nature climate change

REVIEW ARTICLE
PUBLISHED ONLINE: 18 DECEMBER 2014 | DOI: 10.1038/NCLIMATE2430

Effects of tropical deforestation on climate and agriculture

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Tower, ground-based and satellite observations indicate that tropical deforestation results in warmer, drier conditions at the local scale. Understanding the regional or global impacts of deforestation on climate, and ultimately on agriculture, requires modelling. General circulation models show that completely deforesting the tropics could result in global warming equivalent to that caused by burning of fossil fuels since 1850, with more warming and considerable drying in the tropics. More realistic scenarios of deforestation yield less warming and less drying, suggesting critical thresholds beyond which rainfall is substantially reduced. In regional, mesoscale models that capture topography and vegetation-based discontinuities, small clearings can actually enhance rainfall. At this smaller scale as well, a critical deforestation threshold exists, beyond which rainfall declines. Future agricultural productivity in the tropics is at risk from a deforestation-induced increase in mean temperature and the associated heat extremes and from a decline in mean rainfall or rainfall frequency. Through teleconnections, negative impacts on agriculture could extend well beyond the tropics.

Considerable evidence from both modelling and empirical studies indicates that tropical deforestation on many scales influences local, regional, and even global climate[1–3]. Deforestation-driven changes to water availability and climate variability could have strong implications for agricultural production systems and food security in some regions. Here we review the impacts of tropical deforestation on climate in the three major tropical regions at spatial scales from local to global, and we consider the implications for agriculture.

Evidence from global modelling studies

Experiments using general circulation models (GCMs) have greatly influenced our understanding of how the land surface affects climate. GCMs are global, 3D computer models of the climate system that link the atmosphere, oceans, and land surface. They operate on a coarse resolution, often with grids of 1°–5° (latitude and longitude, ~110 km to ~550 km across at the equator). Current models incorporate the hydrologic cycle and an explicit representation of plant canopies and their effect on energy and water fluxes (including radiative and turbulent transfers, and the physical and biological controls on evapotranspiration). The atmosphere and biosphere form a coupled system whereby climate influences vegetation distribution and ecosystem function, which feed back to affect climate[4]. These models have been used to simulate the climatic consequences of global deforestation, pantropical deforestation, and regional-scale deforestation of the Amazon basin, Central Africa, or Southeast Asia.

Global, pantropical, and regional impacts of pantropical deforestation. Complete deforestation of the entire tropics leads to an increase in global mean temperatures, and no change in global mean precipitation. The magnitude of predicted global warming varies from 0.1–0.7 °C (refs 5–7). Thus, at the upper end, deforestation of the tropics would effectively double the observed warming since 1850[8]. Mean precipitation remains unchanged, partly owing to the opposing signals of local and regional impacts and because global averaging minimizes these climatic responses[5,9–11].

Warming is more substantial across the tropics (0.1–1.3 °C), as is drying, (approximately −270 mm yr^{-1} or up to 10–15% of annual rainfall)[7,11]. Amazonia responds more strongly than Southeast Asia or Central Africa. Predicted warming ranges from 0–2 °C (mean of 0.63 °C) over the Amazon basin[7,11–16]. Responses in Southeast Asia and Central Africa are much less severe (−0.2 °C to +0.2 °C and −0.2 °C to +0.4 °C, respectively)[13,14,16,17]. Pantropical deforestation leads to drying in all tropical regions: −146 to −547 mm yr^{-1} (mean −337 mm yr^{-1}) for Amazonia, −44 to −251 mm yr^{-1} (mean −179 mm yr^{-1}) for Southeast Asia, and −63 to −109 mm yr^{-1} (mean −88 mm yr^{-1}) for Central Africa[11–17].

Regional impacts of regional deforestation. Studies using GCMs agree overwhelmingly that continental-scale deforestation in Amazonia, Africa or Southeast Asia leads to a warmer, drier climate over the deforested area. Many factors, including soil type, vegetation, topography, climatology, and distribution of land and water, determine the sensitivity of regional climate to land-cover change[3]. This dependency on region-specific characteristics makes it impossible to predict the consequences of deforestation in one region by extrapolating from observations in another. Amazonia and Central Africa both occupy continuous continental landmasses; Amazonian forest covers an area 25% larger. Africa is hotter and drier due to northward diversion of moisture-laden winds from the east and higher elevation[18]. More fires generate more aerosols there, potentially affecting rainfall. Southeast Asian forests are the most humid, with highest rainfall[18]. They occur on the smallest land area surrounded by vast oceans. This complex land–water distribution makes the ocean response to deforestation very important.

The three tropical areas differ in their sensitivity to deforestation. Simulated complete deforestation of the Amazon alone yields a warmer, drier climate over the deforested area (0.1–3.8 °C, mean 1.9 °C; -140 to -640 mm yr^{-1} (<10-30%, mean −324 mm yr^{-1} or ~15% of annual rainfall)[19–34]. Results are sensitive to model structure. For example, coupling fully interactive oceans to the atmosphere resulted in twice the

