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Agricultural intensification increases deforestation fire activity in Amazonia

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Abstract

Fire-driven deforestation is the major source of carbon emissions from Amazonia. Recent expansion of mechanized agriculture in forested regions of Amazonia has increased the average size of deforested areas, but related changes in fire dynamics remain poorly characterized. We estimated the contribution of fires from the deforestation process to total fire activity based on the local frequency of active fire detections from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors. High-confidence fire detections at the same ground location on 2 or more days per year are most common in areas of active deforestation, where trunks, branches, and stumps can be piled and burned many times before woody fuels are depleted. Across Amazonia, high-frequency fires typical of deforestation accounted for more than 40% of the MODIS fire detections during 2003–2007. Active deforestation frontiers in Bolivia and the Brazilian states of Mato Grosso, Pará, and Rondônia contributed 84% of these high-frequency fires during this period. Among deforested areas, the frequency and timing of fire activity vary according to postclearing land use. Fire usage for expansion of mechanized crop production in Mato Grosso is more intense and more evenly distributed throughout the dry season than forest clearing for cattle ranching (4.6 vs. 1.7 fire days per deforested area, respectively), even for clearings >200 ha in size. Fires for deforestation may continue for several years, increasing the combustion completeness of cropland deforestation to nearly 100% and pasture deforestation to 50–90% over 1–3-year timescales typical of forest conversion. Our results demonstrate that there is no uniform relation between satellite-based fire detections and carbon emissions. Improved understanding of deforestation carbon losses in Amazonia will require models that capture interannual variation in the deforested area that contributes to fire activity and variable combustion completeness of individual clearings as a function of fire frequency or other evidence of postclearing land use.

Keywords: agricultural expansion, Amazon, carbon emissions, combustion completeness, deforestation, fire, land use change, soybeans

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Introduction

Agricultural expansion is the main cause of tropical deforestation (FAO, 2006), highlighting the tradeoffs among ecosystem services such as food production, carbon storage, and biodiversity preservation inherent

in land cover change (Foley *et al.*, 2005). Expansion of intensive agricultural production in southern Amazonia, led by the development of specific crop varieties for tropical climates (Warnken, 1999) and international market demand (Naylor *et al.*, 2005), contributed one-third of the growth in Brazil's soybean output during 1996–2005 (IBGE, 2007). The introduction of cropland agriculture in forested regions of Amazonia also changed the nature of deforestation activities; forest clear-

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ings for mechanized crop production are larger, on an average, than clearings for pasture, and the forest conversion process is often completed in <1 year (Morton et al., 2006). How this changing deforestation dynamic alters fire use and carbon emissions from deforestation in Amazonia is germane to studies of future land cover change (Soares-Filho et al., 2006), carbon accounting in tropical ecosystems (Stephens et al., 2007), and efforts to reduce emissions from tropical deforestation (Gullison et al., 2007).

Fires for land clearing and management in Amazonia are a large anthropogenic source of carbon emissions to the atmosphere (Houghton et al., 2000; DeFries et al., 2002; van der Werf et al., 2006; Gullison et al., 2007). Deforestation fires largely determine net carbon losses (Guild et al., 2004), because fuel loads for Amazon deforestation fires can exceed $200\,Mg\,C\,ha^{-1}$ (e.g. Carvalho et al., 1998). Reductions in forest biomass from selective logging before deforestation are small, averaging $<10\,Mg\,C\,ha^{-1}$ (Asner et al., 2005). In contrast, typical grass biomass for Cerrado or pasture rarely exceeds $10\,Mg\,C\,ha^{-1}$ (Ottmar et al., 2001) and is rapidly recovered during the subsequent wet season (Santos et al., 2003). Yet, the fraction of all fire activity associated with deforestation (Cardoso et al., 2003; Eva & Fritz, 2003; Schroeder et al., 2005) and combustion completeness of the deforestation process remain poorly quantified (Ramankutty et al., 2007).

