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Synergisms among Fire, Land Use, and Climate Change in the Amazon

The Amazon is being rapidly transformed by fire. Logging and forest fragmentation sharply elevate fire incidence by increasing forest desiccation and fuel loads, and forests that have experienced a low-intensity surface fire are vulnerable to far more catastrophic fires. Satellites typically detect thermal signatures from 40 000 to 50 000 separate fires in the Amazon each year, and this number could increase as new highways and infrastructure expand across the basin. Many are concerned that large-scale deforestation, by reducing regional evapotranspiration and creating moisture-trapping smoke plumes, will make the basin increasingly vulnerable to fire. The Amazon may also be affected by future global warming and atmospheric changes, although much remains uncertain. Most models suggest the basin will become warmer throughout this century, although there is no consensus about how precipitation will be affected. The most alarming scenarios project a permanent disruption of the El Niño–Southern Oscillation, leading to greatly increased drought or destructive synergisms between regional and global climate change in the Amazon.

INTRODUCTION

Fire is one of the most potent of all forces in structuring natural ecosystems, and it influences myriad aspects of biological communities and their abiotic environments. When an ecosystem such as a tropical rain forest is burned, the effects can be spectacularly destructive or transformative (1–4). Here, we describe how human activities are radically altering the fire dynamic in tropical forests, with particular emphasis on the Amazon.

The natural fire regimes of different biomes are often relatively distinctive. Such regimes include the intensity and size of fires, their frequency and duration, and their timing with respect to seasonality. Alteration of one or any combination of these factors changes the fire regime, and if this exceeds the resistance or resilience capacity of the ecosystem, then the resulting changes can be dramatic (5). Vegetation and fire regimes interact in a dynamic manner, and each influences the other.

In the Amazon, as elsewhere in the tropics, human activities are altering fire regimes in fundamental ways. Ignition sources increase drastically in human-altered landscapes. Land-use changes, such as logging and forest fragmentation, increase fuel loads, desiccation, and forest flammability. Finally, climatic changes resulting from anthropogenic activities at local (6–9), regional (10–13), and possibly global scales (14) could increase the likelihood of fire. These changes may interact additively or synergistically, reinforcing one another in dangerous positive feedbacks (15, 16).

IGNITION SOURCES

Since the early 1970s, fire incidence has soared in the Amazon. This increase has closely paralleled concerted efforts to open up the Amazon frontier for forest-colonization projects, large-scale agriculture, industrial logging, and urban development. Major highway, road, and infrastructure projects have crisscrossed the basin and continue to proliferate (17–19), facilitating a large influx of immigrants. As a result of such activities, the population of Brazilian Amazonia increased approximately tenfold, from 2 to 20 million, from the early 1960s to 2000 (20).

Along the expanding road network, fire is the primary tool used to clear forest and maintain wide expanses of pastures and farmlands. Nearly 20% of the Brazilian Amazon has been cleared in the last several decades (21), with more than 2 million ha of forest being felled and burned annually in many years (22). Moreover, another 20 million ha of previously cleared lands are intentionally burned each year (23) to maintain pastures and remove secondary vegetation (24). Satellites typically detect thermal signatures of 40 000 to 50 000 separate fires in the Amazon annually (25).

Fires in tropical forest landscapes such as the Amazon fall into three main categories (3). First, deforestation fires, where slashed vegetation is burned, create intense fires that burn for several hours and then may smolder for days. Second, maintenance fires, which consume charred vegetation remnants from the initial deforestation fires, move rapidly as narrow fire lines through grass and early second growth. Third, accidental forest fires, which have escaped into standing forests, vary from extremely low-intensity fires in previously undisturbed forests to very intense fires in previously burned or logged forests.

LAND-USE CHANGES

Rapid alterations in land cover are also strongly affecting fire dynamics in Amazonia. When free from disturbance, tropical rain forests typically have high air and soil humidity, buffered temperatures, and little light and wind in the forest understory (26). These microclimatic conditions are ideal for decomposers such as bacteria, fungi, and termites, which rapidly break down leaf litter and fine wood debris (27) and thereby limit potential fuels on the forest floor. When the forest canopy is intact, fuel moisture remains high, even after several weeks without rain (1). For these reasons, fires have been rare in Amazonian forests in recent millennia (28), and major fires have been potentially limited to megadroughts occurring perhaps once or twice every thousand years (29).

Fires mostly occur in forests where the canopy is damaged. Greater canopy openness elevates solar heating and air flow, which rapidly dries leaf litter and other surface fuels (3, 23, 30, 31). Here, we highlight some key land-use changes, including forest fragmentation, logging, and prior burning, that degrade Amazonian forests and thereby predispose them to fire.