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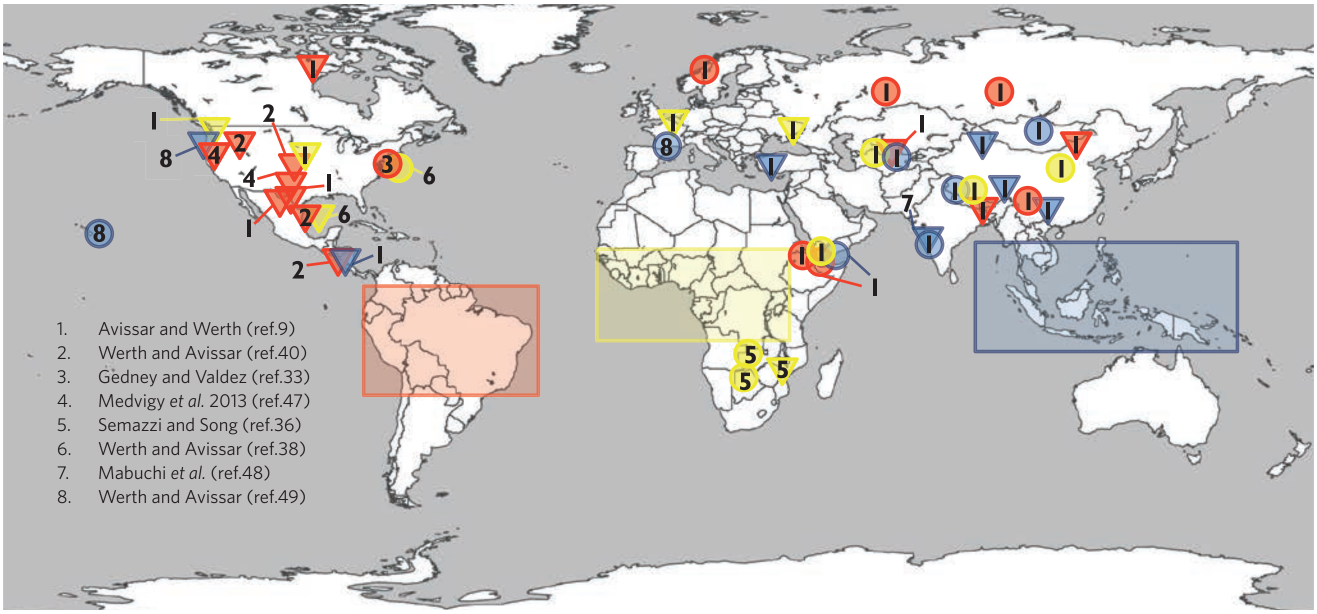

Figure 1 | Extratropical effects on precipitation due to deforestation in each of the three major tropical regions. Increasing (circles) and decreasing (triangles) precipitation result from complete deforestation of either Amazonia (red), Africa (yellow), or Southeast Asia (blue). Boxes indicate the area in which tropical forest was removed in each region. Numbers refer to the study from which the data were derived.

rainfall reduction observed in non-coupled GCM experiments[35]. Few GCM studies have explored complete deforestation in Central Africa alone or Southeast Asia alone. In Central Africa, predicted warming and drying are somewhat less than in Amazonia (0.5–2.5 °C, –2 to –3 mm per day during the dry season, approximately –240 mm or 15% of annual rainfall)[36–38]. In Southeast Asia, responses are milder still (warming of ~0.23 °C, drying of 132 mm yr^{-1})[39].

Extratropical impacts of regional deforestation. Tropical deforestation can lead to extratropical changes in temperature and rainfall. Changes in large-scale atmospheric circulations (for example, geopotential height, Rossby waves, Hadley circulations, and Ferrel cells) allow the propagation of climatic impacts to geographically remote areas through teleconnections[6,9,40–44]. Even relatively small land-cover perturbations in the tropics can lead to impacts at higher latitudes[45,46].

Simulating the complete deforestation of Amazonia reduces rainfall in the US Midwest during the agricultural season as well as the US Northwest and portions of the south[9,40,47] (Fig. 1). In another model, it increases rainfall (particularly in winter) over the eastern seaboard of the US and the northeast Atlantic, extending towards western Europe and possibly affecting precipitation in Europe[33]. Effects of deforesting the Amazon extend all the way to Asia[9].

In response to modelled deforestation of Central Africa, rainfall is reduced over the Gulf of Mexico, and parts of the US Midwest and the US Northwest, while it is enhanced over the Arabian Peninsula[9,38]. These impacts are similar to those resulting from deforestation of the Amazon. Declining precipitation also occurs in Ukraine and Southern Europe, whereas an increase occurs in parts of China and western Asia. Another study demonstrates climatic impacts in southern Africa, with enhanced rainfall in the centre and reductions in the east[36].

Deforestation in Southeast Asia can influence climate within and beyond the region through effects on the Asian monsoon circulation. Deforestation strengthens the summer monsoon winds, which increases lower atmosphere convergence over southern China. Simultaneously deforestation weakens convergence and decreases precipitation over the west coast of India[48]. Rainfall increases on the west coast of India in another study, and it also increases in southwestern China, while declining further east in China[9]. Werth and Avissar[49] found weaker long-range teleconnections from Southeast Asian than from Amazonian or African deforestation: precipitation increased during some months of the year in Hawaii and southern Europe and decreased in the US Northwest.

Clearly, large-scale changes in land cover can have remote climatic impacts; however, the sign, magnitude and location of impacts vary[50]. In most cases, effects depend on the region deforested or the model used. Coarse-resolution models can mask effects revealed by finer-resolution models[47]. Remote impacts of total pantropical deforestation do not correspond to the sum of the separate effects of deforestation in each of the three regions. For instance, while a teleconnection to California is not activated when Amazonia, Central Africa or Southeast Asia is deforested individually, deforesting all three at once leads to reduced winter rainfall there[9]. Some models suggest that deforestation has only local implications and do not predict any extratropical impacts[7] or only weak impacts[16]. The physical mechanisms underpinning teleconnections are still not fully understood and point to the need for enhanced knowledge of the fundamental physics of ocean–land–atmosphere interactions as well as improvements in the way these physical processes are embedded in GCMs[51].

More realistic deforestation scenarios using GCMs

Historically, GCM studies have applied unrealistically large perturbations such as one-time complete deforestation of the Amazon basin. Recent modelling has simulated more realistic deforestation scenarios at the regional scale, incorporating different patterns, rates, and scales of deforestation. As expected, climate impacts of slow, prolonged, and incomplete deforestation differ from the impacts of sudden, complete deforestation[6,7,9,14,32,52].

