doi:10.1038/nature10717

The Amazon basin in transition

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Agricultural expansion and climate variability have become important agents of disturbance in the Amazon basin. Recent studies have demonstrated considerable resilience of Amazonian forests to moderate annual drought, but they also show that interactions between deforestation, fire and drought potentially lead to losses of carbon storage and changes in regional precipitation patterns and river discharge. Although the basin-wide impacts of land use and drought may not yet surpass the magnitude of natural variability of hydrologic and biogeochemical cycles, there are some signs of a transition to a disturbance-dominated regime. These signs include changing energy and water cycles in the southern and eastern portions of the Amazon basin.

Humans have been part of the vast forest–river system of the Amazon basin for many thousands of years, but expansion and intensification of agriculture, logging and urban footprints during the past few decades have been unprecedented. The human population of the Brazilian Amazon region increased from 6 million in 1960 to 25 million in 2010, and the forest cover for this region has declined to about 80% of its original area[1]. Efforts to curb deforestation have led to a steep decline in forest clearing in the Brazilian Amazon, from nearly 28,000 $\mathrm{km}^2\,\mathrm{yr}^{-1}$ in 2004 to less than 7,000 $\mathrm{km}^2\,\mathrm{yr}^{-1}$ in 2011[1]. However, this progress remains fragile. The river system produces about 20% of the world's freshwater discharge[2], and the forest biomass holds about 100 billion tonnes of carbon (C; refs 3, 4), which is equivalent to more than 10 years' worth of global fossil-fuel emissions. Maintaining the biotic integrity of the biome and the ecosystem services it provides to local, regional and global communities will require improved understanding of the vulnerability and resilience of Amazonian ecosystems in the face of change.

Here we provide a framework for understanding the linkages between natural variability, drivers of change, responses and feedbacks in the Amazon basin (Fig. 1). Although the basin-wide carbon balance remains uncertain, evidence is emerging for a directional change from a possible sink towards a possible source. Where deforestation is widespread at local and regional scales, the dry season duration is lengthening and wet season discharge is increasing. We show that the forest is resilient to considerable natural climatic variation, but global and regional climate change forcings interact with land-use change, logging and fire in complex ways, generally leading to forest ecosystems that are increasingly vulnerable to degradation.

Natural and anthropogenic climatic variation

Changes in Amazonian ecosystems must be viewed in the context of the natural variation in climate[5,6] and soils[7] across the region, as well as natural cycles of climatic variation and extreme events. A climatic gradient spans the Amazon basin (Fig. 2), from the continuously rainy northwest to the wet/dry climate and long dry season of the southern and eastern regions, including the Cerrado (woodland/savannah) in the southeast. This climatic gradient is largely coincident with a gradient in land-use change, with more conversion to agriculture in the drier eastern and southern regions, indicating the interconnectedness of biophysical and socio-economic processes.

The El Niño/Southern Oscillation (ENSO) profoundly affects rainfall in the Amazon basin[5], especially the eastern portion; there is decreased flow of the Amazon River and some of its major tributaries during El Niño years, and increased flow and increased flooding during La Niña years[6]. The ENSO effect is superimposed over a 28-year cycle of variation in precipitation[5,6] such that the biggest floods occur when La Niña coincides with the wet phase in the 28-year cycle; this coincidence last occurred in the mid-1970s (Fig. 3). The worst droughts occur when El Niño coincides with the dry phase of the longer-term cycle, such as the 1992 drought. The Atlantic Multidecadal Oscillation also affects the region, contributing to, for example, the 2005 drought, which resulted in the lowest river levels recorded until then in southern and western tributaries[8]. Although much has been learned about extreme events and decadal-scale cycles, no discernable long-term trend has yet been identified in the total discharge of the Amazon River[9].

Forests are resistant to seasonal droughts

The ability of roots to access deep soil water[10] and to redistribute it[11] helps to maintain evergreen canopies during dry seasons, demonstrating the adaptation of Amazon forest species to seasonal drought. The combination of access to deep soil water and less cloudiness permits continued plant photosynthesis throughout most of the dry season[12]. However, transitional forests and Cerrado ecosystems, where mean annual precipitation is less than 1,700 mm and the dry season lasts for ≥4 months, show clear evidence of dry season declines in evapotranspiration and therefore potential water stress[13]. Many tree species in the Amazon and Cerrado produce a flush of new green leaves near the end of every dry season, which is often detected in satellite images as an

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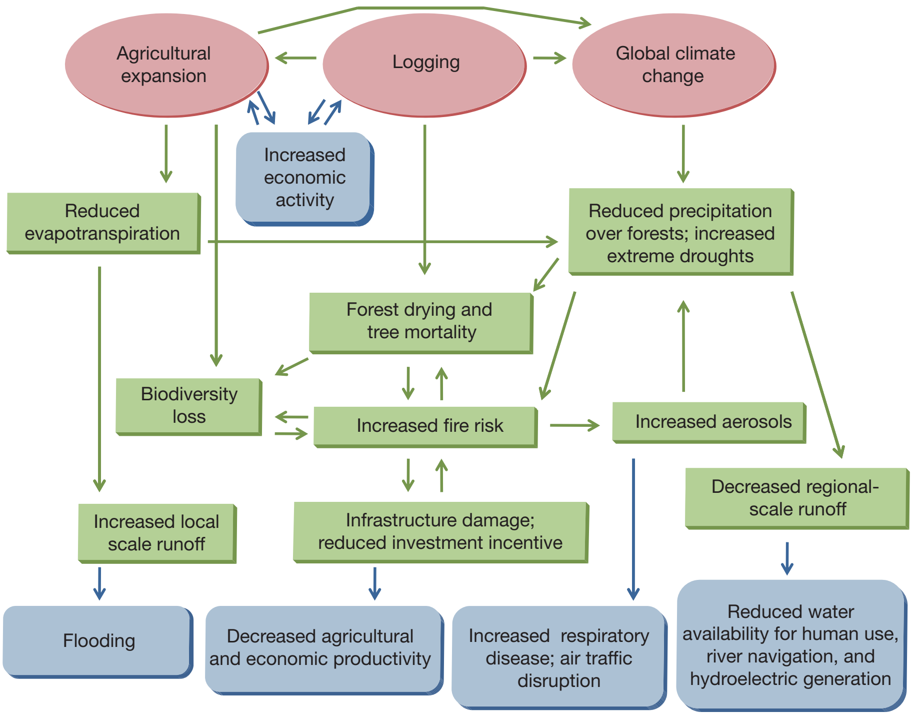

