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The Effects of Tropical Vegetation on Rainfall

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Abstract

Vegetation modifies land-surface properties, mediating the exchange of energy, moisture, trace gases, and aerosols between the land and the atmosphere. These exchanges influence the atmosphere on local, regional, and global scales. Through altering surface properties, vegetation change can impact on weather and climate. We review current understanding of the processes through which tropical land-cover change (LCC) affects rainfall. Tropical deforestation leads to reduced evapotranspiration, increasing surface temperatures by 1–3 K and causing boundary layer circulations, which in turn increase rainfall over some regions and reduce it elsewhere. On larger scales, deforestation leads to reductions in moisture recycling, reducing regional rainfall by up to 40%. Impacts of future tropical LCC on rainfall are uncertain but could be of similar magnitude to those caused by climate change. Climate and sustainable development policies need to account for the impacts of tropical LCC on local and regional rainfall.

Contents

1. INTRODUCTION

Vegetation alters the properties of the surface and mediates moisture, energy, and trace gas fluxes between the surface and the atmosphere (1). Impacts of vegetation on energy, momentum, and moisture fluxes are known as biophysical effects. Impacts of vegetation on fluxes of CO_2, trace gases, and aerosols are known as biogeochemical effects. These biophysical and biogeochemical effects result in complex impacts on weather and climate (2–6).

Changes in vegetation, known as land-use and land-cover change (LULCC) or simply land-cover change (LCC), alter these land-atmosphere fluxes, impacting local, regional, and global climate. Although it is well established that tropical deforestation results in local warming, the impacts on rainfall are more uncertain and have been the subject of several previous reviews (4, 7–9). This complexity results from vegetation impacting rainfall through a variety of interacting complex mechanisms acting over a range of different scales, from local (one kilometer to hundreds of kilometers) to regional (hundreds to thousands of kilometers).

Our key aim in this review is to provide a comprehensive synthesis of the multiple ways that vegetation and LCC may impact rainfall. Section 2 outlines the processes and mechanisms through which tropical vegetation and LCC impact rainfall. Section 3 synthesizes current understanding of how these processes impact local- to regional-scale rainfall. Section 4 outlines the impacts of historical and future LCC on rainfall. Section 5 discusses current challenges in simulating impacts of LCC on rainfall. Section 6 describes Earth-system feedbacks. Section 7 sets out priorities for future research. Finally, Section 8 outlines impacts and policy implications.

2. SURFACE PROPERTIES AND FLUXES

The presence of vegetation alters key properties of the land surface (Section 2.1), impacting fluxes of energy, moisture, momentum, trace gases, and aerosol between the surface and atmosphere (Section 2.2).

2.1. Vegetation Impacts On Surface Properties

Figure 1 summarizes the ways vegetation can alter the properties of a surface. **Table 1** summarizes the differences in key surface properties between tropical forest and pasture.

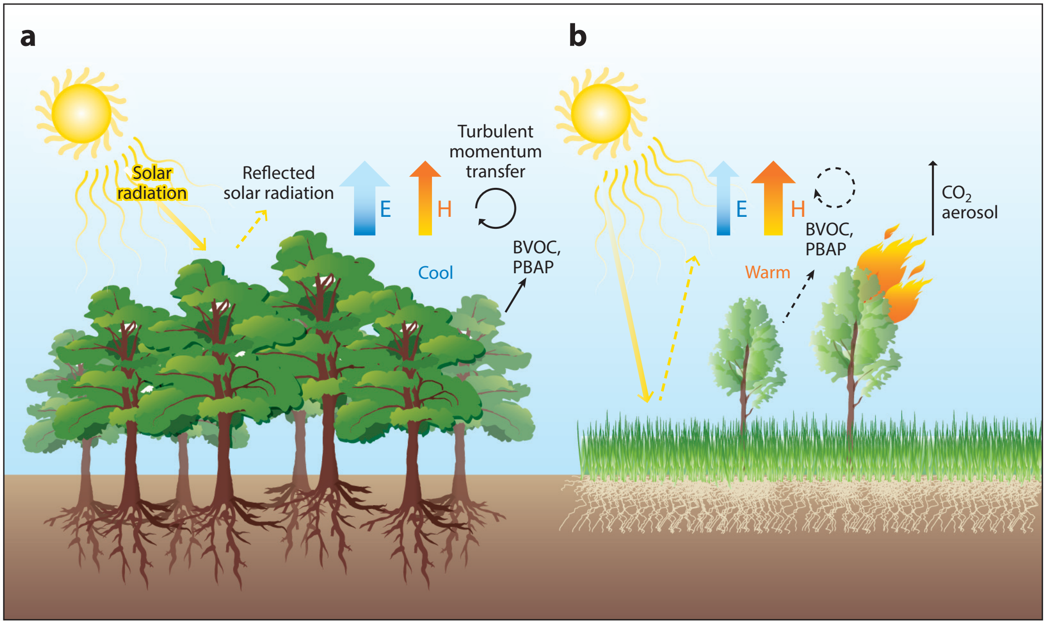

Figure 1

Surface properties of vegetation. A tropical (*a*) forest is compared to (*b*) pasture. Forests have lower albedo, greater roughness length, and greater rooting depth, resulting in higher evaporation (E) and latent heat fluxes and lower sensible heat fluxes (H). Fires associated with tropical deforestation and pasture maintenance result in greater emissions of biomass-burning aerosol.

2.1.1. Albedo. Albedo is the fraction of incident solar radiation that is reflected by the surface and plays a key role in the surface energy budget. Vegetation alters surface albedo: The albedo of grassland, pasture, crops, or dry soil is typically higher than the albedo over forest. Tropical forests have albedo of 0.12 to 0.13, whereas pasture, crops, or dry soil have albedo of 0.14 to 0.19 (10–12). Some ecosystems have a strong seasonal cycle in albedo driven by phenology (13), although this is less important in the tropics.

Tropical deforestation leads to an increase in surface albedo, although the magnitude of this increase is uncertain. Modeling studies of Amazon deforestation assume regional increases of albedo vary between ~0.04 and 0.09 (14), consistent with the albedo difference between forest and pasture. However, realistic patterns of tropical LCC cause more complex changes in albedo. Observations in West Africa show that albedo does not vary linearly with changes in tree cover and that albedo is particularly sensitive at low tree cover fractions (15). The albedo of abandoned agriculture regenerating to secondary rainforest returns to values of undisturbed forest within 10

Table 1 Comparison of surface properties of tropical forest and pasture. Adapted from Gash & Nobre (10)

	Tropical forest	Pasture
Vegetation height (m)	30	0.5
Canopy cover (%)	100	85
Leaf area index	5.2	1–2.7
Albedo	0.13	0.18

to 15 years, meaning that regional increases in albedo over deforested regions interspersed with areas of secondary forest may be less than 0.03 (11). Even with consistent LCC scenarios, changes in albedo simulated by five general climate models (GCMs) vary by up to a factor of three in West Africa (16).

In regions of snowfall, vegetation can extend above the accumulated snow, leading to a much lower albedo than that would occur for bare soil or low vegetation, which is buried by snow. This effect is important over high-latitude forests, but snow-covered regions are minimal in the tropics; as such, we do not discuss them further.

2.1.2. Leaf area index. Leaf area index (LAI) is a measure of leaf surface area per unit ground area ($m^2 m^{-2}$) and is an important property of the land surface, as it modulates transfer of moisture to the atmosphere via transpiration. In the Amazon, tropical forest has a mean LAI of 5.2, whereas values for pasture range from 1 to 2.7 (**Table 1**). Higher values of LAI are typically associated with higher rates of evapotranspiration (e.g., 17, 18) due to the increased surface area available for gas exchange.

2.1.3. Surface roughness. Surface roughness describes the efficiency of momentum transfer between the surface and atmosphere. Different vegetation has different surface roughness depending on vegetation height and LAI (**Table 1**). Forests typically have greater surface roughness than other natural land covers, resulting in faster transfer of energy between surface and atmosphere. Deforestation therefore results in a reduction in surface roughness length, reducing the turbulent transfer of momentum and energy between the surface and atmosphere. However, a highly heterogeneous land surface with numerous forest patches could have higher surface roughness than unperturbed forest.

2.1.4. Rooting depth. The depth of plant roots controls the depth of soil over which plants can access soil moisture. A synthesis of observations of rooting depth finds maximum rooting depths of 7.0 ± 1.2 m for trees, 5.1 ± 0.8 m for shrubs, and 2.6 ± 0.1 m for herbaceous species (19). The deeper roots of trees compared to shrubs and grasses permit access to deeper soil water, which helps to maintain moisture fluxes during the dry season when surface soil moisture is reduced (20).

2.2. Impacts of Vegetation on Surface Fluxes

The impact of vegetation on surface properties results in vegetation altering the fluxes of energy, momentum, trace gases, and aerosols between the surface and the atmosphere.

2.2.1. Evapotranspiration. Terrestrial evapotranspiration (E) is water transferred from the land surface to the atmosphere and is a combination of physical evaporation from soil and vegetation and biological transpiration from vegetation. Transpiration involves the uptake of soil moisture by plant roots and loss through leaf stomata during photosynthesis. Soil moisture therefore has a strong control on E both through altering evaporation from the land surface and through controlling availability of moisture for vegetation (21). Estimates of E using different approaches can differ substantially, hindering our understanding of the impact of LCC (22). On the global scale, models estimate that transpiration contributes 42% of total E (ranging across models from 25% to 64%) (22), lower than the 61 ± 15% inferred from 81 observationally based studies (23). Despite this uncertainty, both studies confirm that vegetation has a strong control on moisture fluxes between the surface and atmosphere.

Forests have higher rates of E compared to other land covers (24), due to low albedo, high LAI, deep roots, and high aerodynamic roughness. Higher LAI results in greater rainfall interception,

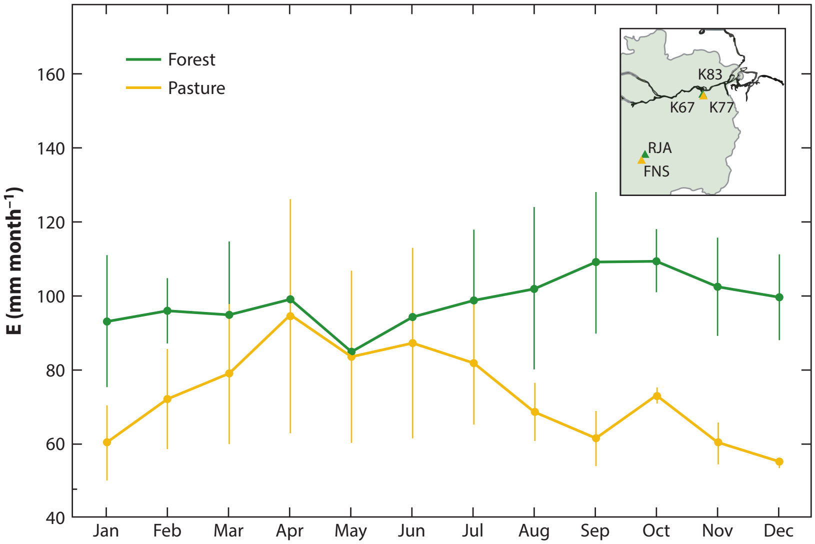

Figure 2

Evaporation (E) over different tropical land covers. Seasonal variation in E over forest (*dark green*) and pasture (*orange*) in the Amazon. The ET data are from the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) BrasilFlux database (33, 198). Forest data come from three sites across Brazil (K67, K83, and RJA), and pasture data come from two sites (K77 and FNS). Error bars show the standard deviations across the sites for each month.

allowing subsequent evaporation, and also provides a larger surface area for transpiration (see Section 2.1). **Figure 2** compares E from different land covers in the Amazon, as measured using eddy covariance flux towers. These data are consistent with measurements from the southwest Amazon, which show that E over pasture is 20% lower in the wet season and 40% lower in the dry season compared to E over tropical forests (12). Satellite retrievals estimate that the mean E of tropical forests (1,080 mm/year) is more than 80% greater than tropical grasslands (580 mm/year) (23). The contribution of transpiration to total E depends on vegetation, varying from 62% in tropical grassland to 70% in tropical forests (23).