Partial versus complete deforestation. Medvigy *et al.*[53] simulated both complete and 'business-as-usual' (BAU) deforestation of the Amazon (incremental forest loss with 40% of the Amazon deforested by 2050). Their model operated at a resolution usually limited to regional models: a 25-km grid over South America and the nearby oceans, gradually coarsening to a 200-km grid over the rest of the world. For complete deforestation, this variable resolution model

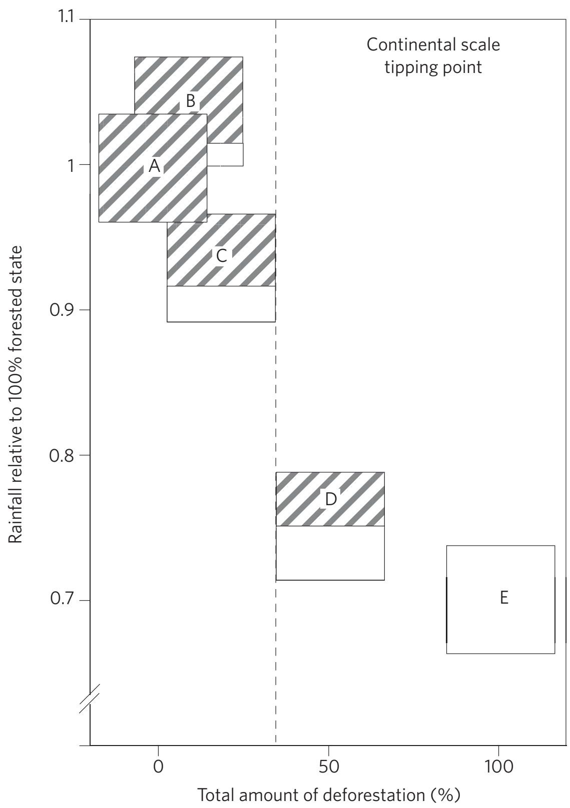

Figure 2 | Effect of tropical deforestation on rainfall at a continental scale. Global circulation models suggest that for low levels of deforestation, regional rainfall may be similar to or slightly higher than (B) rainfall in undisturbed forest (A). As deforestation expands, rainfall declines (C). A tipping point may occur when deforestation reaches 30 - 50% (D), after which rainfall is substantially reduced. A fully deforested state (E) results in the greatest decline in rainfall. Hatching indicates proportion of undisturbed forest.

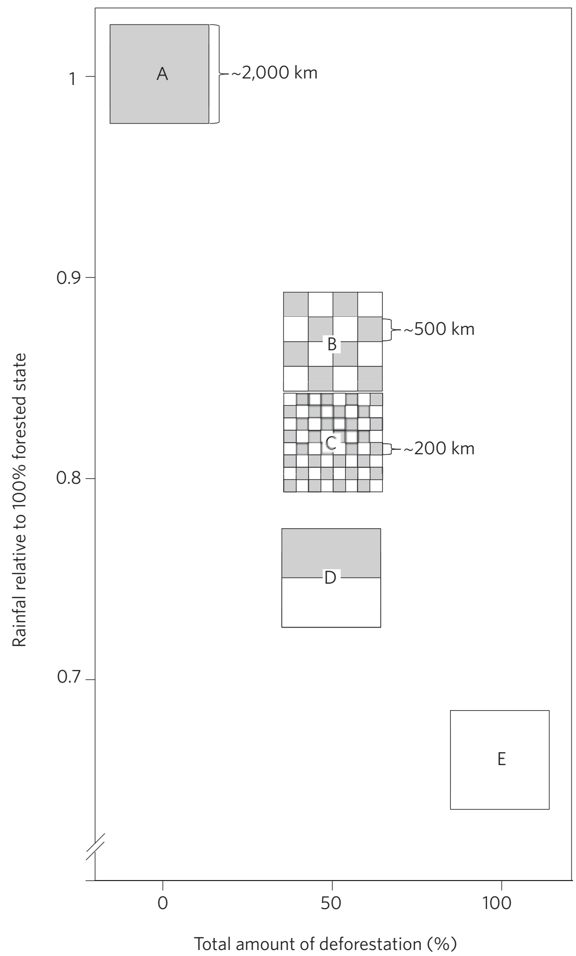

Figure 3 | Effect of pattern and total extent of deforestation on rainfall at continental scales. Boxes are 4,000,000 km^2, or 2,000 km on a side. Box A represents rainfall for the fully forested state. Rainfall is reduced, when deforestation is spread among 50% of the cells in a 500-km grid (B). Rainfall is reduced further with a smaller grid size (200 km) (C). Evenly distributed patches result in a smaller reduction than that reported in other studies for a single large patch, also comprising 50% of the landscape (D). A fully deforested state (E) results in the greatest reduction in rainfall. Data from ref. 35.

predicted a smaller reduction in precipitation (–62 mm yr^{-1}) than most previous coarse-resolution GCMs. In addition, the northwest Amazon became drier and the southeast Amazon became wetter. BAU deforestation yielded less severe impacts on precipitation than complete deforestation during certain times of the year and in some regions. In both BAU and complete deforestation scenarios, extreme cold events became more common in Columbia and Argentina, far from modelled deforestation. However, widespread climatic impacts occurred outside of the deforested area in the complete deforestation scenario that did not occur in the BAU scenario, including a 400 km northward shift in the Atlantic intertropical convergence zone (ITCZ).

Where previous GCMs of complete pantropical deforestation showed a modest to substantial decrease in rainfall, a gradual decline in forest cover resulted in a modest increase in annual rainfall for Central Africa and Southeast Asia. The increase ranged from 65–105 mm yr^{-1} in Central Africa (approximately 4–7%) and from –22 to +123 mm yr^{-1} in Southeast Asia (approximately –1 to +5%)[54].

The rate of deforestation does not strongly affect climate impacts. Castillo and Gurney[54] reduced forest across the tropics by 0.5, 1, 2, and 5% per year down to a target of 10% remaining per forest functional type. Temperature and precipitation were sensitive to rate only in Southeast Asia, but the response was not linear. The Amazon was the only region where annual rainfall declined significantly with tree cover, and even there drying did not respond linearly to deforestation rate.

Critical thresholds at large scales. A number of GCM studies that incorporate various levels of deforestation suggest that tropical forest clearing beyond ~30–50% may constitute a critical threshold for Amazonia, beyond which reduced rainfall triggers a significant decline in ecosystem structure and function (Fig. 2)[4,21,55–59]. In our assessment, this type of threshold may also apply in Africa, where the land-mass is similarly large. However, the threshold may differ in Southeast Asia, where the land–ocean balance is very different.