Figure 1 | Interactions between global climate, land use, fire, hydrology, ecology and human dimensions. Forcing factors are indicated with red ovals; processes addressed in this Review are indicated by green boxes and arrows; and consequences for human society are indicated by blue boxes with rounded corners.

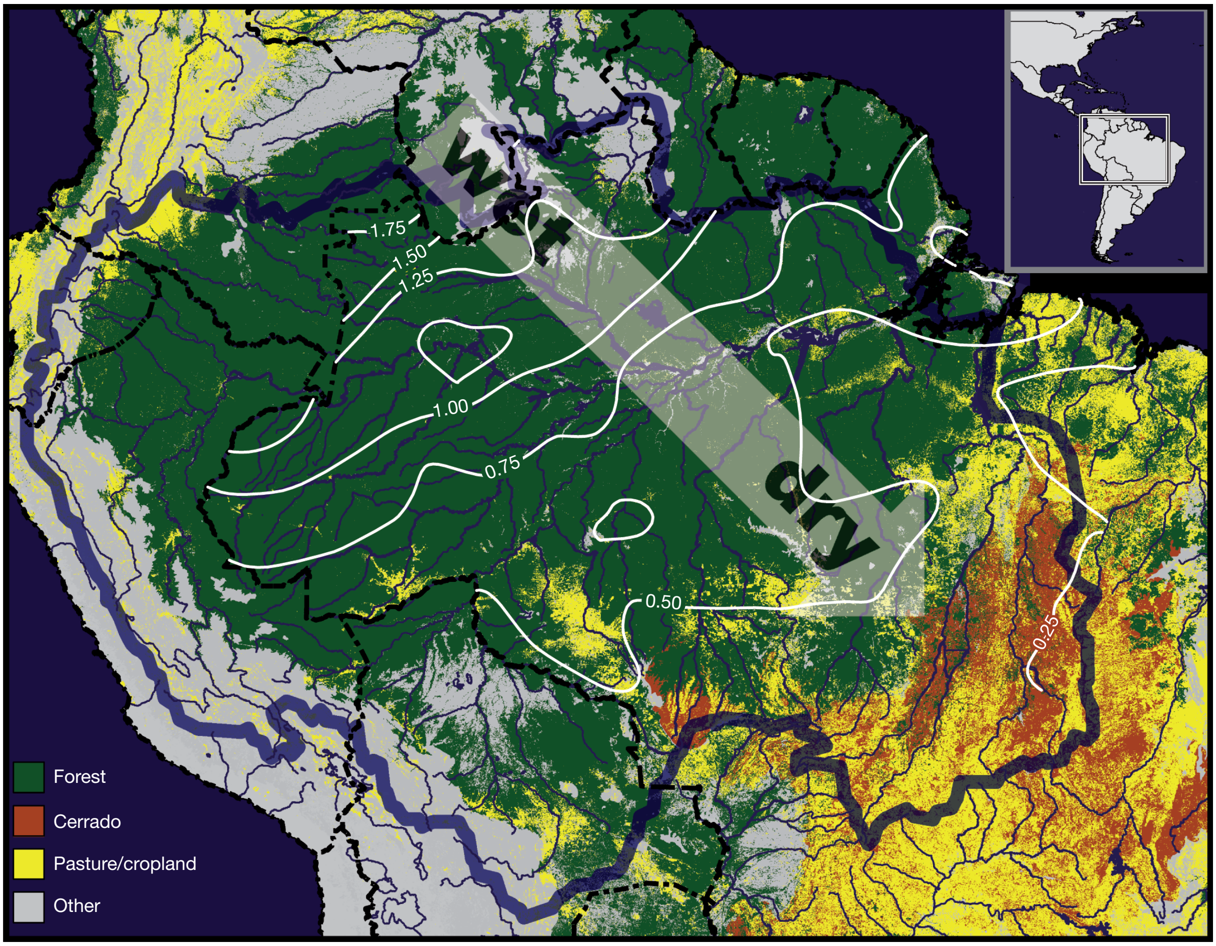

Figure 2 | Climatic gradient across the Amazon basin. Main figure, the hydrologic Amazon basin is demarcated by a thick blue line; isopleths of mean daily precipitation during the three driest months of the year[97] (in mm; white lines) are overlain onto four land-cover classes[98,99] (key at bottom left). These isopleths are presented only for areas within Brazil, because of lack of adequate data elsewhere. The arrow emphasizes the trend from continuously wet conditions in the northwest to long and pronounced dry seasons in the southeast, which includes Cerrado (savannah/woodland) vegetation. National boundaries are demarcated by broken black lines. Inset, map showing area of main figure (boxed).

