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Large-scale impoverishment of Amazonian forests by logging and fire

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Amazonian deforestation rates are used to determine human effects on the global carbon cycle[1–3] and to measure Brazil's progress in curbing forest impoverishment[1,4,5]. But this widely used measure of tropical land use tells only part of the story. Here we present field surveys of wood mills and forest burning across Brazilian Amazonia which show that logging crews severely damage 10,000 to 15,000 $km^2\,yr^{-1}$ of forest that are not included in deforestation mapping programmes. Moreover, we find that surface fires burn additional large areas of standing forest, the destruction of which is normally not documented. Forest impoverishment due to such fires may increase dramatically when severe droughts provoke forest leaf-shedding and greater flammability; our regional water-balance model indicates that an estimated 270,000 km^2 of forest became vulnerable to fire in the 1998 dry season. Overall, we find that present estimates of annual deforestation for Brazilian Amazonia capture less than half of the forest area that is impoverished each year, and even less during years of severe drought. Both logging and fire increase forest vulnerability to future burning[6,7] and release forest carbon stocks to the atmosphere, potentially doubling net carbon emissions from regional land-use during severe El Niño episodes. If this forest impoverishment is to be controlled, then logging activities need to be restricted or replaced with low-impact timber harvest techniques, and more effective strategies to prevent accidental forest fires need to be implemented.

Human uses of tropical forests vary greatly in their ecological impacts. Ranchers and farmers 'deforest' land in preparation for cattle pasture and crops by clear-cutting and burning patches of forest. Loggers do not clear-cut and burn, but perforate forests by harvesting or damaging many trees. Rubber tapping and similar activities use the forest at very low intensity through the harvest of animals, fruits, latex and other "non-timber products"[8–11]. Deforestation by ranchers and farmers has a greater effect on forest carbon content, forest hydrology, and the diversity of native plant and animal species than other forest uses[9–14] and has become the main parameter by which human effects on tropical forests are measured. Part of the appeal of this forest versus non-forest approach to assessing human effects on tropical forests is its tractability. Forest conversion to agriculture is readily monitored from space using imagery from the Landsat Thematic Mapper (TM) satellites, permitting the development of deforestation maps of large regions at a reasonable cost and speed[4,5].

This binary approach to the analysis of human effects on tropical forests neglects those forest alterations that reduce tree cover, but do not eliminate it, such as logging and surface fires in standing forests. The forest openings created by logging and accidental surface fires are visible in Landsat TM images, but they are covered over by regrowing vegetation within 1 to 5 years, and are easily misclassified in the absence of accompanying field data[15]. Although logging and forest surface fires usually do not kill all trees, they severely damage forests. Logging companies in Amazonia kill or damage 10–40% of the living biomass of forests through the harvest process[9,10,16]. Logging also increases forest flammability by reducing forest leaf canopy coverage by 14–50%[7,9,10,16,17], allowing sunlight to penetrate to the forest floor, where it dries out the organic debris created by the logging. Fires ignited on agricultural lands can penetrate logged forests[7,17,18], killing 10–80% of the living biomass[6,17] and greatly increasing the vulnerability of these forests to future burning[6,19]. Fires from agricultural lands can also penetrate those undisturbed forests that have lost portions of their leaf canopies because of severe seasonal drought[19].

We estimated the area of Brazilian Amazonian forest that is impoverished each year through logging by interviewing 1,393 wood mill operators, representing more than half of the mills located in 75 logging centres (Table 1); these logging centres are responsible for >90% of Amazonian timber production. In each interview, we obtained the mill's harvest records of roundwood (tree trunks) for 1996 and 1997 and the harvest rate (m^3 of timber per ha of forest), thereby calculating the forest area required to supply each centre's timber production. The accuracy of the roundwood harvest rates reported by mill operators was tested by comparing these interview data with direct measurements of roundwood harvest in