Recent work emphasizes the resilience of Amazonia, and by implication, other tropical forest areas, suggesting that this critical threshold may be higher than 50%. Evidence for resilience highlights the constraints and uncertainties of models, especially coarse resolution models, which predict ecosystem decline. Processes of convection, cloud formation, cloud microphysics and aerosol interactions are not well represented in most models, and yet they are critical to generating rainfall[8]. Clouds also alter incoming solar radiation, which has the potential to feedback to climate through direct effects on photosynthesis[2].

On the other hand, both positive and negative feedbacks occur, and even direct responses may interact with externally forced cyclical or directional climate dynamics to push the system toward an altered state[2]. Indeed, a much lower critical threshold for deforestation than

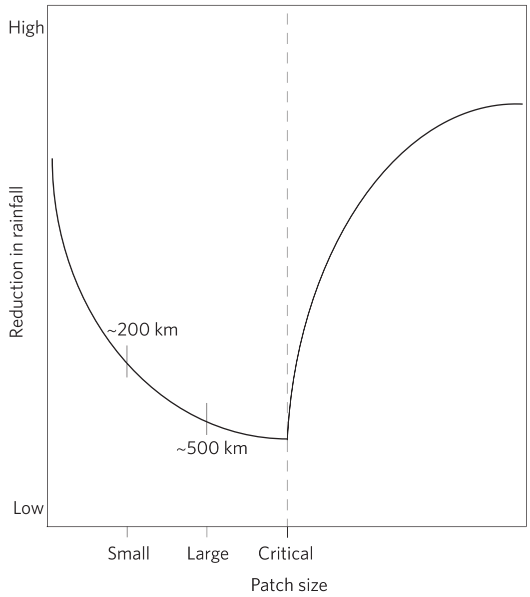

Figure 4 | Critical patch size at continental scales. At very large scales, for areas with a high proportion of forest loss (50%), rainfall is reduced less as patch size increases up to a critical patch size. Beyond this point rainfall is dramatically reduced.

30–50% may exist if forest loss occurs in the right place. A new hypothesis by Makarieva and colleagues emphasizes the role of forests as a 'biotic pump' for atmospheric moisture[51]. It underscores the importance of evapotranspiration, condensation and gradients in atmospheric moisture over the well-documented temperature gradients on which the prevailing paradigm is based. This hypothesis remains controversial, but strongly suggests that even small-scale deforestation, if it occurs in coastal areas, could disrupt the movement of moisture inland from the ocean and lead to drying of continental interiors[51,60].

Concentrated versus dispersed deforestation. The pattern of deforestation can also influence how regional climate is modified. Nobre *et al.*[35] found that rainfall over the Amazon basin is related to the spatial continuity of deforestation. As expected, complete deforestation led to the greatest reductions in rainfall (26–42%). When deforestation was evenly distributed in a checkerboard pattern over only 50% of relatively small cells (1.85° × 1.85° grid), rainfall was reduced by less (14–22%). When the same level of deforestation occurred over a grid with cells nine times as large (5.5° × 5.5°), the reduction in rainfall was even smaller (12–15%, Fig. 3). While somewhat surprising, these results are consistent with research that demonstrates the importance of large patches of forest in promoting or sustaining rainfall downwind[61]. The authors attribute the amelioration of rainfall losses by large patches to the effects of both total amount and continuity of forested areas on convection processes.

Most importantly, this landscape, while deforested 50%, did not result in the dramatic rainfall reductions predicted by earlier studies (up to 30% reduction[21,56,58]). Evenly distributed patches clearly behave differently from a single large patch. It is likely that a critical patch size exists even in a continental-scale mosaic (Fig. 4), beyond which rainfall is substantially reduced. Given the results above, the critical patch size must be larger than 500 km on a side for a continental-scale area that is half deforested.

Regional models decoupled from the global system

Regional scale models have smaller grid sizes than GCMs, but they are often not connected to the entire global system. The smallest grid cells (400 km^2) are 30–750 times smaller than cells in the models described above. Regional models are able to simulate convection induced by abrupt spatial changes in vegetation and orographic precipitation[62,63], processes typically not captured by GCMs with ~1°–5° grids[64,65]. As in GCMs, the representation of clouds is still limited.

Impacts and critical thresholds at small scales. In contrast to the lower rainfall induced by large clearings modelled at coarse scales, small clearings modelled at regional scales can result in enhanced local rainfall over the deforested area[66–68]. Along borders between forested and deforested regions, mesoscale models predict enhanced convection and, potentially, enhanced rainfall over deforested areas[69–74]. Rising hot air over the deforested area causes an influx of moist air from the adjacent forested area. Thus, although clearing lowers evapotranspiration from the deforested area, winds bring moisture into it. Following convection and cloud formation, rainfall may ensue (Fig. 5).

Simulations of rainfall over parcels of forest and pasture of different sizes and shapes established that rainfall tends to concentrate over deforested patches[66]. A realistic fishbone pattern of deforestation in Amazonia led to enhancement of shallow clouds and localized rainfall. This enhancement was apparent during the dry season when synoptic forcing is weak[72]. In other words, in the absence of driving winds from further away, local air movement due to vegetation discontinuities can bring rain to deforested patches[1,66].

The orientation as well as the size of deforested patches can modify their impact on regional climate. When Saad *et al.*[75] modelled deforestation in rectangular patches (from 4,500 to 63,000 km^2) in northern Amazonia, precipitation increased downwind and decreased upwind in deforested patches[75]. In smaller patches, precipitation downwind increased more than precipitation upwind declined, resulting in a net increase in rainfall over the entire deforested patch (Fig. 6). The magnitude of the enhancement declined as patch size increased. Thus, the smaller the patch, the greater the increase in rainfall. In patches with the long side oriented more perpendicular to the prevailing winds, net changes in rainfall were smaller and switched from positive to negative at a patch size of 15,000 km^2 (Fig. 6a). For patches aligned with the prevailing wind, net precipitation switched from an increase to a decrease at a patch size of 50,000 km^2 (Fig. 6b). In patches larger than the critical size, a net decrease occurred. The magnitude of the decline tended to increase with patch size but remained less than half that observed in Nobre's continental array of similarly sized patches[35].