Satellite fire detections have provided a general indication of spatial and temporal variation in fire activity across Amazonia for several decades (e.g. Setzer & Pereira, 1991; Prins & Menzel, 1992; Elvidge et al., 2001 Schroeder et al., 2005; Giglio et al., 2006a; Koren et al., 2007). However, specific information regarding fire type or fire size can be difficult to estimate directly from active fire detections because satellites capture a snapshot of fire energy rather than a time-integrated measure of fire activity (Giglio et al., 2006a). Overlaying active fire detections on land cover maps provides a second approach to classify fire type. Evaluating fire detections over large regions of homogenous land cover can be instructive (e.g. Mollicone et al., 2006; Aragão et al., 2007), but geolocation errors and spurious fire detections may complicate these comparisons, especially in regions of active land cover change and high fire activity such as Amazonia (Eva & Fritz, 2003; Schroeder et al., 2008). Finally, postfire detection of burn-scarred vegetation is the most data-intensive method to quantify carbon emissions from fires. Two recent approaches to map burn scars with Moderate Resolution Imaging Spectroradiometer (MODIS) data show great promise for identifying large-scale fires (Roy et al., 2005; Giglio et al., 2006b), yet neither algorithm is capable of identifying multiple burning events in the

same ground location typical of deforestation activity in Amazonia. Deriving patterns of fire type, duration and intensity of fire use, and combustion completeness directly from satellite fire detections provides an efficient alternative to more data and labor-intensive methods to estimate carbon emissions from land cover change.

We assess the contribution of deforestation to fire activity in Amazonia based on the intensity of fire use during the forest conversion process, measured as the local frequency of MODIS active fire detections. High-confidence fire detections on 2 or more days in the same dry season are possible in areas of active deforestation, where trunks, branches, and other woody fuels can be piled and burned many times. Low-frequency fire detections are typical of fires in Cerrado woodland savannas and for agricultural maintenance, because grass and crop residues are fully consumed by a single fire. The frequency of fires at the same location, or fire persistence, has been used previously to assess Amazon forest fire severity (Elvidge et al., 2001), adjust burned area estimates in tropical forest ecosystems (Giglio et al., 2006b), and scale combustion completeness estimates in a coarse-resolution fire emission model (van der Werf et al., 2006). We build on these approaches to characterize fire activity at multiple scales. First, we compare the frequency of satellite fire detections over recently deforested areas with that over other land cover types. We then assess regional trends in the contribution of high-frequency fires typical of deforestation activity to the total satellite-based fire detections for Amazonia during 2003–2007. Finally, we compare temporal patterns of fire usage among individual deforested areas with different postclearing land uses, based on a recent work to separate pasture and cropland following forest conversion in the Brazilian state of Mato Grosso with vegetation phenology data (Morton et al., 2006). The goals of this research are to (1) test whether fire frequency distinguishes between deforestation fires and other fire types and (2) characterize fire frequency as a function of postclearing land use to enable direct interpretation of MODIS active fire data for relevant information on carbon emissions.

