Keywords
vegetation, land-cover change, land-atmosphere interaction, rainfall

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.
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 CO₂, 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 discusses current challenges in simulating impacts of LCC on rainfall. Section 5 outlines the impacts of historical and future 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 forest is compared to 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 (m² 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,
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.

Evaporation allows 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 CO₂ 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, 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 are 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.
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 are 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 reanalyzer, 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) is 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 estimate whether 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 induces 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 ± 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 ± 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 in changes in the Indian monsoon (126, 127). Forest loss has been linked to a decline in 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.
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 reduce 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 km² of forest loss and 0.8 million km² 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 ways 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 begins. 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 that is 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 on rainfall than 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...
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\textsubscript{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

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**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 (star, mean; line, median; boxes, 25th and 75th percentiles; whiskers, 5th and 95th percentiles).
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\textsubscript{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\textsubscript{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 cause 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

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