The cumulative impact of small-scale deforestation on mean regional rainfall may be small (with possible enhancement initially), as increases in some areas balance declines elsewhere. However, as the size of the cleared area grows, a net increase is likely to switch to a decrease, with the magnitude of the decline increasing as deforestation expands. The greater magnitude of decline within an array of clearings than within a single patch suggests a complex interaction among patch size, the existence of additional deforested patches nearby, and the total area deforested (Box 1). While differences in model structure and uncertainties play a part, contrasting results at small and large scales probably depict the very real effect of multiple scale-dependent processes[1]. The effects of mesoscale circulations induced by heterogeneous land cover can be subtle and are considered insignificant by some[76]. Large-scale winds can weaken or mask smaller-scale circulations[1]. In models, effects are often more dramatic, or only detectable, during the dry season when large-scale land–ocean interactions are less influential[69,71,72,74,75].

Effects of deforestation in mesoscale models. While temperature effects tend to persist, the decline in mean rainfall has generally been smaller in mesoscale studies of Amazonian deforestation[65,69,71,72,74,77] than in GCM simulations[23,32,33,40,42,56,78]. A different mesoscale modelling approach, based on empirically derived relationships between

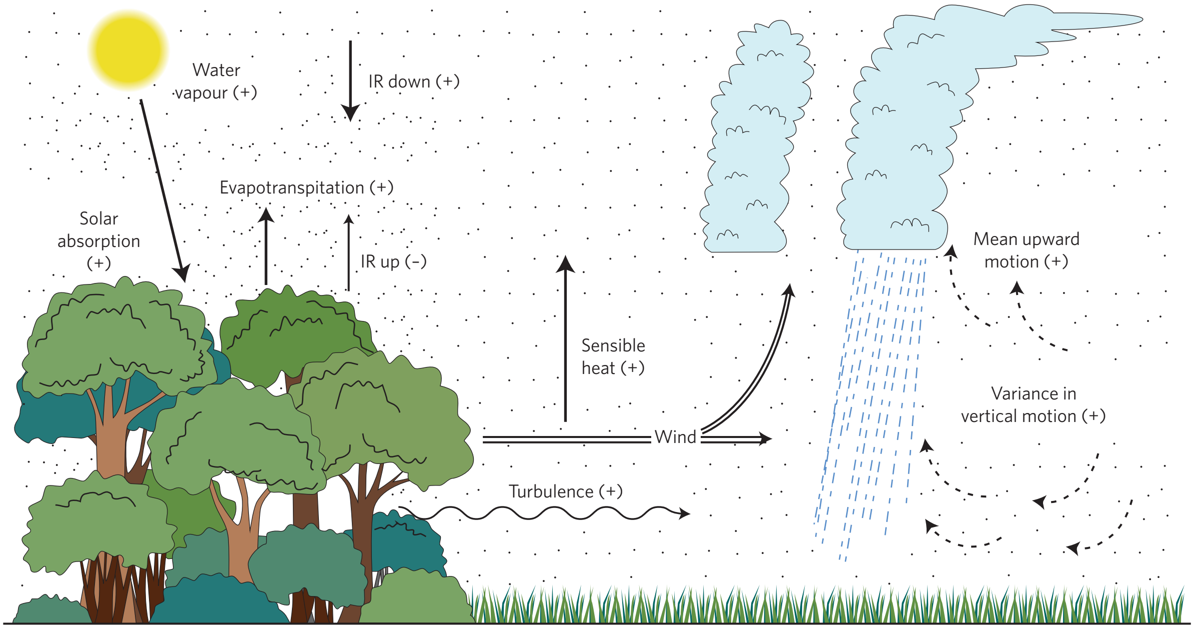

Figure 5 | Atmospheric dynamics induced by the boundary between forest and non-forest. Rainfall may be caused by convection that develops at the edge of forest vegetation. Rising hot air over the deforested area causes an influx of moist air from the adjacent forested area. Figure reproduced with permission from ref. 120, courtesy of Richard A. Anthes © 1984, American Meteorological Society.

vegetation and rainfall along air mass trajectories, resulted in strong effects on rainfall[61]. Spracklen *et al.*[61] found that clearing 40% of the Amazon results in a 12% reduction in wet-season rainfall and a 21% reduction in dry-season rainfall across the Amazon basin. It also results in a 4% decline in rainfall in the Rio de la Plata basin, thousands of kilometres south of the Amazon.

West African monsoon circulation, which provides more than 75% of the annual rainfall in West African countries, is sensitive to deforestation in mesoscale models[79,80]. Monsoon wind flow increases in response to simulated complete deforestation of West Africa. Greater flow leads to a large and uniform reduction in rainfall (40% to 50%) in all months of the year across West Africa from the coast to the Sahel[80]. Complete deforestation of the Congo Basin also leads to intensification of the West African monsoon. Rainfall in the Sahel region increases while precipitation over the Guinea coast decreases. Over the entire Congo basin, temperature increases up to 2–4 °C and rainfall is reduced up to 50%. Declines in soil moisture and cloud cover feed back to cause further warming[81].

A more realistic pattern of deforestation was simulated with mesoscale models by Baidya Roy *et al.*[82] to investigate the impact of deforestation in timber concessions (areas licensed for logging) on precipitation in adjacent national parks of Gabon and the Republic of Congo. The concessions were deforested completely, resulting in cleared patches from 100 km^2 to >100,000 km^2 over a landscape of 6 million km^2 (comparable to the model landscape of Nobre *et al.*[35]). During the wet season, rainfall declines up to 15% in some parks, particularly in the highlands where precipitation is orographic. In other national parks, rainfall increases. Rainfall is influenced by upwind deforestation along the path of atmospheric moisture moving inland from the ocean (consistent with other work[60,61,75]).