Methods

Data

We analyzed active fire detections from the MODIS sensors aboard the Terra (2002–2007) and Aqua (2003–2007) satellite platforms to determine spatial and temporal patterns in satellite fire detections from deforestation in Amazonia during this period. Combined, the MODIS sensors provide two daytime (10:30/13:30
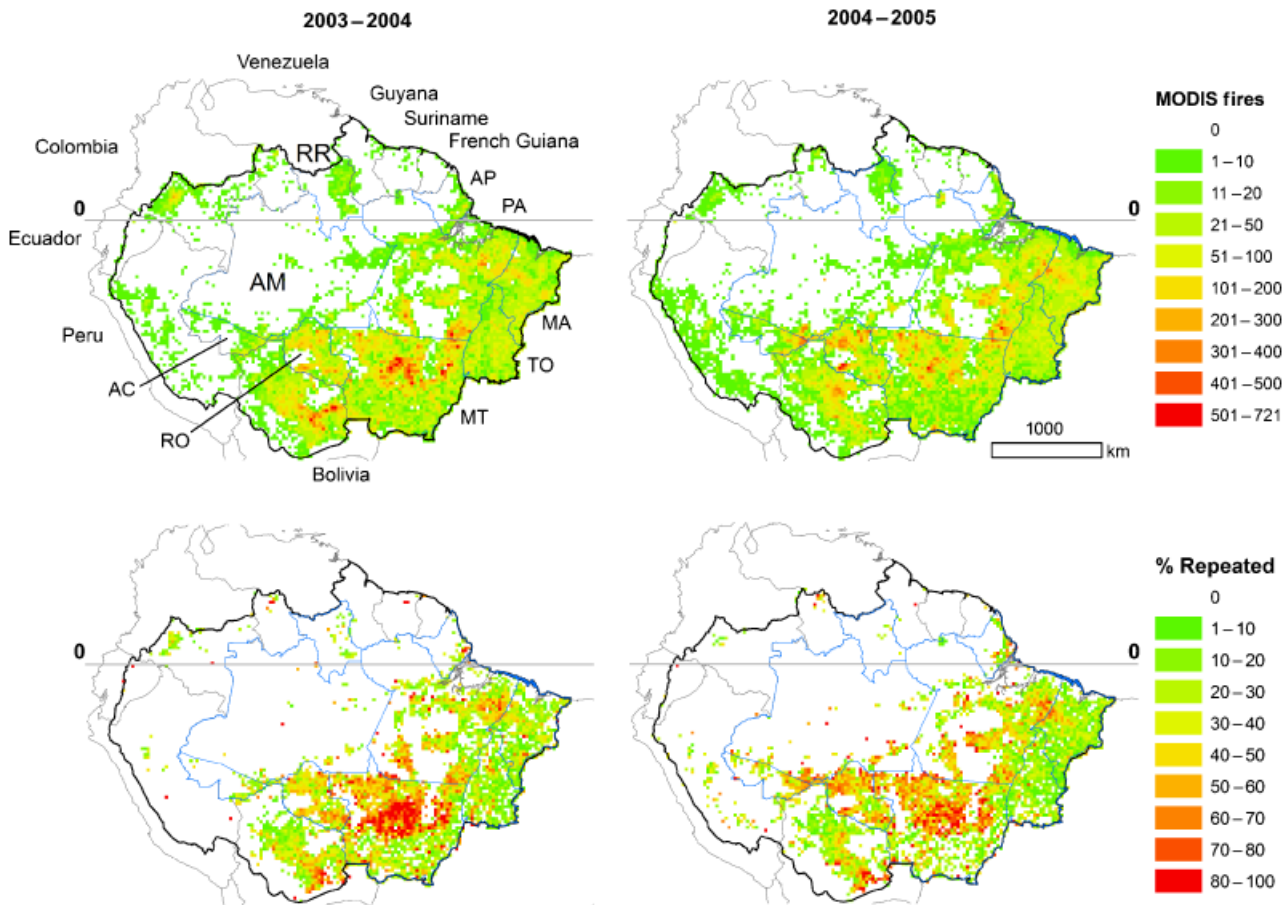
2003–2004   2004–2005

Fig. 1 Total high-confidence fire detections across the Amazon Basin (upper) and percentage of all fires detected on 2 or more days during the same dry season (lower) summarized at 0.25° resolution. North of the equator, the fire year is July–June (July 2003–June 2004, July 2004–June 2005); south of the equator, the fire year is January–December (2004, 2005). Outlines show country borders (gray), Brazilian state boundaries (blue), and the extent of the Amazon Basin (black). In clockwise order, letter codes for Brazilian states are as follows: AP, Amapá; PA, Pará; MA, Maranhão; TO, Tocantins; MT, Mato Grosso; RO, Rondônia; AC, Acre; AM, Amazonas; RR, Roraima.

hours local time) and two night-time (22:30/01:30 hours local time) observations of fire activity. Figure 1 shows the location of the study area and administrative boundaries of the nine countries that contain portions of the Amazon Basin. For data from 2002–2006, the date and center location of each MODIS active fire detection, satellite (Terra or Aqua), time of overpass, 4 micron brightness temperature (band 20/21), and confidence score were extracted from the Collection 4 MODIS Thermal Anomalies/Fire 5-min swath (Level 2) product at 1-km spatial resolution (MOD14/MYD14) (Justice *et al.*, 2006). Beginning in 2007, MODIS products were transitioned to Collection 5 algorithms. Data for January 1–November 1, 2007 were provided by the Fire Information for Resource Management System (FIRMS) at the University of Maryland, College Park (http:// maps.geog.umd.edu) based on the Collection 5 processing code. Seasonal differences in fire activity north and south of the equator related to precipitation (Schroeder

et al., 2005) were captured using different annual calculations. North of the equator, the fire year was July–June; south of the equator, the fire year was January–December.

