Anthropogenic land cover change impact on climate extremes during the 21st century

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Abstract
Anthropogenic land cover change (LCC) can have significant impacts at regional and seasonal scales but also for extreme weather events to which socio-economical systems are vulnerable. However, the effects of LCC on extreme events remain either largely unexplored and/or without consensus following modelling over the historical period (often based on a single model), regional or idealized studies. Here, using simulations performed with five earth system models under common future global LCC scenarios (the RCP8.5 and RCP2.6 Representative Concentration Pathways) and analyzing 20 extreme weather indices, we find future LCC substantially modulates projected weather extremes. On average by the end of the 21st century, under RCP8.5, future LCC robustly lessens global projections of high rainfall extremes by 22% for heavy precipitation days (> 10 mm) and by 16% for total precipitation amount of wet days (PRCPTOT). Accounting for LCC diminishes their regional projections by > 50% (70%) in southern Africa (northeastern Brazil) but intensifies projected dry days in eastern Africa by 29%. LCC does not substantially affect projections of global and regional temperature extremes (<5%), but it can impact global rainfall extremes 2.5 times more than global mean rainfall projections. Under an RCP2.6 scenario, global LCC impacts are similar but of lesser magnitude, while at regional scale in Amazon or Asia, LCC enhances drought projections. We stress here that multi-coupled modelling frameworks incorporating all aspects of land use are needed for reliable projections of extreme events.

1. Introduction
Health, energy, agriculture and other socioeconomic sectors are highly sensitive to extreme weather events and their changes, as emphasized in the Special Report on Extreme Events of the Intergovernmental Panel on Climate Change (IPCC) (IPCC SREX 2012). Moreover, there has been considerable scientific/media interest regarding weather extremes in recent years (Coumou and Rahmstorf 2012, Herring et al 2019). Under a business-as-usual future warming scenario (Representative Concentration Pathway, RCP8.5), extreme absolute temperatures (daily minimum temperature (Tnmin) and daily maximum temperature (Tmax)) and high temperature percentiles (percentage of days when Tmax >90th percentile (TX90p) and percentage of days when Tnmin >90th percentile (TN90p); see Methods for descriptions of extreme indices) are simulated by climate models to be enhanced globally by more than the mean temperature but with similar spatial patterns (IPCC SREX 2012, Sillmann et al 2013). Such models also project increased frequency and intensity of annual extreme precipitation percentiles (e.g. total precipitation from days >95th percentile (R95p)) in most regions, along with a large spatial variability for droughts (e.g. consecutive dry days (CDD)) and high rainfall extremes (e.g. seasonal heavy
precipitation days R10mm or Max. 5 day precipitation Rx5day) (Sillmann et al 2013).

Land cover change (LCC) can affect the exchange of water, momentum, heat, greenhouse gases (e.g. CO₂, CH₄, N₂O), non-greenhouse gases (e.g. biogenic volatile organic compounds) and aerosols across the surface-atmosphere interface. Typically, LCC modifies the atmospheric state/dynamics by altering the biophysical characteristics of the land surface, e.g. its albedo, soil moisture/evapotranspiration and roughness, which in turn modify the climate system (Pielke et al 2011, Mahmood et al 2014, Lawrence and Vandecar 2015, Perugini et al 2017).

Some regions with extensive historical LCC (Europe and North America) have experienced biophysical decreases in annual mean temperature of a magnitude similar to the concomitant increase in greenhouse gases (de Noblet-Ducoudré et al 2012). However, considerable disagreement is evident in model responses; most models show mid-latitude decreases of most hot extreme indices (Pitman et al 2012, Christidis et al 2013, Li et al 2018, Chen and Dirmeyer 2019), while other models simulate increases (Avila et al 2012, Findell et al 2017, Lejeune et al 2018, Li et al 2018, Chen and Dirmeyer 2019) in response to historical LCC. For instance, three out of four models of the ‘land-use and climate, identification of robust impacts’ (LUCID) intercomparison project simulated a decrease in extremely warm daytime temperatures over the northern mid-latitudes during summer due to historical LCC (Pitman et al 2012). More recently, using an observational constraint for local biophysical effects of LCC applied to several CMIP5 climate models, (Lejeune et al 2018) found historical deforestation increased extreme hot temperatures in northern mid-latitudes. The results also indicated greater impact on hot temperatures compared with mean temperatures. Using a single climate model, (Findell et al 2017) reached similar conclusions. Results from a set of climate models have shown the impact of future land use change on extreme local temperatures could be of similar magnitude to the changes arising from a +0.5 °C global mean surface temperature change (Hirsch et al 2018).