In mesoscale models, deforestation of the Indochina Peninsula reduces summer monsoonal precipitation over the peninsula itself as well as over east China and near the Tibetan Plateau, while monsoonal precipitation is strengthened over the seas to the east[83,84]. The frequency of high rainfall events increases in areas where total rainfall is enhanced. Notably, rainfall tends to increase downwind of the deforestation while decreasing upwind — a dynamic also observed for Africa[81] and similar to that observed at a smaller scale in the Amazon[75].

Observational Evidence

While modelling is an essential tool for understanding the way deforestation affects climate at regional and global scales, ultimately observations are needed to assess the models. In many tropical areas, deforestation has occurred at large scales only in the past several decades and in areas lacking long-term, widespread, robust meteorological data. Land use change has coincided with externally forced climate change, making attribution difficult. For these reasons, observational data at larger spatial scales should be viewed with the same skepticism as are model results. These data are an indication of

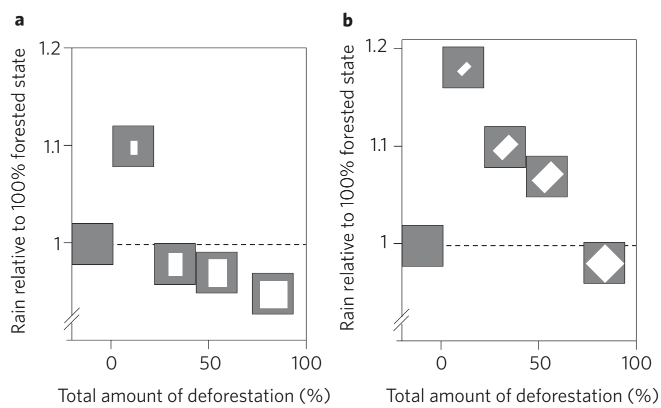

Figure 6 | Effect of increasing patch size on rainfall at a local scale. **a**,**b**, Patches (30–350 km on a side) aligned against the prevailing winds (**a**) switch from positive to negative effect on rainfall at a smaller patch size than patches aligned with the prevailing winds (**b**). Dashed line indicates the level corresponding to no change from fully forested. Deforested patches (clear areas) are drawn to scale. Data from ref. 75.

Box 1 | Interactions among patch size, spatial pattern and extent of deforestation.

Linking the work on single clearings of various sizes (Fig. 6) to the work on the spatial pattern of multiple clearings (Fig. 3) allows us to understand the interaction among patch size, spatial pattern, and extent of deforestation[35]. Saad *et al.*[75] focus on how rainfall responds as a single clearing grows in size, and Nobre *et al.*[35] put that single clearing into a continental array to ask whether size still matters if there are many such clearings and thus the total area deforested is also substantially greater. A single patch reaches a tipping point from rainfall enhancement to reduction by 50,000 km^2. A continental array of similarly sized patches likewise shows a reduction, but of greater magnitude, suggesting a compounding effect of patches in proximity or total area deforested. When patches in the array get even bigger while maintaining the same total area deforested, rainfall is reduced less than it is in smaller patches. This reduced impact may result from the effect of large undisturbed blocks of forest on regional climate. A tipping point must exist for patches in continental scale arrays as well. As patches become larger still, the number and extent of vegetation discontinuities will decline, and with them the local rainfall enhancement that mitigates drying in smaller patches. This may be the scale at which deforestation patches occur in those models that show the 30–50% deforestation threshold. Thus, those results may reflect a critical patch size across the continent rather than a critical threshold for total area deforested. These new studies indicate a complex interaction among patch size, the existence of additional deforested patches nearby, and total area deforested, as suggested in the early model of Avissar and colleagues[64].

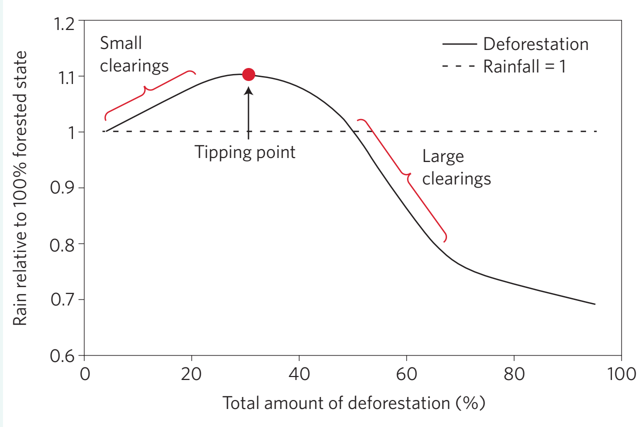

Figure B1 | Model of the effect of clearing size and proportion of area deforested on rainfall. Data from ref. 64.

potential impacts that may be borne out with more time, more spatially extensive and intensive sampling, or as the scale or extent of deforestation expands to reveal a strong, consistent signal at regional scales[1,2].

Effects at small spatial scales. Direct measurements of the atmosphere above forested and deforested land in Amazonia indicate that surface temperature increases and evapotranspiration is reduced when tropical forest is converted to pasture, particularly in the dry season[67,85–88]. Satellite data confirm that, even during dry periods, evapotranspiration continues to feed moisture back into the atmosphere in forests but not in cleared areas[89,90], often at higher rates than prescribed by many models[4]. Controls on and microscale effects of evapotranspiration are a particularly important area for further model development, as accurate model projections of temperature and rainfall depend critically on the link between the water cycle and the energy budget[4,51].

Effects at medium spatial scales. Observations reveal both increases and decreases in cloud cover with deforestation. In areas of substantial deforestation in the Amazon, higher detectable heat flux from the deforested land produces a deeper convective boundary layer and enhances thermally driven circulations that lead to more cloud cover over deforested areas[67]. Satellite data show that current patterns of Amazonian deforestation enhance shallow cumulus cloud cover over deforested areas[76,91–94].

In contrast, satellite imagery of lowland Costa Rica and Nicaragua indicate that deforested areas remain relatively cloud free during the dry season while forested areas have well-developed cumulus cloud fields[95,96]. Costa Rica, roughly 100 km wide, sits between two oceans in a Central American landmass 15 times smaller than the Amazon. Thus, the ocean may dampen some of the expected mesoscale changes that have been observed in the Amazon, where the land–ocean ratio is greater.