Deforestation typically leads to a reduction in E. The widespread conversion of forests to agriculture has increased runoff, partly due to reduced E (25, 26). Expansion of agricultural land in Mato Grosso, Brazil, from 2000 to 2009 has caused a 25% reduction in E (27). However, some land-cover transitions may not reduce E. Rubber plantations have higher annual mean E compared to the tropical seasonal forest that they replaced in Southeast Asia (28). Afforestation in dry land regions may increase E, possibly at the expense of local stream flows, although precise impacts are context dependent (29). Trees along forest edges may transpire more than trees within the interior of forests due to different micrometeorological conditions at the forest boundary (30). Forest fragmentation may therefore lead to increased E which may offset some of the reductions in regional E due to deforestation (30). In contrast, the largest trees are responsible for 70% of E in the Amazon (31), potentially suggesting that selective logging may substantially reduce regional E.

2.2.2. Energy fluxes. Energy fluxes from the surface to the atmosphere are split into sensible heat fluxes, which increase atmospheric temperature, and latent heat fluxes, which represent the energy required to exchange water from liquid to gas phase during E. The ratio between sensible and latent heat fluxes is known as the Bowen ratio. On the global scale, latent heat accounts for

48% to 88% of net surface radiation over the continents (32). Through modifying E, vegetation alters the partitioning of surface net radiation between sensible and latent heat fluxes.

Observations comparing the surface energy budget over forest and pasture are relatively scarce due to the difficulty of making surface observations in a region with a dense, tall canopy. Higher E over forests compared to pasture leads to higher latent heat and lower sensible heat fluxes (i.e., a lower Bowen ratio) (33). Flight measurements over the Central African Republic measured Bowen ratios of 0.2 over the forest, compared to 0.45 over savannah (34), and two diurnal cycles of surface flux measurements in the Amazon showed even larger differences in Bowen ratio, with values of approximately 0.28 over rainforest compared to 1.25 over pasture (35). Bowen ratios over a forest site in southwest Amazonia showed little seasonal variability, varying between 0.3 and 0.4, whereas a pasture site showed increased Bowen ratios from 0.3–0.6 in the wet season to 0.6–0.8 in the dry season (12).

Lower albedo over forests compared to pasture leads to higher net radiation and increased sensible and latent heat fluxes (see Section 2.1). The overall impact of vegetation on sensible heat fluxes is therefore a balance between the effect of net radiation enhancing warming over forests and the effect of E reducing warming over forests via changes in the Bowen ratio. In the tropics, Bowen ratio impacts tend to dominate, leading to enhanced warming from conversion of forest to pasture.

2.2.3. Trace gas and aerosol fluxes. Vegetation alters the fluxes of trace gases and aerosols between the surface and the atmosphere. Forests contain more biomass compared to other land covers and thus deforestation is a source of atmospheric carbon. LCC has resulted in total cumulative carbon emissions of a similar magnitude to that from fossil fuel emissions (36), and it has contributed 10–20% of anthropogenic CO_2 emissions over the past few decades.

The impacts of LCC on aerosol and trace gas fluxes have been reviewed recently (6). Tropical LCC is associated with large changes in atmospheric aerosol (37). Undisturbed tropical forests are characterized by low aerosol number and mass concentrations, as well as high organic mass fractions (38, 39). Aerosol is predominately from the oxidation of biogenic volatile organic compounds or from primary biological aerosol particles (PBAP), both emitted by the forest ecosystem.

Fire is rare in undisturbed tropical forests, but is used to clear vegetation and trees. In the Amazon, there is a strong link between deforestation rate, aerosol emissions from fires, and regional aerosol optical depth (40). Aerosol emissions from fires results in areas of deforestation being characterized by high aerosol mass and number concentrations (39).

3. VEGETATION IMPACTS ON PRECIPITATION

Changes in surface fluxes can alter rainfall on local (Section 3.1), regional and global (Section 3.2) scales. Here we define local scales as those ranging from the boundary layer depth to the mesoscale (one kilometer to hundreds of kilometers).

3.1. Local Scale (One Kilometer to Hundreds of Kilometers)

Sharp transitions in vegetation, such as those caused by deforestation, can produce strong gradients in surface fluxes with an impact on the atmospheric boundary layer (BL). The land surface and BL above tropical forests is typically cooler (41) than adjacent land covers. Analysis of satellite data shows that loss of tropical forests increases mean annual maximum surface temperatures by up to 2 K (42). This local temperature response is a net result of altered surface fluxes. Increased albedo causes a reduction in surface net radiation, resulting in surface cooling and a negative radiative forcing (RF) at top of atmosphere (TOA). At the same time, reductions in E reduce latent heating and increase sensible heating, warming the surface. Reductions in E can also reduce atmospheric water vapor leading to a small negative TOA RF (43), although this is likely to be overridden through positive RF from reductions in low-level cloud cover (44). Lastly, a reduction in surface roughness reduces turbulent exchange of heat from the surface, also contributing to a warmer surface. Overall, tropical deforestation leads to a local warming as the warming from altered E and surface roughness dominates over the cooling due to changes in albedo (45).

This demonstrates the importance of both changes in available energy and changes in how the energy is redistributed through the atmosphere by nonradiative mechanisms (45, 46). Through these nonradiative interactions, deforestation can lead to large changes in the local surface temperature, substantially greater than suggested by changes in the TOA radiation budget (46). In regions of rapid LCC in the tropics, deforestation may have accounted for up to 75% of the observed surface warming between 1950 and 2010 (46).

The BL over pastures is warmer, drier, and deeper compared to the BL over forests, particularly in the dry season (47). This gradient in temperature between forest and nonforest land covers can cause local circulations analogous to sea breezes (48). A range of modeling studies confirm the presence of vegetation-induced breezes, including mesoscale models over the Amazon (49–52), large-eddy models simulating conditions in West Africa (53, 54) and Australia (55), as well as large-eddy simulation studies with more idealized surface forcings (56–60).

Vegetation breezes can persist even in the presence of strong background winds (61), but the orientation of the background flow relative to the surface patterns is important. Background flow parallel to the land-surface boundaries has little impact on the strength of the vegetation breeze, whereas if it is perpendicular, the vegetation breeze intensity is reduced, although this can increase convergence on the upwind side of a cool patch (60). Background flow can also advect the mesoscale circulation patterns downwind (35).

The key features of the surface variability that impact vegetation breezes are the amplitude and length scale of the surface forcing. Heterogeneities need to be larger than the BL depth, otherwise the surface variability is removed by turbulent mixing, producing similar results to a homogeneous surface (54, 57, 62). Although circulations can develop on a range of scales, they are most intense and persistent at length scales of 10–20 km (49, 54). Surface variability at larger scales is broken down into smaller circulations, which are quicker to develop (58). This is because weak surface flux anomalies embedded within the large patch can break up the larger circulation, and the larger circulation can itself perturb the surface fluxes, generating smaller-scale heterogeneities that initiate smaller circulations.

Vegetation breezes can alter cloud and rainfall patterns, providing a mechanism for mesoscale vegetation-rainfall feedbacks (**Figure 3**). The convergence zones created by vegetation breezes produce an enhancement of cloud (54, 55, 63) and rainfall (51, 53, 64) over deforested regions. There is also some evidence that subsidence over forest patches acts to suppress convection and rainfall (53, 54). Garcia-Carreras & Parker (53) show with a large-eddy simulation that although the rainfall enhancement is focused on the land-surface boundary, with a 4–6-fold increase compared to a homogeneous surface, the suppression of rainfall extends further into the remaining forest, tens of kilometers away. In the Amazon, this coupling is most important during the dry season, when the background conditions are less conducive to the initiation of convection (64).

The mechanism for the enhancement of convection over convergence zones is both dynamic and thermodynamic (54). Air over forest tends to have higher afternoon equivalent potential temperature, due to a lower albedo, and shallower BL, with less dilution by entrainment. Conversely, air over the less vegetated region tends to have lower convective inhibition, due to warmer temperatures and a deeper BL. Mesoscale convergence contributes up to 0.5 m s^{-1} in vertical velocity.

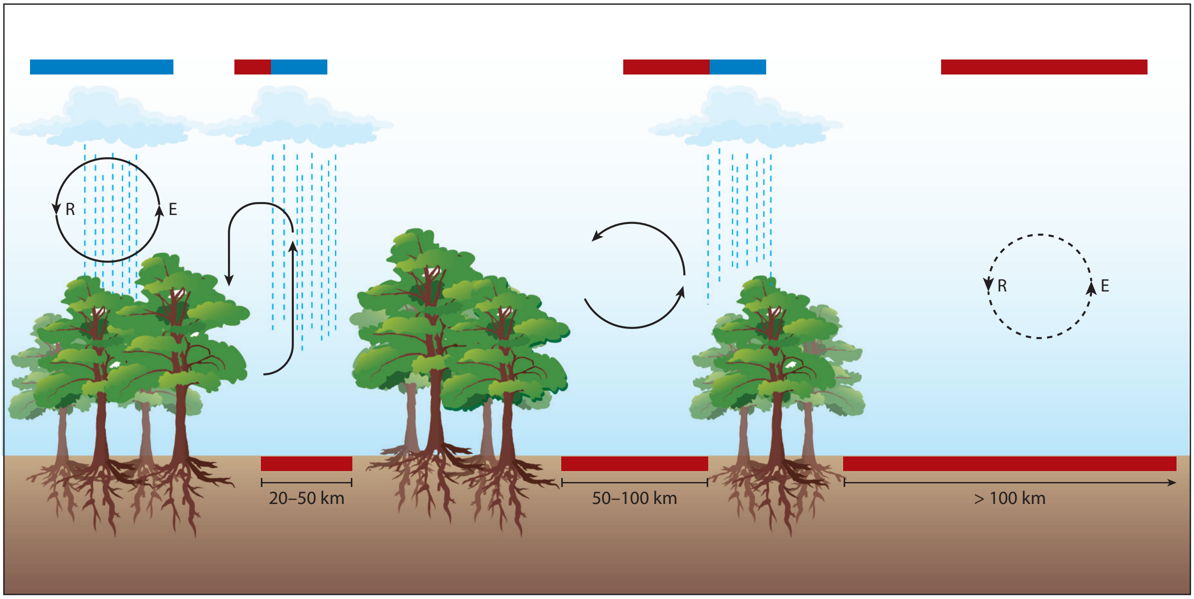

Figure 3

Effects of tropical deforestation on rainfall. Deforestation leads to reduced evapotranspiration (E), resulting in a warmer land surface (*red soil*). Small patches of deforestation (<100 km) cause atmospheric circulations leading to regions of increased (*blue*) and decreased (*red*) rainfall. At larger scales, deforestation reduces rainfall recycling, leading to reduced regional rainfall (R).

In addition, convergence brings in air from over the forest, into the deeper BL over the warmer surface, favoring initiation of convection on the less vegetated side of the land-surface boundary. When convective inhibition is weak, the thermodynamic impact is most important, as it provides better conditions for enhanced convective development, whereas in areas with high convective inhibition, the mesoscale uplift is most important, as it can provide the additional updraught speed to overcome the barrier.