Forest Fragmentation

The rapid pace of Amazon deforestation is causing widespread habitat fragmentation. By 1988, the area of forest that was fragmented (<100 km^2 in area) or vulnerable to edge effects (<1 km from clearings) was over 150% larger than the total area deforested (32). In Brazilian Amazonia, nearly 20 000 km of new forest edges are being created each year (33), and this figure rises to 32 000 to 38 000 km per year if forest edges created by

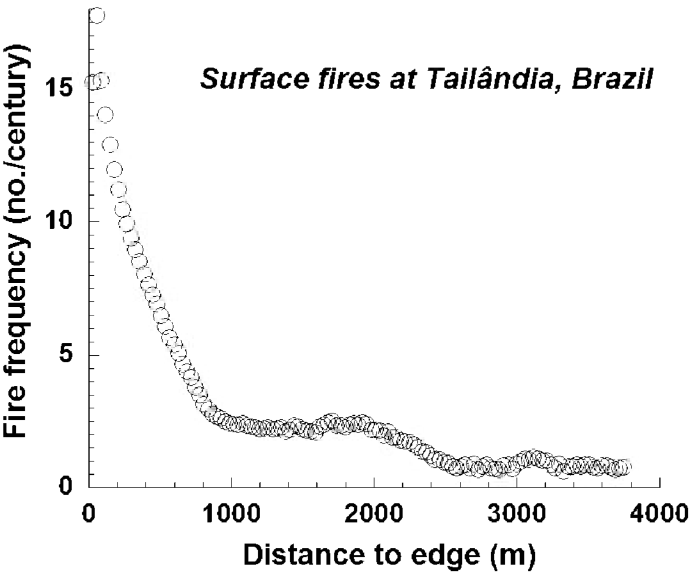

Figure 1. Dramatically elevated frequency of surface fires near forest edges in eastern Amazonia (adapted from Cochrane and Laurance [46]). Fire frequency (number per century) was estimated based on 12–14 y of satellite observations.

logging operations are included (34). At least one-third of the Brazilian Amazon has now been altered by deforestation, fragmentation, and edge effects (25), and by 2002, nearly half (47%) of the region showed evidence of human activity (35).

Habitat fragmentation affects the ecology of Amazonian forests in many ways, such as altering the diversity and composition of fragment biota (36, 37) and changing ecological processes like pollination and nutrient cycling (38, 39). Fragmentation also alters rain forest dynamics, causing sharply elevated rates of tree mortality, damage, and canopy-gap formation (40), apparently as a result of elevated desiccation (26), increased wind turbulence (41), and proliferating lianas (42) near fragment edges. These changes lead to a substantial loss of live biomass in fragments (43), and increased wood debris (44) and leaf litter (45) near fragment margins.

Forest fragments are typically juxtaposed with cattle pastures or slash-and-burn farming plots, which are regularly burned. Destructive fires can readily penetrate into forest fragments (31), especially during periodic El Niño droughts, when desiccation-stressed trees lose many leaves and fuel loads become particularly dry (16). Fire frequency is strongly linked to the distance from forest edges (15), with edge-related fires sometimes burning kilometers into the forest (Fig. 1) (46). The relationship between forest burning and distance from forest edges is nonlinear but quite striking, explaining up to 92% of observed forest burning (47). Many forest fragments are also selectively logged (48), and this further increases their vulnerability to fire.

Logging

Industrial logging is expanding rapidly in the Amazon, most dramatically in the southern and eastern parts of the basin (49–51). The amount of forest logged is comparable to that being deforested each year. From 1999–2002, for example, from 1.2 to 2.0 million ha of forest were logged annually in the Brazilian Amazon, equivalent to 60–123% of the forest area destroyed each year (50).

Tropical logging is selective because just one to a few dozen trees may be harvested per hectare of forest. Forest damage can be substantial, however, because the bulldozers used during logging operations create networks of forest roads, kill many nonharvested trees, increase soil erosion and stream sedimentation, and fragment the forest canopy (52, 53). As regional timber markets develop, forests are often relogged several times to harvest additional tree species. The damage to repeatedly logged forests can be intense, with 40–50% of the canopy cover destroyed (53).

Logging greatly increases the likelihood of forest fires (30, 54). Logging operations produce large quantities of dead, flammable slash in the understory, while canopy damage allows light and wind to penetrate to the understory and increase desiccation. This results in intense fires (2) and high rates of fire spread (47). Across the Brazilian Amazon, at least 76% of logged forests had canopy damage severe enough to render the forest highly vulnerable to droughts and fires (55).

In the Amazon, as in many tropical regions, industrial logging is the first step toward large-scale forest destruction (56). Logging creates an economic impetus for road building, which in turn initiates a wave of spontaneous forest colonization, hunting, and land speculation (25, 57, 58). Forest is destroyed both purposefully by colonists and ranchers and accidentally as fires leak into forests from nearby farmlands. From 1999–2004, 16% of forest logged in Amazonia was destroyed in the first year after logging, and 32% was destroyed within 4 y of logging (55).

Positive Feedbacks in Fire Dynamics

Surface fires are emerging as an important threat to Amazonian forests. Once initially damaged by a surface fire, closed-canopy forests are far more vulnerable to subsequent fires. The initial surface fire appears almost benign (Fig. 2). Except for treefall gaps and other areas of unusual fuel structure, fires spread slowly as narrow ribbons of flames a few tens of centimeters in height (59). Little is consumed by the fire other than leaf litter. Seedlings and small saplings suffer scorched foliage but canopy trees appear relatively unscathed. The energy released in the fire line is very low (50 kW m^{-1}) (2), but its slow advance makes it deadly to thin-barked tropical trees because it persists for many seconds at the tree base (1). An initial fire kills ~40% of all trees (>10 cm diameter) but only 10% of the standing biomass because most large trees initially survive, although more die in the following 2–3 y (2, 60).