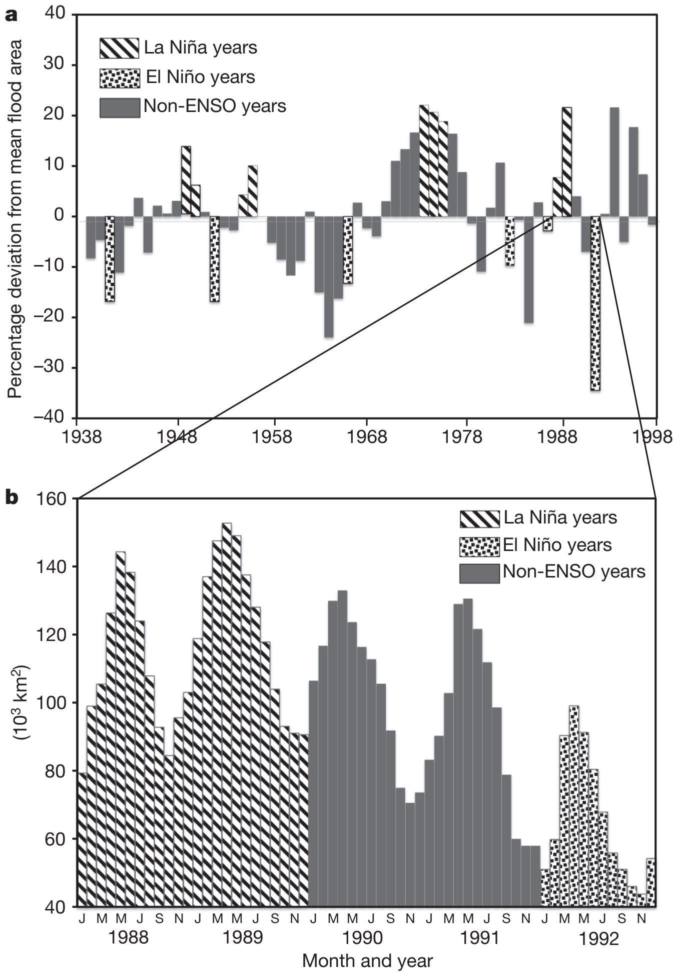

Figure 3 | Decadal and seasonal variation in flood area. The long-term record of simulated interannual variation in percentage deviation from mean flood area (**a**) illustrates how the ENSO events are superimposed over a 28-year cycle of high- and low-precipitation phases[100]. Recurrent seasonal patterns of flooded area (10^3 km^2) for five selected years (**b**) are superimposed over the interannual variation. Striped bars, La Niña years; stippled bars, El Niño years; solid bars, non-ENSO years.

increase in vegetation indices that involve ratios of red and near-infrared reflectance[14,15]. The relation between these satellite-based indices of seasonal greenness and ecosystem productivity remains an unresolved focus of debate in these studies, but in any case, this response represents a short-term phenomenon.

Multi-year or extreme drought

Experimental manipulations and observations of permanent forest plots address responses to multi-year and extreme drought. Two long-term drought experiments have produced remarkably similar results, demonstrating that adaptation to seasonal drought can be overwhelmed by multi-year drought[16,17]. These studies demonstrated a physiological adaptation of the trees, which maintained a relatively constant water tension in the xylem (isohydry) in both wet and dry seasons; but this adaptation may eventually lead to mortality when roots are unable to extract enough soil water during multi-year droughts[18]. After diverting 35–50% of total rainfall for three years using below-canopy panels and gutters, plant-available soil moisture stores became depleted, wood production declined by about 30–60%, tree mortality nearly doubled, and live above-ground biomass decreased by about 18–25% (refs 16, 17). Mortality rates increased to nearly three times that in the control plot during years 4–7 of rainfall exclusion[17].

The severe 2005 drought in the southwestern Amazon—when dry season temperatures were 3–5 °C warmer than normal and rainfall over the Solimões River basin was only 33–65% of average values[8]—may have exceeded the adaptive capacity of many forest species. Analysis of 51 long-term monitoring plots across Amazonia showed that, relative to pre-2005 conditions, most forest plots subjected to increased water deficit in 2005 lost several tons of living tree biomass carbon per hectare, owing to a marginally non-significant decline in growth and a significant increase in mortality of trees[19]. A similarly severe but more extensive drought occurred again in 2010, affecting more than half of the basin and resulting in the lowest discharge ever recorded at Manaus[20,21]. Susceptibility to drought is likely to vary regionally, depending on the climate (total precipitation and its seasonal distribution) and soil water storage properties (texture and depth) to which the existing vegetation types (for example, Cerrado woodlands, tall-statured central Amazon forests, and transition forests) are physiologically adapted. Furthermore, there is evidence that certain taxa are more vulnerable to drought-induced mortality[17,22]. Despite this regional variability, the observations of natural droughts and the drought manipulation experiments indicate similar trends of mortality in response to dry season intensity[23].

Land-use change and regional climate

Land use is changed to capture agricultural and forestry revenues, and results in trade-offs with multiple ecosystem services, such as C storage, climate regulation, hydrologic balance and biodiversity (Fig. 1).

The drivers of deforestation

Road paving is one of the economic activities that stimulates deforestation[24]. Further clearing occurs along networks of ‘unofficial roads’ that result from the interacting interests of colonist farmers and loggers[25]; loggers minimize their costs by buying the right to log private lands. Although practices vary widely across the region, most small land holders (<200 ha) have kept more than 50% of their land in some combination of mature and secondary forest[26].