Our analysis considered a high-confidence subset of all MODIS fire detections to reduce the influence of false fire detections over small forest clearings in Amazonia (Schroeder *et al.*, 2008). For daytime fires, only those 1-km fire pixels having >330 K brightness temperature in the 4-μm channel were considered. This threshold is set based on a recent work to identify true and false MODIS fire detections with coincident high-resolution satellite imagery (Schroeder *et al.*, 2008), comparisons with field data (D. Morton, unpublished data), and evidence of unrealistic MODIS fire detections over small historic forest clearings in Mato Grosso state with >20 days of fire detections (fire days) per year in 3 or more consecutive years, none of which exceeded 330 K during the day. Daytime fire detections >330 K correspond to

a MOD14/MYD14 product confidence score of approximately 80/100. The subset of high-confidence fires includes all night-time fire detections, regardless of brightness temperature. Differential surface heating between forested and cleared areas during daylight hours that may contribute to false detections (Schroeder *et al.*, 2008) should dissipate by the 22:30 or 01:30 hours local time overpasses for Terra and Aqua, respectively. Subsequent references to MODIS fire detections refer only to the high-confidence subset of all 1-km fire pixels described earlier.

Identifying high-frequency fires

The simple method we propose for separating deforestation and agricultural maintenance fires is based on evidence for repeated burning at the same ground locations. The spatial resolution of our analysis is defined by the orbital and sensor specifications of the MODIS sensors and the 1-km resolution bands used for fire detection. The geolocation of MODIS products is highly accurate, and surface location errors are generally <70 m (Salomonson & Wolfe, 2004). However, due to the orbital characteristics of the Terra and Aqua satellite platforms, the ground locations of each 1-km pixel are not fixed. We analyzed three static fire sources from gas (Urucu, Amazonas, Brazil: 65.3°W, 4.86°S), mining (Chuquicamata, Antofagasta, Chile: 68.89°W, 22.31°S), and steel production (CST, Espírito-Santo, Brazil: 40.43°W, 20.24°S) in South America to identify the spatial envelope for MODIS active fire detections referencing the same ground location. Over 98% of the high-confidence 2004 MODIS active fire detections from Terra and Aqua for these static sources were within 1 km of the ground location of these facilities. Therefore, we used this empirically derived search radius to identify repeated burning of forest vegetation during the conversion process. High-frequency fire activity was defined as fire detections on two or more days within a 1-km radius during the same fire year. The time interval between fire detections is not considered in this analysis, such that fires on consecutive and nonconsecutive days at the same ground location are treated equally. A 1-km radius is also consistent with fire spread rates of 200–5000 m h^{-1} (4.8–140 km day^{-1}) for grass, grass/shrub, and deforestation fuel types (Scott & Burgan, 2005), such that even slow-moving grassland fires would spread beyond the 1-km search limit on sequential days. Fires which burn on consecutive days at the same ground location can occur where fuel loads are very high, as is the case in deforestation fires when woody fuels that are piled together may smolder for several days.

We calculated the frequency of fire detections using a neighborhood search algorithm. Specifically, the variety of days on which fires were detected was determined for each cell of the standard MODIS 250-m grid using a search radius of 1 km to interpret the center locations of all high-confidence fire detections for each year. This gridded product of fire days was then used to select those fire detections contributing to high-frequency fire activity and characterize fire frequency for recent deforestation events.

Fire types in Amazonia

To determine whether active fire detections associated with the conversion of forest to other land uses are unique in terms of fire frequency, we compared active fire detections from recently deforested areas with four additional types of fire management. In the following text, we describe the test datasets used to evaluate patterns in active fire detections for maintenance of cattle pastures, indigenous reserves in Cerrado savanna-woodland land cover, small properties associated with government settlement programs, and sugarcane production regions.

We used data on recent deforestation and land use following deforestation to identify and characterize active fire detections associated with forest conversion. Data for the annual deforestation increment in the Brazilian Amazon were acquired from the Brazilian National Institute for Space Research (INPE) PRODES (Program for the estimation of deforestation in the Brazilian Amazon), available at http://www.obt. inpe.br/prodes. Deforestation was mapped using high-resolution Landsat Thematic Mapper or Chinese-Brazilian Environmental Research Satellite data from approximately August of each year 2001–2005 (INPE, 2007).

We developed our approach for identifying deforestation fires with data for Mato Grosso state. For individual deforestation events >25 ha in size, we also evaluated differences in patterns of active fire detections for conversion of forest to pasture, forest to mechanized agriculture, and forest conversions not in agricultural production (NIP). The postclearing land use for each deforestation event was identified previously using phenological information from time series of MODIS data at 250 m resolution (Morton *et al.*, 2006). Finally, we examined fire activity in the year before deforestation detection by PRODES, year of forest clearing, and for as many years postclearing as possible to characterize the nature of fire usage during the conversion process. These comparisons provide the timing, frequency, and degree of repeated burning detected by the MODIS sensors for forest conversion to different

land uses. We selected annual deforestation from 2003–2005 to utilize combined Terra and Aqua fire observations. Because few areas are deforested without the use of fire in Amazonia, deforestation events without any MODIS fire detections provide a measure of the extent of omission due to satellite observation (e.g. orbital, sensor, and atmospheric) and fire characteristics (size, intensity, and timing).