Following the initial fire, canopy cover is reduced below 65%, and fuel loads rapidly increase as the dying vegetation rains to the ground. Subsequent fires are far more severe if they occur before forest recovery. In recurring fires, flame lengths, flame depths, rates of spread, residence times, and fire-line intensities are all far greater than in initial burns (2). Secondary fires can kill 40% of the remaining stems, corresponding to 40% of the live biomass, and in this case, large trees have no survival advantage over smaller trees. Canopy cover is reduced sharply to <35%, and the forest dries quickly (2). Weedy vines and grasses, some of which are quite flammable even when green, quickly colonize twice-burned forests (31).

Burning greatly alters forest composition and structure. Common tree species suffer the greatest mortality, but rare species are most likely to be locally extirpated (31). Prospects for species recovery are diminished because surface fires sharply reduce seed availability in the litter and upper-soil layers (61), while flowering and fruiting of trees in and near burned forests decrease (62, 63). Such conditions strongly favor windborne, light-demanding pioneer species. Within burned forests, unburned patches and gallery forests are key seed sources for postfire recovery, but recurring fires quickly reduce the size and number of unburned areas (31) and kill regenerating vegetation. This further diminishes prospects for recovery of mature-forest plant and animal species (64).

Figure 2. Although slow-moving, surface fires have remarkably destructive effects on rain forests. (Photo: M.A. Cochrane)

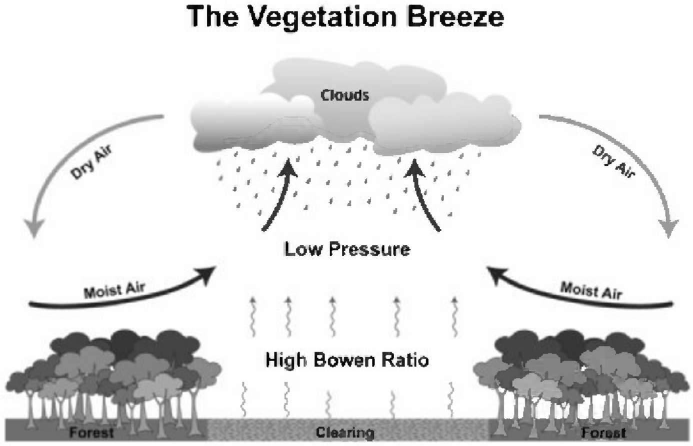

Figure 3. The vegetation-breeze phenomenon, which promotes forest desiccation in the vicinity of pastures and clearings.

Surface fires can create a dangerous positive feedback whereby each successive fire becomes more likely (31) and more severe because of higher fuel loads and fire intensities (2). Such destabilizing dynamics are common in fragmented landscapes where frequent burning in nearby pastures and farms is a source of recurring ignition. Under such circumstances, the margins of forest fragments can literally "implode" over time, as forest margins collapse in response to a withering recurrence of surface fires (46, 65).

CLIMATIC CHANGES

Local and Regional-scale Phenomena

Major changes in land cover could have important effects on local and regional climates, which in turn may increase the likelihood of forest fires. The loss and fragmentation of forest cover can alter local and regional climates in several ways.

First, habitat fragmentation can promote forest desiccation via a phenomenon known as the vegetation breeze (Fig. 3). This occurs because fragmentation leads to the juxtaposition of cleared and forested lands, which differ greatly in their physical characteristics. Air above forests tends to be cooled by evaporative cooling (from evapotranspiration of water vapor), whereas such cooling is much reduced above clearings (this increases the Bowen ratio, which is the ratio of sensible to latent heat). As a result, the air over clearings heats up and rises, reducing local air pressure and drawing moist air from surrounding forests into the clearing. As the rising air cools, the moisture it carries condenses into convective clouds that may produce rainfall over the clearing. The air is then recycled—as cool, dry air—back over the forest (6, 7).

The net effect of the vegetation breeze is that forest clearings promote local atmospheric circulations that may increase rainfall but, paradoxically, draw moist air away from nearby rain forest (Fig. 3). In regions with prevailing winds, some rain generated by the vegetation breeze may fall on downwind forests, not just in clearings, and desiccation would be most severe in upwind forests. In the Amazon, vegetation-breeze effects have been observed in clearings as small as a few hundred hectares, but these effects appear to peak when clearings are roughly 100–150 km in diameter (8). The vegetation breeze is essentially a large-scale edge effect; satellite observations in Rondônia, Brazil, suggest that the desiccating effects of major clearings can extend up to 20 km into adjoining forests (9).

