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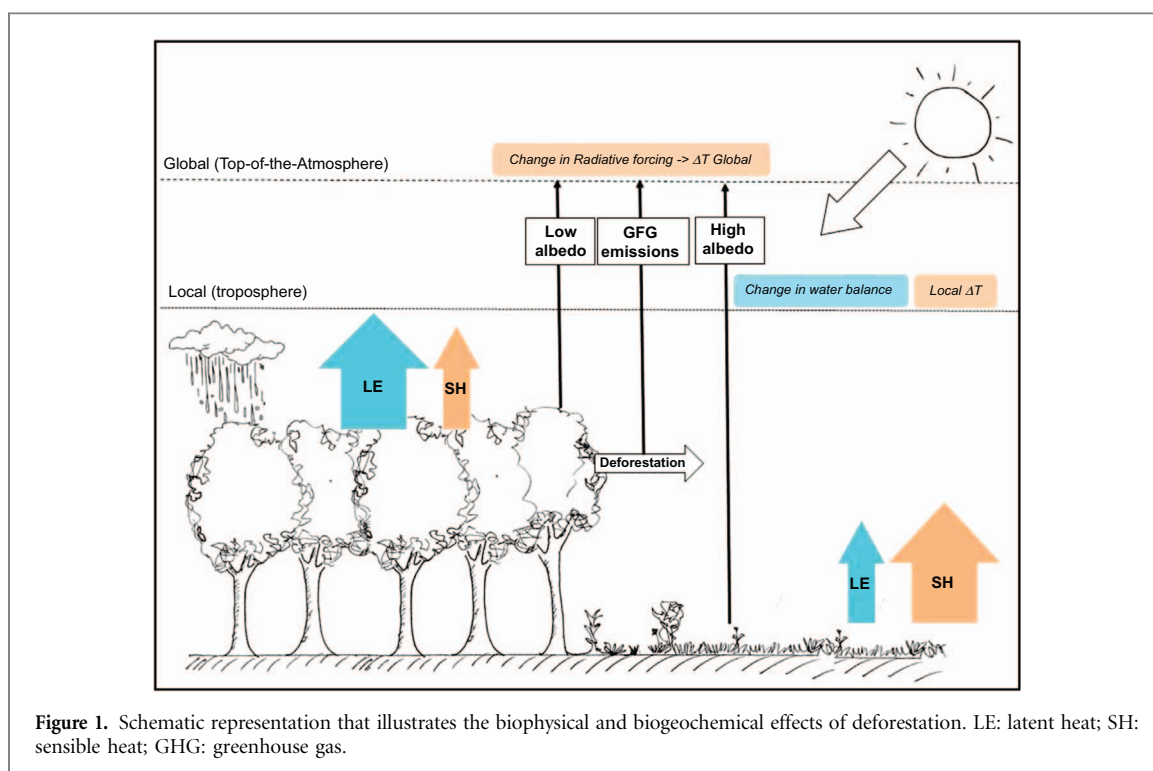
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Abstract

Anthropogenic land cover changes (LCC) affect regional and global climate through biophysical variations of the surface energy budget mediated by albedo, evapotranspiration, and roughness. This change in surface energy budget may exacerbate or counteract biogeochemical greenhouse gas effects of LCC, with a large body of emerging assessments being produced, sometimes apparently contradictory. We reviewed the existing scientific literature with the objective to provide an overview of the state-of-the-knowledge of the biophysical LCC climate effects, in support of the assessment of mitigation/adaptation land policies. Out of the published studies that were analyzed, 28 papers fulfilled the eligibility criteria, providing surface air temperature and/or precipitation change with respect to LCC regionally and/or globally. We provide a synthesis of the signal, magnitude and uncertainty of temperature and precipitation changes in response to LCC biophysical effects by climate region (boreal/temperate/tropical) and by key land cover transitions. Model results indicate that a modification of biophysical processes at the land surface has a strong regional climate effect, and non-negligible global impact on temperature. Simulation experiments of large-scale (i.e. complete) regional deforestation lead to a mean reduction in precipitation in all regions, while air surface temperature increases in the tropics and decreases in boreal regions. The net global climate effects of regional deforestation are less certain. There is an overall consensus in the model experiments that the average global biophysical climate response to complete global deforestation is atmospheric cooling and drying. Observed estimates of temperature change following deforestation indicate a smaller effect than model-based regional estimates in boreal regions, comparable results in the tropics, and contrasting results in temperate regions. Regional/local biophysical effects following LCC are important for local climate, water cycle, ecosystems, their productivity and biodiversity, and thus important to consider in the formulation of adaptation policy. However before considering the inclusion of biophysical climate effects of LCC under the UNFCCC, science has to provide robust tools and methods for estimation of both country and global level effects.



1. Background

Land cover changes (LCC) have a recognized effect on climate through two different processes: modifications in the net flux of greenhouse gases such as CO_2 , from changes in vegetation and soil carbon (biogeochemical effects); and variations of the surface energy budget mediated by albedo, evapotranspiration, and roughness (biophysical effects) (Pielke *et al* 1998, Betts 2000, Lee *et al* 2011, Anderson-Teixeira *et al* 2012, Mahmood *et al* 2014, Zhang *et al* 2014, Li *et al* 2015, Alkama and Cescatti 2016).

The international policy process within the United Nation Framework Convention on Climate Change (UNFCCC) focuses entirely on biogeochemical effects of greenhouse gas sources and sinks on global radiative forcing (RF).

Globally, net biogeochemical LCC effects have contributed around 30% of CO_2 emissions since pre-industrial times, with net LCC emissions declining over the last decade due to a reduction in deforestation rates primarily in Brazil, and reforestation in regions such as the USA, Europe, China and India. Since the year 2000, LCC contributed just under 10% of total anthropogenic CO_2 emissions (Smith *et al* 2013, Smith *et al* 2014, Le Queré *et al* 2015). The land sector as a whole, including CH_4 and N_2O flux from agriculture, contributes around 24% of total anthropogenic greenhouse gas emissions (Smith *et al* 2013, Smith *et al* 2014, Tubiello *et al* 2015).

The land surface and LCC contribute to biophysical effects in the following way (figure 1): incoming solar energy is partly reflected back into the atmosphere depending on the surface albedo (reflectiveness), and partly absorbed at the surface and

subsequently partitioned into latent and sensible heat fluxes depending on the soil water balance, canopy conductance and vegetation aerodynamic properties (roughness) (Costa and Foley 2000, Feddema *et al* 2005, Davin and de Noblet-Ducoudré 2010, Mahmood *et al* 2014).