We utilized data on historic deforestation and recent land use changes to identify maintenance fires on agricultural lands in Mato Grosso state. The dataset is derived from areas that were deforested before the initial year of PRODES digital data (1997–2000 analysis), buffered by 1 km from remaining forest edges to exclude fires from new deforestation. Next, we removed areas that underwent conversion from pasture to cropland during 2001–2004 (Morton *et al.*, in press) and previously cleared areas that were identified as secondary forest (Morton *et al.*, 2007a). The resulting dataset isolates old deforestation not associated with forest edges, secondary forest, or recent conversion to cropland.

To identify patterns of fire detections for extensive grassland fires in Cerrado regions, we selected 18 indigenous reserves in Mato Grosso and Tocantins states covering more than 42 000 km². Fire is used during the dry season on some indigenous reserves to facilitate hunting, but extensive land cover change is rare (Nepstad *et al.*, 2006).

Small properties are an additional challenge for separating evidence of fire activity in the same location. To test the influence of property size on fire frequency, we considered a subset of the demarcated Instituto Nacional de Colonização e Reforma Agrária (INCRA) land reform settlements in Mato Grosso without large

deforestation events (>25 ha) in either 2004 or 2005 (N = 127). The typical lot size in these settlements is 100 ha, of which 20–50 ha may be cleared for agricultural use.

Although some sugarcane is grown in the Amazon region, the majority of Brazil's sugarcane industry is located in the southern and northeastern regions of the country. São Paulo State had more than 3 million hectares planted in sugarcane in 2005. We evaluated active fire detections in 31 municipalities in São Paulo state with >20 000 ha of sugarcane planted in 2005 (IBGE, 2007) to calculate the degree of high-frequency fire associated with sugarcane production.

Basin-wide analysis

We analyzed the high-confidence subset of the MODIS active fire data record for the entire Amazon Basin to distinguish the contribution of deforestation and agricultural maintenance fires to overall fire activity during 2003–2007. We provide fire-type statistics for each Amazon country and Brazilian state. Finally, we summarize the ratio of high-frequency to low-frequency fires at 0.25° spatial resolution to evaluate interannual variations in deforestation fire activity across the basin.

Results

Deforestation fires

High-frequency fire activity (>2 fire days per year) is common in areas of recent deforestation but rare for other fire types in Amazonia (Table 1). Deforestation in Mato Grosso state had more total fire detections than all

Table 1 Combined MODIS Terra and Aqua fire detections associated with deforestation, indigenous reserves, agricultural maintenance, and small properties in government settlement areas in the Brazilian state of Mato Grosso and sugarcane production in São Paulo state according to the number of days with fire detections in the same year

Fire location	Area (km²)	2004 MODIS fire days				Area (km²)	2005 MODIS fire days			
		1 (%)	2 (%)	3+ (%)	Total		1 (%)	2 (%)	3+ (%)	Total
Deforestation	10 009	2573 (19)	2684 (20)	7946 (60)	13 203	8279	2600 (33)	2449 (31)	2817 (36)	7866
Cropland	1807	374 (7)	468 (9)	4192 (83)		658	259 (20)	172 (14)	836 (66)	
Pasture	6159	1892 (26)	1970 (27)	3491 (47)		5297	1823 (34)	1744 (32)	1804 (34)	
NIP	698	108 (41)	67 (25)	90 (34)		932	133 (39)	106 (31)	106 (31)	
Small (<25 ha)	1345	199 (36)	179 (32)	173 (31)		1392	264 (43)	200 (32)	155 (25)	
Indigenous	42 598	3300 (84)	600 (15)	21 (1)	3921	42 598	3877 (82)	480 (16)	38 (2)	4395
São Paulo sugarcane	24 219	782 (84)	138 (15)	10 (1)	930	24 219	799 (79)	182 (18)	30 (3)	1011
Maintenance	35 013	718 (73)	160 (16)	111 (12)	989	35 013	497 (76)	68 (16)	54 (8)	619
Small producers	7598	328 (73)	68 (15)	54 (12)	450	7598	230 (73)	55 (18)	29 (9)	314

Fire frequency for 2004 and 2005 deforestation events is calculated for the year of deforestation detection, and clearings >25 ha are classified based on postclearing land use as cropland, pasture, or not in production (NIP).