Second, the conversion of forests to pasture or savannah reduces the rate of evapotranspiration because grass and shrubs have far less leaf surface area than do forests (66). Declining evapotranspiration could potentially decrease rainfall and cloud cover and increase albedo and surface temperatures. Moisture recycling via evapotranspiration is probably especially important in the hydrological regime of the Amazon because it is both vast and far from the ocean. However, the regional effects of large-scale deforestation are far from fully understood. For example, several modeling studies suggest that Amazonian deforestation could reduce basinwide precipitation by roughly 20–30%, but these studies have relied on a simplistic assumption of complete, uniform forest clearing (e.g., 67–69). Model results based on actual (*circa* 1988) deforestation patterns in Brazilian Amazonia have been less dramatic, with deforested regions predicted to experience modest (6–8%) declines in rainfall, moderate (18–33%) reductions in evapotranspiration, higher surface temperatures, and greater wind speeds (from reduced surface drag), which could affect moisture convergence and circulation (10, 11). It is even possible that moderate forest loss and fragmentation could *increase* net regional precipitation, as a result of the vegetation breeze, although the main effect would be to remove moisture from forests and redistribute it over adjoining clearings. The greatest concern is that if deforestation reaches some critical but unknown threshold, Amazonian rainfall could decline abruptly as the regional hydrological system collapses (12, 13).

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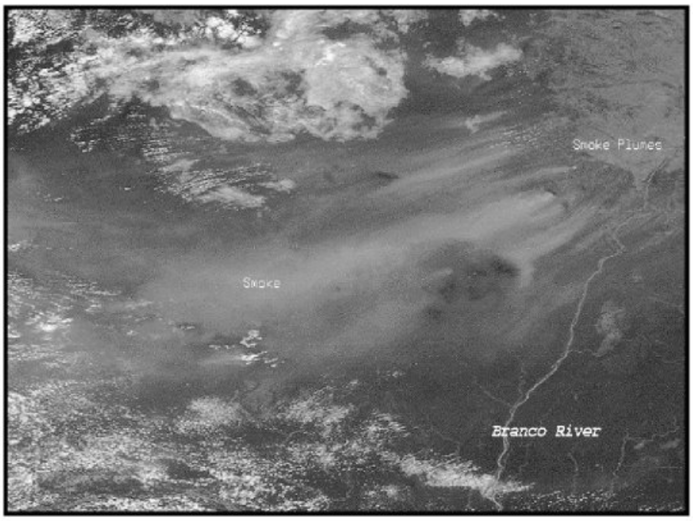

Figure 4. Thermal-satellite scene of northern Amazonia in early 1998, illustrating the paucity of clouds in the vicinity of heavy smoke plumes (image courtesy of National Aeronautics and Space Administration).

Two further effects of forest loss are caused by the massive smoke plumes (Fig. 4) produced by forest and pasture fires. Smoke hypersaturates the atmosphere with cloud condensation nuclei (microscopic particles in aerosol form) that bind with airborne water molecules and thereby inhibit the formation of raindrops (70). In addition, by absorbing solar radiation, smoke plumes warm the atmosphere, inhibiting cloud formation. As a result of these two phenomena, large fires can create rain shadows that extend hundreds of kilometers downwind (71). Moreover, because tropical fires are lit during the dry season, both phenomena reduce rainfall during the critical dry-season months, when plants are already moisture stressed and most vulnerable to fire.

Global-scale Phenomena

Although much remains uncertain, the Amazonian climate is also expected to be altered by global warming and atmospheric changes. By 2100, global mean temperatures are projected to rise by 1.8–4.0°C, and the Amazon is likely to become warmer, but more so in the west than east (72). Rainfall may decline; some global circulation models (GCMs) predict moderate reductions in precipitation (72), whereas other predictions are much more severe (14). Further, excepting northwestern Amazonia, the basin might experience longer intervals between rainfall events (73). This is important because fire susceptibility is more closely related to the amount of time since last rain than to total rainfall (1, 31).

Some GCMs predict a truly dire future for the Amazon. The most alarming, by Cox et al. (14), projects sharp (>9°C) temperature increases and a dramatic reduction (64%) in basinwide rainfall, resulting in a large-scale dieback of forests after 2050. By 2100, modeled conditions are so extreme that over half of the Amazon is expected to become a virtual desert (74). The driving force behind this model is the establishment of a perpetual El Niño state in Amazonia. Under El Niño conditions, much of the Amazon becomes hotter and drier. Because up to 90% of Amazon forest burning occurs in El Niño years (2, 75), any potential increases in El Niño frequency or intensity could have grave implications for forests.

Other evidence, however, suggests that the projections by Cox et al. (14, 74) are too pessimistic. A comparison of 20 different models of El Niño–Southern Oscillation (ENSO) variability showed that most projected little or no change in future ENSO conditions (76). Moreover, the models that predicted the largest future changes (shifts to permanent El Niño or La Niña states) were poorest at simulating historical ENSO variability (76). In addition, the draconian projections of Cox et al. seem at variance with known historical changes in the Amazon. Despite considerable Pleistocene cooling and drying, for instance, Amazonian forests were evidently more stable in their geographic distribution than was previously thought (77, 78). Finally, regional circulation models (RCMs), which better represent local topography, geographic features, and land-cover changes than do GCMs (79), suggest that Amazonian vegetation might be surprisingly resistant to climate change (78, 80).