The effects of land surface albedo change can be quantified in terms of RF (Betts 2000, Pielke *et al* 2002), and this has been used in attempts to quantify the global significance of biophysical effects of historical LCC compared to CO_2 fluxes (Betts 2000, Marland *et al* 2003, Schwaiger and Bird 2010). The Intergovernmental Panel on Climate Change (IPCC) estimates that historical anthropogenic LCC has increased the land surface albedo, with an associated negative effect on RF of -0.15 [-0.25 to -0.05] W m^{-2} relative to the pre-industrial level, compared with the biogeochemical radiative forcing from all anthropogenic changes in atmospheric CO_2 concentration (i.e. fossil fuels and LCC) of 1.68 [1.33 to 2.03] W m^{-2} (Myhre *et al* 2013). There are additional biophysical LCC effects on surface temperature that are not radiative, which tend to offset the impact of albedo changes at the global scale. However, due to the high uncertainties in quantifying their impacts, the IPCC concluded there is low agreement on the sign of the net change in global mean temperature because of biophysical LCC effects (Myhre *et al* 2013).

The partitioning of available energy into latent and sensible heat fluxes exerts a direct and significant local impact (warming or cooling) mainly on near-surface air temperature (Pielke *et al* 2002), yet the impact on the global average air temperature is limited even under extreme scenarios of LCC. Davin and De Noblet-Ducoudré (2010) reported that the global

mean effect on temperature from total global deforestation associated with changes in evapotranspiration is approximately five times smaller than the albedo effect but with an opposite sign: $+0.24$ °C versus -1.36 °C respectively. The assessment of the true global significance of biophysical forcing feedbacks is not trivial, since the LCC in a region may give rise to non-linear changes in climate in remote areas through teleconnections (Pielke *et al* 2002, Pielke *et al* 2011, Mahmood *et al* 2014, Lawrence and Vandecar 2015).

The net local/regional impacts are dependent on the type of LCC and on local conditions. Forested landscape is generally darker (lower albedo) than open land, especially in northern regions during seasons with snow cover (Betts 2000). Deforestation, with few exceptions, leads to higher albedo and decreased net radiation at the surface (Alton 2009), with a potential reduction of surface temperatures (Betts 2000, Bonan 2008, Devaraju *et al* 2015). The albedo-induced decrease of temperature following deforestation can be locally offset by the warming effect due to a decrease of latent heat flux, with a resulting net warming effect of the surface, along with a decrease of precipitation (Henderson-Sellers *et al* 1993, Pielke *et al* 2002, Feddema *et al* 2005, Bala *et al* 2007, Jackson *et al* 2008, Nobre *et al* 2009, Arora and Montenegro 2011, Luyssaert *et al* 2014, Mahmood *et al* 2014, Spracklen and Garcia-Carreras 2015, Lawrence and Vandecar 2015). Latent heat fluxes are usually larger over forests compared to herbaceous vegetation due to deeper rooting, greater transpiring leaf area, and increased roughness (Pielke *et al* 1998, Nobre *et al* 2009, Davin and de Noblet-Ducoudré 2010, Ban-Weiss *et al* 2011). Conversion from forest to grassland tends to reduce the surface roughness thus decreasing the turbulent exchange of heat in the boundary layer (Davin and de Noblet-Ducoudré 2010, de Noblet-Ducoudré *et al* 2012).

In summary, deforestation causes two opposite biophysical effects: a radiative cooling effect due to the increase in surface albedo and a non-radiative warming effect due to the concomitant decrease in evapotranspiration and in surface roughness (Sanderson *et al* 2012). The balance of the two effects has a strong latitudinal correlation. Deforestation in the boreal zones induces a cooling dominated by the increase of albedo, with some net warming effects dominated by reduced evapotranspiration in the summer (Betts 2000, Bala *et al* 2007, Brovkin *et al* 2013a, Davin and de Noblet-Ducoudré 2010, Schwaiger and Bird 2010, De Wit *et al* 2014). In the tropics the net impact is typically a warming due to the dominant influence of evapotranspiration and surface roughness (Henderson-Sellers *et al* 1993, Pielke *et al* 2002, Feddema *et al* 2005, Bala *et al* 2007, Jackson *et al* 2008).

A consultation carried out in June 2014 as part of the EU Project, LUC4C (www.luc4c.eu), with 36 respondents at international level (UNFCCC government delegates) mainly involved in the land sector

negotiations, found 60% of respondents un-aware (or with low awareness) of the biophysical climate effects of LCC. However, when provided some background information, more than half of the respondents replied that the future climate change policy process should also consider the regional temperature and precipitation biophysical LCC effects to maximize synergies between local and global climate mitigation and adaptation policies. One emerging question was how to provide a simple climate metric that summarizes the changes in temperature and precipitation due to biophysical impacts.

Several studies have already advocated for a more comprehensive assessment of the net climate effect of LCC policies on climate, beyond the global warming potential (e.g. Pielke *et al* 2002, Marland *et al* 2003, West *et al* 2011, Castillo *et al* 2012, Davies-Barnard *et al* 2014, Bright *et al* 2015), although without providing specific metrics or composite indices because of barriers encountered due to scale and uncertainty issues linked to the radiative and non-radiative biophysical effects.

While assessments of the full climate impacts of anthropogenic LCC are incomplete without considering biophysical effects, the high level of uncertainties in quantifying their impacts to date have made it impractical to offer clear advice on which policy makers could act. Given the growing body of scientific literature on the biophysical climate impacts of LCC, and the policy relevance, this review aims to: (i) produce a synthesis of the LCC biophysical interplay with regional and global climate and (ii) provide an evidence base to policy makers on which to judge the need for an assessment of biophysical changes caused by land-based mitigation/adaptation policies.

2. Methods

The systematic quantitative review of the LCC biophysical climate impacts presented in this study is based on peer-reviewed articles that focus on surface air temperature (T) and precipitation (P) changes. The review focuses on changes due to explicit LCC transitions, in order to characterize the potential biophysical effect of a defined land cover change, e.g. land conversion from forest to grassland, or from shrub land to bare land etc. Most of the model-based papers that consider global biophysical effects on temperature are based on LCC projections driven by socio-economic scenarios (Defries *et al* 2002, Pielke *et al* 2002, Matthews *et al* 2003, Sitch *et al* 2005, Betts *et al* 2007, Davin *et al* 2007, Findell *et al* 2009, Paeth *et al* 2009, Menon *et al* 2010, Pielke *et al* 2011, Ban-Weiss *et al* 2011, Boisier *et al* 2012, de Noblet-Ducoudré *et al* 2012, Port *et al* 2012, Dass *et al* 2013, Brovkin *et al* 2013a, Jones *et al* 2013, Trail *et al* 2013, Boysen *et al* 2014, Davies-Barnard *et al* 2014). For these studies it is impossible to separate the net

effect of each explicit regional LCC on climate signal since results are derived from mixed LCC transitions.