The response of mature convective systems to the land surface may be different compared to the initiation of storms. Convection-permitting modeling results from West Africa show different responses of initiating afternoon storms, which tend to form over boundaries and less vegetated regions, and organized nocturnal rain, which tends to rain more over forest (65). Idealized simulations of one organized convection event interacting with a variable surface in West Africa (66) show that such systems can have complex sensitivities to convective available potential energy (CAPE), the convective inhibition (CIN), and humidity. This suggests that the mean response to the surface may be an average of varied responses between storms, and that the mean response in any region may depend on the balance of rainfall generated by short-lived storms and long-lived systems.

Our process-based understanding of vegetation breezes and their impact on clouds and rainfall is derived primarily from modeling studies, due to the difficulty of observing the breezes directly. Vegetation breezes, however, have been directly observed in aircraft observations over West Africa, where coherent circulations coincident with land surface–induced temperature anomalies persisted over several hours (67). Cospectral analysis shows that the coupling was significant only for length scales larger than 5–10 km, consistent with the modeling studies. Persistent winds in ground measurements consistent with vegetation breezes have also been observed (68, 69).

Satellite data confirm variability in cloud occurrence across sharp gradients in vegetation, consistent with the presence of vegetation breezes controlling the location of cloud initiation.

Enhanced cloud cover over less vegetated regions has been observed in the southern Amazon (35, 70–73), West Africa (67), the United States (74) and Northeast Asia (75). In contrast, enhanced clouds over more vegetated surfaces have been observed over Central America (76), Europe (77), and a range of arid regions (55, 78, 79). In contrast to other studies over the Amazon, shallow cumulus is found to preferentially form over forests in the northeastern Amazon (80). The majority of studies across the Amazon have focused on deforestation patches in the heavily deforested southern Amazon, where the analysis is complicated by biomass-burning aerosol associated with deforestation and the coincidence of meteorological and land-cover gradients (80). Over the Sahel, negative correlations between dry season fires and following wet season rainfall suggest reduced rain over devegetated regions (81), potentially driven by increased albedo (82).

Most observational studies have primarily focused on shallow or mid-level clouds formed by afternoon convection, but some evidence indicates that deep convective systems rain preferentially over forest (72, 73). Satellite rainfall products also show an enhancement of rainfall over deforested land adjacent to forest in the Amazon (41, 83–85), although where surface conditions were more homogeneous, rainfall is higher over forest compared to pasture (84). Significant correlations between forest cover change and rainfall in the Amazon have been found on the 30–50 km scale (86). Deforestation has also been linked to increased elevation of cloud base in Central America (87).

As the scale of deforestation increases from ~1 km to 10s km, thermally driven circulations may diminish (58), and changes in surface roughness may become more important (88, 89). Over areas of pasture larger than 10 km, reductions in surface roughness can combine with increases in sensible heat fluxes to induce mesoscale circulations that cause redistribution of precipitation (**Figure 3**) (88). As the scale of deforestation in the southern Amazon has increased in the past few decades, dynamically driven circulations from changes in roughness length may now dominate over thermally driven circulations (89). This highlights the importance of accounting for realistic deforestation patterns.

Rainfall patterns are further impacted by aerosol from biomass burning. Aerosol has complex impacts on rainfall, operating on local, regional, and global scales. Biomass-burning aerosol has been implicated in local reductions in convective rainfall over Africa (90, 91). Smoke from fires absorbs and scatters radiation, reducing net radiation at the surface, increasing atmospheric heating, and stabilizing the lower atmosphere (92, 93). High dry season aerosol concentrations in the Amazon may delay the onset of rainfall through decreasing cloud droplet size and increasing the height at which precipitation is initiated (94).

Satellite observations show that, outside major tropical forest regions, afternoon rainfall is more likely to occur over drier soils adjacent to wet soils (95), via processes that are analogous to those described here for deforested regions. Repeating the analysis with a range of global and regional models, including ERA-Interim reanalyzes, produced the opposite feedback, with rainfall enhancement over wet soils across all models; the cause of this discrepancy can be attributed specifically to the parameterization of convection (96). This is consistent with the poor coupling between low-level convergence and moist convection in models with parameterized convection. Although the feedback of propagating convective systems with the surface is not certain, observations over West Africa show that they can be initiated by land surface–induced mesoscale flows, with one in eight mesoscale convective systems initiating over land-surface gradients (95). However, propagating systems, which dominate rainfall in much of West Africa and can cause local rainfall maxima at night rather than in the afternoon, may rain more over vegetation where CAPE and the total column water vapor (TCWV) are higher. Since global models struggle to capture these propagating systems (97), this highlights the need for improved parameterizations of convection for global models to fully capture interactions between deforestation and rainfall.

People living within regions of rapid tropical deforestation hold clear perceptions of the impacts of LCC on local and regional climate. In general, these perceptions are of links between forest loss and reduced rainfall, at odds with a range of satellite and modeling studies. In the southern Amazon, people link deforestation to reduced rainfall and increased rainfall irregularity (98). In Borneo, deforestation is linked to concerns over increased temperature, air pollution, and loss of clean water sources (99). Communities living within 5 km of forested national parks in Southeast Asia attached great importance to the forests for providing rainfall and moderating temperatures (100). Research is needed to understand potential inconsistencies between local perceptions and modeling studies.

3.2. Large Scale (Hundreds to Thousands of Kilometers)

On the large scale (hundreds to thousands of kilometers), LCC can impact atmospheric moisture and precipitation through changes to large-scale properties of the atmosphere. Atmospheric transport links water from oceanic and terrestrial sources to rainfall over land (101), with important moisture exchange processes occurring on the way. A key mechanism is E (102), through which vegetation transfers water to the atmosphere, increasing atmospheric humidity and potentially rainfall (**Figure 3**). In continental regions, far from oceanic sources of moisture, water from E can contribute a major fraction of atmospheric moisture (103). Continental moisture recycling (also known as precipitation recycling) is the process where moisture evaporated from land returns as precipitation on land (104). Approximately 40% of global terrestrial rainfall is sourced from terrestrial E (103). For the Amazon, regional recycling ratio estimates range from 17% to 41%, depending on the spatial scale and methodology (104, 105), although in the southwest corner of the basin, precipitation recycling may be as high as 70% (103). The recycling ratio is estimated to be 10–40% over India (106) and 50% over the Congo (107). Through reductions in E, deforestation can reduce downwind atmospheric moisture and rainfall (108).

Several studies have attempted to examine deforestation impacts on rainfall through analysis of long-term climate records. Substantial reductions in forest cover in Thailand are linked to a 30% reduction in rainfall in September (109). Over Borneo, deforestation is observed to be strongly related to increased temperature and reduced rainfall (110). Other studies have explored changes over the past few decades across the Amazon. However, the scarcity of meteorological stations, the relatively short satellite data record, and the role of Atlantic sea surface temperatures (SSTs) in driving large-scale climate variability (111–113) complicate such analysis. An analysis of a 15-year time series (1974–1990) of outgoing longwave radiation indicates an increase in convection over the western Amazon, but no significant changes over the southern Amazon where most deforestation had occurred (114). A synthesis of model simulations was used to show that deforestation extent in 2010 (11.5% of original forest extent in the Amazon) led to a 1.8% reduction in the rainfall in the Amazon (14). This reduction is less than the interannual variability in rainfall and may help explain why negative trends in rainfall are not observed (115). Increasing variability in rainfall over the Amazon during the past few decades (116, 117) has been linked to increased SST, confounding a potential signal from deforestation. Additional work is needed to understand the seasonal effects of LCC.

It is crucial to understand how the atmosphere responds to LCC, through changes in moisture convergence. Process-based modeling experiments have been used to separate the major deforestation-induced changes (albedo, surface roughness, and E) over the Congo (118). In these experiments, increased albedo causes cooling and reduces regional precipitation, whereas changes to roughness length and E induce a dipole over the Congo with reduced precipitation in the western Congo and increased precipitation in the eastern Congo.

Simulations of regional and global-scale deforestation have been completed with GCMs and regional climate models (RCMs). These simulations predict that regional deforestation increases surface temperatures by 1–3 K, matching findings from remote sensing studies (42, 119, 120). Model studies of deforestation in the Congo find that changes in albedo cause a small cooling, which is offset by a warming caused by a decrease in E and roughness length (118, 121). Tropical deforestation leads to an increase in simulated global average surface air temperature of 0.16 ± 0.26 K (122).

Most studies of the impacts of regional-scale deforestation on precipitation focus on the Amazon (9). A synthesis of modeling studies finds that complete deforestation of the Amazon would lead to an annual mean Amazon basin rainfall change of $-16.5 \pm 13\%$ (mean ± standard deviation) (14). Reductions in rainfall tend to increase with increasing deforestation extent; however, the relationship is unlikely to be linear (123). Some studies have suggested sharp reductions in rainfall after some threshold deforestation is reached (8).

There are considerably fewer studies in tropical regions outside the Amazon. **Table 2** synthesizes regional studies that have been conducted outside the Amazon. Studies of deforestation in the Congo Basin in Africa predict $-16 \pm 17\%$ change in regional rainfall, similar to reductions simulated for the Amazon. It has been suggested that LCC has greater impacts on rainfall when it occurs in regions close to the ocean (124), but there have been relatively few studies of the impacts of deforestation in maritime regions such as Borneo (125). LCC has also been implicated

Table 2 Model studies of deforestation impacts on rainfall

Reference	LCC period	Model	Rainfall response
India			
126	1987 to 2005	WRF-CLM, 36-km simulations	Up to −10 mm/day monsoon rainfall
127	1700 to 1850	MIROC, 2.8° simulations	−2 mm/day (∼−25%)
191	1951 to 2005	RegCM4.0 RCM, 27-year simulations	Reduction in moderate rainfall events
Congo			
121	Deforestation scenario for 2050	COSMO-CLM2 RCM, 25 km, 21-year simulations	−2.6% to −3.4%
192	Complete deforestation	LMD GCM, 5.6° × 2°, 1-year simulations	+3.4%
193	Complete deforestation	ICTP RCM, 50-km, 8-year simulations	−30% to −50%
194	Complete deforestation	BATS coupled to an SDM	−10%
195	Complete deforestation	NCAR GCM, 2.8°, 10-year simulations	−10%
196	Complete deforestation and conversion to bare soil	HadAM3 GCM, 2.5° × 3.75°, 25-year simulations	−8% to −16%
197	Deforestation scenario for 2050	REMO RCM, 0.5° simulations	−30% to −50%
118	Complete deforestation	ICTP RegCM3 RCM + BATS, 50-km, 11-year simulations	−42% (western Congo, 5°S–5°N, 10°E–20°E)
West Africa			
150	Historical LCC	7 GCMs	−2% (−0.07 mm/day) over Guinea
15	Historical LCC 1950 to 1990	5 GCMs	−4% to −25% over Sahel

Abbreviations: GCM, general circulation model; LCC, land-cover change; RCM, regional climate model; SDM, statistical dynamical model; SST, sea surface temperature.

in changes in the Indian monsoon (126, 127). Forest loss has been linked to a decline in rainfall across India but the studies do not account for changes in aerosol or irrigation (126). Deforestation of the Cerrado in South America has caused a reduction in E and moisture recycling (128, 129).

A major uncertainty is how the atmospheric circulation responds to the initial LCC-induced changes to surface flux. Latent heat release from forests over the Amazon strengthens the atmospheric heating gradient between land and ocean, enhancing the low-level atmospheric flow of moisture into the Amazon basin (130). Other studies suggest that deforestation-induced warming results in reduction in surface pressure causing increased moisture convergence (118).

Smoke from deforestation fires can further modify rainfall patterns. Smoke aerosol from vegetation fires reduces net radiation at the surface, increasing atmospheric heating and stabilizing the lower atmosphere (92, 93). These changes can lead to 10% to 40% reduction in regional precipitation (91, 131, 132). Aerosol from fires can also delay wet season onset over the Amazon (133).