Hence, at present, it is exceedingly difficult to predict the future impact of global warming on the Amazon, given the great variation among different models, although most agree that the southeast Amazon is at greatest risk of moderate to severe reductions in dry-season rainfall (81). If projections of broader-scale drying and warming trends should prove correct, then large expanses of the Amazon could become more prone to fire this century. This is especially so because forests in the southern, eastern, and north-central parts of the basin are already at or near the physiological limits of tropical rain forest (82), and because forest-conversion pressure and fire incidence are most intense in these drier and more seasonal areas (83).

CONCLUSIONS

A growing consensus among GCMs is that the Amazonian climate will continue to warm this century (72). Warmer and potentially drier conditions will make forests susceptible to burning more frequently, and for longer periods, allowing greater penetration of fires into forest remnants. So long as agricultural land uses rely on fire as a land-clearing and maintenance tool, ignition sources along forest edges will always be present. Forest vulnerability will be greatly increased by large-scale forest fragmentation (84) and logging, which are being promoted by rapidly expanding highways and infrastructure (18). Because recycling of evapotranspiration is responsible for 25–50% of Amazonian precipitation (85–87), regional rainfall is likely to decline in concert with increasing deforestation. Moreover, although much is uncertain, a growing concern is that regional and global climatic changes might operate synergistically or in concert (88), exacerbating the overall impact on forests. The nonlinear nature of many of the processes that link fire occurrence to landscape and climate changes makes modeling of fire and its effects a great challenge in the Amazon. Unless fundamental changes occur in the way human-dominated landscapes are managed, increasing expanses of Amazonian forests will be subjected to fire regimes for which they are not evolutionarily equipped to survive.

References and Notes

1. Uhl, C. and Kauffman, J.B. 1990. Deforestation, fire susceptibility, and potential tree responses to fire in the eastern Amazon. *Ecology 71*, 437–449.
2. Cochrane, M.A., Alencar, A., Schulze, M.D., Souza, C. Jr., Nepstad, D., Lefebvre, P. and Davidson, E. 1999. Positive feedbacks in the fire dynamic of closed canopy tropical forests. *Science 284*, 1832–1835.
3. Cochrane, M.A. 2003. Fire science for rainforests. *Nature 421*, 913–919.
4. Barlow, J. and Peres, C.A. 2008. Fire-mediated dieback and compositional cascade in an Amazonian forest. *Philos. Trans. Roy. Soc. Lon. B 363*, 1787–1794.
5. Holling, C.S. 1973. Resilience and stability of ecological systems. *Ann. Rev. Ecol. Syst. 4*, 1–23.
6. Silva Dias, P.L. and Regnier, P. 1996. Simulation of mesoscale circulations in a deforested area of Rondônia in the dry season. In: *Amazonian Deforestation and Climate*. Gash, J., Nobre, C., Roberts, J. and Victoria, R. (eds). John Wiley & Sons, San Francisco, pp. 531–547.
7. Baidya Roy, S. and Avissar, R. 2000. Scales of response of the convective boundary layer to land-surface heterogeneity. *Geophys. Res. Lett. 27*, 533–536.
8. Avissar, R. and Liu, Y. 1996. A three-dimensional numerical study of shallow convective clouds and precipitation induced by land-surface forcing. *J. Geophys. Res. 101*, 7499–7518.