This review focuses on surface air temperature (2 meters) and precipitation for two main reasons: (i) they are the main variable of interest for policy makers at local and regional level, and (ii) they result from the combined effect of biophysical radiative and non-radiative processes, thus representing the synthesis variables of biophysical effect on climate.

The literature research was performed mainly on Google Scholar, using the following search terms (in various combinations): land cover change, biophysical effects, temperature, precipitation, climate change, deforestation. The resulting papers were then screened on the basis of the eligibility criteria listed below. Each study must:

- Report variation in surface air (2 meters) temperature (T) and/or precipitation (P) caused by an explicit transition in LCC;
- Consider annual average change values of T and/or P;
- Report the effects at the regional and/or global level. Studies reporting only site specific effects are not included due to the lack of representativeness at the regional/global level;
- Report only the variation in T or P due to biophysical factors, i.e. separately from any biogeochemical effect;
- Be published after January 2000.

Out of the 127 published studies that were analyzed (full list in supplementary information available at stacks.iop.org/ERL/12/053002/mmedia), 28 fulfilled the eligibility criteria, out of which 3 papers were based on observations and 25 were based on model outputs (table 1). The observation-driven assessments were based on *in situ* measurements (Lee *et al* 2011, Zhang *et al* 2014) or satellite observations (Alkama and Cescatti 2016) adopting one of two approaches (a) the space-for-time analogy (Lee *et al* 2011, Zhang *et al* 2014), meaning that spatial differences in surface air temperature between areas with different land cover have been interpreted as the climate signal of hypothetical LCC over time; (b) a time series analysis, assessing recent land cover transitions through time from satellite imagery (Alkama and Cescatti 2016). Modeling papers fulfilling the eligibility criteria include only LCC extreme scenarios of complete change of an explicit land cover category into another either over the globe, or for specific climate zones (tropical/temperate/boreal) or sub-regions (e.g. Amazon).

Data on P and T were collected in a database and transferred to common units (e.g. precipitation anomalies were transformed from mm per day to mm per year).

Since biophysical effects vary greatly in sign and magnitude depending on the latitude and ecosystems where they occur (Betts 2000, Bala *et al* 2007, Davin and de Noblet-Ducoudré 2010, Schwaiger and Bird 2010, Brovkin *et al* 2013b, De Wit *et al* 2014), data were grouped into one of three main climate zones (Boreal, Temperate and Tropical), using the classification reported by the original papers, providing the average, range (max-min) and standard deviation (when at least three entries were available) of the data clustered for each LCC transition. A single study may provide results for LCC effects in more than one geographic region within the same climate zone (e.g. Amazon, Africa, South-East Asia), (e.g. Voltaire and Royer 2005) or for different biomes within a climate zone (e.g. grassland, forest) (e.g. Snyder *et al* 2004). We note that model experiments do not use standardized definitions of the climatic zones thus these may differ slightly between studies, both in terms of LCC extent, and the area over which changes in biophysical effects are calculated. Nevertheless modeling studies included in our work are considering idealized land cover change, where 100% of the land cover is removed/changed for the whole climate zone or globe to assess the effect on temperature or precipitation of each land cover change. Given the huge extension of such land cover conversion, the modeling studies are considered to be comparable to each other.

Results were presented in ‘Regional’ or ‘Global’ sub-classes as follows: ‘Regional LCC effects’ are the regional (i.e. same climate zone) averaged changes of annual ΔT in response to the corresponding regional LCC while ‘Global LCC effects’ are the global net changes of annual ΔT in response to regional or global LCC.

Data were further grouped according to LCC transition type, categorizing specific transitions between ‘forest’ land and other major land cover types, but also grouping into generic ‘deforestation’ or ‘forestation’ cases.

Observed and modeled data were treated separately since they are not directly comparable, mainly due to differences in the scale of LCC they consider.

3. Review results and discussion

3.1. Temperature: regional effects

Eighteen studies reported data on changes in annual regional surface air temperature due to regional LCC (table 2). Figures 2(a) and (b) summarize the range of changes in surface air temperature due to biophysical factors in different climate zones for the two main LCC transitions: forestation and deforestation.

3.1.1. Boreal

In the boreal zone (table 2(a)), model simulations indicated regional cooling due to deforestation, ranging

Table 1. Summary characteristics of the papers included in the analysis. ΔT , ΔP : change in surface air temperature (2 meters) and precipitation in response to land cover change. SST: sea-surface temperature.