Tropical deforestation may have remote effects, known as teleconnections (134). Strong effects are simulated in some studies (134, 135), whereas other studies find that the remote effects of deforestation are typically weak (136, 137). Conversion of the Amazon to crops in a coupled climate model alters the rising branch of the Hadley circulation, impacting precipitation in sub-Saharan Africa, Mexico, the southwestern United States, and extratropical South America (138).

4. LAND-COVER CHANGE AND IMPACTS ON RAINFALL

Humans have extensively modified the land surface (139). Agriculture now covers approximately 43% of global ice-free land surface (140), replacing natural forests, savannah, and grassland. More than 50% of the land surface has been altered by human activity as >25% of forests have been permanently cleared (36). Most historical LCC has occurred in temperate regions with, until recently, less LCC in the tropics (36). Rapid LCC has occurred in the past few decades, with 2.3 million km^2 of forest loss and 0.8 million km^2 of forest gain over the period 2000 to 2012, and the greatest rates of forest loss now occur in the tropics (141).

In the Amazon, 20% of the original forest has been converted to pasture, crops, and other land covers (142). Other ecosystems have experienced much larger fractional conversion, with 80% of original Atlantic forest in southern Brazil having been modified (143). Rates of forest loss in the Amazon have declined over most of the past decade; in contrast, increased forest loss is occurring in Indonesia (141). Large changes in tropical land cover are projected in coming decades, with as much as 40% of the Brazilian Amazon deforested by 2050 under a business-as-usual scenario (144).

Tropical deforestation exhibits a large degree of spatial variability. In the Amazon, "fishbone" deforestation patterns on the kilometer scale are common, caused by small cropland regions along roads. Representing this pattern in a model requires horizontal resolution that is higher than even current generation RCMs. The spatial pattern of deforestation in the southern Amazon has increased from the ~km- to the 10s-km scale over the past few decades with potentially important impacts on rainfall (88).

Deforestation in the tropics does not always lead to the establishment of permanent agriculture. Agriculture can often be abandoned after a few years, and shifting cultivation allows secondary forest to establish. Secondary forest can be a dominant land cover in many tropical regions (145). Representing this complex land cover can be a challenge for models. Different land-cover transitions occur across different regions of the tropics. Development of tree plantations (e.g., rubber, oil palm, acacia) is important in Southeast Asia and West Africa, with large projected increases in future decades (146). These different LCC transitions will alter land-surface properties in different ways, likely resulting in different impacts on rainfall.

Recent assessments have been made on the impacts of historical and future LCC on rainfall. Future scenarios of tropical LCC lead to increased skin temperature and reduced E, soil moisture, cloud cover, and rainfall in five different GCMs (147). Deforestation scenarios for the Amazon result in a 5% reduction in rainfall (148), which is smaller than the ∼15% reduction in idealized scenarios of complete Amazon deforestation (8, 14). Using LAI as a proxy for E, Spracklen et al. (108) estimate that following a business-as-usual scenario, by 2050 Amazon deforestation would reduce region rainfall by 12% in the wet season and 21% in the dry season. Future LCC scenarios lead to reduced monsoon rainfall in five GCMs (149). Historical LCC over West Africa also results in simulated reductions in rainfall (16, 150, 151).

5. CURRENT CHALLENGES IN UNDERSTANDING IMPACTS OF VEGETATION ON RAINFALL

Modeling studies of the impacts of LCC on rainfall have typically studied either the local scale or regional to global scales. Models with high spatial resolution are able to explicitly capture realistic land-surface heterogeneity. However, computational constraints limit such high-resolution studies to limited geographical extents and short time periods. These studies are therefore restricted to simulating the impacts of small-scale deforestation on local rainfall. On the opposite spatial scale, global GCMs have studied the impact of large-scale, regional to global deforestation on regional precipitation. Information provided in these studies, particularly the deforestation extent and properties, has often been inadequate (3). Computational constraints restrict these studies to coarse spatial resolution, with grid cells typically 1–5° or 100–500 km across in the tropics. This limits GCM simulations to impacts of regional-scale deforestation (e.g., Amazon basin wide) on regional-scale precipitation. The coarse resolution means that complex spatial land-cover transitions cannot be represented (7). RCM studies, with resolutions of 25–50 km, are able to simulate more realistic deforestation scenarios, but are still unable to fully represent the complex spatial pattern of deforestation down to the kilometer scale. Simulations with RCMs demonstrate complex spatial shifts in rainfall in response to Amazonian deforestation (135, 152) that cannot be resolved by coarse resolution, global GCMs. Some higher resolution models simulate smaller reductions in rainfall in response to deforestation (152), although the sensitivity of rainfall response to model resolution across previous studies is weak (14).

Large-scale simulations include parameterizations of convection, which may not adequately represent links between the land surface and atmosphere (7). Models with a horizontal resolution of less than ∼4 km are capable of permitting convection, and they show some substantial improvements in the representation of convective rainfall (96) and representation of the impacts of LCC (153). Recent advances in computational power have allowed larger domain simulations to be conducted at these resolutions. Over West Africa, initiation of convection occurs preferentially over tree-grass boundaries in a convection-permitting simulation (65).

Treatment of LCC is often too simplistic and does not represent the complex reality of tropical LCC. Conversion of tropical forest to bare soil causes reductions in regional precipitation of 460 ± 100 mm year^{-1}, substantially more than the reduction of 220 ± 260 mm year^{-1} when tropical forest is converted to pasture (122). Most studies on Amazon deforestation assume trees are replaced with pasture. Simulations where tropical forests are replaced with six common tropical crops also cause reductions in rainfall, dependent on whether the crops are irrigated (154). Recent studies have attempted to account for the complex nature of LCC, replacing forest with a mixture of secondary forest and forest regrowth in addition to crops and bare soil (121).

Tropical deforestation and biomass burning are closely linked, but they have largely been studied in isolation. There have been few, if any, studies of the combined impacts of LCC and changes in biomass-burning aerosol.

Simulations have been completed both with atmosphere-only GCMs, where ocean SSTs are prescribed, and with coupled ocean-atmosphere models. Nobre et al. (155) find coupled ocean-atmosphere models are more sensitive to deforestation. Others find little sensitivity (136), although the 20-year simulations in this study might not be sufficient to capture ocean-atmosphere coupling.

Although observational evidence exists for local-scale processes identified by models, namely the presence of vegetation breezes and their impacts on clouds and rainfall, it is more difficult to find evidence to support the conclusions from large-scale models on the impacts of deforestation on rainfall. The most straightforward way to try and identify a link between deforestation and rainfall is either to determine whether rainfall has changed after deforestation over a region has started, or to look at whether spatial patterns in the surface correlate with rainfall patterns. Both of these approaches, however, have significant limitations. Over long time periods, natural variability as well as global climate change can lead to large changes in regional-scale rainfall, so attributing causality is difficult. For example, long-term measurements of rainfall over the Amazon mostly show either no trend or an increase in rainfall over the Amazon basin since deforestation began. Spatial correlations, however, can make use of spatially gridded satellite rainfall estimates, but again can suffer from difficulties in proving causality. In particular, increased rainfall is likely to lead to increased vegetation cover, so there is the issue of separating cause and effect for any positive correlation between forest cover and rainfall.

Figure 4 shows ranging predictions of the impact of deforestation on rainfall in large-scale models, which highlights the degree of uncertainty in these models. Uncertainties may even be larger than shown here, as any potential systematic bias introduced by parameterizations of convection is not apparent. Although high-resolution modeling studies will provide a better quantification of the atmospheric impacts of deforestation, such simulations remain computationally expensive; as such, global simulations over long time periods will continue to be relatively coarse and rely on parameterizations of convection for the foreseeable future. As models become increasingly complex, and begin to include explicit couplings to the land surface, any bias linked to land-atmosphere interactions may be amplified as their impact is aggregated over long time periods.

A relatively new, and still controversial, hypothesis suggests that forests play an even greater role in rainfall than that simulated by models (156, 157). Forest E is suggested to drive important horizontal gradients in atmospheric pressure that result in moisture convergence and greatly enhanced rainfall over forests. New research is required to support or refute this hypothesis.

6. EARTH-SYSTEM FEEDBACKS

Changes in rainfall due to LCC can result in further changes in vegetation and rainfall. Locally enhanced rainfall over the deforested patches may enhance vegetation growth, leading to a negative feedback (51). On the regional scale, reductions in rainfall could have impacts on remaining forest. Deforesting more than 30–50% of the Amazon could reduce rainfall by 40% over nondeforested regions (130), impacting the resilience of remaining forest (158). This could lead to a positive feedback whereby reduced rainfall due to deforestation causes additional forest loss, leading to further reductions in rainfall (159). Tree species adapted to wetter climates are expected to be most vulnerable to future rainfall reductions (160, 161). Reductions in rainfall also increase the susceptibility of remaining forest to fire, causing tree mortality and forest degradation (162, 163). However, the Amazon forest persisted through a substantially drier period during the Last Glacial

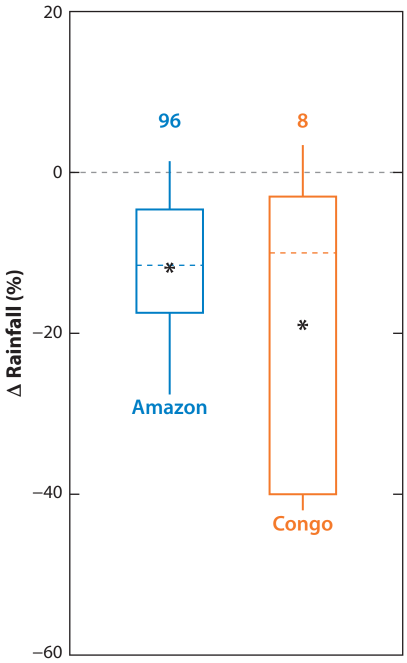

Figure 4

Simulated impacts of tropical deforestation on rainfall. Results are shown for complete deforestation of the Amazon (14) and Congo (studies synthesized in **Table 2**). Numbers at the top indicate the number of simulations included. The box and whiskers show the variability across simulations (*asterisk*, mean; *line*, median; *boxes*, 25th and 75th percentiles; *whiskers*, 5th and 95th percentiles).

Maximum (21,000 years ago) (164), potentially suggesting that the forest has some resilience to climate changes. Long simulations with an interactive land surface are required to understand the implications of altered rainfall on vegetation.

Undisturbed tropical forests are also experiencing global change. These changes are leading to increasing biomass in undisturbed tropical forests across the Amazon (165), Africa (166), and Borneo (167). However, there is little understanding of how such increases in biomass are altering moisture and energy fluxes. Rising atmospheric CO_2 concentrations cause reductions in E, impacting the hydrological cycle (168, 169), with this effect predicted to contribute to asymmetrical changes in tropical land rainfall over the next century (170). Also, evidence from long-term monitoring plots in the Amazon show that the rate of biomass increase is in decline (171).

7. PRIORITIES FOR FUTURE RESEARCH

Improved quantification of the impacts of LCC on rainfall requires improved understanding of land-atmosphere interactions and how these are modified by LCC. Here, we identify priorities for future research.

There is still considerable uncertainty regarding how LCC alters surface properties and fluxes. Across a range of GCMs, identical LCC results in substantial differences in simulated changes in albedo, LAI, and resulting moisture and heat fluxes (16). As such, careful evaluation of models is required, so that weaknesses can be identified, and representation improved. Evaluation requires detailed observations of land-atmosphere fluxes across a range of land covers and geographic locations. Finding adequate observations with which to test and constrain models remains a challenge, with limited in situ data and considerable uncertainties in satellite retrievals.

Much previous work has focused on the Amazon, even though most historical tropical deforestation has occurred elsewhere (143). More research is needed in other regions of rapid land-use change, such as West Africa and Southeast Asia, to better understand the impacts of different land-cover transitions (e.g., forest-to-plantation) in different synoptic environments. Typical patterns of deforestation also differ between regions, with smaller-scale patches of deforestation typical in much of Africa and some parts of South America and Asia.