Table 2 Number of high-confidence MODIS Terra and Aqua fire detections (1-km pixels) for the nine states of the Brazilian Legal Amazon during 2003–2007 as a function of fire frequency

State	Fire days	2003		2004		2005		2006		2007*	
Mato Grosso	1	27 036	43%	37 575	41%	33 711	51%	20 875	57%	39 592	50%
	2	12 938	21%	19 992	22%	16 848	25%	8851	24%	22 434	28%
	3 +	22 359	36%	33 979	37%	15 853	24%	7078	19%	17 475	22%
	Total	62 333		91 546		66 412		36 804		79 501	
Para	1	18 501	69%	25 729	58%	28 439	59%	20 423	66%	21 068	54%
	2	6072	23%	11 738	27%	13 182	27%	7255	24%	11 821	30%
	3 +	2407	9%	6626	15%	6581	14%	3140	10%	6321	16%
	Total	26 980		44 093		48 202		30 818		39 210	
Maranhao	1	12 566	72%	12 954	73%	16 388	71%	8397	80%	16 592	65%
	2	3538	20%	3425	19%	4906	21%	1528	15%	6285	25%
	3 +	1378	8%	1463	8%	1784	8%	559	5%	2760	11%
	Total	17 482		17 842		23 078		10 484		25 637	
Rondonia	1	8018	62%	11 107	55%	12 523	47%	8911	52%	7227	51%
	2	3394	26%	6114	30%	8427	32%	5272	31%	4435	32%
	3 +	1470	11%	2886	14%	5745	22%	2791	16%	2382	17%
	Total	12 882		20 107		26 695		16 974		14 044	
Tocantins	1	7732	86%	11 139	81%	12 540	83%	6140	86%	20 243	73%
	2	921	10%	1987	14%	2050	14%	807	11%	6153	22%
	3 +	306	3%	693	5%	526	3%	200	3%	1288	5%
	Total	8959		13 819		15 116		7147		27 684	
Amazonas	1	2253	68%	1795	78%	4068	55%	3145	66%	2089	65%
	2	727	22%	386	17%	1874	25%	1038	22%	665	21%
	3 +	342	10%	121	5%	1479	20%	573	12%	477	15%
	Total	3322		2302		7421		4756		3231	
Acre	1	1893	73%	1159	76%	3894	50%	1274	87%	1368	83%
	2	540	21%	249	16%	2479	32%	169	12%	245	15%
	3 +	174	7%	120	8%	1340	17%	18	1%	43	3%
	Total	2607		1528		7713		1461		1656	
Roraima	1	3955	54%	1075	91%	583	96%	811	93%	1866	69%
	2	1958	27%	82	7%	26	4%	49	6%	535	20%
	3 +	1427	19%	21	2%	1	0%	8	1%	313	12%
	Total	7340		1178		610		868		2714	
Amapa	1	687	56%	828	65%	1121	69%	492	69%	447	83%
	2	180	15%	251	20%	345	21%	113	16%	73	14%
	3 +	355	29%	204	16%	152	9%	112	16%	19	4%
	Total	1222		1283		1618		717		539	

*Data through November 1, 2007.
States are listed in decreasing order of fire activity.

other fire types in Table 1 combined and seven times the number of fires detected in the same location on 2 or more days during 1 year. High-frequency fire activity accounted for 27% of high-confidence MODIS detections associated with small producers in Mato Grosso 2004 and 2005, but the total number of detections was small ($N = 764$), suggesting that property size is not the main component of the pattern of repeated fire usage associated with deforestation. Fires detected on 2 days at the same location are rare within indigenous reserves and agricultural areas of Mato Grosso state or sugar-

cane production municipalities in São Paulo state; fires on 3 or more days are almost exclusively linked to deforestation.