Few studies have investigated the response of precipitation extremes to global LCC and the results have shown less consensus (Pitman et al 2012, Mahmood et al 2014). Many studies/reviews have recommended careful attribution and assessment of the effects of historical and future LCC on weather extremes given the lack of systematic assessment and poor consensus of results (Pitman et al 2009, Pielke et al 2011, IPCC SREX 2012, Mahmood et al 2014, Perugini et al 2017, Quesada et al 2017a, Spracklen et al 2018, IPCC SRCCCL et al 2019).

The effects of LCC on extreme events remain either largely unexplored and/or without consensus after modelling over the historical period (Pitman et al 2012, Lejeune et al 2018) often based on a single model (Avila et al 2012, Christidis et al 2013, Findell et al 2017, Li et al 2018, Chen and Dirmeyer 2019), regional and/or idealized studies (Bagley et al 2014, Hua et al 2015, Cherubini et al 2018, Hu et al 2019) or restricted to a few extreme temperature indices (Hirsch et al 2018, IPCC SRCCCL et al 2019).

Here, using global simulations performed with five earth system models (ESMs) under two common LCC scenarios (i.e. RCP2.6 and RCP8.5) which exhibit similar spatial patterns of LCC compared to the recent decades (Riahi et al 2011, Ward et al 2014) and analyzing various extreme weather indices, we show that future LCC substantially modulates projected weather extremes. We selected the 20 extreme weather indices considered most important regarding social decision-making processes (see Methods).

2. Methods

2.1. Models, experiments and variables

LUCID is a major international intercomparison exercise intended to diagnose the robust biophysical impacts of LCC using as many climate models as possible forced with the same LCC (http://lucidproject.org.au/). The LUCID-CMIP5 simulations analyzed here are the same as those described in (Brovkin et al 2013) and (Boysen et al 2014). Focusing on the impacts of future LCC, several modelling groups from the Coupled Model Intercomparison Project Phase 5 (CMIP5) performed simulations without anthropogenic land use changes from 2006 to 2100. Here, we used outputs of precipitation (pr, according to CMIP5 nomenclature), surface air temperature (tas), minimum and maximum air temperatures (tasmin and tasmax, respectively) from the five CMIP5 models (CanESM2, HadGEM2-ES, IPSL-CM5A-LR, MPI-ESM-LR and MIROC-ESM) during the final 30 year period of each experiment (2071–2100). RCP8.5 simulations represent the CMIP5 runs with all forcings, including future anthropogenic land use change and LCC forcings based on the RCP8.5 scenario. L2A85 simulations represent the same runs as RCP8.5 but without anthropogenic land use change and LCC forcings (after 2005), with atmospheric CO₂ concentration prescribed from the RCP8.5 scenario (RCP8.5 simulation). In other words, the difference between the RCP8.5 and L2A85 simulations (i.e. RCP8.5 – L2A85) corresponds to the pure biophysical effects of future anthropogenic land use change and LCC. The RCP8.5 scenario includes spatially explicit future LCC characterized by an expansion of croplands and pastures driven by the food demand in an increasing population context and it corresponds to a radiative forcing of >8.5 W m⁻² by 2100 (CO₂ concentration: ∼936 ppm in 2100) (Boysen et al 2014). Future tree cover changes between the RCP8.5 and L2A85 simulations are ∼4 million km² by 2100, among these five LUCID-CMIP5 models; see spatial patterns of tree cover changes in