Paper	Variable	Climate zone(s)	Source	Circulation model	Vegetation model	SST dynamics
Alkama and Cescatti 2016	ΔT	Boreal-Temperate-Tropical	Observed (satellite data)	—	—	—
Arora and Montenegro 2011	ΔT	Global-Tropical-Temperate-Boreal	Modeled	CanESM1	CTEM	Interactive
Bathiany <i>et al</i> 2010	ΔT , ΔP	Tropical-Boreal	Modeled	MPI-ESM	JSBACH	Interactive
Claussen <i>et al</i> 2001	ΔT	Tropical-Boreal	Modeled	CLIMBER-2 (2.3)	VECODE	Interactive
Costa and Foley 2000	ΔP	Tropical	Modeled	GENESIS AGCM	IBIS	Not Specified
Dass <i>et al</i> 2013	ΔT	Boreal	Modeled	MPI-ESM	JSBACH	Interactive
Davin and de Noblet-Ducoudré 2010	ΔT	Global	Modeled	IPSL	ORCHIDEE	Interactive
Devaraju <i>et al</i> 2015	ΔT , ΔP	Global-Tropical-Temperate-Boreal	Modeled	CAM5.0	CLM4.0	Interactive
Gates and Ließ 2001	ΔT , ΔP	Temperate	Modeled	ECHAM4	Not Specified	Prescribed
Feddema <i>et al</i> 2005	ΔT	Tropical	Modeled	DOE-PCM	CLM3.0	Interactive
Gibbard <i>et al</i> 2005	ΔT	Global	Modeled	CAM3	CLM3.0	Interactive
Hasler <i>et al</i> 2009	ΔP	Tropical	Modeled	Multi Model Ensemble	—	—
Kleidon and Heimann 2000	ΔT , ΔP	Tropical	Modeled	ECHAM4	Not Specified	Prescribed
Lee <i>et al</i> 2011	ΔT	Boreal-Temperate-Tropical	Observed (ground based)	—	—	—
Lejeune <i>et al</i> 2014	ΔT	Tropical	Modeled	COSMO-CLM	CLM3.5	Prescribed
Medvigy <i>et al</i> 2012	ΔP	Tropical	Modeled	OLAM	ED2	Prescribed
Nobre <i>et al</i> 2009	ΔP	Tropical	Modeled	CPTEC	SSiB	Prescribed
Schneck and Mosbrugger 2011	ΔT , ΔP	Tropical	Modeled	ECHAM-5	—	Interactive
Semazzi and Song 2001	ΔT , ΔP	Tropical	Modeled	CCM3	LSM	Not Specified
Snyder <i>et al</i> 2004	ΔT , ΔP	Tropical-Temperate-Boreal	Modeled	CCM3-IBIS	IBIS	Prescribed
Snyder 2010	ΔT , ΔP	Tropical	Modeled	CCM3	IBIS	Prescribed
Voltaire and Royer 2004	ΔP	Tropical	Modeled	ARPEGE-Climat GCM	ISBA	Prescribed
Voltaire and Royer 2005	ΔT , ΔP	Tropical	Modeled	ARPEGE-Climat	ISBA	Prescribed/Interactive
Werth and Avissar 2002	ΔP	Tropical	Modeled	NASA- GISS mod. II	Not Specified	Prescribed
Werth and Avissar 2005	ΔP	Tropical	Modeled	NASA-GISS	Not Specified	Not Specified
West <i>et al</i> 2011	ΔT	Boreal-Temperate-Tropical	Modeled	Not Specified	Not Specified	Not Specified
Zhang <i>et al</i> 2001	ΔT , ΔP	Tropical	Modeled	CCM1-Oz	BATS1e	Not Specified
Zhang <i>et al</i> 2014	ΔT	Boreal-Tropical	Observed (ground based)	—	—	—

from $-4\text{ }^{\circ}\text{C}$ to $-0.82\text{ }^{\circ}\text{C}$. The largest cooling, on average, resulted after the conversion from forest to bare land although the highest single value reported was from a deforestation experiment with conversion to grassland (Devaraju *et al* 2015). Boreal evergreen forest vegetation has lower albedo than grasses both during the growing season (evergreen leaves are darker than deciduous leaves and herbaceous vegetation) and during winter, when tree crowns shade the underlying snow layer and reduce the albedo considerably (Betts 2000). Only one study (Bathiany *et al* 2010) investigated both boreal deforestation and forestation and showed a warming in the forestation case, with deforestation (-18.55 million of km^2) and forestation ($+26.72$ million of km^2) having similar magnitude of signals of opposite sign (respectively $-1.1\text{ }^{\circ}\text{C}$ and $+1.2\text{ }^{\circ}\text{C}$).

Observations show a large range in results for deforestation ($-0.95\text{ }^{\circ}\text{C}$ to $+0.04\text{ }^{\circ}\text{C}$) with ground measurement studies (Zhang *et al* 2014, Lee *et al* 2011) showing a consistent cooling while satellite data (Alkama and Cescatti 2016) gives a small warming ($+0.04\text{ }^{\circ}\text{C}$). On average there is a cooling effect of deforestation ($-0.59\text{ }^{\circ}\text{C}$) that is smaller when compared to the model based outputs ($-2.18\text{ }^{\circ}\text{C}$). Most likely this is because observations focus on small-scale deforestation while modeled studies consider stylized and large-scale LCC. Concerning the scale issue, Lorenz and Pitman (2014) have demonstrated that the climatic response increases with the size of deforestation. Furthermore, large-scale deforestation in climate models triggers large feedbacks through e.g. ocean and sea-ice dynamics that may amplify the climate impacts

Table 2. Regional surface air temperature change (°C) as a result of regional LCC grouped by land conversion type and climate zone. (*) Number refers to a single value.

From	To	Mean/value*	Stdev	Max	Min	Entries
(a) Boreal						
MODELLED						
Grassland	Forest	1.20*	—	—	—	1 ¹
Forest	Grassland	-1.96	1.44	-0.82	-4.00	4 ¹⁻⁴
Forest	Bare land	-2.41	0.73	-1.50	-3.20	4 ^{3,6}
Deforestation		-2.18	1.08	-0.82	-4.00	8 ¹⁻⁶
Forestation		1.2*	—	—	—	1 ¹
OBSERVED						
Deforestation		-0.59	0.54	0.04	-0.95	3 ⁷⁻⁹
Forestation		0.59	0.54	0.95	-0.04	3 ⁷⁻⁹
(b) Temperate						
MODELLED						
Grassland	Bare land	0.55	0.47	1.10	0.00	4 ⁶
Forest	Bare land	-0.82	0.52	-0.10	-1.30	4 ^{6,10}
Forest	Cropland	-0.30*	—	—	—	1 ⁵
Forest	Grassland	-0.8*	—	—	—	1 ²
Shrub land	Bare land	0.30*	—	—	—	1 ⁶
Other land	Forest	0.56*	—	—	—	1 ¹⁰
Deforestation		-0.73	0.45	-0.10	-1.30	6 ^{2,5,6,10}
Forestation		0.56*	—	—	—	1 ¹⁰
OBSERVED						
Deforestation		0.50	—	1.2	-0.21	2 ^{7,8}
Forestation		-0.50	—	0.21	-1.2	2 ^{7,8}
(c) Tropical						
MODELLED						
Shrubland	Bare land	0.55	0.62	1.20	-0.40	5 ⁶
Shrubland	Cropland	0.50*	—	—	—	1 ⁵
Forest	Cropland	1.02	0.71	2.00	0.29	5 ^{5,11,12}
Forest	Grassland	0.33	0.76	2.50	-0.30	21 ^{2,4,9,13-17}
Forest	Bare land	1.06	0.23	1.50	0.80	8 ^{6,18}
Grassland	Forest	-0.17	0.12	-0.10	-0.40	6 ^{1,9}
Deforestation		0.60	0.74	2.5	-0.30	34 ^{2-6,11-18}
Forestation		-0.17	0.12	-0.10	-0.40	6 ¹
OBSERVED						
Deforestation		0.41	0.57	1.06	-0.23	4 ⁷⁻⁹
Forestation		-0.87	—	-0.67	-1.06	2 ^{8,9}

¹Bathiany *et al* (2010); ²Devaraju *et al* (2015); ³Dass *et al* (2013); ⁴Claussen *et al* (2001); ⁵West *et al* (2011); ⁶Snyder *et al* (2004); ⁷Lee *et al* (2011); ⁸Alkama and Cescatti (2016); ⁹Zhang *et al* (2014); ¹⁰Gates and Ließ (2001); ¹¹Lejeune *et al* (2014); ¹²Feddema *et al* (2005); ¹³Voldoire and Royer (2005); ¹⁴Semazzi and Song (2001); ¹⁵Schneck and Mosbrugger (2011); ¹⁶Zhang *et al* (2001); ¹⁷Kleidon and Heimann (2000); ¹⁸Snyder (2010).