Mato Grosso had both the highest total fire activity and greatest fraction of high-frequency fire activity during 2003–2007 of any state in Brazilian Amazonia (Table 2). Combined with fires in neighboring Pará and Rondônia states, these three states contributed 83% of the fires that burn on 2 or more days and 74% of the total fire activity in the Brazilian portion of the Amazon Basin during this period. Interannual variability in the

Table 3 Number of high-confidence MODIS Terra and Aqua fire detections (1-km pixels) within the Amazon Basin during 2003–2007, summarized at the national level according to the frequency of fire detections

Country	Fire days	2003		2004		2005		2006		2007*	
Brazil	1	82 641	58%	103 361	53%	113 267	58%	70 468	64%	110 492	57%
	2	30 268	21%	44 224	23%	50 137	25%	25 082	23%	52 646	27%
	3 +	30 218	21%	46 113	24%	33 461	17%	14 479	13%	31 078	16%
	Total	143 127		193 698		196 865		110 029		194 216	
Bolivia	1	9611	77%	23 368	65%	18 918	68%	13 143	64%	15 383	53%
	2	1797	14%	8343	23%	5705	20%	3885	19%	6558	23%
	3 +	1029	8%	4396	12%	3287	12%	3440	17%	7094	24%
	Total	12 437		36 107		27 910		20 468		29 035	
Peru	1	1418	92%	815	95%	2453	87%	1240	92%	1800	79%
	2	107	7%	36	4%	319	11%	84	6%	360	16%
	3 +	19	1%	6	1%	45	2%	21	2%	125	5%
	Total	1544		857		2817		1345		2285	
Colombia	1	958	95%	2019	79%	486	96%	480	96%	2784	72%
	2	54	5%	427	17%	20	4%	19	4%	818	21%
	3 +	0	0%	107	4%	0	0%	0	0%	244	6%
	Total	1012		2553		506		499		3846	
Venezuela	1	515	67%	323	79%	227	76%	179	87%	599	75%
	2	146	19%	50	12%	61	20%	13	6%	155	19%
	3 +	107	14%	37	9%	10	3%	14	7%	43	5%
	Total	768		410		298		206		797	
Guyana	1	833	80%	198	96%	203	94%	228	88%	210	94%
	2	133	13%	8	4%	8	4%	28	11%	13	6%
	3 +	80	8%	0	0%	4	2%	4	2%	0	0%
	Total	1046		206		215		260		223	
Suriname	1	155	72%	67	86%	95	98%	14	100%	66	97%
	2	42	20%	11	14%	2	2%	0	0%	2	3%
	3 +	18	8%	0	0%	0	0%	0	0%	0	0%
	Total	215		78		97		14		68	
French Guiana	1	33	94%	24	62%	67	70%	61	87%	35	71%
	2	2	6%	9	23%	7	7%	3	4%	7	14%
	3 +	0	0%	6	15%	22	23%	6	9%	7	14%
	Total	35		39		96		70		49	
Ecuador	1	4	100%	20	40%	41	43%	8	73%	12	21%
	2	0	0%	4	8%	3	3%	3	27%	0	0%
	3 +	0	0%	26	52%	51	54%	0	0%	46	79%
	Total	4		50		95		11		58	

*Data through November 1, 2007.
Countries are listed in decreasing order of fire activity.

total number of fires highlights drought conditions in Roraima state during 2003 and widespread drought in 2005 affecting Rondônia, Acre, and Amazonas states. The fraction of total fire activity from burning on 2 or more days also increased during drought years in these states. Fire detections were highest in 2005 for Pará and Amapá states, although these regions were less affected by drought conditions; the fraction of repeated fire activity did not increase in 2005 compared with other years. After a decrease in the fire activity in Brazilian Amazonia during 2006, fires in 2007 returned to a similar level as seen in 2004 and 2005, led by increased fire activity in southeastern Amazonia. Major contribu-

tions to this increase in 2007 were from low-frequency fires in Tocantins and Maranhão states and additional high-frequency fires in Mato Grosso and Pará. Overall, fires on 2 or more days during the same dry season accounted for 36–47% of the annual fire activity in Brazilian Amazonia during 2003–2007, with greater contributions from repeated fires in years with highest fire activity.

At the national scale, fire activity in Brazil (85%) and Bolivia (13%) accounted for 98% of all fire detections in the Amazon Basin during 2003–2007 (Table 3). High-frequency fires contribute a large fraction of MODIS detections in both countries, with peak repeated fire

activity during 2004 in Brazil and 2007 in Bolivia. Small contributions to overall fire activity from other Amazon countries are primarily low-frequency fires, with the notable exceptions of 2004 and 2007 in Colombia, 2003 in Guyana and Suriname, and 2003 and 2007 in Venezuela.