See Methods
supplementary figure S1, available online at stacks.iop.org/ERL/15/034002/mmedia). RCP2.6 and L2A26 simulations are similar to RCP8.5 and L2A85 descriptions but for the RCP2.6 scenario. The RCP2.6 scenario assumes a peak radiative forcing of 3.1 W m$^{-2}$ before 2100 followed by a decline toward 2.6 W m$^{-2}$ and a CO$_2$ concentration of around 420 ppm by 2100. In the RCP2.6 scenario, the climate change mitigation is partly achieved by an increase in the area used for the production of bioenergy crops. Moreover, global pasture area remains almost constant in RCP2.6 over the 21st century while the increase in production of meat products is associated to RCP2.6 deforestation with similar spatial patterns (supplementary figure S2). Only four models were available for RCP2.6/L2A26 simulations (CanESM2, IPSL-CM5A-LR, MPI-ESM-LR and MIROC-ESM). Harmonization and implementation of future LCC into the five CMIP5 models used in our study are detailed in (Hurt et al 2011) and (Brovkin et al 2013). Note that RCP2.6 and RCP8.5 scenarios project decreases in global forest area loss rates in the 21st century relative to current rates, which can then be considered conservative future LCC forcings (Ward et al 2014).

2.2. Multi-regional assessment
Changes of temperature and precipitation indices were calculated for the 26 sub-continental regions defined by the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (IPCC SREX 2012). The 26 SREX regions are: Alaska/Northwest Canada (AL), eastern Canada/Greenland/Iceland, western North America, central North America, eastern North America, central America/Mexico, the Amazon (AMZ), Northeast Brazil (NEB), the west coast of South America (WSA), southeastern South America, northern Europe (NEU), central Europe (CEU), southern Europe/the Mediterranean (MED), the Sahara (SAH), western Africa (WAF), eastern Africa (EAF), southern Africa (SAF), northern Asia (NAS), western Asia (WAS), central Asia (CAS), the Tibetan Plateau (TIB), eastern Asia (EAS), southern Asia (SAS), Southeast Asia (SEA), northern Australia (NAS) and southern Australia/New Zealand (SAU). Supplementary figure S3 displays the 26 IPCC regions.

2.3. Robustness and statistical significance
Two statistical tests were implemented to analyze the likely effects of LCC on extreme weather indices and to discuss their statistical significance: (i) model agreement on direction of change and (ii) statistical significance of simulated changes. The first significance test was passed when at least four out of the five models for RCP8.5 (i.e. 80% of the models) or three out of the four models displayed the same anomaly sign (i.e. 75% of the models) for RCP2.6. The second was passed when the multi-model ($n = 5$) mean changes were significant at the 0.05 level. For this significance assessment and for each simulated change, the rank-based non-parametric Mann–Whitney–Wilcoxon (MWW) test was applied on two sets of 30 year future simulations (e.g. with and without LCC simulations on the 2071–2100 period). When the two statistical tests are passed, results are presented as robust. The main reason for using the non-parametric MWW statistical test is that it tends to be more powerful and better suited for non-normally distributed datasets compared with parametric statistical tests such as the student t-test.

As the distribution of climate indices is not necessarily Gaussian, the MWW statistical test might be more appropriate for testing the null hypothesis of the difference between the two sets of 30 year future simulations (e.g. RCP8.5 – L2A85) for a given index.

2.4. Extreme indices
We focused on the mean temperature and rainfall ($T_{\text{mean}}$ and $P_{\text{mean}}$) and 20 extreme temperature and rainfall indices defined by the World Meteorological Organisation expert team on climate change detection and indices applied to the RCP8.5/RCP2.6 and L2A85/L2A26 simulations over the same period. To aid comparison between models, extreme indices calculated on the model’s native grids were interpolated to the common medium resolution grid of the MIROC-ESM model ($2.8^\circ \times 2.8^\circ$) using bilinear interpolation.

