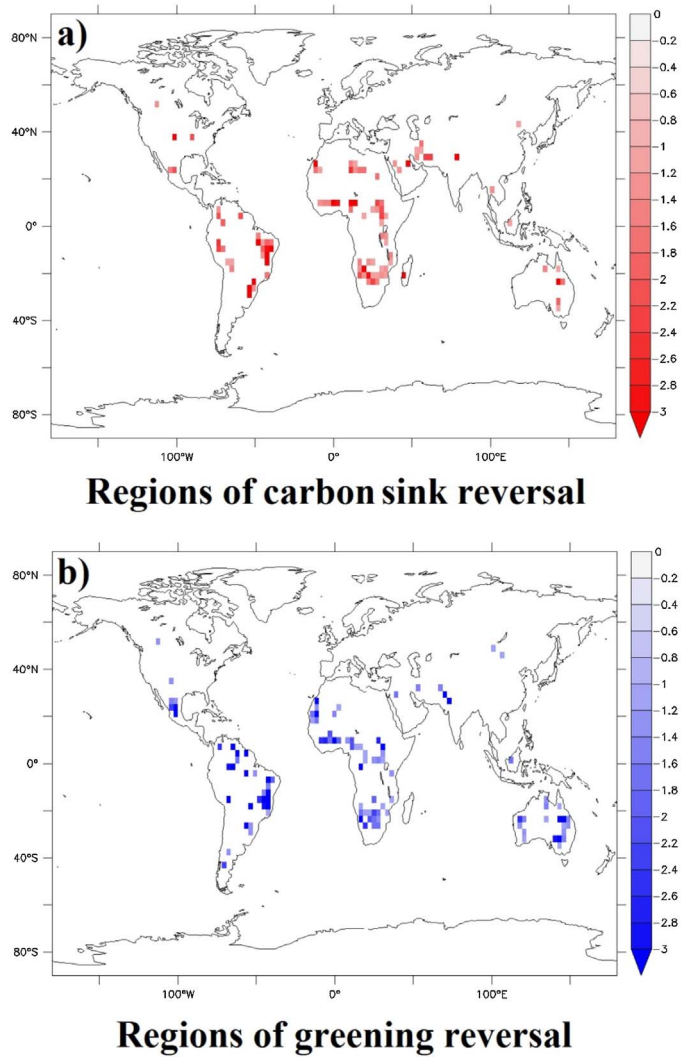

Figure 4. Local reversals in projected terrestrial (*a*) carbon sink and (*b*) greening, due to future LULCC. Colored areas depict ratio only where net changes of (*a*) C_{TOT} and (*b*) LAI due to LULCC are greater in absolute values than projected positive changes due to all forcings except LULCC (values of the ratio between the net effects of LULCC *vs.* the sum of all forcings are displayed). Non-dimensional units.

in regions like South America and Southern part of Africa. Accounting for future LULCC leads the models to simulate regional reversals of projected increased carbon sinks and greening, particularly located at the edges of the Amazon and African rainforests. The multi-ESM framework under RCP8.5 LULCC scenario forges a lower road path compared to previous studies [16, 21, 38, 52] who found LULCC to greatly affect and sometimes reverse the projected terrestrial carbon stocks of the 21st century under business-as-usual warming scenarios.

Nonetheless, on top of the negative impact of LULCC on future land carbon sequestration and greening, the latest research reveals other adverse effects: the present-day reduction of the Amazon Basin carbon sink efficiency [56], the consideration of the Nitrogen-Phosphorus cycles [34, 51], the biogenic volatile organic compound feedback [57] and the land management [11, 23, 58] neglected in current intercomparison model exercises. All these factors could further reduce the land carbon sink and, under high emission scenarios and severe climate change [5, 59] or severe LULCC scenario [52], they could even reverse the terrestrial sink in to a source.

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