9. Silva Dias, M.A.F., Rutledge, S., Kabat, P., Silva Dias, P.S., Nobre, C., Fisch, G., Dolman, A.J., Zipser, E., et al. 2002. Cloud and rain processes in a biosphere-atmosphere interaction context in the Amazon Region *J. Geophys. Res. 107*, 8072. (doi: 10.1029/2001JD00035)
10. Walker, G., Sud, Y. and Atlas, R. 1995. Impact of ongoing Amazonian deforestation on local precipitation: a GCM simulation study. *Bull. Am. Meteor. Soc. 76*, 346–361.
11. Sud, Y., Yang, R. and Walker, G. 1996. Impact of in situ deforestation in Amazonia on the regional climate: general circulation model simulation study. *J. Geophys. Res. 101*, 7095–7109.
12. Avissar, R., Silva Dias, P., Silva Dias, M. and Nobre, C. 2002. The Large-scale Biosphere-atmosphere Experiment in Amazonia (LBA): insights and future research needs. *J. Geophys. Res. 107*, 8086. (doi:10.1029/2002JD002704)
13. Baidya Roy, S. and Avissar, R. 2002. Impact of land use/land cover change on regional hydrometeorology in the Amazon. *J. Geophys. Res. 107*, 8037. (doi:10.1029/2000JD000266)
14. Cox, P.M., Betts, R., Jones, C., Spall, S. and Totterdell, I. 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature 408*, 184–187.
15. Cochrane, M.A. 2001. Synergistic interactions between habitat fragmentation and fire in evergreen tropical forests. *Conserv. Biol. 15*, 1515–1521.
16. Laurance, W.F. and Williamson, G. 2001. Positive feedbacks among forest fragmentation, drought, and climate change in the Amazon. *Conserv. Biol. 15*, 1529–1535.
17. Fearnside, P.M. 2002. Avança Brasil: environmental and social consequences of Brazil's planned infrastructure in Amazonia. *Environ. Manage. 30*, 735–747.
18. Laurance, W.F., Cochrane, M.A., Bergen, S., Fearnside, P., Delamonica, P., Barber, C., D'Angelo, S. and Fernandes, T. 2001. The future of the Brazilian Amazon. *Science 291*, 438–439.
19. Soares-Filho, B., Nepstad, D., Curran, L., Cerqueira, G., Garcia, R., Ramos, C., Voll, E., McDonald, A., Lefebvre, P. and Schlesinger, P. 2006. Modelling conservation in the Amazon Basin. *Nature 440*, 520–523.
20. Laurance, W.F., Albernaz, A. and Da Costa, C. 2001. Is deforestation accelerating in the Brazilian Amazon? *Environ. Conserv. 28*, 305–311.
21. National Institute for Space Research (INPE). 2005. Projeto Prodes: Monitoramento da Floresta Amazônica Brasileira por Satélite. INPE, San José dos Campos, Brazil (http://www.obt.inpe.br/prodes/).
22. Laurance, W.F., Albernaz, A., Fearnside, P., Vasconcelos, H. and Ferreira, L. 2004. Deforestation in Amazonia. *Science 304*, 1109.
23. United Nations Environment Program (UNEP). 2002. *Spreading Like Wildfire—Tropical Forest Fires in Latin America and the Caribbean: Prevention, Assessment and Early Warning*. UNEP, Panama, 96 pp.
24. Kauffman, J.B., Cummings, D. and Ward, D. 1998. Fire in the Brazilian Amazon: 2. Biomass, nutrient pools and losses in cattle pastures. *Oecologia 113*, 415–427.
25. Laurance, W.F. 1998. A crisis in the making: responses of Amazonian forests to land use and climate change. *Trends Ecol. Evol. 13*, 411–415.
26. Kapos, V. 1989. Effects of isolation on the water status of forest patches in the Brazilian Amazon. *J. Trop. Ecol. 5*, 173–185.
27. Chambers, J.Q., Higuchi, N., Schimel, J., Ferreira, L. and Melack, J. 2000. Decomposition and carbon cycling of dead trees in tropical forests of the central Amazon. *Oecologia 122*, 380–388.
28. Sanford, R.L., Saldarriaga, J., Clark, K., Uhl, C. and Herrera, R. 1985. Amazon rainforest fires. *Science 227*, 53–55.
29. Meggers, B.J. 1994. Archeological evidence for the impact of mega-Niño events on Amazonian during the past two millennia. *Climate Change 28*, 321–338.
30. Holdsworth, A.R. and Uhl, C. 1997. Fire in Amazonian selectively logged rain forest and the potential for fire reduction. *Ecol. Applic. 7*, 713–725.
31. Cochrane, M.A. and Schulze, M.D. 1999. Fire as a recurrent event in tropical forests of the eastern Amazon: effects on forest structure, biomass, and species composition. *Biotropica 31*, 2–16.
32. Skole, D. and Tucker, C.J. 1993. Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978 to 1988. *Science 260*, 1905–1910.
33. This average figure is based on an analysis of annual forest-cover change in Brazilian Amazonia from 1993 to 1999, using high-resolution Landsat data, conducted by W. Chomentowski, D. Skole, and M. Cochrane.
34. Broadbent, E.N., Asner, G.P., Keller, M., Knapp, D.E., Oliveira, P. and Silva, J.N. 2008. Forest fragmentation and edge effects from deforestation and selective logging in the Brazilian Amazon. *Biol. Conserv. 141*, 1745–1757.
35. Barreto, P., Souza, C., Noguerón, R., Anderson, A., Salomão, A. and Wiles, J. 2006. *Human Pressure on the Brazilian Amazon Forests*. World Resources Institute, Washington, DC, 84 pp.