International and national demands for cattle and livestock feed are increasingly driving land-use change. Direct conversion of forest to cropland in 2003, mostly by large land holders, represented 23% of the deforestation in forest and Cerrado regions of the state of Mato Grosso[27]. Although cattle pasture remains the dominant use of cleared land, the growing importance of larger and faster conversion to cropland, mostly for soybean export, has defined a trend of forest loss in Amazonia since the early 2000s.

Although selective logging is not an immediate land-use change, it often leads to deforestation. From 1999 to 2003, the area annually logged in the Amazon basin was similar in magnitude to the area deforested[28]. Logged areas are accessible by logging roads and are likely to be cleared within only a few years after initial disturbance[29], and those that are not cleared have a high risk of burning[30]. On the other hand, reduced-impact logging has been demonstrated to be economically viable, while causing only modest and transient effects on carbon storage and water exchange[31]. Expansion of protected areas has also played an important role in reducing deforestation in the Brazilian Amazon (Fig. 4)[32].

Deforestation alters the energy balance

Incoming air from the Atlantic Ocean provides about two-thirds of the moisture that forms precipitation over the Amazon basin[33]. The remainder is supplied through recycling of evapotranspiration, primarily driven by the deep-rooted Amazon trees.

A large number of observational and modelling studies have suggested that deforestation causes two main changes in the energy and water balance of the Amazon basin, as follows. First, partitioning of the net radiation that is absorbed by the land surface changes, with a decrease in the latent heat flux and an increase in the sensible heat flux, primarily because deforestation results in less vegetation being available to transpire water to the atmosphere. Second, replacing the dark rainforest with more reflective pasturelands or crops results in a decrease in solar radiation absorbed by the land surface. Reforestation can reverse these

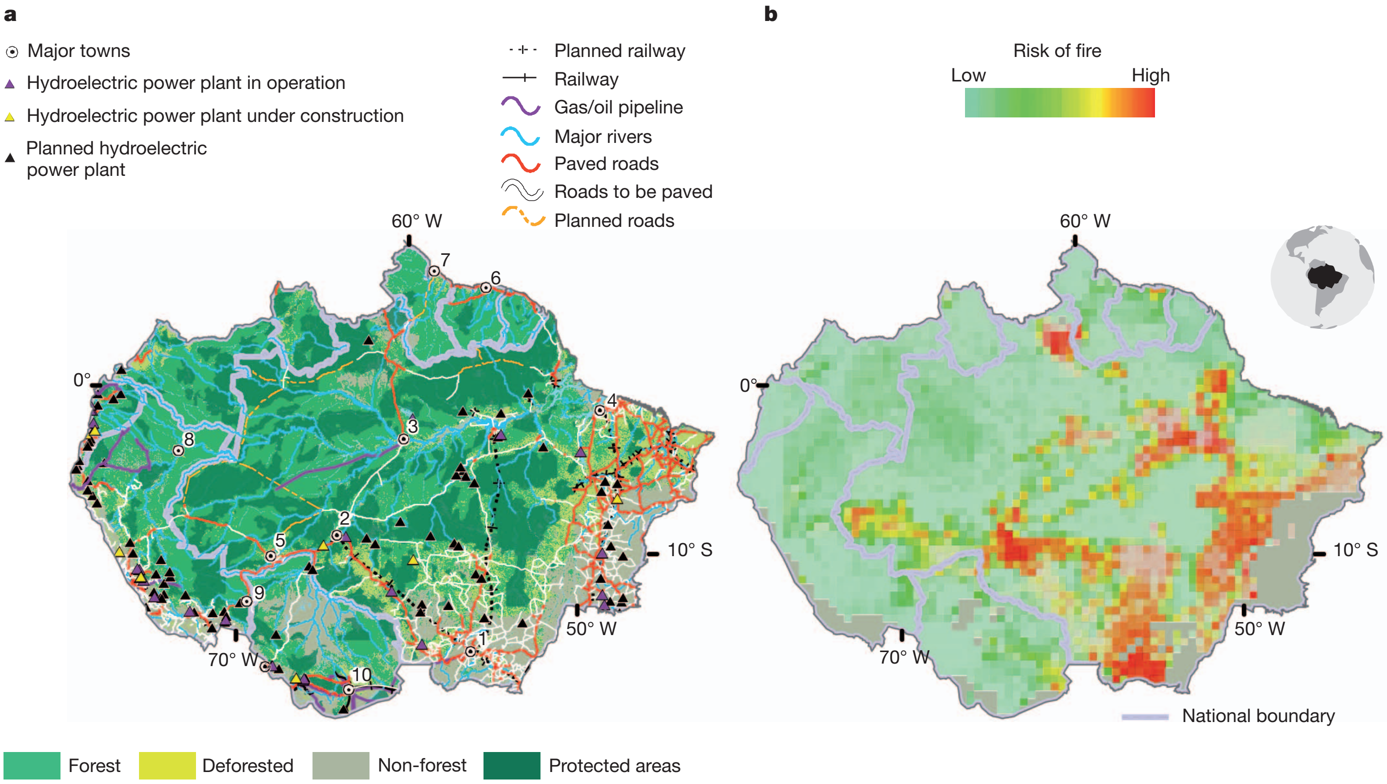

Figure 4 | The Amazon basin today and future fire risks. a, Protected areas and major planned infrastructure. **b**, The risk of fire by 2050[96] under business-as-usual deforestation and climate change scenarios[24]. The numbers in **a** indicate the following cities: 1, Cuiabá; 2, Porto Velho; 3, Manaus; 4, Belém; 5, Rio Branco; 6, Paramaribo; 7, Georgetown; 8, Iquitos; 9, Puerto Maldonado; 10, Santa Cruz de la Sierra.

trends. Within a few years of pasture abandonment, regrowing Amazonian forests establish rates of evapotranspiration and reflectivity that are close to those measured in mature forests, even though they have not yet recovered the biomass and species diversity of a mature forest[34,35].