Many model studies impose unrealistic and dramatic LCCs, such as complete deforestation of the Amazon. Studies with more realistic deforestation patterns and land-cover transitions are needed, although signals are likely to be more complicated and may require more careful interpretation. Differences in the simulated impact of deforestation on rainfall are partly driven by spatial extent of deforestation as well as the area over which regional changes in rainfall are calculated (172). Future studies need to carefully define and report the simulation and analysis conditions.

Deforestation impacts rainfall through processes acting from the kilometer through to the global scale. We currently lack the tools to represent this full range of processes, given the competing needs of high-resolution and large-domain simulations. Studies have therefore focused on local-scale and regional-scale impacts in isolation. This separation of scales in past research is particularly problematic because these scales produce opposite feedbacks between forest loss and rainfall; whereas large-scale deforestation appears to reduce rainfall, small-scale forest loss may enhance rainfall over the deforested patches. These two results are not mutually exclusive, as larger-scale studies are concerned with total rainfall, whereas mesoscale studies are concerned with the initiation of convection, and how rainfall is distributed over different land covers. It is necessary, however, to understand how these different processes affect each other.

Propagating convective systems can provide a large proportion of total rainfall (173), but the impact of LCC on these systems is largely unknown. Large-scale models struggle to produce propagating convective systems at all, at least in part due to fundamental limitations with current parameterizations of convection (97). However, these systems can be hundreds of kilometers across; thus, the domains of large eddy models are not large enough to simulate their entire lifecycle—which is why they primarily focus either on initiation of convection or rainfall from shallower, afternoon convection.

To overcome these issues, it is necessary to simulate regional-scale domains at high enough resolutions to resolve local-scale processes, an approach that has recently become possible with advances in computer power. In these regional models, regional-scale circulations are still constrained, to some extent, by the lateral boundary conditions, but they still allow interactions between local- and continental-scale processes (174). Similarly, this approach could be used to describe feedbacks between LCC and regional-scale circulations. Currently, little is known about whether local-scale feedbacks affect the larger scales, or whether larger scales simply affect the environment for local-scale feedbacks.

Heterogeneous land cover can control the initiation of deep convection, but the extent of the land-surface contribution is likely to be highly location dependent. In two distinctive ways, mature propagating convective systems can also be affected by the land-surface type they travel over. One way is by altering rainfall rates when a convective system travels from one land-surface type to another (65), and the second, by affecting the trajectory of the propagating system, which may preferentially travel over one land-surface type as opposed to another. LCC can therefore alter the climatology of propagating convective systems, by altering both the location and frequency of initiations and their direction of travel. Although some qualitative information exists, for example on the impact of low-level moisture gradients on propagating convective systems (175), significant work is required to understand the role of boundary-layer conditions on the full lifecycle of propagating systems, as well as evidence for these processes as a result of past land-use change.

8. IMPACTS AND POLICY IMPLICATIONS

It is widely recognized that tropical deforestation leads to large CO_2 emissions, and policies to address emissions from deforestation (such as the United Nations Reduced Emissions from Deforestation and Degradation—REDD+—program) are being explored. However, such policies only account for the carbon emissions from LCC. Land-atmosphere interactions resulting from tropical deforestation may lead to larger regional climate changes than those attributed to the CO_2 released from deforestation (176). These changes in local and regional climate will have substantial implications for people's livelihoods and regional economies, further reinforcing the importance of protecting tropical forests (177).

The changes in surface temperature and rainfall due to LCC will affect crop production in surrounding agricultural regions (176). LCC may drive 8% to 17% reductions in moisture availability over important agricultural regions, leading to 5% to 17% reductions in potential crop yield, which is comparable to reductions projected on the basis of future climate change (178). Further expansion of agriculture in the Amazon could even lead to overall reductions in total agricultural output, as reductions in output driven by deforestation-induced rainfall reductions offset increases driven by increased agricultural area (179). Changes in climate due to future expansion of cropland in West Africa are also similar to those due to climate change (180). Conversely, retaining forest patches may benefit local agriculture through reducing temperature extremes (181).

There have been fewer studies of the impacts of reforestation or afforestation on rainfall. The impacts may be smaller than those attributed to deforestation, given either the smaller spatial areas reforested or the time taken for the surface properties of reforested areas to recover to that of forest (122). Simulations of savannah woodlands restoration in Australia suggest a cooling and a 12% reduction in summer drying of near-surface soil (182). Some afforestation projects are intentionally attempting to modify rainfall through planting trees in areas where the natural vegetation is grassland or savanna. Afforestation of 100 km by 100 km areas of desert leads to simulated cooling and increased mesoscale rainfall in a convection-permitting model (183). Some proposed large-scale projects in the Sahel and China involve foresting long, narrow (10–15-km) strips of land. In these situations, local-scale processes are likely to be significant, potentially suppressing rainfall over the afforested area, while increasing rainfall on either side. It is unclear what the overall impact would be on rainfall or how this would affect the survivability of the afforested area.

The Amazon region has experienced extreme seasonal floods and droughts in the past few decades (184), but the contribution of LCC to these events is unknown. Simulated impacts of deforestation include increased drought conditions in an RCM, suggesting deforestation enhances the severity of droughts (185). Conversion of mid-latitude forests to agriculture has also been shown to increase the occurrence of hot, dry summers (186).

The import and export of atmospheric moisture between regions and the contribution of E (187) have led to the term atmospheric watersheds, or precipitation sheds (188). Understanding how to incorporate such interactions into policy mechanisms is now needed (189, 190).

The interactions between tropical land cover and local and regional climate results in links between different United Nations sustainable development goals (SDGs) that need to be accounted for. Through these interactions, Life on Land (SDG15) is linked to Climate Action (SDG13), Clean Water and Sanitation (SDG6), Zero Hunger (SDG2), and No Poverty (SDG1). We need to better appreciate these links and build them into development strategies.

SUMMARY POINTS

1. Vegetation modifies land-surface properties, mediating the exchange of energy, moisture, trace gases, and aerosols between the land and the atmosphere.
2. Tropical deforestation leads to reduced evapotranspiration and reduced surface roughness, increasing local surface temperatures by 1–3 K.
3. Patches of deforestation at scales less than around 100 km can induce boundary layer circulations, leading to a redistribution of local rainfall with increased rainfall over some regions and decreased rainfall elsewhere.
4. Reductions in evapotranspiration lead to reductions in moisture recycling, and extensive tropical deforestation can reduce regional rainfall by up to 40%.
5. The impacts of future tropical land-cover change on rainfall are uncertain but could be of similar magnitude to those caused by climate change.

FUTURE ISSUES

1. New observations of land-atmosphere fluxes across a range of land covers are urgently needed to improve understanding of how land-cover change alters surface properties and fluxes and to constrain model predictions.
2. Much previous work has focused on impacts of deforestation in the Amazon; future work needs to focus on other regions including emerging deforestation frontiers.
3. Model developments are needed so that regional-scale domains can be simulated at high enough resolutions to resolve realistic surface patterns and convection.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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LITERATURE CITED

1. Bonan GB. 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science* 320:1444–49
2. Pielke RA, Avissar R, Raupach M, Dolman AJ, Zeng XB, Denning AS. 1998. Interactions between the atmosphere and terrestrial ecosystems: influence on weather and climate. *Glob. Change Biol.* 4:461–75
3. Pielke RA, Pitman A, Niyogi D, Mahmood R, McAlpine C, et al. 2011. Land use/land cover changes and climate: modeling analysis and observational evidence. *Clim. Change* 2:828–50

4. Mahmood R, Pielke RA, Hubbard KG, Niyogi D, Dirmeyer PA, et al. 2014. Land cover changes and their biogeophysical effects on climate. *Int. J. Climatol.* 34:929–53
5. Liu SG, Bond-Lamberty B, Boysen LR, Ford JD, Fox A, et al. 2017. Grand challenges in understanding the interplay of climate and land changes. *Earth Interact*. 21:1–43
6. Heald CL, Spracklen DV. 2015. Land use change impacts on air quality and climate. *Chem. Rev.* 115:4476–96
7. Pielke RA, Adegoke J, Beltran-Przekurat A, Hiemstra CA, Lin J, et al. 2007. An overview of regional land-use and land-cover impacts on rainfall. *Tellus B* 59:587–601
8. Lawrence D, Vandecar K. 2015. Effects of tropical deforestation on climate and agriculture. *Nat. Clim. Change* 5:27–36
9. D'Almeida C, Vörösmarty CJ, Hurtt GC, Marengo JA, Dingman SL, Keim BD. 2007. The effects of deforestation on the hydrological cycle in Amazonia: a review on scale and resolution. *Int. J. Climatol.* 27:633–47
10. Gash JHC, Nobre CA. 1997. Climatic effects of Amazonian deforestation: some results from ABRACOS. *Bull. Am. Meteorol. Soc.* 78:823–30
11. Giambelluca TW, Holscher D, Bastos TX, Frazao RR, Nullet MA, Ziegler AD. 1997. Observations of albedo and radiation balance over postforest land surfaces in the eastern Amazon Basin. *J. Climate* 10:919–28
12. von Randow C, Manzi AO, Kruijt B, de Oliveira PJ, Zanchi FB, et al. 2004. Comparative measurements and seasonal variations in energy and carbon exchange over forest and pasture in South West Amazonia. *Theor. Appl. Climatol.* 78:5–26
13. Richardson AD, Keenan TF, Migliavacca M, Ryu Y, Sonnentag O, Toomey M. 2013. Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. *Agric. For. Meteorol.* 169:156–73
14. Spracklen DV, Garcia-Carreras L. 2015. The impact of Amazonian deforestation on Amazon basin rainfall. *Geophys. Res. Lett.* 42:9546–52
15. Fuller DO, Ottke C. 2002. Land cover, rainfall and land-surface albedo in West Africa. *Clim. Change* 54:181–204
16. Boone AA, Xue YK, De Sales F, Comer RE, Hagos S, et al. 2016. The regional impact of Land-Use Land-cover Change (LULCC) over West Africa from an ensemble of global climate models under the auspices of the WAMME2 project. *Clim. Dyn.* 47:3547–73
17. Bruijnzeel L, Mulligan M, Scatena FN. 2011. Hydrometeorology of tropical montane cloud forests: emerging patterns. *Hydrological Process*. 25:465–98
18. Vourlitis GL, de Souza Nogueira J, de Almeida Lobo F, Sendall KM, de Paulo SR, et al. 2008. Energy balance and canopy conductance of a tropical semi-deciduous forest of the southern Amazon Basin. *Water Resour. Res.* 44:W03412
19. Canadell J, Jackson RB, Ehleringer JR, Mooney HA, Sala OE, Schulze ED. 1996. Maximum rooting depth of vegetation types at the global scale. *Oecologia* 108:583–95
20. Nepstad DC, Decarvalho CR, Davidson EA, Jipp PH, Lefebvre PA, et al. 1994. The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. *Nature* 372:666–69
21. Seneviratne SI, Corti T, Davin EL, Hirschi M, Jaeger EB, et al. 2010. Investigating soil moisture-climate interactions in a changing climate: a review. *Earth-Sci. Rev.* 99:125–61
22. Wang KC, Dickinson RE. 2012. A review of global terrestrial evapotranspiration: observation, modeling, climatology, and climatic variability. *Rev. Geophys.* 50:RG2005
23. Schlesinger WH, Jasechko S. 2014. Transpiration in the global water cycle. *Agric. For. Meteorol.* 189:115–17
24. Zhang L, Dawes WR, Walker GR. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resour. Res.* 37:701–8
25. Sterling SM, Ducharne A, Polcher J. 2013. The impact of global land-cover change on the terrestrial water cycle. *Nat. Clim. Chang.* 3:385–90
26. Coe MT, Latrubesse EM, Ferreira ME, Amsler ML. 2011. The effects of deforestation and climate variability on the streamflow of the Araguaia River, Brazil. *Biogeochemistry* 105:119–31