(Davin and de Noblet-Ducoudré 2010). On the contrary, observations detect only local effects at the surface and first order interactions with the boundary layer, not large-scale feedbacks. Additionally the idealized modeling experiments often do not consider the progressive recovery of vegetation in forest clearings that are detected by observations (Alkama and Cescatti 2016).

3.1.2. Temperate region

The temperate region shows similar LCC biophysical responses to those observed for the boreal zone, although of smaller magnitude (table 2(b), figure 2(a) and (b)). This may be a consequence of the increasing influence of the warming effect derived from the

reduction of evapotranspiration during the growing season, which runs counter to the still dominant albedo effect on the net biophysical temperature dynamics (Gates and Ließ 2001, Davin and de Noblet-Ducoudré 2010, Snyder *et al* 2004). As a consequence, in model experiments, deforestation (evapotranspiration related warming, albedo related cooling) always resulted in a net cooling ($-0.73 \pm 0.45^\circ\text{C}$), with a mean of $-0.82 \pm 0.52^\circ\text{C}$ for conversion of forest to bare land, -0.8°C in the forest to grassland conversion, and -0.30°C in the forest to cropland conversion, whereas forestation resulted in a net warming ($+0.56^\circ\text{C}$). By contrast, shrubland and grassland conversions to bare land led to a warming of 0.30°C and $0.55 \pm 0.47^\circ\text{C}$, respectively.

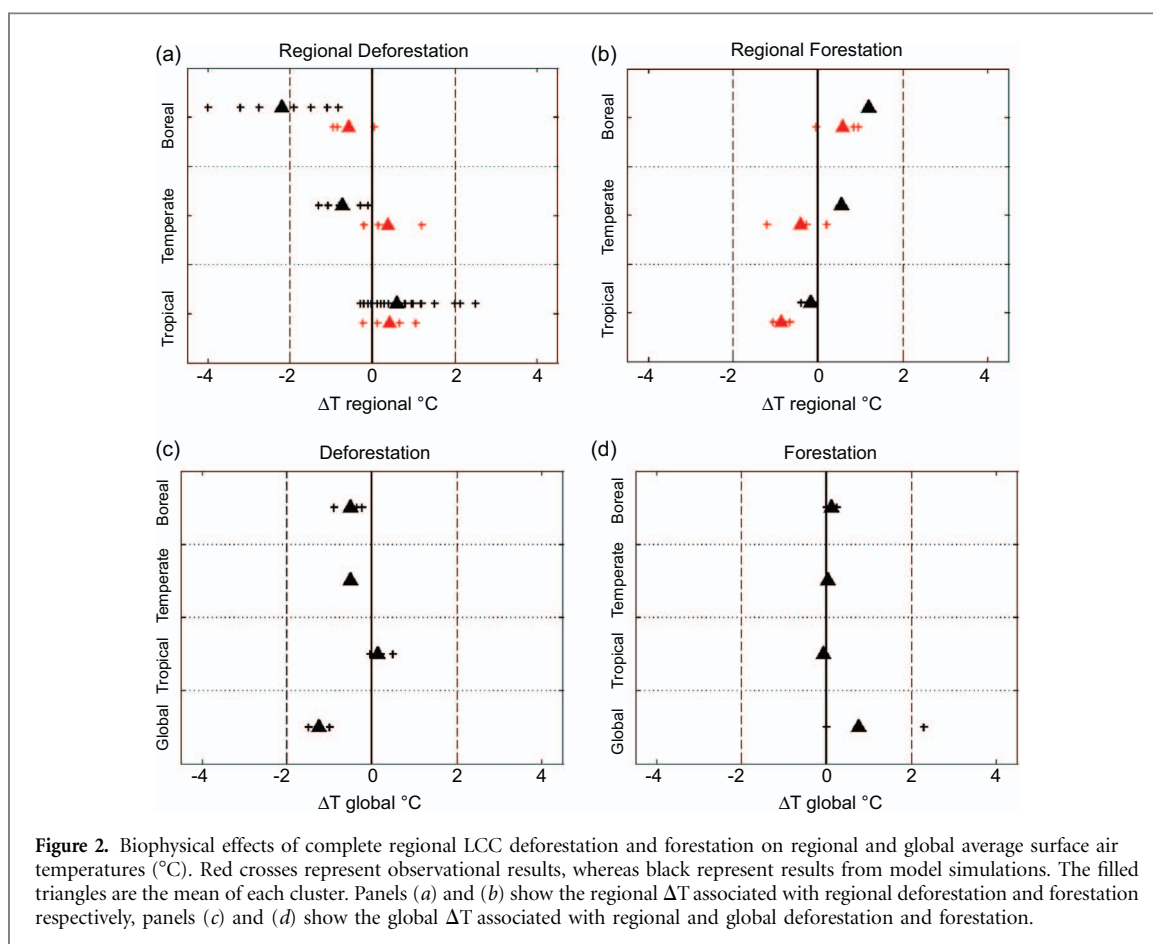


Figure 2. Biophysical effects of complete regional LCC deforestation and forestation on regional and global average surface air temperatures ($^{\circ}\text{C}$). Red crosses represent observational results, whereas black represent results from model simulations. The filled triangles are the mean of each cluster. Panels (a) and (b) show the regional ΔT associated with regional deforestation and forestation respectively, panels (c) and (d) show the global ΔT associated with regional and global deforestation and forestation.