Atmospheric convection and precipitation are driven by the fluxes of energy and water from the land surface. Where clearings for cattle pastures extend tens of kilometres outward from a road, the air above the deforested areas warms up more quickly and tends to rise and draw moist air from the surrounding forest, creating so-called 'vegetation breezes'. This decreases rainfall over the forest while increasing cloudiness, rainfall and thunderstorms over the pasture[36]. Heterogeneous deforestation at large scales (hundreds to thousands of km^2) leads to more complex circulation changes, with suppressed rainfall over core clearings, particularly at the beginning and the end of the wet season, and unchanged or increased rainfall over large remnant forest patches[37,38]. These changes also affect water and light availability, and the C uptake of the remaining forests, but those effects are not yet well quantified.

At deforestation scales greater than 10^5 km^2, numerical models consistently suggest that a significant decrease in basin-wide precipitation will occur[39] due to: (1) a decrease in the evapotranspiration from deforested regions and resultant downwind transport of water vapour; and (2) a decrease in net absorbed solar energy and a consequent general weakening of the continental-scale low-pressure system that drives precipitation over the basin.

Deforestation, climate and river discharge

Taken alone, a decrease in regional precipitation would result in decreased discharge. However, the integrated response of a river system depends on the balance between precipitation and evapotranspiration effects (Fig. 1). Deforestation within a particular watershed would cause reduced evapotranspiration and increased discharge, but deforestation at the continental scale could cause reduced regional precipitation and a tendency towards decreased river discharge[39].

A large disturbance and a long data record are needed to detect unambiguously the effect of deforestation on the discharge from a large river, given the large interannual and decadal variation in precipitation. For most of the major tributaries of the Amazon River, the area deforested is not yet large enough to be able to attribute changes in discharge specifically to deforestation. Similarly, a temporal trend in sediment load could not be distinguished from highly variable interannual and seasonal variation for the Madeira River, which drains the southwestern Amazon basin[40]. However, for the Tocantins River[41] and Araguaia River[42] systems, which drain parts of the Cerrado and rainforest environments in the southeastern Amazon, the relative contributions of climate variability and deforestation have been teased apart. From 1955 to 1995, the area of pasture and cropland in the Tocantins basin increased from about 30% to 50% and annual river discharge increased by about 25%, but changes in precipitation were not statistically significant. Changes of the same magnitude have occurred in the Araguaia River since the 1970s, and sediment load increased by 28% with deforestation. In both rivers, discharge increased mostly during the wet season, when flooding risks are greatest. If deforestation approaches this magnitude in other tributaries, it is likely that land-use change will enhance flooding and sediment transport.

Regional climate change

The IPCC fourth assessment climate change model runs show the highest probability of significant precipitation decrease predicted for southeastern Amazonia, where deforestation is greatest and where the climate and ecosystems transition from short-dry-season rainforest to long-dry-season savannah ecosystems[43,44]. Various global and regional climate modelling approaches have suggested that once deforestation exceeds about 40% of the entire Amazon basin, a 'tipping point' might be passed[45], whereby decreased energy and moisture released to the atmosphere from the largely deforested landscape would result in reduced convection and precipitation, and a shift in the forest–savannah boundary or large-scale dieback of rainforest.

A number of deficiencies in the structure and application of global climate models suggest that the uncertainty of these simulated outcomes and estimated tipping points is very high. A few examples include: (1) many of the models simulate too little precipitation in the Amazon owing to incomplete representation of the role of the Andes in continental circulation and large-scale convection over the core of the western Amazon, and also owing to coarse representation of the land surface with respect to small-scale meteorological processes[43]; (2) inter-annual variation of sea surface temperatures in the tropical Pacific and tropical north Atlantic Ocean are closely associated with extreme flood and drought events in the Amazon[5,8,20], but these teleconnections to the Amazon are not yet adequately represented in global climate models; and (3) the biophysical response of vegetation to increasing atmospheric CO_2, including effects on evapotranspiration, may be one of the largest unknowns for the future of the Amazon forests. The probability of simulated forest dieback due to decreased rainfall is greatly reduced when a strong CO_2 fertilization response is included in a vegetation model[44], but the scale of the actual impact of increasing CO_2 on photosynthetic efficiency remains a large source of uncertainty.

In summary, the changes in precipitation and discharge associated with deforestation already observed in the southern and eastern Amazon demonstrate a potential for significant vegetation shifts and further feedbacks to climate and discharge. Numerical models strongly suggest that potential future deforestation may also cause feedbacks to large-scale climate and vegetation distribution, but the models have deficiencies that prevent confident prediction of the magnitude or spatial distribution of deforestation that would lead to a significant region-wide decrease in precipitation—including whether a threshold, or tipping point, exists whereby the basin could slip into a dry, stable state. Focusing on a theoretical and difficult-to-define tipping point for the entire basin may divert the scientific community from the important large-scale regional changes that are already taking place, such as lengthening of the dry season[37,38] and increases in river discharge[41,42] in ecologically and agriculturally important transition zones of the eastern and southern flanks of the basin.