27. Lathuillière MJ, Johnson MS, Donner SD. 2012. Water use by terrestrial ecosystems: temporal variability in rainforest and agricultural contributions to evapotranspiration in Mato Grosso, Brazil. *Environ. Res. Lett.* 7:024024
28. Giambelluca TW, Mudd RG, Liu W, Ziegler AD, Kobayashi N, et al. 2016. Evapotranspiration of rubber (*Hevea brasiliensis*) cultivated at two plantation sites in Southeast Asia. *Water Resour. Res.* 52:660–79
29. van Dijk AIJM, Keenan RJ. 2007. Planted forests and water in perspective. *Forest Ecol. Manag.* 251:1–9
30. Giambelluca TW, Ziegler AD, Nullet MA, Truong DM, Tran LT. 2003. Transpiration in a small tropical forest patch. *Agric. For. Meteorol.* 117:1–22
31. Kunert N, Aparecido LMT, Wolff S, Higuchi N, dos Santos J, et al. 2017. A revised hydrological model for the Central Amazon: the importance of emergent canopy trees in the forest water budget. *Agric. For. Meteorol.* 239:47–57
32. Trenberth KE, Fasullo JT, Kiehl J. 2009. Earth's global energy budget. *Bull. Am. Meteorol. Soc.* 90:311–23
33. Restrepo-Coupe N, da Rocha HR, Hutyra LR, da Araujo AC, Borma LS, et al. 2013. What drives the seasonality of photosynthesis across the Amazon basin? A cross-site analysis of eddy flux tower measurements from the Brasil flux network. *Agric. For. Meteorol.* 182–183:128–44
34. Delon C, Druilhet A, Delmas R, Durand P. 2000. Dynamic and thermodynamic structure of the lower troposphere above rain forest and wet savanna during the EXPRESSO campaign. *J. Geophys. Res. Atmos.* 105:14823–40
35. Roy SB, Avissar R. 2002. Impact of land use/land cover change on regional hydrometeorology in Amazonia. *J. Geophys. Res. Atmos.* 107(D20):LBA 4-1–12
36. Hurtt GC, Chini LP, Frolking S, Betts RA, Feddema J, et al. 2011. Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Clim. Change* 109:117–61
37. Artaxo P, Rizzo LV, Brito JF, Barbosa HMJ, Arana A, et al. 2013. Atmospheric aerosols in Amazonia and land use change: from natural biogenic to biomass burning conditions. *Faraday Discuss*. 165:203–35
38. Poschl U, Martin ST, Sinha B, Chen Q, Gunthe SS, et al. 2010. Rainforest aerosols as biogenic nuclei of clouds and precipitation in the Amazon. *Science* 329:1513–16
39. Martin ST, Andreae MO, Artaxo P, Baumgardner D, Chen Q, et al. 2010. Sources and properties of Amazonian aerosol particles. *Rev. Geophys.* 48:RG2002
40. Reddington CL, Butt EW, Ridley DA, Artaxo P, Morgan WT, et al. 2015. Air quality and human health improvements from reductions in deforestation-related fire in Brazil. *Nat. Geosci.* 8:768–71
41. Negri AJ, Adler RF, Xu LM, Surratt J. 2004. The impact of Amazonian deforestation on dry season rainfall. *J. Climate* 17:1306–19
42. Alkama R, Cescatti A. 2016. Biophysical climate impacts of recent changes in global forest cover. *Science* 351:600–4
43. Davin EL, de Noblet-Ducoudre N, Friedlingstein P. 2007. Impact of land cover change on surface climate: relevance of the radiative forcing concept. *Geophys. Res. Lett.* 34:L13702
44. Ban-Weiss GA, Bala G, Cao L, Pongratz J, Caldeira K. 2011. Climate forcing and response to idealized changes in surface latent and sensible heat. *Environ. Res. Lett.* 6:034032
45. Davin EL, de Noblet-Ducoudre N. 2010. Climatic impact of global-scale deforestation: radiative versus nonradiative processes. *J. Climate* 23:97–112
46. Bright RM, Davin E, O'Halloran T, Pongratz J, Zhao KG, Cescatti A. 2017. Local temperature response to land cover and management change driven by non-radiative processes. *Nat. Clim. Chang.* 7:296–302
47. Dias M, Rutledge S, Kabat P, Dias PLS, Nobre C, et al. 2002. Cloud and rain processes in a biosphere-atmosphere interaction context in the Amazon Region. *J. Geophys. Res. Atmos.* 107:LBA 39-1–18
48. Pielke RA. 2001. Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall. *Rev. Geophys.* 39:151–77
49. Roy SB, Weaver CP, Nolan DS, Avissar R. 2003. A preferred scale for landscape forced mesoscale circulations? *J. Geophys. Res. Atmos.* 108:8854
50. Da Silva RR, Avissar R. 2006. The hydrometeorology of a deforested region of the Amazon basin. *J. Hydrometeorol.* 7:1028–42
51. Roy SB. 2009. Mesoscale vegetation-atmosphere feedbacks in Amazonia. *J. Geophys. Res. Atmos.* 114:D20111

52. Saad SI, da Rocha HR, Dias M, Rosolem R. 2010. Can the deforestation breeze change the rainfall in Amazonia? A case study for the BR-163 Highway region. *Earth Interact.* 14:1–25
53. Garcia-Carreras L, Parker DJ. 2011. How does local tropical deforestation affect rainfall? *Geophys. Res. Lett.* 38:L19802
54. Garcia-Carreras L, Parker DJ, Marsham JH. 2011. What is the mechanism for the modification of convective cloud distributions by land surface-induced flows? *J. Atmos. Sci.* 68:619–34
55. Esau IN, Lyons TJ. 2002. Effect of sharp vegetation boundary on the convective atmospheric boundary layer. *Agric. For. Meteorol.* 114:3–13
56. Avissar R, Schmidt T. 1998. An evaluation of the scale at which ground-surface heat flux patchiness affects the convective boundary layer using large-eddy simulations. *J. Atmos. Sci.* 55:2666–89
57. Raasch S, Harbusch G. 2001. An analysis of secondary circirculations and their effects caused by small-scale surface inhomogeneities using large-eddy simulation. *Bound. Layer Meteor.* 101:31–59
58. Patton EG, Sullivan PP, Moeng CH. 2005. The influence of idealized heterogeneity on wet and dry planetary boundary layers coupled to the land surface. *J. Atmos. Sci.* 62:2078–97
59. Prabha TV, Karipot A, Binford MW. 2007. Characteristics of secondary circulations over an inhomogeneous surface simulated with large-eddy simulation. *Bound. Layer Meteor.* 123:239–61
60. Suhring M, Maronga B, Herbort F, Raasch S. 2014. On the effect of surface heat-flux heterogeneities on the mixed-layer-top entrainment. *Bound. Layer Meteor.* 151:531–56
61. Weaver CP, Avissar R. 2001. Atmospheric disturbances caused by human modification of the landscape. *Bull. Am. Meteorol. Soc.* 82:269–81
62. Baldi M, Dalu GA, Pielke RA. 2008. Vertical velocities and available potential energy generated by landscape variability—theory. *J. Appl. Meteorol. Climatol.* 47:397–410
63. Weaver CP. 2004. Coupling between large-scale atmospheric processes and mesoscale land-atmosphere interactions in the US Southern Great Plains during summer. Part I: Case studies. *J. Hydrometeorol.* 5:1223–46
64. Wang JF, Bras RL, Eltahir EAB. 2000. The impact of observed deforestation on the mesoscale distribution of rainfall and clouds in Amazonia. *J. Hydrometeorol.* 1:267–86
65. Hartley AJ, Parker DJ, Garcia-Carreras L, Webster S. 2016. Simulation of vegetation feedbacks on local and regional scale precipitation in West Africa. *Agric. For. Meteorol.* 222:59–70
66. Adler B, Kalthoff N, Gantner L. 2011. Initiation of deep convection caused by land-surface inhomogeneities in West Africa: a modelled case study. *Meteorol. Atmos. Phys.* 112:15–27
67. Garcia-Carreras L, Parker DJ, Taylor CM, Reeves CE, Murphy JG. 2010. Impact of mesoscale vegetation heterogeneities on the dynamical and thermodynamic properties of the planetary boundary layer. *J. Geophys. Res. Atmos.* 115:D03102
68. Doran JC, Shaw WJ, Hubbe JM. 1995. Boundary-layer characteristics over areas of inhomogeneous surface fluxes. *J. Appl. Meteorol.* 34:559–71
69. Souza EP, Renno NO, Dias M. 2000. Convective circulations induced by surface heterogeneities. *J. Atmos. Sci.* 57:2915–22
70. Chagnon FJF, Bras RL, Wang J. 2004. Climatic shift in patterns of shallow clouds over the Amazon. *Geophys. Res. Lett.* 31:L24212
71. Cutrim E, Martin DW, Rabin R. 1995. Enhancement of cumulus clouds over deforested lands in Amazonia. *Bull. Am. Meteorol. Soc.* 76:1801–5
72. Wang JF, Chagnon FJF, Williams ER, Betts AK, Renno NO, et al. 2009. Impact of deforestation in the Amazon basin on cloud climatology. *PNAS* 106:3670–74
73. Durieux L, Machado LAT, Laurent H. 2003. The impact of deforestation on cloud cover over the Amazon arc of deforestation. *Remote Sens. Environ.* 86:132–40
74. Rabin RM, Stadler S, Wetzel PJ, Stensrud DJ, Gregory M. 1990. Observed effects of landscape variability on convective clouds. *Bull. Am. Meteorol. Soc.* 71:272–80
75. Sato T, Kimura F, Hasegawa AS. 2007. Vegetation and topographic control of cloud activity over arid/semiarid Asia. *J. Geophys. Res. Atmos.* 112:D24109
76. Nair US, Lawton RO, Welch RM, Pielke RA. 2003. Impact of land use on Costa Rican tropical montane cloud forests: sensitivity of cumulus cloud field characteristics to lowland deforestation. *J. Geophys. Res. Atmos.* 108:D74206