ClimDEX is a climate indices package that provides an easy interface for efficient computation of extreme weather indices and computes values based on daily precipitation and minimum and maximum temperatures (see http://clivar.org/panels-and-working-groups/etccdi/etccdi.php/). We used a selected panel of 20 extreme indices fully described in supplementary table S1. Figures 1–3 focus on a sample of the most impacted (at global and annual scales) temperature and precipitation extreme indices (six each). Supplementary figures S4–S6 correspond to figures 1–3, respectively, but for less impacted extreme temperature (TXx, TN90p, TXn, TNn, CDD and HDD) and precipitation (R95p, CDD, R99p, CWd, Rx1day) indices. For clarity reasons, we mostly present and discuss results on the long-term period (2071–2100) and for the RCP8.5 scenario.

3. Results
3.1. Global contribution of LCC to extreme weather
When considering only LCC effects at the end of the 21st century under RCP8.5 scenario, we find they do not robustly affect projected temperature extremes, i.e. contributions to projected changes in extremes are
5% for all models and all temperature indices together with a strong inter-model spread (Figure 1, upper panel: $T_{\text{mean}}$ and $TN_x$ in °C, WSDI in days, TX10p, TN10p and TX90p in % and Supplementary figure S4, upper panel: $TN_n$, TXx and TXn in °C, TN90p in % and CSDI in days). However, LCC affects rainfall extremes significantly and much more than temperature extremes (figure 1, lower panel; green bars indicate robust and significant changes—i.e. multi-model global mean significant at the 0.05 level and where four out of five models simulate the same global change sign). Each symbol represents the individual model contribution.

Accounting for LCC in models robustly reduces global projections of daily precipitation >10 mm (R10mm in mm) by 22% and of total precipitation amount of wet days (PRCPTOT in mm) by 16%, on average. LCC also contributes to reduced projections of very heavy precipitation days (R20mm in mm) by 5% and of annual maximum consecutive 5 days precipitation (Rx5day) by 2%. ESMs simulate large ranges varying from $[-61\%; -47\%]$ (HadGEM2-ES) to $[+5\%; +7\%]$ (IPSL-CM5A-LR) for R10mm/PRCPTOT, respectively. Based on the indices shown in figure 1, our results show that LCC can affect global rainfall (albeit not temperature) extremes more than mean conditions ($P_{\text{mean}}$). The range of global contributions of LCC to projections of temperature and rainfall extremes is $[-0.64\%; +1.42\%]$ and $[-21.8\%; +0.54\%]$, respectively (supplementary table S2).

Under RCP2.6 scenario, all global changes in extreme climate indices induced by LCC have the same sign as under RCP8.5 scenario (except for $TN_x$).
Figure 2. Spatial patterns of changes in (a) temperature and (b) precipitation indices in response to future LCC (RCP8.5 scenario), averaged over 2071–2100. Mean and extreme weather indices are indicated in the bottom left corner of each panel (see Methods for the description of extreme weather indices). Only grid points where four out of five LUCID-CMIP5 models simulate the same anomaly sign and where changes are significant at the 0.05 level are shown (white/blank otherwise).

Figure 3. Regional relative contributions of impacts of future LCC on projected changes in mean and extreme weather indices (%) in 26 IPCC regions (RCP8.5 scenario). Upper and lower mosaics represent the percentage contributions for temperature and rainfall indices, respectively. Contributions are calculated relative to future regional projections with all other forcings, similar to figure 2 but for each of the 26 IPCC regions. A black dot is added when regional changes are robust (i.e. multi-model regional mean significant at the 0.05 level and where four out of five models simulate the same regional change sign).
supplementary S7). Moreover, as well as under RCP8.5 scenario, extreme temperatures projections are very few affected by LCC under RCP2.6 scenario (supplementary S7, upper panel).