36. Laurance, W.F., Lovejoy, T., Vasconcelos, H., Bruna, E., Didham, R., Stouffer, P., Gascon, C., Bierregaard, R., et al. 2002. Ecosystem decay of Amazonian forest fragments: a 22-year investigation. *Conserv. Biol. 16*, 605–618.
37. Laurance, W.F., Nascimento, H., Laurance, S., Andrade, A., Ribeiro, J., Giraldo, J., Lovejoy, T., Condit, R., et al. 2006. Rapid decay of tree-community composition in Amazonian forest fragments. *Proc. Nat. Acad. Sci. USA 103*, 19010–19014.
38. Didham, R.K., Ghazoul, J., Stork, N.E. and Davis, A. 1996. Insects in fragmented forests: a functional approach. *Trends Ecol. Evol. 11*, 255–260.
39. Klein, B.C. 1989. Effects of forest fragmentation on dung and carrion beetle communities in central Amazonia. *Ecology 70*, 1715–1725.
40. Laurance, W.F., Ferreira, L., Rankin-De Merona, J. and Laurance, S. 1998. Rain forest fragmentation and the dynamics of Amazonian tree communities. *Ecology 79*, 2032–2040.
41. Laurance, W.F. 2004. Forest-climate interactions in fragmented tropical landscapes. *Phil. Trans. Roy. Soc. Lon. B 359*, 345–352.
42. Laurance, W.F., Perez-Salicrup, D., Delamonica, P., Fearnside, P., D'Angelo, S., Jerozolinski, A., Pohl, L. and Lovejoy, T. 2001. Rain forest fragmentation and the structure of Amazonian liana communities. *Ecology 82*, 105–116.
43. Laurance, W.F., Laurance, S.G., Ferreira, L., Rankin-de Merona, J., Gascon, C. and Lovejoy, T. 1997. Biomass collapse in Amazonian forest fragments. *Science 278*, 1117–1118.
44. Nascimento, H. and Laurance, W.F. 2004. Biomass dynamics in Amazonian forest fragments. *Ecol. Applic. 14*, S127–S138.
45. Vasconcelos, H.L. and Laurance, W.F. 2005. Influence of habitat, litter type, and soil invertebrates on leaf-litter decomposition in a fragmented Amazonian landscape. *Oecologia 144*, 456–462.
46. Cochrane, M.A. and Laurance, W.F. 2002. Fire as a large-scale edge effect in Amazonian forests. *J. Trop. Ecol. 18*, 311–325.
47. Cochrane, M.A., Skole, D., Matricardi, E., Barber, C. and Chomentowski, W. 2004. Selective logging, forest fragmentation and fire disturbance: implications of interaction and synergy. In: *Working Forests in the Neotropics: Conservation through Sustainable Management?* Zarin, D. (ed). Columbia University Press, New York, pp. 310–324.
48. Peres, C.A. and Michalski, F. 2006. Synergistic effects of habitat disturbance and hunting in Amazonian forest fragments. In: *Emerging Threats to Tropical Forests*. Laurance, W.F. and Peres, C.A. (eds). University of Chicago Press, Chicago, pp. 105–127.
49. Nepstad, D., Veríssimo, A., Alencar, A., Nobre, C., Lima, E., Lefebvre, P., Schlesinger, P., Potter, C., et al. 1999. Large-scale impoverishment of Amazonian forests by logging and fire. *Nature 398*, 505–508.
50. Asner, G.P., Knapp, D., Broadbent, E., Oliveira, P., Keller, M. and Silva, J. 2005. Selective logging in the Brazilian Amazon. *Science 310*, 480–482.
51. Matricardi, E., Skole, D., Cochrane, M., Qi, J., Pedlowski, M. and Chomentowski, W. 2007. Multi-temporal assessment of selective logging in the Brazilian Amazon using Landsat data. *Int. J. Remote Sens. 28*, 63–82.
52. Johns, J.S., Barreto, P. and Uhl, C. 1996. Logging damage in planned and unplanned logging operations in the eastern Amazon. *For. Ecol. Manage. 89*, 59–77.
53. Uhl, C., Barreto, P., Veríssimo, A., Vidal, E., Amaral, P., Barros, A.C., Souza, C. Jr., Johns, J., et al. 1997. Natural resource management in the Brazilian Amazon. *BioScience 47*, 160–168.
54. Kauffman, J.B. and Uhl, C. 1990. Interactions of anthropogenic activities, fire, and logging in rain forests in the Amazon basin. In: *Fire in the Tropical Biota*. Goldammer, J.G. (ed). Springer-Verlag, Berlin, pp. 117–134.
55. Asner, G., Broadbent, E., Oliveira, P., Keller, M., Knapp, D. and Silva, J. 2006. Condition and fate of logged forests in the Brazilian Amazon. *Proc. Nat. Acad. Sci. USA 103*, 12947–12950.
56. Laurance, W.F. 2001. Tropical logging and human invasions. *Conserv. Biol. 15*, 4–5.
57. Veríssimo, A., Barreto, P., Tarifa, R. and Uhl, C. 1995. Extraction of a high-value natural source from Amazon: the case of mahogany. *For. Ecol. Manage. 72*, 39–60.
58. Fearnside, P.M. 1997. Protection of mahogany: a catalytic species in the destruction of rain forests in the American tropics. *Environ. Conserv. 24*, 303–306.
59. Cochrane, M.A. and Schulze, M.D. 1998. Forest fires in the Brazilian Amazon. *Conserv. Biol. 12*, 948–950.
60. Barlow, J., Peres, C., Lagan, B. and Haugaasen, T. 2003. Large tree mortality and the decline of forest biomass following Amazonian wildfires. *Ecol. Lett. 6*, 6–8.
61. Van Nieuwstadt, M., Sheil, D. and Kartawinata, K. 2001. The ecological consequences of logging in the burned forests of East Kalimantan, Indonesia. *Conserv. Biol. 15*, 1183–1186.
62. Kinnaird, M.F. and O'Brien, T. 1998. Ecological effects of wildfire on lowland rainforest in Sumatra. *Conserv. Biol. 12*, 954–956.