77. Teuling AJ, Taylor CM, Meirink JF, Melsen LA, Miralles DG, et al. 2017. Observational evidence for cloud cover enhancement over western European forests. *Nat. Commun.* 8:14065
78. Ray DK, Nair US, Welch RM, Han QY, Zeng J, et al. 2003. Effects of land use in Southwest Australia: 1. Observations of cumulus cloudiness and energy fluxes. *J. Geophys. Res. Atmos.* 108:4414
79. Garcia-Carreras L, Marsham JH, Spracklen DV. 2017. Observations of increased cloud cover over irrigated agriculture in an arid environment. *J. Hydrometeorol.* 18:2161–72
80. Heiblum RH, Koren I, Feingold G. 2014. On the link between Amazonian forest properties and shallow cumulus cloud fields. *Atmos. Chem. Phys.* 14:6063–74
81. Saha MV, Scanlon TM, D'Odorico P. 2016. Suppression of rainfall by fires in African drylands. *Geophys. Res. Lett.* 43:8527–33
82. Saha MV, D'Odorico P, Scanlon TM. 2017. Albedo changes after fire as an explanation of fire-induced rainfall suppression. *Geophys. Res. Lett.* 44:3916–23
83. Chagnon FJF, Bras RL. 2005. Contemporary climate change in the Amazon. *Geophys. Res. Lett.* 32:L13703
84. Knox R, Bisht G, Wang JF, Bras R. 2011. Precipitation variability over the forest-to-nonforest transition in southwestern Amazonia. *J. Climate* 24:2368–77
85. Funatsu BM, Dubreuil V, Claud C, Arvor D, Gan MA. 2012. Convective activity in Mato Grosso state (Brazil) from microwave satellite observations: comparisons between AMSU and TRMM data sets. *J. Geophys. Res. Atmos.* 117:D16109
86. Debortoli NS, Dubreuil V, Hirota M, Rodrigues S, Lindoso DP, Nabucet J. 2017. Detecting deforestation impacts in Southern Amazonia rainfall using rain gauges. *Int. J. Climatol.* 37:2889–900
87. Lawton RO, Nair US, Pielke RA, Welch RM. 2001. Climatic impact of tropical lowland deforestation on nearby montane cloud forests. *Science* 294:584–87
88. Khanna J, Medvigy D. 2014. Strong control of surface roughness variations on the simulated dry season regional atmospheric response to contemporary deforestation in Rondonia, Brazil. *J. Geophys. Res. Atmos.* 119:13067–78
89. Khanna J, Medvigy D, Fueglistaler S, Walko R. 2017. Regional dry-season climate changes due to three decades of Amazonian deforestation. *Nat. Clim. Chang.* 7:200–204
90. Tosca MG, Diner DJ, Garay MJ, Kalashnikova OV. 2015. Human-caused fires limit convection in tropical Africa: first temporal observations and attribution. *Geophys. Res. Lett.* 42:6492–501
91. Hodnebrog O, Myhre G, Forster PM, Sillmann J, Samset BH. 2016. Local biomass burning is a dominant cause of the observed precipitation reduction in southern Africa. *Nat. Commun.* 7:11236
92. Kolusu SR, Marsham JH, Mulcahy J, Johnson B, Dunning C, et al. 2015. Impacts of Amazonia biomass burning aerosols assessed from short-range weather forecasts. *Atmos. Chem. Phys.* 15:12251–66
93. Zhang Y, Fu R, Yu HB, Qian Y, Dickinson R, et al. 2009. Impact of biomass burning aerosol on the monsoon circulation transition over Amazonia. *Geophys. Res. Lett.* 36:L10814
94. Andreae MO, Rosenfeld D, Artaxo P, Costa AA, Frank GP, et al. 2004. Smoking rain clouds over the Amazon. *Science* 303:1337–42
95. Taylor CM, de Jeu RAM, Guichard F, Harris PP, Dorigo WA. 2012. Afternoon rain more likely over drier soils. *Nature* 489:423–26
96. Taylor CM, Birch CE, Parker DJ, Dixon N, Guichard F, et al. 2013. Modeling soil moisture-precipitation feedback in the Sahel: importance of spatial scale versus convective parameterization. *Geophys. Res. Lett.* 40:6213–18
97. Stephens GL, L'Ecuyer T, Forbes R, Gettelman A, Golaz JC, et al. 2010. Dreary state of precipitation in global models. *J. Geophys. Res. Atmos.* 115:D24211
98. Dubreuil V, Funatsu BM, Michot V, Nasuti S, Debortoli N, et al. 2017. Local rainfall trends and their perceptions by Amazonian communities. *Clim. Change* 143:461–72
99. Meijaard E, Abram NK, Wells JA, Pellier AS, Ancrenaz M, et al. 2013. People's perceptions about the importance of forests on Borneo. *PLOS ONE* 8:e73008
100. Sodhi NS, Lee TM, Sekercioglu CH, Webb EL, Prawiradilaga DM, et al. 2010. Local people value environmental services provided by forested parks. *Biodivers. Conserv.* 19:1175–88
101. Gimeno L, Dominguez F, Nieto R, Trigo R, Drumond A, et al. 2016. Major mechanisms of atmospheric moisture transport and their role in extreme precipitation events. *Annu. Rev. Environ. Resour.* 41:117–41

102. Shukla J, Mintz Y. 1982. Influence of land-surface evapo-transpiration on the Earth's climate. *Science* 215:1498–501
103. van der Ent RJ, Savenije HHG, Schaefli B, Steele-Dunne SC. 2010. Origin and fate of atmospheric moisture over continents. *Water Resour. Res.* 46:W09525
104. Gimeno L, Stohl A, Trigo RM, Dominguez F, Yoshimura K, et al. 2012. Oceanic and terrestrial sources of continental precipitation. *Rev. Geophys.* 50:RG4003
105. Zemp DC, Schleussner CF, Barbosa HMJ, van der Ent RJ, Donges JF, et al. 2014. On the importance of cascading moisture recycling in South America. *Atmos. Chem. Phys.* 14:13337–59
106. Sujith K, Saha SK, Pokhrel S, Hazra A, Chaudhari HS. 2017. The dominant modes of recycled monsoon rainfall over India. *J. Hydrometeorol.* 18:2647–57
107. Sori R, Nieto R, Vicente-Serrano SM, Drumond A, Gimeno L. 2017. A Lagrangian perspective of the hydrological cycle in the Congo River basin. *Earth Syst. Dynam.* 8:653–75
108. Spracklen DV, Arnold SR, Taylor CM. 2012. Observations of increased tropical rainfall preceded by air passage over forests. *Nature* 489:282–85
109. Kanae S, Oki T, Musiake K. 2001. Impact of deforestation on regional precipitation over the Indochina Peninsula. *J. Hydrometeorol.* 2:51–70
110. McAlpine CA, Johnson A, Salazar A, Syktus J, Wilson K, et al. 2018. Forest loss and Borneo's climate. *Environ. Res. Lett.* 13(4):044009
111. Fernandes K, Giannini A, Verchot L, Baethgen W, Pinedo-Vasquez M. 2015. Decadal covariability of Atlantic SSTs and western Amazon dry-season hydroclimate in observations and CMIP5 simulations. *Geophys. Res. Lett.* 42:6793–801
112. Haylock MR, Peterson TC, Alves LM, Ambrizzi T, Anunciacao YMT, et al. 2006. Trends in total and extreme South American rainfall in 1960–2000 and links with sea surface temperature. *J. Climate* 19:1490–512
113. Depaiva E, Clarke RT. 1995. Time trends in rainfall records in Amazonia. *Bull. Am. Meteorol. Soc.* 76:2203–9
114. Chu PS, Yu ZP, Hastenrath S. 1994. Detecting climate-change concurrent with deforestation in the Amazon Basin—Which way has it gone? *Bull. Am. Meteorol. Soc.* 75:579–83
115. Panday PK, Coe MT, Macedo MN, Lefebvre P, Castanho A. 2015. Deforestation offsets water balance changes due to climate variability in the Xingu River in eastern Amazonia. *J. Hydrol.* 523:822–29
116. Chen TC, Yoon JH, St. Croix KJ, Takle ES. 2001. Suppressing impacts of the Amazonian deforestation by the global circulation change. *Bull. Am. Meteorol. Soc.* 82:2209–16
117. Gloor M, Brienen RJW, Galbraith D, Feldpausch TR, Schongart J, et al. 2013. Intensification of the Amazon hydrological cycle over the last two decades. *Geophys. Res. Lett.* 40:1729–33
118. Bell JP, Tompkins AM, Bouka-Biona C, Sanda IS. 2015. A process-based investigation into the impact of the Congo basin deforestation on surface climate. *J. Geophys. Res. Atmos.* 120:5721–39
119. Li Y, Zhao MS, Mildrexler DJ, Motesharrei S, Mu QZ, et al. 2016. Potential and actual impacts of deforestation and afforestation on land surface temperature. *J. Geophys. Res. Atmos.* 121:14372–86
120. Sabajo CR, le Maire G, June T, Meijide A, Roupsard O, Knohl A. 2017. Expansion of oil palm and other cash crops causes an increase of the land surface temperature in the Jambi province in Indonesia. *Biogeosciences* 14:4619–35
121. Akkermans T, Thiery W, Van Lipzig NPM. 2014. The regional climate impact of a realistic future deforestation scenario in the Congo Basin. *J. Climate* 27:2714–34
122. Perugini L, Caporaso L, Marconi S, Cescatti A, Quesada B, et al. 2017. Biophysical effects on temperature and precipitation due to land cover change. *Environ. Res. Lett.* 12:053002
123. Badger AM, Dirmeyer PA. 2016. Diagnosing nonlinearities in the local and remote responses to partial Amazon deforestation. *J. Geophys. Res. Atmos.* 121:9033–47
124. van der Molen MK, Dolman AJ, Waterloo MJ, Bruijnzeel LA. 2006. Climate is affected more by maritime than by continental land use change: a multiple scale analysis. *Glob. Planet. Change* 54:128–49
125. Takahashi A, Kumagai T, Kanamori H, Fujinami H, Hiyama T, Hara M. 2017. Impact of tropical deforestation and forest degradation on precipitation over Borneo Island. *J. Hydrometeorol.* 18:2907–22
126. Paul S, Ghosh S, Oglesby R, Pathak A, Chandrasekharan A, Ramsankaran R. 2016. Weakening of Indian summer monsoon rainfall due to changes in land use land cover. *Sci. Rep.* 6:32177

127. Yamashima R, Matsumoto J, Takata K, Takahashi HG. 2015. Impact of historical land-use changes on the Indian summer monsoon onset. *Int. J. Climatol.* 35:2419–30
128. Spera SA, Galford GL, Coe MT, Macedo MN, Mustard JF. 2016. Land-use change affects water recycling in Brazil's last agricultural frontier. *Glob. Change Biol.* 22:3405–13
129. Arantes AE, Ferreira LG, Coe MT. 2016. The seasonal carbon and water balances of the Cerrado environment of Brazil: past, present, and future influences of land cover and land use. *ISPRS-J. Photogramm. Remote Sens.* 117:66–78
130. Boers N, Marwan N, Barbosa HMJ, Kurths J. 2017. A deforestation-induced tipping point for the South American monsoon system. *Sci. Rep.* 7:41489
131. Tosca MG, Randerson JT, Zender CS, Flanner MG, Rasch PJ. 2010. Do biomass burning aerosols intensify drought in equatorial Asia during El Niño? *Atmos. Chem. Phys.* 10:3515–28
132. Lee D, Sud YC, Oreopoulos L, Kim KM, Lau WK, Kang IS. 2014. Modeling the influences of aerosols on pre-monsoon circulation and rainfall over Southeast Asia. *Atmos. Chem. Phys.* 14:6853–66
133. Gu Y, Liou KN, Jiang JH, Fu R, Lu S, Xue Y. 2017. A GCM investigation of impact of aerosols on the precipitation in Amazon during the dry to wet transition. *Clim. Dyn.* 48:2393–404
134. Werth D, Avissar R. 2002. The local and global effects of Amazon deforestation. *J. Geophys. Res. Atmos.* 107:D208087
135. Medvigy D, Walko RL, Otte MJ, Avissar R. 2013. Simulated changes in Northwest US climate in response to Amazon deforestation. *J. Climate* 26:9115–36
136. Voldoire A, Royer JF. 2005. Climate sensitivity to tropical land surface changes with coupled versus prescribed SSTs. *Clim. Dyn.* 24:843–62
137. Findell KL, Knutson TR, Milly PCD. 2006. Weak simulated extratropical responses to complete tropical deforestation. *J. Climate* 19:2835–50
138. Badger AM, Dirmeyer PA. 2016. Remote tropical and sub-tropical responses to Amazon deforestation. *Clim. Dyn.* 46:3057–66
139. Foley JA, DeFries R, Asner GP, Barford C, Bonan G, et al. 2005. Global consequences of land use. *Science* 309:570–74
140. Ramankutty N, Evan AT, Monfreda C, Foley JA. 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Glob. Biogeochem. Cycle* 22:GB1003
141. Hansen MC, Potapov PV, Moore R, Hancher M, Turubanova SA, et al. 2013. High-resolution global maps of 21st-century forest cover change. *Science* 342:850–53
142. Davidson EA, de Araujo AC, Artaxo P, Balch JK, Brown IF, et al. 2012. The Amazon basin in transition. *Nature* 481:321–28
143. Salazar A, Baldi G, Hirota M, Syktus J, McAlpine C. 2015. Land use and land cover change impacts on the regional climate of non-Amazonian South America: a review. *Glob. Planet. Change* 128:103–19
144. Soares BS, Nepstad DC, Curran LM, Cerqueira GC, Garcia RA, et al. 2006. Modelling conservation in the Amazon basin. *Nature* 440:520–23
145. Giambelluca TW. 2002. Hydrology of altered tropical forest. *Hydrol. Process.* 16:1665–69
146. Warren-Thomas E, Dolman PM, Edwards DP. 2015. Increasing demand for natural rubber necessitates a robust sustainability initiative to mitigate impacts on tropical biodiversity. *Conserv. Lett.* 8:230–41
147. Quesada B, Arneth A, de Noblet-Ducoudre N. 2017. Atmospheric, radiative, and hydrologic effects of future land use and land cover changes: a global and multimodel climate picture. *J. Geophys. Res. Atmos.* 122:5113–31
148. Wright JS, Fu R, Worden JR, Chakraborty S, Clinton NE, et al. 2017. Rainforest-initiated wet season onset over the southern Amazon. *PNAS* 114:8481–86
149. Quesada B, Devaraju N, de Noblet-Ducoudre N, Arneth A. 2017. Reduction of monsoon rainfall in response to past and future land use and land cover changes. *Geophys. Res. Lett.* 44:1041–50
150. Sy S, de Noblet-Ducoudre N, Quesada B, Sy I, Dieye AM, et al. 2017. Land-surface characteristics and climate in West Africa: models' biases and impacts of historical anthropogenically-induced deforestation. *Sustainability* 9:1917
151. Wang GL, Yu M, Xue YK. 2016. Modeling the potential contribution of land cover changes to the late twentieth century Sahel drought using a regional climate model: impact of lateral boundary conditions. *Clim. Dyn.* 47:3457–77