3.2. Spatial response of extreme weather to LCC

Figure 2 shows spatial patterns of weather extreme changes corresponding to figure 1 in response to future LCC for mean and extreme temperature indices (figure 2(a)) together with mean and extreme precipitation indices (figure 2(b)), under RCP8.5 scenario. On average, biophysical cooling in response to LCC is simulated in most mid- to high-latitude regions with robust signals (black contours in figure 2). This contrasts with the patterns of extreme cold indices with widespread warming of TNx in response to LCC (up to +0.4 K), particularly in the tropics and Asia or with slight increase of cold days and nights (TX10p and TN10p, respectively; figure 2(a)) in mid-latitudes, particularly in Europe. Large and robust LCC-induced increases in hot extreme indices (WSDI and TX90p) are simulated in eastern Asia and northeastern USA. Spatial patterns of extreme temperature indices strongly mimic those of $T_{\text{mean}}$ with significant spatial correlations ($p$-value < 0.05) across regions ($r_{\text{spatial}}$ ($T_{\text{mean}}$, $T_{\text{extreme indices}}$) >0.71), except for cold extremes: TX10p, TN10p and CSDI (supplementary table S2).

Concerning rainfall extremes, LCC impacts are relatively more substantial with global decreases of total precipitation amount of wet days and even more pronounced with heavy precipitation days (R10mm). These spatial patterns, as well as R1mm and R20mm ones, are usually slightly different from $P_{\text{mean}}$ patterns but mimic them above tropical deforested areas (figure 2(b)), non-significant spatial correlations between extreme rainfall indices and $P_{\text{mean}}$, $r_{\text{spatial}}$ ($P_{\text{mean}}$, $P_{\text{extreme indices}}$) in supplementary table S2, final column.

3.3. Regional contribution of LCC to extreme weather

At regional scale, in each of the 26 IPCC regions (see Methods and supplementary figure S3), LCC contribution to modulation of rainfall extremes is even more marked than at global scale (figure 3, supplementary table S2). Figure 3 shows the relative contributions of LCC to the projected changes of a selection of 6 temperature and 6 precipitation indices ($y$-axis) in each of the 26 IPCC regions ($x$-axis). Regions whose rainfall extremes are affected most negatively by LCC (lower panel) are Northeast Brazil (NEB), southern and eastern Africa (SAF, EAF) and East Asia and the Tibetan Plateau (EAS, TIB). The most negatively impacted variables across regions are PRCPPTOT, CWD and R1mm. LCC contributes to dampen the regional projected changes of R10mm and PRCPPTOT by >50% (70%) in SAF (NEB). Furthermore, including LCC in ESMs robustly enhances the projected dry days (opposite of R1mm, figure 3 and supplementary table S2) by 29% (12%–15%) in EAF (SAF, WAS, TIB and EAS).

At regional level for the projections of extreme temperature indices, the LCC contribution is relatively minor, ranging from −7.5% (TXx in NAU) to +4.4% (TNx in WSA). For extreme precipitation indices, this contribution is much more important, ranging from −70% (R10mm, CWD and PRCPPTOT in NEB, and, R99p, R10mm and CWD in SAF) to more than +50% (e.g. Rx1day in SAH and WAS). Extreme precipitation indices are almost linearly reduced when tropical deforestation increases (left part of the graphics, red fitting lines, $\Delta$TreeFrac < 0%, almost linear relation; supplementary figure S8).

Under RCP2.6 scenario, LCC impacts on regional weather extremes are weaker and less significant compared to RCP8.5 (supplementary figure S9). Interestingly, even if strong mitigation measures as the ones considered in RCP2.6 are taken, the deforestation in Amazon region (AMZ) or in Asia (e.g. SEA) would substantially increase the extreme drought indices projected (supplementary figure S9).