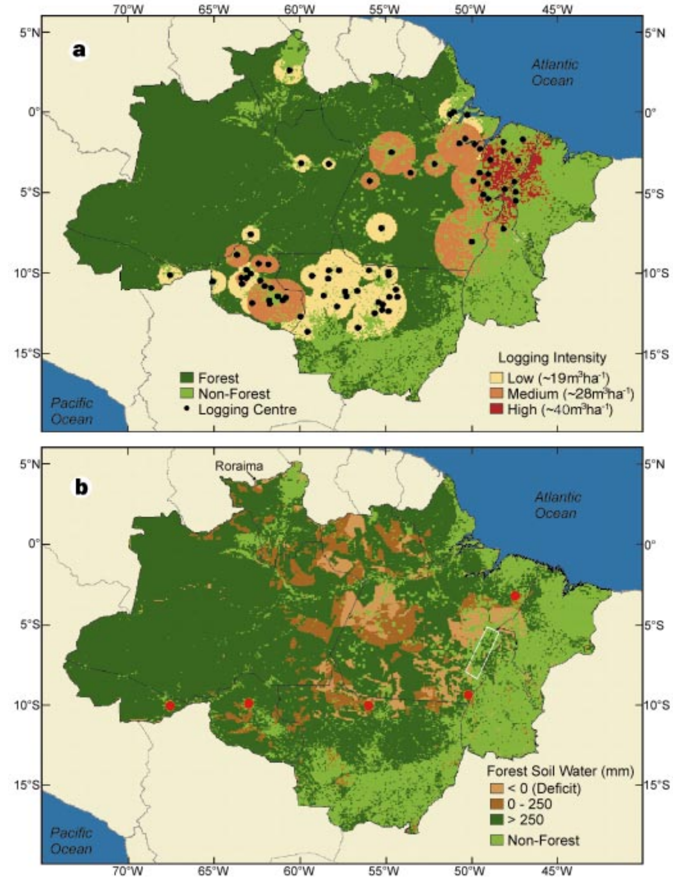

Figure 1 Patterns of forest logging and severe soil water deficits. **a**, Forest regions in Brazilian Amazonia that lie within the average extraction distances of 75 logging centres which account for >90% of Amazonian timber production. Extraction intensities are 'low' (19 m^3 Ha^{-1}), 'moderate' (28 m^3 Ha^{-1}) and 'high' (40 m^3 Ha^{-1}). State boundaries of the Brazilian Amazon and national boundaries of neighbouring countries are displayed. **b**, Estimated forest plant-available soil water content to five metres depth, at the end of the 1998 dry season (30 September). Forests with a soil water deficit (<0 mm) had depleted all plant-available water in the upper 5 m of soil, and we predict that they were highly vulnerable to fire. Forests with <250 mm of plant-available soil water may have also been vulnerable to fire. Red dots indicate locations of landholder interviews, from west to east: Rio Branco, Acre; Ariquemes, Rondônia; Alta Floresta, Mato Grosso; Santana do Araguaia, Pará; and Paragominas, Pará. The white rectangle indicates the region of the aeroplane study of forest fire occurrence.

~100-ha forest plots that had been harvested at low ($n = 12$) (ref. 9, and A.V., E.L., R. Júnior and C. Leão, unpublished report), moderate ($n = 7$, unpublished data, Tropical Forest Foundation) and high ($n = 3$)[10] harvest intensities. In each comparison, harvest rates measured directly in the forest were within the 95% confidence interval of the average harvest rates reported by mill operators in the nearest logging centre. Mahogany mills were excluded from this study because their immediate effect on the forest is very small compared to other types of logging, and the volume of mahogany extraction is <5% of total Amazonian production (although mahogany extraction may encourage additional human activities in forests)[16].

The area of standing forest subjected to surface fire each year was assessed by interviewing 202 landholders in five regions along a 2,200-km transect through the states of Pará, Mato Grosso, Rondônia and Acre. The properties had a total area of 9,200 km^2, and were randomly selected within each of four size categories. In each interview, the landholders drew onto satellite images the forest areas

Table 1 Roundwood production, logging intensity and rates (1996–97), and deforestation (1997) in the Brazilian Amazon