63. Barlow, J. and Peres, C. 2006. Effects of single and recurrent wildfires on fruit production and large vertebrate abundance in a central Amazonian forest. *Biodiv. Conserv. 15*, 985–1012.
64. Barlow, J. and Peres, C. 2004. Ecological responses to El Niño–induced surface fires in central Amazonia: management implications for flammable tropical forests. *Phil. Trans. Roy. Soc. Lon. B 359*, 367–380.
65. Gascon, C., Williamson, G. and Fonseca, G. 2000. Receding edges and vanishing reserves. *Science 288*, 1356–1358.
66. Jipp, P., Nepstad, D., Cassel, K. and de Carvalho, C. 1998. Deep soil moisture storage and transpiration in forests and pastures of seasonally dry Amazônia. *Clim. Change 39*, 395–412.
67. Nobre, C.A., Sellers, P. and Shukla, J. 1991. Amazonian deforestation and regional climate change. *J. Clim. 4*, 411–413.
68. Dickinson, R. and Kennedy, P. 1992. Impacts on regional climate of Amazon deforestation. *Geophys. Res. Lett. 19*, 1947–1950.
69. Lean, J. and Rowntree, P. 1993. A GCM simulation of the impact of Amazonian deforestation on climate using an improved canopy representation. *Q. J. Roy. Meteor. Soc. 119*, 509–530.
70. Rosenfeld, D. 1999. TRMM observed first direct evidence of smoke from forest fires inhibiting rainfall. *Geophys. Res. Lett. 26*, 3105–3108.
71. Freitas, S., Silva Dias, M. and Silva Dias, P. 2000. Modeling the convective transport of trace gases by deep and moist convection. *Hybrid Methods Engin. 3*, 317–330.
72. International Panel on Climate Change (IPCC). 2007. *Climate Change 2007: The Physical Science Basis*. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M. and Miller, H. (eds). Cambridge University Press, Cambridge, UK, 1009 pp.
73. Tebaldi, C., Hayhoe, K., Arblaster, J. and Meehl, G. 2006. Going to the extremes: an intercomparison of model-simulated historical and future changes in extreme events. *Climate Change 79*, 185–211.
74. Cox, P.M., Betts, R., Collins, M., Harris, P., Huntingford, C. and Jones, C. 2004. Amazonian forest dieback under climate-carbon cycle projections for the 21st century. *Theoret. Appl. Climatol. 78*, 137–156.
75. Alencar, A., Nepstad, D. and Vera Diaz, M. 2006. Forest understory fire in the Brazilian Amazon in ENSO and no-ENSO years: area burned and committed carbon emissions. *Earth Interact. 10*, 1–17.
76. Collins, M. 2005. The CMIP modeling groups, El Niño or La Niña–like climate change? *Climate Dynam. 24*, 89–104.
77. Bush, M.B. and Silman, M. 2004. Observations on late Pleistocene cooling and precipitation in the lowland Neotropics. *J. Quatern. Sci. 19*, 677–684.
78. Cowling, S.A. and Shin, Y. 2006. Simulated ecosystem threshold responses to co-varying temperature, precipitation and atmospheric CO_2 within a region of Amazonia. *Glob. Ecol. Biogeogr. 15*, 553–566.
79. Cook, K.H. and Vizy, E. 2006. South American climate during the Last Glacial Maximum: delayed onset of the South American monsoon. *J. Geophys. Res. 111*, D02110. (doi: 10.1029/2005JD005980)
80. Levi, P.E., Cannell, M. and Friend, A. 2004. Modeling the impact of future changes in climate, CO_2 concentration and land use on natural ecosystems and the terrestrial carbon sink. *Glob. Environ. Change 14*, 21–30.
81. Malhi, Y., Roberts, J.T., Betts, R.A., Killeen, T.J., Li, W.H. and Nobre, C.A. 2008. Climate change, deforestation, and the fate of the Amazon. *Science 319*, 169–172.
82. Nepstad, D., Carvalho, C., Davidson, E., Jipp, P., Lefebre, P., Negreiros, G., Silva, E., Stone, T., et al. 1994. The role of deep roots in the hydrological cycles of Amazonian forests and pastures. *Nature 372*, 666–669.
83. Laurance, W.F., Albernaz, A., Schroth, G., Fearnside, P., Venticinque, E. and Da Costa, C. 2002. Predictors of deforestation in the Brazilian Amazon. *J. Biogeogr. 29*, 737–748.
84. Aragao, L.E.O.C., Malhi, Y., Barbier, N., Lima, A., Shimabukuro, Y., Anderson, L. and Saatchi, S. 2008. Interactions between rainfall, deforestation and fires during recent years in the Brazilian Amazonia. *Philos. Trans. Roy. Soc. Lon. B 363*, 1779–1785.

85. Eltahir, E.A.B. and Bras, R.L. 1996. Precipitation recycling. *Rev. Geophysics 34*, 367–378.
86. Li, W. and Fu, R. 2004. Transition of the large-scale atmospheric and land surface conditions from dry to wet season over Amazonia as diagnosed by the ECMWF re-analysis. *J. Climate 17*, 2637–2651.
87. Cowling, A.S., Shin, Y., Pinto, E. and Jones, C.D. 2008. Water recycling by Amazonian vegetation: coupled versus uncoupled vegetation-climate interactions. *Philos. Trans. Roy. Soc. Lon. B 363*, 1865–1871.
88. Johnson, E.A. and Cochrane, M.A. 2003 Disturbance regime interactions. In: *Climate Change and Biodiversity: Synergistic Impacts*. Lovejoy, T. and Hannah, L. (eds). Advances in Applied Biodiversity Science, No. 4. Conservation International, Washington, DC, pp. 39–44.
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