152. Medvigy D, Walko RL, Avissar R. 2011. Effects of deforestation on spatiotemporal distributions of precipitation in South America. *J. Climate* 24:2147–63
153. Vanden Broucke S, Van Lipzig N. 2017. Do convection-permitting models improve the representation of the impact of LUC? *Clim. Dyn.* 49:2749–63
154. Badger AM, Dirmeyer PA. 2015. Climate response to Amazon forest replacement by heterogeneous crop cover. *Hydrol. Earth Syst. Sci.* 19:4547–57
155. Nobre P, Malagutti M, Urbano DF, de Almeida RAF, Giarolla E. 2009. Amazon deforestation and climate change in a coupled model simulation. *J. Climate* 22:5686–97
156. Sheil D, Murdiyarso D. 2009. How forests attract rain: an examination of a new hypothesis. *Bioscience* 59:341–47
157. Makarieva AM, Gorshkov VG. 2007. Biotic pump of atmospheric moisture as driver of the hydrological cycle on land. *Hydrology Earth Syst. Sci.* 11:1013–33
158. Zemp DC, Schleussner CF, Barbosa HMJ, Rammig A. 2017. Deforestation effects on Amazon forest resilience. *Geophys. Res. Lett.* 44:6182–90
159. Zemp DC, Schleussner CF, Barbosa HMJ, Hirota M, Montade V, et al. 2017. Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. *Nat. Commun.* 8:14681
160. Esquivel-Muelbert A, Baker TR, Dexter KG, Lewis SL, ter Steege H, et al. 2017. Seasonal drought limits tree species across the Neotropics. *Ecography* 40:618–29
161. Esquivel-Muelbert A, Galbraith D, Dexter KG, Baker TR, Lewis SL, et al. 2017. Biogeographic distributions of neotropical trees reflect their directly measured drought tolerances. *Sci. Rep.* 7:8334
162. Brando PM, Balch JK, Nepstad DC, Morton DC, Putz FE, et al. 2014. Abrupt increases in Amazonian tree mortality due to drought-fire interactions. *PNAS* 111:6347–52
163. Le Page Y, Morton D, Hartin C, Bond-Lamberty B, Pereira JMC, et al. 2017. Synergy between land use and climate change increases future fire risk in Amazon forests. *Earth Syst. Dynam.* 8:1237–46
164. Wang XF, Edwards RL, Auler AS, Cheng H, Kong XG, et al. 2017. Hydroclimate changes across the Amazon lowlands over the past 45,000 years. *Nature* 541:204–7
165. Baker TR, Phillips OL, Malhi Y, Almeida S, Arroyo L. 2004. Increasing biomass in Amazonian forest plots. *Philos. Trans. R. Soc. Lond. B* 359:353–65
166. Lewis SL, Lopez-Gonzalez G, Sonké B, Affum-Baffoe K, Baker TR, et al. 2009. Increasing carbon storage in intact African tropical forests. *Nature* 457:1003
167. Qie L, Lewis SL, Sullivan MJP, Lopez-Gonzalez G, Pickavance GC, et al. 2017. Long-term carbon sink in Borneo's forests halted by drought and vulnerable to edge effects. *Nature Commun.* 8:1966
168. Halladay K, Good P. 2017. Non-linear interactions between CO_2 radiative and physiological effects on Amazonian evapotranspiration in an Earth system model. *Clim. Dyn.* 49:2471–90
169. Keenan TF, Hollinger DY, Bohrer G, Dragoni D, Munger JW, et al. 2013. Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise. *Nature* 499:324–27
170. Kooperman GJ, Chen Y, Hoffman FM, Koven CD, Lindsay K, et al. 2018. Forest response to rising CO_2 drives zonally asymmetric rainfall change over tropical land. *Nat. Clim. Change* 8:434–40
171. Brienen RJW, Phillips OL, Feldpausch TR, Gloor E, Baker TR, et al. 2015. Long-term decline of the Amazon carbon sink. *Nature* 519:344–48
172. Pitman AJ, Lorenz R. 2016. Scale dependence of the simulated impact of Amazonian deforestation on regional climate. *Environ. Res. Lett.* 11:094025
173. Mathon V, Laurent H, Lebel T. 2002. Mesoscale convective system rainfall in the Sahel. *J. Appl. Meteorol.* 41:1081–92
174. Marsham JH, Dixon NS, Garcia-Carreras L, Lister GMS, Parker DJ, et al. 2013. The role of moist convection in the West African monsoon system: insights from continental-scale convection-permitting simulations. *Geophys. Res. Lett.* 40:1843–49
175. Birch CE, Parker DJ, O'Leary A, Marsham JH, Taylor CM, et al. 2013. Impact of soil moisture and convectively generated waves on the initiation of a West African mesoscale convective system. *Q. J. R. Meteorol. Soc.* 139:1712–30
176. Coe MT, Brando PM, Deegan LA, Macedo MN, Neill C, Silvério DV. 2017. The forests of the Amazon and Cerrado moderate regional climate and are the key to the future. *Trop. Conserv. Sci.* 10:1940082917720671

177. Gullison RE, Frumhoff PC, Canadell JG, Field CB, Nepstad DC, et al. 2007. Tropical forests and climate policy. *Science* 316:985–86
178. Bagley JE, Desai AR, Dirmeyer PA, Foley JA. 2012. Effects of land cover change on moisture availability and potential crop yield in the world's breadbaskets. *Environ. Res. Lett.* 7:014009
179. Oliveira LJC, Costa MH, Soares BS, Coe MT. 2013. Large-scale expansion of agriculture in Amazonia may be a no-win scenario. *Environ. Res. Lett.* 8:024021
180. Ahmed KF, Wang GL, You LZ, Anyah R, Zhang CR, Burnicki A. 2017. Projecting regional climate and cropland changes using a linked biogeophysical-socioeconomic modeling framework: 2. Transient dynamics. *J. Adv. Model. Earth Syst.* 9:377–88
181. Cohn A. 2017. Leveraging climate regulation by ecosystems for agriculture to promote ecosystem stewardship. *Trop. Conserv. Sci.* 10:1940082917720672
182. Syktus JI, McAlpine CA. 2016. More than carbon sequestration: biophysical climate benefits of restored savanna woodlands. *Sci. Rep.* 6:29194
183. Wulfmeyer V, Branch O, Warrach-Sagi K, Bauer HS, Schwitalla T, Becker K. 2014. The impact of plantations on weather and climate in coastal desert regions. *J. Appl. Meteorol. Climatol.* 53:1143–69
184. Marengo JA, Espinoza JC. 2016. Extreme seasonal droughts and floods in Amazonia: causes, trends and impacts. *Int. J. Climatol.* 36:1033–50
185. Bagley JE, Desai AR, Harding KJ, Snyder PK, Foley JA. 2014. Drought and deforestation: Has land cover change influenced recent precipitation extremes in the Amazon? *J. Climate* 27:345–61
186. Findell KL, Berg A, Gentine P, Krasting JP, Lintner BR, et al. 2017. The impact of anthropogenic land use and land cover change on regional climate extremes. *Nat. Commun.* 8:989
187. Dirmeyer PA, Brubaker KL, DelSole T. 2009. Import and export of atmospheric water vapor between nations. *J. Hydrol.* 365:11–22
188. Keys PW, van der Ent RJ, Gordon LJ, Hoff H, Nikoli R, Savenije HHG. 2012. Analyzing precipitationsheds to understand the vulnerability of rainfall dependent regions. *Biogeosciences* 9:733–46
189. Bright RM. 2015. Metrics for biogeophysical climate forcings from land use and land cover changes and their inclusion in life cycle assessment: a critical review. *Environ. Sci. Technol.* 49:3291–303
190. West PC, Narisma GT, Barford CC, Kucharik CJ, Foley JA. 2011. An alternative approach for quantifying climate regulation by ecosystems. *Front. Ecol. Environ.* 9:126–33
191. Halder S, Saha SK, Dirmeyer PA, Chase TN, Goswami BN. 2016. Investigating the impact of land-use land-cover change on Indian summer monsoon daily rainfall and temperature during 1951–2005 using a regional climate model. *Hydrol. Earth Syst. Sci.* 20:1765–84
192. Polcher J, Laval K. 1994. The impact of African and Amazonian deforestation on tropical climate. *J. Hydrol.* 155:389–405
193. Nogherotto R, Coppola E, Giorgi F, Mariotti L. 2013. Impact of Congo Basin deforestation on the African monsoon. *Atmos. Sci. Lett.* 14:45–51
194. Varejao-Silva MA, Franchito SH, Rao VB. 1998. A coupled biosphere-atmosphere climate model suitable for studies of climatic change due to land surface alterations. *J. Climate* 11:1749–67
195. Semazzi FHM, Song Y. 2001. A GCM study of climate change induced by deforestation in Africa. *Clim. Res.* 17:169–82
196. Osborne TM, Lawrence DM, Slingo JM, Challinor AJ, Wheeler TR. 2004. Influence of vegetation on the local climate and hydrology in the tropics: sensitivity to soil parameters. *Clim. Dyn.* 23:45–61
197. Paeth H, Born K, Girmes R, Podzun R, Jacob D. 2009. Regional climate change in tropical and Northern Africa due to greenhouse forcing and land use changes. *J. Climate* 22:114–32
198. Saleska SR, da Rocha HR, Huete AR, Nobre AD, Artaxo P, Shimabukuro YE. 2013. *LBA-ECO CD-32 Flux Tower Network Data Compilation, Brazilian Amazon: 1999–2006. Data set.* Distrib. Active Archive Cent., Oak Ridge Nat. Lab., Oak Ridge, TN. **http://dx.doi.org/10.3334/ORNLDAAC/1174**