Fire as cause and consequence of change

The probability of fire is clearly affected by climate and land use, the latter providing the majority of ignition sources today[46]. Fire also affects regional climate through a complex set of biophysical and socioeconomic feedback processes (Fig. 1).

Smoke changes cloud physics and rainfall

During the wet season, the air over most of the Amazon region is as pristine as air over the open ocean—only a few hundred aerosol particles per cm^3 of air[47]—inspiring the term 'green ocean'[48]. In stark contrast, burning for land clearing, pasture management and charcoal production, and escaped forest fires during the dry season, increase aerosols to more than 40,000 particles per cm^3 of air in some regions[47]. This smoke and haze affects the microphysical processes within clouds that determine how droplets are formed, making droplets too small to precipitate as rain, thus reducing local rainfall and increasing cloud lifetime[49]. The water vapour remaining in the atmosphere ascends to higher altitudes, where it invigorates thunderstorm formation and lightning strikes, but not necessarily rain. During the dry season, satellite-based measurements of aerosol optical depth were inversely correlated with precipitation[50]. In addition to locally smoke-inhibited rainfall, fires cause further plant stress due to ozone pollution[51] and thick haze that reduces light availability and photosynthesis[52]. Generally, plants are most productive with some scattered light at intermediate levels of aerosol thickness, but conditions during the biomass burning season often exceed this optimum[52].

Drought increases fire susceptibility

The tall, dense tree canopy of central Amazonian forests creates a humid microclimate at ground level, which naturally protects the forest from fire[53]. However, several lines of evidence indicate that this natural resistance may be changing: (1) about 39,000 km^2 of Amazon forest burned during the El Niño drought of 1998[54], including intact, closed-canopy forests; (2) both logging and drought-induced tree mortality allow sunlight to penetrate clearings in the canopy, which dries out the forest floor, rendering it more flammable[53]; (3) after a forest is burned once, it is more likely to burn again, because a burned forest dries out more easily[30]; and (4) ignition sources have also increased owing to pasture management and charcoal making[46]. Although Brazil has made great strides in recent years to reduce rates of deforestation[1], the frequency of fire has not decreased[55], and prospects for continued forest degradation resulting from fires escaping nearby agricultural areas may be a growing risk in many regions.

Fires alter forest characteristics

After fires sweep through Amazonian forests, tree mortality ranges from 8% to 64% of mature stems (≥10 cm diameter at breast height)[56]. More frequent and/or more severe fires tend to increase tree and liana mortality[57]. Big trees are generally better adapted to surviving fire, but tend to be the first to suffer from drought[19,22,57]. Although surviving stems can benefit from the initial pulse of fire-released nutrients and reduced competition, fire-induced mortality reduces overall canopy cover, biomass, and species richness[57,58]. The decline in plant species diversity also reduces the abundance of fruits and invertebrates, thereby changing the food supply of birds and other animals[56]. Frequent fire could change the structure, composition and functioning of vegetation by selecting fire-adapted species and favouring more flammable species (for example, grasses), thus leading to a more savannah-like ecosystem[59].

Multiple fires retard forest regrowth

Fire is used as a tool to help clear land for cattle pasture and to slow the invasion of woody shrubs, but pastures are often abandoned after a few years, when grass productivity declines and weeds can no longer be effectively controlled. Despite tremendous diversity in rates of regrowth among secondary forests from different regions of the basin, the rate of secondary forest regrowth following pasture abandonment was found to be negatively correlated with the number of fires that occurred while in the pasture phase[60]. Nitrogen (N) loss during burning alters the natural patterns of phosphorus limitation on highly weathered soils. In a study of secondary forests growing on abandoned pastures and croplands, several soil and foliage indicators of N limitation were strongest in the youngest forest stands and became less pronounced as the forests aged[61]. After decades of forest regrowth, the N cycle gradually recuperates, establishing a N-rich mature forest, but the rate of recuperation, as well as the rate of forest regrowth, depends, in part, on the legacy of previous land use and fire.

Disturbance effects on greenhouse gases

Changes in greenhouse-gas emissions due to disturbance processes must be placed in the context of natural emissions. Amazonian forests and wetlands are significant natural sources of methane[62–64] and nitrous oxide[65,66] (Fig. 5). Unfortunately, a net carbon balance for the region remains elusive.

Mature forests may be accumulating carbon

Repeated sampling of about 100 permanent plots in the RAINFOR network scattered across nearly all Amazonian countries indicates that mature Amazonian forests have been accumulating carbon at an estimated rate of $0.4\,\mathrm{Pg\,C\,yr^{-1}}$ ($1\,\mathrm{Pg} = 10^{15}\,\mathrm{g}$; 95% confidence interval range of estimate, $0.29–0.57\,\mathrm{Pg\,C\,yr^{-1}}$) in the decades before the 2005 drought[19]. The fastest growing trees are in the foothills of the Andes, where the soils are generally younger and more fertile[7], but where the trees are generally smaller and shorter-lived[3,4]. In contrast, the biggest and slowest growing trees occur in the oldest and more nutrient-poor soils of the lowland central and eastern parts of the basin[67]. The soils of mature forests on highly weathered Oxisols and Ultisols are unlikely to