Observations show an opposite result compared to the model experiments, i.e. a warming associated with deforestation (0.50°C) and a cooling effect associated with forestation (-0.50°C), but with uncertainty regarding the sign. Using observation data from a network of surface stations with contrasting land cover, Lee *et al* (2011) reports that the temperate sites show weaker radiative (albedo) cooling but stronger non-radiative (heat-exchange) warming compared with the boreal sites, with a resulting effect of -0.21°C ranging from -0.74°C to 0.32°C , while Alkama and Cescatti (2016) from satellite retrieval observe a clear systematic warming ($1.2 \pm 0.02^{\circ}\text{C}$) following deforestation. As stated in the previous section, observations capture only local effects of small scale LCC and are therefore not directly comparable with idealized model simulations of large scale land transformations.

The net impact of changes in albedo and evapotranspiration on climate from deforestation depends greatly on local climate in all regions (Bonan 2008), but particularly so in temperate latitudes where the opposing radiative (albedo) effects and non-radiative (heat exchange) effects are of comparable size and different sign, so that they compensate leading to small and uncertain net annual temperature changes (Pitman *et al* 2011). Depending on the location, the dominant effect may be an average annual warming (e.g. in grassland regions of Central US, mostly affected by evapotranspiration reduction),

or cooling (e.g. in the steppe region of Asia, mostly affected by albedo increase) (Snyder *et al* 2004). In the temperate climate zone, large heterogeneity in terms of albedo and evapotranspiration associated to the different spatial scale of LCC transitions between the observed and modeled data could explain these contrasting results. Furthermore, the observations by Alkama and Cescatti (2016) and Lee *et al* (2011) refer to a recent decade characterized by warming and consequent reduction of snow cover compared to the reference period used for model simulations, which may explain the greater importance of changes in evapotranspiration and the reduction of the snow-albedo effect in the observations.

3.1.3. Tropical region

In the tropics, published papers on deforestation show a systematic and pronounced biophysical warming (table 2(c), figure 2 (a) and (b)). In model experiments, the deforestation-induced warming is $0.60 \pm 0.74^{\circ}\text{C}$ with only small variation as a function of the final land cover. Shrub land conversion to cropland or bare ground leads to a warming effect of 0.50°C or $0.55 \pm 0.62^{\circ}\text{C}$, respectively, with the smallest effect found in Australia (Snyder *et al* 2004). Forestation shows opposite results but of lower magnitude, with a cooling effect of $-0.17 \pm 0.12^{\circ}\text{C}$ in the modeled data.

Observations show the same warming effect of deforestation with a comparable magnitude to the

Table 3. Changes in global average surface air temperature (°C) due to regional LCC. (*) Number refers to a single value.

LCC	Mean/value*	Stdev	Max	Min	Entries
<i>Boreal Deforestation</i>	−0.49	0.36	−0.23	−0.90	3 ²⁻⁴
<i>Boreal Forestation</i>	0.13	—	0.25	0.01	2 ^{1,6}
<i>Temperate Deforestation</i>	−0.50*	—	—	—	1 ²
<i>Temperate Forestation</i>	0.04*	—	—	—	1 ²
<i>Tropical Deforestation</i>	0.16	0.26	0.5	−0.04	4 ^{2,4,5}
<i>Tropical Forestation</i>	−0.07	—	−0.06	−0.07	2 ^{1,6}

¹Bathiany *et al* (2010); ²Devaraju *et al* (2015); ³Dass *et al* (2013); ⁴Claussen *et al* (2001); ⁵Snyder (2010); ⁶Arora and Montenegro (2011)

Table 4. Changes in global average surface air temperature (°C) due to global LCC for different LCC transitions. (*) Number refers to a single value.

From	To	Mean/value*	Stdev	Max	Min	Entries
<i>Bare land</i>	<i>Grassland</i>	−0.1*	—	—	—	1 ⁴
<i>Bare land</i>	<i>Forest</i>	2.30*	—	—	—	1 ⁴
<i>Cropland</i>	<i>Forest</i>	−0.05	—	0.00	−0.01	2 ²
<i>Forest</i>	<i>Grassland</i>	−1.25	—	−1.0	−1.50	1 ^{1,3}
<i>Deforestation</i>		−1.25	—	−1.0	−1.50	2 ^{1,3}
<i>Forestation</i>		0.76	1.33	2.30	−0.01	3 ^{3,4}

¹Devaraju *et al* (2015); ²Arora and Montenegro (2011); ³Davin and de Noblet-Ducoudré (2010); ⁴Gibbard *et al* (2005)

modeled data ($0.41 \pm 0.57^\circ\text{C}$), while showing a cooling effect of -0.87°C in case of forestation (Zhang *et al* 2014, Alkama and Cescatti 2016), five times higher than that detected by models.

In general, the studies confirm that the change in evapotranspiration is the dominant biophysical factor in the tropics as opposed to albedo in the boreal (and to some degree also in the temperate) zone. Reduction in leaf area index due to deforestation typically triggers a warming as a result of reduced latent heat flux and corresponding increased sensible heat flux. The smaller modelled effects of forestation compared to deforestation in Bathiany *et al* (2010), who compared the two types of LCC, was interpreted as being partly due to lower productivity in recently established regrowing forests due to changes towards a dryer microclimate of land that had previously been deforested. Furthermore, the amount of converted area is typically much less in forestation experiments, where there are more limited areas available for forestation, compared to the amount of land available for forest removal in the deforestation experiments. In Bathiany *et al* (2010) the reforested area in the tropical zone is less than half of the deforested area (+10.52 and −23.07 million km² respectively). Another explanation is that a reforested canopy may take years before reaching the same structural and biophysical characteristics of a mature forest. Some models simulate growth of forest from bare ground with changing biophysical characteristics, e.g. Arora and Montenegro (2011) state that as vegetation grows on the afforested fraction of grid cells the albedo changes rapidly within the first 5–7 years.

3.2. Temperature: global effects

In table 3 and figure 2(c) and (d), we summarize changes in global average temperature due to regional LCC, while table 4 and figure 2(c) and (d) show the changes in global average temperature due to global LCC model experiments.

The modeled regional LCC effects on global annual average surface air temperatures (table 3, figure 2(c) and (d)) suggest that the effects on regional temperature (table 2) propagate globally in terms of a similar sign of ΔT signal, but the magnitude of global temperature change is smaller. Forestation experiments show negligible alterations of the global annual average surface air temperature, ranging from 0.13°C (boreal region) to -0.07°C (tropical region). Both boreal ($-0.49 \pm 0.36^\circ\text{C}$) and temperate (-0.5°C) regional deforestations have larger impact on global surface air temperatures, compared to tropical deforestation ($0.16 \pm 0.26^\circ\text{C}$). Even though the mean of model results for boreal deforestation indicates regionally a larger cooling compared to temperate deforestation, both induce the same cooling of about -0.5°C globally. This may be due to different teleconnections (Hasler *et al* 2009, Snyder *et al* 2010, Pielke *et al* 2011), or a consequence of the difference in the global distribution of present boreal and temperate forests.