State	Total no. of logging centres	Total no. of mills	Mills studied (%)	Roundwood production* (10^6 m^3)	Intensity of logging† (% of production)			Forest area affected (km^2 yr^{-1})			Original forest area[4] (km^2)
					Low	Med.	High	Logging‡ 1996–97	Deforestation[4] 1993–95	Deforestation[4] 1996	
Acre	1	25	55	0.3	100	0	0	120–210	720	430	152,394
Amapa	2	89	80	0.2	100	0	0	80–140	0	0	137,444
Amazonas	3	20	60	0.7	100	0	0	290–500	950	1,020	1,531,122
Maranhão	2	52	49	0.7	0	0	100	160–200	830	1,060	145,766
Mato Grosso	22	708	48	9.8	100	0	0	4,080–7,000	7,610	6,540	527,570
Pará	24	1,324	43	11.9	11	61	28	3,560–4,910	5,470	6,130	1,183,571
Rondônia	19	272	55	3.9	25	75	0	1,320–1,920	3,310	2,430	212,214
Roraima	1	25	52	0.2	100	0	0	80–140	230	210	172,425
Tocantins	1	18	53	0.1	100	0	0	40–70	490	320	30,325
Total	75	2,533	48	27.8	49	41	10	9,730–15,090	19,610	18,140	4,092,831

* Logging centres, by our definition, produce at least 100,000 m^3 of roundwood each year, and are responsible for >90% of Brazilian Amazonian roundwood production.
† Low-intensity logging, 19 (14–24) m^3 ha^{-1}; moderate intensity, 28 (24–32) m^3 ha^{-1}; high intensity, 40 (35–45) m^3 ha^{-1}. Values here are mean (95% confidence interval).
‡ See text for definition.

on their property that had been deforested and the forest areas that had burned by surface fire (without prior forest felling), in 1994 and 1995. The accuracy of these landholder maps was tested by comparing them, in one study region, with a 1995 Landsat TM image. Forest surface fire scars were identified within the image by analysis of spectral characteristics, and areas of deforestation were identified visually. Within the 640 km^2 test area, all of the forest surface fires and deforestation burns reported by landholders were detected in the Landsat image. However, the landholders underestimated the area of surface fires by 43% and of deforestation by half.

We estimate that 10,000–15,000 km^2 of undisturbed forest were logged per year in 1996 and 1997 by the 2,533 wood mills operating in Brazilian Amazonia, based on the 95% confidence interval of the harvest intensities reported by mill operators. Hence, annual logging in these years affected a forest area that was 50–90% the size of the area that was completely deforested in 1996[4] (Table 1). Virtually all of the forests of eastern Amazonia lie within the average harvest distance of logging centres in Pará and Maranhão states, and are being harvested at high (40 $m^3\,ha^{-1}$) and moderate (28 $m^3\,ha^{-1}$) intensities (Fig. 1a).

Within properties surveyed in the fire study, the area of standing forest that was affected by surface fire in 1994 and 1995 (310 km^2) was 1.5 times greater than the area that was deforested in those years (200 km^2). Most of the forests that experienced surface fire in Paragominas and Rondônia had already been logged, but large areas of undisturbed forest burned in Santana do Araguaia and Mato Grosso. Although extrapolation of this data set to the entire Amazon is not warranted, these data indicate that the area of Amazon forest affected by surface fire each year may be similar in scale to the area affected by deforestation.

The area of forest surface fires may be much larger during periods of severe drought, such as occurred during the 1997–98 El Niño/Southern Oscillation (ENSO) episode when 15,000 km^2 of standing forest may have burned in the northern Amazonian state of Roraima alone (Brazilian Government, unpublished report). We assessed the potential for large-scale, drought-induced Amazonian forest burning as a result of this ENSO episode using a regional water balance model. The model tracks soil water beginning on 1 May 1997, the end of the 1997 rainy season, when we assume that the soil was fully charged with water. Amazonian forests can tap the water stored in deep soil layers to maintain evapotranspiration during periods of low rainfall[13,20]. We assume that forests become flammable only when soil moisture is depleted to five metres depth, based on field studies of soil moisture, leaf shedding[13], fine fuel moisture and the propagation of experimental fires (D.C.N., M.C., E.M., F. Brown & J. Guerreros, unpublished data). The maximum amount of plant-available water than can be stored in the soils was calculated for the forested areas of Brazilian Amazonia using soil texture data from 1,147 soil profiles[21–23]. Rainfall data from 1 May 1997 to 30 September 1998 were obtained from 30 to 60 automated weather stations scattered across Brazilian Amazonia (Instituto Nacional de Persquisas Espaciais, unpublished data), which also provided air temperature data that we employed to estimate evapotranspiration using a corrected Thornwaite equation[24]. These estimates of evapotranspiration are within 5% of values measured in an eastern Amazon forest[20].