Measurements across the tropics indicate that rainfall is sensitive to forest cover. Spracklen *et al.*[61] correlated remotely sensed rainfall with vegetation density from back trajectories of air masses that provided the rain. In 60% of tropical areas, air passing over dense tropical forests produced at least twice as much rainfall as air passing over areas with little vegetation. Similarly, rainfall in the cloud forests of Costa Rica is sensitive to upwind vegetative cover[95]. Tree cover was a good predictor of the annual number of rain days, but not total annual rainfall in São Paulo, Brazil from 1962–1992[97]. By implication, although fewer rain events occurred in deforested sites, they were of higher intensity, compared with forested sites.

The seasonality of rainfall has shifted due to deforestation in Brazil. Meteorological stations in Rondônia, Brazil indicate that the wet season has been delayed by ~11 days in deforested regions while it has not changed in forested areas over the last 30 years[98]. These data support mesoscale modelling studies that predict increases in the length of the dry season from 4 to 5 months in Mato Grosso, Brazil[59] and from 5 to 6 months in Rondônia[99]. In contrast, a 75-year record from Porto Velho in northern Rondônia shows that the dry season starts and ends earlier, but its duration has not changed[100].

Evidence for a trend in total annual rainfall in Amazonia over the past several decades is mixed. In contrast to GCM predictions of reduced rainfall, 14 years of high-resolution satellite-based precipitation measurements show more rainfall events over deforested areas in southwest Brazil, but only during the dry season[76]. Rain gauge data from this region and across the Amazon basin suggest that rainfall has increased modestly (<0.5 mm per day) since 1978 when deforestation began[91,102]. Marengo[102] observed a positive trend in the southern Amazon, where deforestation has been concentrated, starting even earlier (1950–1998). Increased discharge from the Amazon River suggests a wetting trend in the basin since 1990, concentrated in the rainy season[103]. Northwest Amazonia, already the wettest part of the basin, shows the strongest increase, whereas southwest Amazonia, where deforestation has been concentrated, shows some drying.

However, some rain gauge analyses contradict these results. The standard precipitation index for the southern Amazon declined between 1970–1999[104]. The modest increase in the south observed by Marengo[102] was masked by a more marked decrease in the northern Amazon, resulting in a decreasing trend over the entire basin up to 1998. Extending the analysis to 2010 revealed a decline in the dry season and no change in the wet season, for both north and south[105]. Similarly, a basin-wide decline from 1975–2003 was more pronounced after 1982 owing to a strong decline in rainfall in the northwest of the basin during the dry season[106].

The length of the time series, its starting point, and inclusion of the most recent 15 years significantly affect the observed trends in rainfall. As the Global Precipitation Measurement (GPM) Satellite (2014 launch) extends the Tropical Rainfall Measuring Mission (TRMM) greater insight is expected the rainfall trend in forested and deforested areas will become clearer. Nevertheless, in some areas, deforestation has coincided with climate change forced by natural regional oscillations. Deforestation everywhere has occurred along with greenhouse-gas induced warming. Both confounding factors make attribution difficult, in addition to problems with the extent and intensity of observations[1,2]. Thus, further work must be done to disentangle the effect of local climate drivers, such as deforestation, from regional or global drivers, including trends and oscillations in atmospheric and sea surface temperatures. A model intercomparison project would be useful in this regard to increase our understanding of how various phenomena and the models themselves contribute to changes induced by deforestation.

Few studies have examined trends in precipitation over Southeast Asia. Monthly precipitation data for the past 40 years from all over Thailand indicate a decrease in precipitation only in September (by ~100mm per month) following the monsoon[107]. Strong monsoon westerlies provide moisture from the ocean to the Indochina Peninsula until the end of August and may mask local impacts of deforestation until the winds disappear in September. Rainfall has declined in Borneo since the 1950s, and the decline has been stronger since the 1980s when deforestation intensified. However, while the island lost 50% of its forest cover, over the same period a slowdown in the Walker circulation reduced rainfall across the region[108]. Thus, while deforestation may have contributed to the decline, further work is needed to demonstrate the effect.

Even fewer studies document changes in precipitation over Africa. Rain gauge plus satellite data from 1979–2004 indicate >20% decline in precipitation from the Congo Basin to the east coast, with the decline more pronounced since 1992[109]. Rainfall declined 0–10% in much of the forested zone from 1900–1998, with pockets declining up to 20–30% and other areas where it increased by up to 10%[110]. Many researchers recognize the possibility that either land-use change or ocean dynamics in the past few decades may be driving the decline.

Impacts of deforestation depend in part on the use of converted forests and this varies by region[1,3,56]. Thus, detecting impacts should vary by region and through time. The purpose of deforestation affects the spatial scale and pattern of clearing, both critical factors. In addition, evapotranspiration varies with the leaf area, canopy architecture, phenology and rooting depth of the replacement vegetation[4]. In models of Amazonia, reductions in rainfall are greater following conversion to soybean cropland than following conversion to pasture[56,111]. Tree crops such as oil palm or pulp/paper plantations currently drive deforestation in Southeast Asia, resulting in less dramatic changes to energy and water balance than conversion to pasture or herbaceous crops. Whereas soil drainage occurs with clearing, the effect of these tree crops is more complex. Central African forests are being cleared for small-scale subsistence agriculture, charcoal and fuelwood, as well as urban expansion and mining. As drivers shift, so will climate impacts. Finally, while at present many of these systems are rain-fed, a warming climate could result in the expansion of irrigation. Where it already occurs, irrigated agriculture tends to increase precipitation and thus confounds — or even reverses — local impacts of deforestation on climate[3,112].