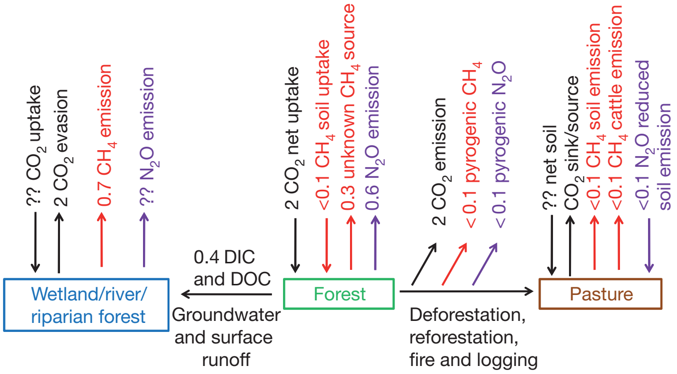

Figure 5 | Estimates of Amazonian greenhouse-gas emissions. Estimates of annual, basin-wide greenhouse-gas fluxes described in the text are presented together here, in a common currency of Pg CO_2-equivalents, using 100-year global warming potentials for CO_2 (black), CH_4 (red) and N_2O (purple). Owing to large uncertainties, all values are rounded to one significant figure, and even these estimates remain subject to debate. Where no estimate is available, "??" is indicated. Note that dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC) may be transported via groundwater and overland flow from upland forests to streamside (riparian) forests, and that CO_2 can be lost (evasion) from river water to the atmosphere.

be significant C sinks[68], although more study is needed on a wider diversity of soils.

The cause of observed biomass increases in mature Amazonian forests remains unknown. Plausible explanations include a rebound from previous human or natural disturbances[69] or a change in resources that limit plant productivity, such as atmospheric CO_2, soil nutrients, or light availability due to changes in radiation, climate and cloudiness[70]. The RAINFOR network is our best indicator of Amazonian above-ground biomass change, but the network is neither a systematic nor a randomized sampling of Amazonian vegetation. Because the network has relatively few small plots covering a vast region, the effects of large-scale natural disturbances over decadal and longer timescales may not be included in the sampling network, leading to an overestimate of a biomass increase[69,71]. Although this challenge to the RAINFOR conclusions has been rebutted[72,73], resolving the issue will require empirical data on the distribution of natural disturbances, which is still poorly known[71]. A recent analysis of satellite images and meteorological data showed that large disturbances (>5 ha) caused by windstorms are rare, with a return interval of about 40,000 years (ref. 74), suggesting that such disturbance effects may not be common enough to undermine extrapolations of carbon uptake rates from the RAINFOR network. However, more work on this topic is needed, including better estimates of the return intervals of smaller disturbances (<5 ha)[71].

Full C accounting should also include exports from forests to aquatic systems. The river water is supersaturated with dissolved CO_2, which is eventually released to the atmosphere at an estimated rate of about 0.5 Pg C yr^{-1} (ref. 75). Estimates of the sources of this C remain poorly constrained—about two-thirds may come from leaf and wood detritus dropped into the river from flooded forests, with about one-third produced by aquatic plants (mats of grasses and other macrophytes) within the river, and a small fraction by algae[76]. Additional possible sources include particulates washed in with soil particles and dissolved organic and inorganic C in ground water[77,78]. We know very little about the C budget of flooded forests and riparian zone forests, which probably contribute significant terrestrially fixed C to streams and rivers[76].

Estimates of CO_2 fluxes based on year-round vertical profiling of atmospheric CO_2 concentrations by aircraft are available now only for part of the eastern Amazon. Fire emissions roughly cancel a modest biological sink during the dry season, so that a wet season source yields an annual net source of C to the atmosphere[79]. This result is consistent with ground-based estimates of slow growing trees and a concentration of land-use change in the eastern part of the basin. It remains to be seen if future aircraft measurements will corroborate the C sink inferred from scattered ground measurements in the more intact forests of the western part of the basin.

Disturbing forests causes net C and N loss

The net effect of Amazonian deforestation and reforestation results in an annual net C source of 0.15–0.35 Pg C (ref. 80). Adding C emissions from fire and logging extends the range to an annual net release of 0.2–0.8 Pg C (ref. 80). The estimated mean annual C emission from deforestation and burning of Cerrado is 0.07 Pg C for 2003 to 2008[81]. These estimates are improving, in part because of advances in the technology for analysing satellite images[82] to combine spatially explicit deforestation rates with regionally specific estimates of forest-C stocks[83].

Pyrogenic CH_4 emissions from conversion of Amazonian and Cerrado native vegetation to pasture are about 1.0 and 0.4 Tg CH_4 yr^{-1}, respectively[81], but this does not include shifting cultivation or wildfire. Annual pyrogenic N_2O emissions from conversion of Amazonian forest to pasture are about 0.01 Tg N as N_2O (ref. 81), but this does not include shifting cultivation or wildfire.

When forests are replaced by cattle pastures, they can either gain[84] or lose[85] soil C. Losses are more common where soil C stocks are initially large, and gains are more common when management inputs (fertilizer, herd rotation, overgrazing avoidance) are greatest[86]. However, changes in soil C stocks are usually dwarfed by much larger losses in tree biomass. In contrast, the sparse and short-statured trees of the Cerrado have less above-ground biomass than an Amazonian forest, but the C stocks in roots and soil organic matter of the Cerrado (100 Mg C ha^{-1} in the top 1 m of soil) can be 2–7 times higher than the above-ground stocks[87]. Well-managed cultivated pastures may provide enough C inputs to maintain soil C[88], but most pastures in the Cerrado region are in advanced stages of degradation, where C inputs are too low to sustain high soil C storage.