4. Discussion

Our study overcomes the limits and uncertainties of previous assessments to determine robust LCC-induced biophysical climate impacts on regional/global extreme projections for two RCP scenarios in a coupled multi-model assessment framework. Our study shows that LCC can affect global rainfall extremes more than mean rainfall conditions (up to 2.5 times more) and 17 times more than temperature extremes on average (i.e. the ratio of average relative LCC contribution to future rainfall extremes versus average relative LCC contribution to future temperature extremes). Such findings contrast with some previous studies over the historical period that found lack of consensus (Pitman et al. 2012, Li et al. 2018, Chen and Dirmeyer 2019), a small response for precipitation extremes (Pitman et al. 2012), or a particularly significant response for temperature extremes (Avila et al. 2012, Christidis et al. 2013, Findell et al. 2017, Hirsch et al. 2018, Lejeune et al. 2018). Comparing RCP2.6 and RCP8.5 results (figure 1 versus supplementary figure S7) show that our results are even more likely and robust because all changes in global extreme temperature and precipitation indices induced by LCC have the same sign (except TNx). The magnitude of changes is however lower mainly because tropical deforestation projected in RCP2.6 is lower than in RCP8.5 (Ward et al. 2014) and partly because HadGEM2-ES which exhibit the highest changes in RCP8.5 is absent from the results in RCP2.6 (see Methods).
Hot and cold temperature extremes are influenced by several LCC-induced compensating phenomena simulated differently across ESMs: (i) physical mechanisms (albedo-driven versus evapotranspiration-driven temperature changes), (ii) regional response (tropical deforestation versus other LCC elsewhere), and (iii) local versus non-local LCC effects (Pielke et al 2011, Mahmood et al 2014, Winckler et al 2019). ESM uncertainties, which are additive in the simulation of each phenomenon, clearly lead to large inter-model spread, as for $T_{\text{mean}}$ (figure 1, upper panel). However, albedo-driven temperature response is predominant during daytime and winter events, while evapotranspiration-driven temperature response dominates during night-time and summer events (Sillmann et al 2013, IPCC SRCCL et al 2019). Thus, $TXn$, $TN10p$ and $TX10p$ (which correspond to winter days and nights, events with ‘sun and snow’) tend to be cooled as future global LCC increases Earth’s albedo (Boysen et al 2014, Quesada et al 2017a, IPCC SRCCL et al 2019), while $TNx$ (maximum temperature of summer nights, ‘no sun and less snow’ events) is warmed as evapotranspiration is decreased, which coincides on average with simulated signals for extreme annual temperature indices (figure 1, upper panel; supplementary figures S4–S6) and at seasonal scale (supplementary figures S10–S13).

Mean and extreme rainfall are globally reduced by LCC, particularly above regions of intense deforestation (figures 2 and 3). Extreme rainfall and drought responses to LCC are driven predominantly by evapotranspiration change and moisture availability (Seneviratne et al 2010, Quesada et al 2017b, IPCC SRCCL et al 2019). On average, after large-scale tropical deforestation, shallower vegetation and reduced foliar density induce less evapotranspiration, less surface water intercepted and less soil-moisture which in turn imply less mean and extreme precipitation, consistent with most studies (Mahmood et al 2014, Perugini et al 2017, Quesada et al 2017a, Spracklen et al 2018, IPCC SRCCL et al 2019).

As there is a nonlinear relation between soil moisture content and temperature distribution (Pall et al 2007, Seneviratne et al 2010, Quesada et al 2012), soil moisture depletion can enhance temperature extremes more than the mean response. The prevailing paradigm of how precipitation changes with warming is that mean rainfall changes are driven by available energy while extreme rainfall changes are primarily constrained by the change in near-surface moisture, with a sensitivity to temperature changes 3 times higher (Pall et al 2007). This phenomenon can be enhanced by two others triggered by future LCC (IPCC SRCCL et al 2019): (i) average decrease in atmospheric water content (mainly after tropical deforestation) and (ii) increase in surface albedo, both of which cause cooling and thus reduce precipitation causing conditions (Clausius–Clapeyron relation). Given those phenomena, high and low rainfall extremes can decrease in response to future LCC more than $P_{\text{mean}}$. At global scale, projections of rainfall extremes are 2–2.5 times more dampened by future LCC than mean rainfall projections for at least two extreme indices (supplementary table S2, ‘Global column’ for PRCPTOT and R10mm versus $P_{\text{mean}}$). IPSL-CM5A-LR results clearly contrast with other model responses (figure 1, green triangle versus other symbols), as found in previous studies studying LCC/climate links (de Noblet-Ducoudré et al 2012, Pitman et al 2012, Sy et al 2017, Quesada et al 2017a). This model simulates local evapotranspiration increase in response to tropical deforestation (+0.60 W m$^{-2}$ for IPSL-CM5A-LR latent heat flux changes above tropical deforested areas, i.e. areas with future decrease in tree fraction, versus $-0.18$, $-1.71$, $-1.10$ and $-2.40$ W m$^{-2}$ for CanESM2, HadGEM2-ES, MPI-ESM-LR and MIROC-ESM, respectively). Such local negative evapotranspiration/tree cover tropical feedback is however not supported by observational data (Spracklen et al 2018) and to simulate it correctly is critical in projecting accurate mean and extreme rainfall responses to LCC (Sy et al 2017).