When a total global deforestation scenario is considered (table 4, figure 2(c)), the overall effect is a net cooling for deforestation (-1.25°C) and a warming in case of forestation ($0.76 \pm 1.33^\circ\text{C}$) (table 4, figure 2(d)). Despite the paucity of the data, it is noteworthy that a global deforestation has been shown to have almost twice the effect in magnitude than a

Table 5. Modelled regional precipitation change (mm yr^{-1}) as a result of regional LCC, grouped by land conversion type and climate zone. (*) Number refers to a single value.

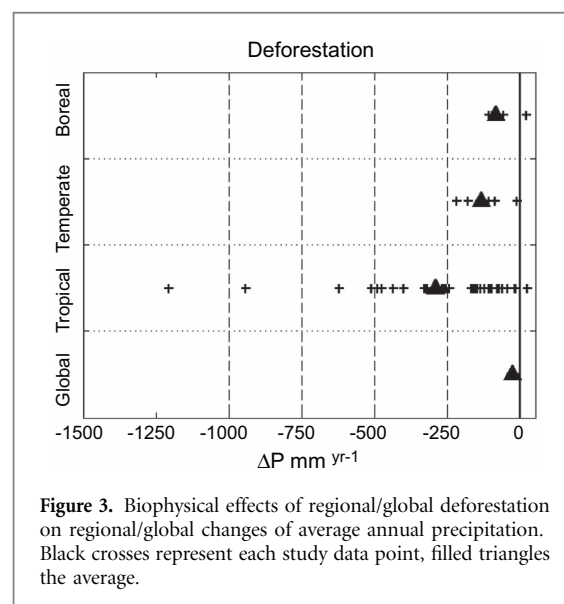
From	To	Mean/value*	Stdev	Max	Min	Entries
(a) Boreal						
Forest	Grassland	-58*	—	—	—	1 ²
Forest	Bare land	-88	51	18	-110	6 ³
Shrubland	Bare land	-73	0.17	0.0	-110	6 ³
Deforestation		-83	47	18	-110	7 ^{2,3}
(b) Temperate						
Forest	Grassland	-11*	—	—	—	1 ²
Forest	Bare land	-154	59	-88	-219	6 ^{3,4}
Grassland	Bare land	-155	61	-73	-219	8 ³
Shrubland	Bare land	-110*	—	—	—	2 ³
Deforestation		-133	76	-11	-219	7 ²⁻⁴
(c) Tropical						
Forest	Grassland	-219	263	22	-1204	28 ^{2,5-9,11-15}
Forest	Bare land	-467	102	-329	-621	12 ^{3,10}
Shrubland	Bare land	-314	117	-146	-438	9 ³
Grassland	Forest	41	23	79	20	5 ¹
Forestation		41	23	79	20	5 ¹
Deforestation		-288	248	22	-1204	42 ^{2,3,5-8,10-17}
(d) Global						
Forest	Grassland	-54*	—	—	—	1 ²
Deforestation		-54*	—	—	—	1 ²

¹Bathiany *et al* (2010); ²Devaraju *et al* (2015); ³Snyder *et al* (2004); ⁴Gates and Ließ (2001); ⁵Voldoire and Royer (2005); ⁶Semazzi and Song (2001); ⁷Schneck and Mosbrugger (2011); ⁸Zhang *et al* (2001); ⁹Kleidon and Heimann (2000); ¹⁰Snyder (2010); ¹¹Werth and Avissar (2005); ¹²Nobre *et al* (2009); ¹³Hasler *et al* (2009); ¹⁴Costa and Foley (2000); ¹⁵Voldoire and Royer (2004); ¹⁶Medvigy *et al* (2012); ¹⁷Werth and Avissar (2002)

global forestation, probably due to the different areas of land available for complete global deforestation or forestation. These results imply that the cooling of boreal deforestation apparently dominates over warming from tropical deforestation (figure 2(c)). This may be the consequence of both higher local ΔT absolute value in the boreal region, and a wider distribution of boreal and temperate ecozones impact. Moreover, temperate regions display comparable temperature changes to boreal ones, further influencing the cooling effect of a hypothetical global deforestation. In case of forestation, boreal and temperate regions dominate also because of the small effect of tropical forestation on global temperature change.

3.3. Precipitation

Assessments of the biophysical effect of LCC on precipitation available in the literature that met our selection criteria are exclusively from modelling experiments. The 16 articles that fulfilled the criteria for this review involve mainly a reduction of vegetation cover, and mostly cover the tropical climate zone. As expected, at a regional scale, a reduction of vegetation triggers a significant reduction in precipitation amounts due to a modification of the evapotranspiration regime and consequently of the regional water cycle (Snyder *et al* 2004, Hasler *et al* 2009, Bathiany *et al* 2010), although the magnitude varies significantly



with the latitude at which the LCC occurs (table 5, figure 3).

3.3.1. Boreal

The analysis of the boreal climate zone is based on two articles that consistently predict a decrease of precipitation following the removal of forest or shrub vegetation (table 5(a), figure 3). According to Snyder *et al* (2004) the biophysical effect of removal of both

forest and shrub vegetation to bare ground is a reduction in precipitation of up to -110 mm yr^{-1} , about 15% of the annual total precipitation, with means of -88 ± 51 and $-73 \pm 17 \text{ mm yr}^{-1}$ respectively. When forests are replaced by grassland, the decline of precipitation is less, at -58 mm yr^{-1} . Beringer *et al* (2005) suggest that there may be only slight differences in the evapotranspiration ratio (ET/net_Radiation) between different vegetation covers in boreal regions. This is probably due to the fact that in the boreal zone evapotranspiration is limited by the atmospheric demand (determined by net radiation), while in the temperate and tropical zones evapotranspiration is typically limited by the supply of water (Jung *et al* 2010). In addition, this pattern may likely be influenced by the rooting distribution of conifers, where roots concentrate close to the soil surface, quite similar to grasses or shrubs (Schenk and Jackson 2002, Jackson *et al* 1996). Thus the presence/absence of vegetation may be more important than the plant functional type occupying the area.