Amazonian upland forest soils annually take up about 1–3 Tg of CH_4, and pasture soils are probably a small net annual source of <0.1 Tg CH_4 (ref. 65). A significant net emission of CH_4 in upland forests has been measured, which might include termites or anaerobic respiration in waterlogged wood, soil, bromeliads, or moss patches, but the source remains unknown[64]. Enteric fermentation by cattle is estimated to emit 2.6 and 4.1 Tg CH_4 yr^{-1} in Amazonian and Cerrado regions, respectively[81]. Continuing studies point to major hydroelectric reservoirs as an increasing source of methane[76]. On the basis of chamber flux measurements, upland Amazonian forest soils are estimated to emit 1.3 Tg yr^{-1} of N_2O-N (ref. 65), which is about 15% of global non-anthropogenic emissions. Young cattle pastures have higher N_2O emissions compared to forests, but old pastures have lower emissions, so the net effect of deforestation has been a small annual decrease of <0.1 Tg N_2O-N (ref. 65).

Although secondary forests may be significant carbon sinks in other parts of the world[89], they currently contribute little to the net C balance of the Amazon basin, because they are frequently re-cut before they grow large enough to store much C[90]. Indeed, the area of secondary forests is declining where agriculture continues to expand and intensify, leading to continued loss of biomass-C from those regions[91]. Agroforestry and other alternatives to slash-and-burn agriculture for smallholders have not been widely adopted, but the potential for significant C sequestration per hectare and the techniques of nutrient management in these systems have been demonstrated[92,93].

Emerging evidence for a transition

Are impacts of land-use and climate change in the Amazon basin surpassing the natural variability of climate, greenhouse-gas emissions, and cycles of carbon, nitrogen and water? Thanks to increased research in this area, including the Large-scale Biosphere-Atmosphere (LBA) experiment in Amazonia (see the accompanying World View in this issue for a description of the LBA project), we can answer this question for some, but not all consequences of land-use and climate change. For greenhouse gases, the answer is probably 'not yet' with respect to CH_4

and N_2O, because they remain dominated by large emissions from undisturbed wetlands and soils, respectively, but the answer for CO_2 is more complex (Fig. 5). Although a C budget for the basin remains uncertain, deforestation has moved the net basin-wide budget away from a possible late-twentieth-century net C sink and towards a net source. This directional change is consistent with recent results of inverse modelling based on the TransCom3 network of CO_2 measurements, which reports a shift from a sink in the 1980s to a source in the 2000s for the tropical Americas[94]. Much of the Amazon forest is resilient to seasonal and moderate drought, but this resilience can and has been exceeded with experimental and natural severe droughts, indicating a risk of C loss if drought increases with climate change. The forest is also resilient to initial disturbances, but repeated or prolonged disturbance changes forest structure and nutrient dynamics, potentially leading to a long-term change in vegetation composition and C loss. A combination of regional net flux estimates based on aircraft campaign measurements with ground-based studies that elucidate process-level understanding is needed to narrow uncertainties.

With respect to energy and water cycles, at least two of the large river basins on the southeastern flanks of the Amazon forest that also drain the more heavily deforested Cerrado region—the Tocantins and Araguaia basins—have experienced increases in wet season discharge and sediment load. Evidence for changes in temporal and spatial patterns of precipitation, such as extended length of the dry season, is emerging at local and regional scales. We cannot yet answer the questions of whether total precipitation has changed or whether recent severe droughts and other extreme events are clear indicators of patterns expected to persist. Narrowing uncertainties about the effects of deforestation on regional precipitation, temperature and fire risk will require combining realistic spatial patterns of deforestation and degradation with improved mesoscale circulation models of climate.

The emerging evidence of a system in biophysical transition highlights the need for improved understanding of the trade-offs between land cover, carbon stocks, water resources, habitat conservation, human health and economic development in future scenarios of climate and land-use change[24,32,95,96]. Brazil is poised to become one of the few countries to achieve the transition to a major economic power without destroying most of its forests. However, continued improvements in scientific and technological capacity and human resources will be required in the Amazon region to guide and manage both biophysical and socio-economic transitions.

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Acknowledgements We thank the Brazilian Ministry of Science and Technology (MCT), the National Institute for Space Research (INPE) and the National Institute of Amazonian Research (INPA) for designing, leading and managing the LBA project. We also thank D. Wickland (NASA) for more than a decade of leadership and support for the LBA-Eco project component of LBA. We thank the LBA-Eco team members who contributed to discussions on an early draft of this manuscript at a workshop in Foz do Iguaçu in August 2010, and S. Saleska for comments on the manuscript. We thank P. Lefebvre and W. Kingerlee for assistance with figure and manuscript preparation. Development of this manuscript was supported by NASA grants NNX08AF63A and NNX11AF20G.

Author Contributions E.A.D. wrote an initial rough draft and edited the final draft of the paper. M.K. and M.T.C. contributed significant final edits. All of the other co-authors participated in an LBA-Eco team meeting at Foz do Iguaçu on August, 13, 2010, where this manuscript was designed, and either were co-leaders of breakout groups or made significant subsequent contributions of subsections of text or figures. All co-authors also provided edits throughout.

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CORRIGENDUM

doi:10.1038/nature10943

Corrigendum: The Amazon basin in transition

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Nature **481,** 321–328 (2012)

In the 'Natural and anthropogenic climatic variation' section of this Review, we incorrectly referred to the North Atlantic Oscillation as a contributor to the 2005 Amazonian droughts. We should instead have referred to the Atlantic Multidecadal Oscillation, which is an oceanic phenomenon related to anomalies in sea surface temperature in the tropical north Atlantic Ocean and can affect drought in the Amazon Basin. We thank L. Aragao for drawing this error to our attention. This has been corrected in the PDF and HTML versions online.