We also stress that some studies have reported observationally based weather extreme changes in response to LCC (Findell et al 2017, Lejeune et al 2018). However, observationally based methodologies rely on a space-for-time assumption, using comparisons of neighbouring pixels with contrasting land cover to attribute biophysical temperature changes to corresponding LCCs. Those assessments cannot capture large-scale and non-local atmospheric feedback in response to global LCC, contrary to coupled modelling experiments. Those land-cover induced non-local feedbacks have recently been shown substantial and often more important than local effects in different ESMs (Winckler et al 2017, Quesada et al 2017a, Devaraju et al 2018). Consequently, observation-based (Lee et al 2011, Li et al 2015, Alkama and Cescatti 2016) or observationally-constrained modelling methodologies (Lejeune et al 2018) are limited, likely overestimating the warming effects of deforestation because they do not account fully for biophysical effects—i.e. the non-local or remote ones (Perugini et al 2017, Winckler et al 2017, Devaraju et al 2018). Analysis based on multi-coupled modelling frameworks, accounting for both local and non-local LCC effects, as performed in our study, is essential to gain insight into the quantification of LCC impacts on historical and future extreme weather.

5. Conclusions

Our robust multi-model results under realistic LCC scenario show that by the end of the 21st century, under RCP2.6 and RCP8.5 scenarios, future LCC robustly lessens global projections of rainfall extremes. At regional level, our study has crucial consequences...
for climate and policy assessments. LCC is a strong regional driver of extreme weather: across 26 IPCC regions and the 10 rainfall extreme indices, in more than 10% of the cases, LCC modulates regional projections under RCP8.5 by at least 30% (supplementary table S2). Moreover, given the average sensitivity simulated, a local 50% tropical deforestation and global warming under RCP8.5 scenario have similar magnitude impact (but opposite sign) on PRCPTOT (~50 mm) and R10mm (~2 mm, see the most extreme left parts of the red fitted lines in supplementary figure S8).

As only approximately two thirds of global coupled models account for LCC (IPCC et al 2013), IPCC CMIP5 models are likely overestimate global projections of extreme rainfall (rainiest days and spells) and underestimate droughts (dry days), particularly in many tropical deforested areas (i.e. South America, South Africa and East Asia). This study also highlights that although LCC contribution to global radiative forcing (RF) under RCP8.5 is relatively low (~3.7% by 2100 compared with total RF, see figure 12.3 in IPCC AR5 (IPCC et al 2013)), projections of key climate variables like global rainfall extremes are much more sensitive to this forcing (by up to ~22%, figure 1). Our conclusions are robust for the long-term period (2071–2100) with a significant LCC forcing but transient responses can be different because of lower LCC forcing, lower signal-to-noise ratio and higher compensation of climatic effects between boreal versus tropical zones.

Finally, the international policy process within the United Nations Framework Convention on Climate Change focuses only on biogeochemical effects of land-use on global RF (Perugini et al 2017) which constitutes a concern about providing accurate messages on land-based climate mitigation. Therefore, we hope this study, as a challenging prelude to the Land Use Model Intercomparison Project contribution to the Coupled Model Intercomparison Project Phase 6 (Lawrence et al 2016), will encourage further attention on the full effects of global and regional deforestation/ reforestation. This will allow the community to provide robust reliable messages regarding land use impacts on climate and land-based climate mitigation strategies.

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Contributions

SS and BQ conceived the study, designed the analyses and interpreted the results. SS carried out the analyses. BQ wrote the manuscript.

Competing interests

The authors declare no competing financial interests.

Data availability statement

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

Graphic software

Figures were produced using R software version 3.5.0.

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