ENSO-related drought can desiccate large areas of Amazonian forest, creating the potential for large-scale forest fires. Because of the severe drought of 1997 and 1998, we calculate that approximately 270,000 km^2 of Amazonian forest had completely depleted plant-available water stored in the upper five metres of soil by the end of the 1998 dry season. In addition, 360,000 km^2 of forest had less than 250 mm of plant-available soil water left by this time (Fig. 1b). By comparison, only 28,000 km^2 of forests in Roraima had depleted soil water to 5 m depth at the peak of the Roraima forest fires. We estimated the areal extent of forest surface fire in a 45,000-km^2 southeastern Amazonian landscape (Fig. 1b) by recording forest status from an aeroplane at 1,104 sample points along 750 km of transects, late in the 1998 dry season. Approximately 9% of the sample points in this study area were recently-burned standing forest, in which ash was visible on the forest floor. The full extent of forest surface fire in 1998 is not known.

Forest impoverishment through logging and surface fire causes a significant release of carbon to the atmosphere that is not included in existing estimates of the Amazonian carbon balance[1,2]. We made a preliminary estimate of the carbon released from logging by multiplying the area of logging within each harvest intensity class (low, moderate and high, Table 1) by a biomass reduction of 5, 10 and 20%, respectively[9,10,16]. (We assumed that half of the biomass that is killed or damaged either remains alive or makes its way into long-lived wood products.) In 1996, logging released approximately 4–7% of the net annual carbon release estimated for deforestation in Brazilian Amazonia (about $0.3 \times 10^9\ Mg\,yr^{-1}$)[1]. The potential for carbon release from forest surface fire, however, is much bigger. For example, if just one-fifth of the forests that had depleted soil water in 1998 (Fig. 1b) had caught fire (killing 20% of forest biomass), net carbon emissions from this region would have more than doubled current estimates[1,2], thus rising to a total of 10% of the net annual carbon emissions stemming from human activities worldwide[1,3]. This fire-mediated release of carbon to the atmosphere adds to the

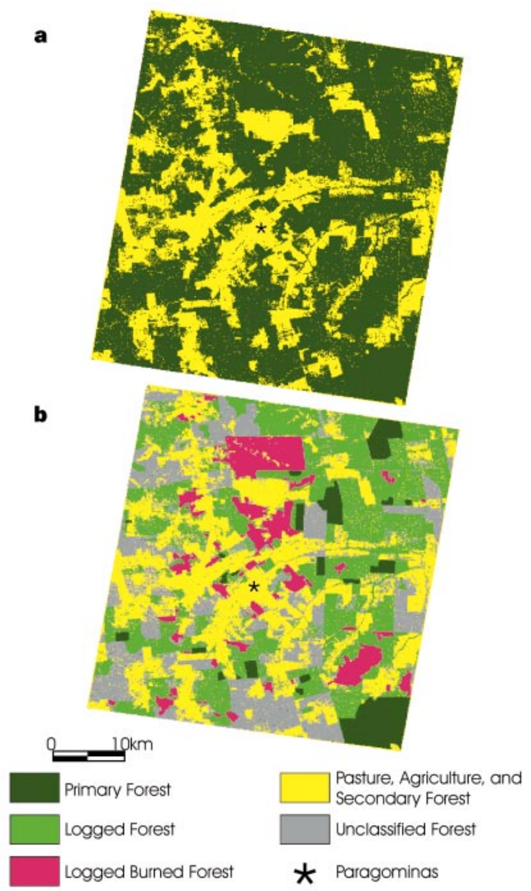

Figure 2 Forest cover in the vicinity of Paragominas, Pará State. **a**, Landsat TM image, 1991, classified as non-forest (pasture, agriculture, secondary forest) and forest. This type of classification is the basis of the Brazilian government's deforestation estimates[4]. According to this analysis, 62% of this landscape supports forest. **b**, The same Landsat TM image with data from interviews of ranch owners (see text) and areas of selective logging detected in the image[15], showing the area of forest that has been logged, and that which has been logged and burned. According to this analysis, only about a tenth of the area conventionally classified as forest supports forest that has not been disturbed.

carbon release that may be provoked by changes in forest metabolism during ENSO events, as predicted by ecosystem models[25].