Linkages to agricultural productivity

Only a small number of modelling studies have begun to link tropical deforestation to water resources and crop productivity. Modelling low to high forest loss outside of protected areas in the Amazon, Oliveira *et al.*[113] showed that pasture productivity declines by 28–33%. Cattle production may cease to be viable in some current strongholds such as Maranhão, Brazil. Over half of the Amazon, soy yields drop by 25%; in a third of the area, they decline by 60%. In addition to this study, which demonstrates local impacts on agriculture, many of the original GCMs determined that large-scale forest conversion in one region could lead to remote climatic impacts that limit food production in other regions, including the US, India and China[9,40,61,112] (Fig. 1).

Changes in mean annual temperature or precipitation may reduce productivity or shift where a particular crop can be grown. An increase in climatic variability, however, can be detrimental to all crops and regions. Intense extremes (very warm years, or very cold nights) can be more harmful than a relatively small change in mean temperature[15,53]. South America already experiences intense cold air anomalies that are harmful to coffee and other crops[114,115]; these anomalies are predicted to increase with deforestation[53].

Deforestation has a significant impact on diurnal temperature variability[1,3]. Observational data from the Amazon indicate

Box 2 | Deforestation affects climate and puts agriculture at risk.

Global models depicting complete tropical deforestation in large grid cells show substantial warming and drying in the tropics; with partial or gradual deforestation the effects are reduced and vary from the Amazon to Africa to Southeast Asia. At the continental scale, for Amazonia (and possibly Africa), 30–50% deforestation may represent a threshold beyond which rainfall reductions significantly alter ecosystem structure and function, with feedbacks resulting in further decline. Deforestation in distributed patches rather than a continuous block moderates the impact. At much smaller scales forest clearing may initially increase rainfall, but a critical threshold occurs here as well.

Increases in some areas and decreases in others can yield modest or non-significant changes in annual precipitation at regional scales. This phenomenon may explain the apparent contradictions between modelling studies that portend reductions and satellite and meteorological records that demonstrate little change or an increase in annual rainfall with current levels of deforestation.

Although the current level and pattern of deforestation may not have pushed tropical climates over a tipping point yet, modelling results at regional to global scales are consistent in their predictions that such a tipping point exists.

The risks of deforestation for local agriculture are a function of a probable increase in mean temperature and decline in mean rainfall across the tropics. However, the spatial and temporal redistribution of rainfall within a region is a major risk as it could lower soil moisture and reduce yields, especially in some areas or during critical agricultural periods. An increase in temperature extremes is also a hazard, especially if high temperatures correspond with periods of low rainfall. Finally, tropical deforestation on a large scale is also likely to affect agriculture outside of the tropics. While the precise location of remote impacts varies among models, teleconnections from the tropics to the mid-latitudes could pose a considerable risk to agriculture in parts of the US, India, and China (among others), due to impacts on rainfall against a background of warmer temperatures.

higher daytime maximum temperatures and cooler night-time air temperatures over pasture than over forest[67]. In large-scale models of future climate with future land use, integration across forested areas (with a contracting temperature range) and deforested areas (with an expanding temperature range) can lead to the prediction of lower diurnal variability at a regional scale[5]. However, field observations at smaller scales suggest that the diurnal temperature range is likely to increase in deforested areas. Future crops must not only tolerate higher mean temperatures, but a wider range of temperature.

Similarly, while total rainfall is important, the seasonal pattern of rainfall is also critical to agricultural productivity. A delay in the onset of the rainy season[98], an increase in the length of the dry season and decreased precipitation during the transition from dry to wet season[59,99] could limit productivity. Changes in the spatial pattern of rainfall[31,53,81] are also likely to affect agricultural production.

In the Amazon, differences between forested and deforested areas appear to be stronger during the dry season[9,40,116–118]. Evidence from both models and observations also shows that dry season precipitation is more strongly affected in Central Africa and Southeast Asia[36,107]. The impact of these changes will depend on the timing of key agricultural activities.

Even when projections of total rainfall are constant, agricultural production will depend on rainfall frequency and intensity as well as seasonal distribution. Infrequent and intense events are characterized by upper soil saturation favouring runoff over infiltration. The same total rainfall, dispersed over frequent and light precipitation events, does not lead to overland flow and provides a consistent resupply of soil moisture to crops. If total rainfall declines, an increase in intensity could exacerbate soil moisture deficits.

Observations at a regional scale in Brazil do show decreasing rainfall frequency and increasing intensity with the proportion of land deforested[97]. In some parts of the Amazon models of deforestation offer contrasting results: a decline in intensity and, for some months, frequency[53]. However, where this shift occurs total rainfall also declines, producing negative impacts on agriculture for a different reason. Following deforestation, a decline in rainfall frequency or total or a shift in seasonality will occur against a background of warmer daytime temperatures, further increasing stress on crops.

The occurrence of extreme climatic events is affected by tropical deforestation and has consequences for agricultural systems. From 1990–2000, flood frequency increased and floods lasted longer as natural forest cover declined in countries across the tropics[119]. Loss of tree cover reduces canopy interception/evaporation and soil infiltration, resulting in greater run-off during heavy rainfall events. Floods can adversely affect crop establishment, survival, growth, and ultimately yield.

In summary, the risks to agriculture associated with deforestation stem primarily from an anticipated increase in mean temperature, a decline in mean rainfall, and a spatial and temporal redistribution of rainfall within a region. Alone or in concert, these factors could lower soil moisture and reduce agricultural yields. An increase in climate extremes also poses a risk, from both high and low temperatures and extreme rainfall (Box 2).

Received 31 July 2014; accepted 10 October 2014; published online 18 December 2014; corrected after print 18 December 2014

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Acknowledgements
Many thanks to Somnath Baidya Roy, Penny Davies, Stephan DeWekker, Donna Lee, Anastassia Makarieva, Antonio Nobre, Jan Pokorny, David Werth and Daniel Zarin. Lia Cattaneo, Christopher Fender, Megan McGroddy, Amber Slatosky, University of Virginia and the Climate and Land Use Alliance provided critical support.

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Competing financial interests
The authors declare no competing financial interests.

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Effects of tropical deforestation on climate and agriculture

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Nature Climate Change **5**, 27–36; 2015; published 18 December 2014; corrected after print 18 December 2014.

In the print version of this Review, the 'published online' date should read 18 December 2014. The online versions are correct.