3.3.2. Temperate region

The LCC impact on precipitation in temperate regions is more complex than for boreal or tropical regions (Field *et al* 2007, Bala *et al* 2007, Bonan 2008) (table 5(b), figure 3). In temperate regions, it is difficult to detect the signature of forest cover changes on rainfall owing to the naturally highly variable frequency of synoptic scale meteorological systems (e.g. frontal depressions) and rainfall patterns, the regional and small scale landscape and topographic variability, the nonlinear changes in the forest cover and the related effects of urbanization, pollution loadings and regional circulation (Field *et al* 2007, Bala *et al* 2007, Bonan 2008).

All modelling studies predict a reduction in annual precipitation (table 5(b)) following a decline in vegetation cover. Deforestation to bare land produces a reduction of about $154 \pm 59 \text{ mm yr}^{-1}$. Removal of any vegetation to bare land produces a similar mean signal (with a wide range from -73 to -219 mm yr^{-1}). As with boreal regions, conversion of forest to grassland produces a smaller reduction in precipitation (-11 mm yr^{-1}) than conversion of any vegetation to bare ground. This result however is highly uncertain since it is based on a single study.

3.3.3. Tropical region

Deforestation to bare land results in a strong decrease of precipitation of about $-467 \pm 102 \text{ mm yr}^{-1}$ for loss of forest and $-314 \pm 117 \text{ mm yr}^{-1}$ for loss of shrubland (table 5(c), figure 3). Similar to boreal and temperate biomes, when forests are substituted with herbaceous plant types, the rainfall reduction is less pronounced ($-219 \pm 263 \text{ mm yr}^{-1}$), although the range is very large and includes a positive change ($+22$ to -1204 mm yr^{-1}).

In the tropical region a significant proportion of rainfall is from recycled moisture released by forest evapotranspiration. Salati and Nobre (1991) estimated that evapotranspiration is responsible for between 50% and 75% of the measured rainfall in tropical forests while Silva Dias *et al* (2009) estimated that about half of the rainfall in the Amazon region originates from moisture supplied by the forests (Sanderson *et al* 2012). This is especially true in the rainy season, when water resources are greatest, and the hydrological changes could significantly alter climate patterns and processes (Malhi *et al* 2008, Phillips *et al* 2009, Kumagai and Porporato 2012), affecting feedback to the atmosphere (Meir *et al* 2006, Bonan 2008). According to Snyder *et al* (2004), when forests or shrublands are substituted with bare land, a reduction of about 30% of annual precipitations occurs (respectively about 500 and 400 mm yr^{-1}). Savannah ecosystems experience the highest impacts (more than 50% of precipitation reduction during the wet season). Bathiany *et al* (2010) projected a smaller reduction of about 10% for localized deforestation scenarios in the different sub-continental tropical zones (about 110 mm yr^{-1}). However, the results converge with Snyder *et al* (2004) in a reduction of about 25% annual precipitations over central Amazon basin (about 360 mm yr^{-1}).

Similar to surface air temperature, there is a strong difference whether deforestation or forestation is considered. Any reduction in vegetation cover has a larger effect than a forestation scenario. According to Bathiany *et al* (2010) in the tropical climate zone complete forestation causes an absolute change in precipitation five to six times lower ($+41 \pm 23 \text{ mm yr}^{-1}$) than complete deforestation (noting as above that the areas involved are different).

4. Conclusions

This work synthesizes results of published modelling and observational studies, focusing on changes in surface air temperature (2 m) and precipitation due to biophysical effects of LCC. Models indicate that large scale (extreme) land cover changes have a strong regional effect on temperature and precipitation, and a non-negligible global impact on temperature. Observational studies also find significant local/regional temperature effects of land cover change. Results indicate potential trade-offs or synergies between local and global mitigation. For example, in boreal areas afforestation may have a small undesirable biophysical global warming effect that runs counter to global climate mitigation through the enhanced carbon sinks, while at the local level, the warming may be considered beneficial to e.g. food production. It should be noted that the boreal albedo effect will become less important in a warmer world when the snow cover will become less abundant (Devaraju *et al*

2015). In tropical areas avoided deforestation is a win-win for global and local mitigation of climate warming when considering biophysical processes, as well as considering biogeochemical processes.

Although over the last few years a big effort has been made in the modelling community to improve the representation of the biophysical and biogeochemical LCC climate impacts, an additional effort is still needed to overcome: (a) the apparent mismatch of scales at which LCC actually occur and those usually adopted in model experiments in ESMs (Rounsevell et al 2014, Tompkins et al 2015), (b) the different temporal and spatial scales of biophysical and biogeochemical processes and (c) the current oversimplified treatment of LCC in ESMs (Rounsevell et al 2014).

The main limitation encountered in this analysis was the difficulty to assess the dependency of the effects on the spatial extent of the LCC. The included model studies dealt with idealized complete global/regional-scale deforestation/forestation experiments using global climate models. A scale dependent quantification of biophysical impact of LCC in different regions would be critical in analyzing the full climate impacts of any realistic LCC policy since LCC decisions are made typically at the national and sub-national level. Until such information is available robustly, it is not clear how the biophysical effects could be incorporated into an international policy framework that aims to assess (monitor, report and verify - MRV) and incentivize country-based action on climate mitigation.

The process of including land-based mitigation in the UNFCCC process has been a matter of long and complex negotiations. The relatively small and currently highly uncertain global effect of biophysical changes on temperature compared to greenhouse gas effects makes it difficult to justify efforts to include it in the complex negotiations of the UNFCCC process at the present time. In fact, the added complications could risk undermining current negotiated text and methods. It would potentially increase Countries' reporting burden within the MRV framework, without having clear and transparent methods of assessment available. That said, the impact of these effects is non-negligible and ignoring them may lead to biased and non-optimal land-based climate policies. Accounting for biophysical effects could potentially further incentivize tropical forest protection through REDD+ and disincentivize boreal reforestation. The climate effectiveness of the latter in particular could become more controversial, so it is essential to increase confidence in the potential direction and magnitude of the global effects of reforestation projects at different spatial scales.

The local biophysical climate effects following LCC are more robust and larger in magnitude than global effects. These changes will influence ecosystems, their

productivity and biodiversity, and the water cycle. Policies at the local to regional level that aim to address both mitigation and adaptation objectives will thus be more effective if they include assessment of the biophysical effects that may either exacerbate or counteract global biogeochemical climate change effects.

New high-resolution observational datasets are becoming available for improving model LCC biophysical representation that have the potential to lead to more robust evidence, tools and metrics for policy makers to evaluate LCC-climate impacts.

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