Logging and fire can virtually eliminate previously undisturbed forest in regions with seasonal drought and high concentrations of wood mills, such as Paragominas in eastern Amazonia (Fig. 1b). Thirty years after settlement, 62% of the land surface in a 3,600-km^2 area surrounding Paragominas is classified as "forested" using conventional deforestation mapping techniques (Fig. 2a); one-half of this land surface is mandatory forest reserve on private land. But when we map those forests that have been logged or burned (based on our interviews of landholders and detection of logging and forest fire scars in Landsat TM images[15]), we find that only about a tenth of the area classified as forest supports undisturbed forest. (Fig. 2b). This 'cryptic' forest impoverishment may be even more common in some other Amazonian regions. Landholders reported a higher incidence of forest surface fires in southern Pará and Mato Grosso, where seasonal drought is more severe than in Paragominas.

Satellite-based deforestation monitoring is an essential tool in studies of human effects on tropical forests because it documents the most extreme form of land use, over large areas, and at low cost. But this monitoring needs to be expanded to include forests affected by logging and surface fire if it is to accurately reflect the full magnitude of human influences on tropical forests. Large-scale burning of tropical forest during severe ENSO episodes may impoverish vast areas of these species- and carbon-rich ecosystems; such episodes are increasing in frequency, possibly in response to the accumulation of greenhouse gases in the atmosphere[26]. These considerations point to the need to either restrict the logging industry in Amazonia, or to replace conventional logging practices in moist tropical forest regions with low-impact harvest techniques[17,27]. Cost-effective investments in the prevention of accidental forest fires by Amazonian farmers and ranchers are also needed[28]. Both of these changes are unlikely to occur unless access to these forest lands provided by expanding road networks, electrical grids and water transport systems is sharply curtailed[28]. □

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An amniote-like skeleton from the Early Carboniferous of Scotland

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The origin of tetrapods occurred in the Late Devonian period[1], and the earliest known taxa were aquatic[2]. A gap of 30 million years has separated these early forms from the first record of terrestrial tetrapods, in the Late Viséan (Early Carboniferous)[3]. Here we report the discovery of a small, highly ossified, post-cranial skeleton of a terrestrially adapted, amniote-like tetrapod from the Mid Viséan; this specimen shows the earliest known pentadactyl manus. The skeleton is associated with a gracile humerus that has a constricted shaft and exhibits torsion between proximal and distal articulations. These features are associated with the maintenance of postural support and are strong evidence of locomotion on land[4]. The specimen pushes back the known occurrence of terrestrial vertebrates closer to the origin of tetrapods. Phylogenetic analysis places this new animal close to undisputed amniotes occurring in the Westphalian, indicating that, by the Mid–Late Viséan, amniotes already had a long, but previously unrecorded, history. The origin of amniotes seems to have occurred early in the Carboniferous and was part of a rapid diversification of tetrapods at this time[3,5,6].

The specimen occurs in a loose, weathered block of the Cheese Bay Shrimp Bed[7]. The Shrimp Bed is a localized facies within a sequence of discontinuous exposures interrupted by intrusions and faults, bounded by the Garleton Hills Volcanic Rocks and the MacGregor Marine Bands[8]. It is considered to be equivalent in age to the Wardie Shales (Fig. 1), in which the snake-like tetrapod *Lethiscus* was found[5]. The laminated dolomites and mudstones containing the Shrimp Bed were probably deposited in a thermally stratified freshwater lake or brackish lagoon[7]. The shrimp *Tealliocaris* is abundant and specimens show excellent preservation of delicate antennae and legs, indicating little postmortem disturbance[9]. The fauna also includes hydroids, scorpions[10] and occasional specimens of fishes found elsewhere in the Scottish Viséan[7,11]. The tetrapod described here is the only one to be recorded from this locality.

Tetrapoda Goodrich 1930
Reptiliomorpha Säve-Söderbergh 1934