Spatial patterns of high-frequency fire activity in 2004 and 2005 highlight active deforestation frontiers in Mato Grosso, Rondônia, and Pará states in Brazil and in southeastern Bolivia (Fig. 1). Isolated locations of high-frequency fire activity can also be seen across other portions of the Amazon Basin, but these areas have low total fire detections. Differences in the total fire activity and high-frequency fire detections between 2004 and 2005 highlight the influence of drought conditions in western Amazonia on fire frequency. Total fire detections in central Mato Grosso decreased slightly between 2004 and 2005, while fire detections in drought-stricken northern Rondônia, southern Amazonas, and eastern Acre states in Brazil show higher total fire activity in 2005 than in 2004. The number of 0.25° cells with >50% of fire activity occurring on 2 or more days is similar during 2004 ($n = 733$) and 2005 ($n = 773$), but the spatial distribution is broader in 2005 than in 2004, as fires associated with deforestation activity in Mato Grosso, Pará, and southern Rondônia spread west into northern Rondônia, Acre, and southern Amazonas states. In addition to deforestation-linked fires, slow-moving forest fires and contagion of other accidental burning events may also have contributed to the higher fraction of repeated fire activity in these regions.

Patterns of fire use stratified by postclearing land use

Among deforested areas in Mato Grosso, the intensity of fire usage varies according to postclearing land use (Fig. 2). Forest conversion for cropland exhibits the most frequent fire usage; more than 50% of the 2004 cropland deforestation events had fire detections on 3 or more days during the 2004 dry season and 14% burned on 10 or more days. Over 70% of the forest clearings with fires on more than 5 days were subsequently used for cropland. Because of more frequent fire usage in preparation for mechanized agriculture, few areas deforested for cropland in 2004 had no high-confidence fire detections during 2004 (12%).

Deforestation for pasture averaged less than half as many fire days as deforestation for cropland, measured as either the maximum (pasture, 1.7; cropland, 4.6) or mean (pasture, 1.15; cropland, 3.0) days of fire detection per clearing. Even among very large clearings (>200 ha), fire usage was significantly higher for cropland deforestation than forest clearing for pasture (Wilcoxon rank test, $P < 0.0001$). Only 13% of all
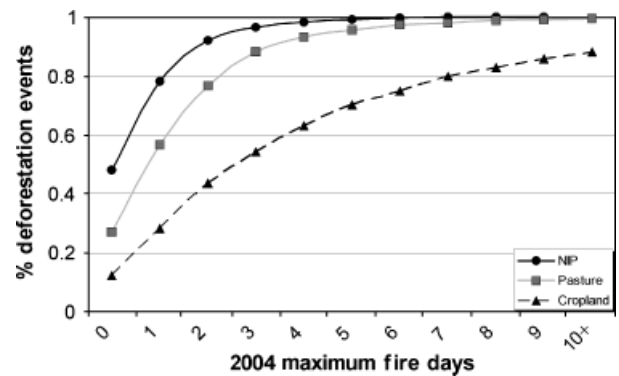

Fig. 2 Intensity of fire use for 2004 deforestation events >25 ha in Mato Grosso state according to postclearing land use [cropland, pasture, and not in production (NIP)], measured as the maximum fire frequency in each deforested area during 2004.

deforestation events for pasture >200 ha averaged 3 or more fire days in any year, suggesting that mechanized forest clearing and high-frequency burning are more related to postclearing land use than clearing size. For both pasture and cropland deforestation, polygons in which the conversion occurs within 1 year have a greater number of fire days in the year that the deforestation was detected than conversions occurring over 2 or more years (Wilcoxon rank test, $P < 0.0001$), consistent with the expectation that higher fire frequency leads to higher combustion completeness.

For those areas that showed no clear pasture or cropland phenology in the years following deforestation, fire activity was minimal. Nearly 50% of the areas described as NIP showed no high-confidence fires in 2004, and only 22% of these deforestation events exhibited fires on 2 or more days typical of other deforestation events.

The timing of fire use during the dry season also differed for cropland and pasture deforestation (Fig. 3). Deforestation fire activity may begin during the late dry season (September–November) in the year before the deforestation is mapped and continue for several years postclearing as the initial forest biomass is gradually depleted to the desired conditions for cropland or pasture use. September was the most common month of fire activity for all types of deforestation in Mato Grosso in 2004. More than 70% of the fires associated with 2004 deforestation for pasture during 2003–2005 occurred during the late dry season (August–October). In contrast, fire activity for conversion to cropland was more evenly distributed through the dry season, with 45% of fire detections occurring in May–July.

Burning activities initiated in the early dry season for both pasture and cropland deforestation continue to burn in subsequent months. The highest percentage of
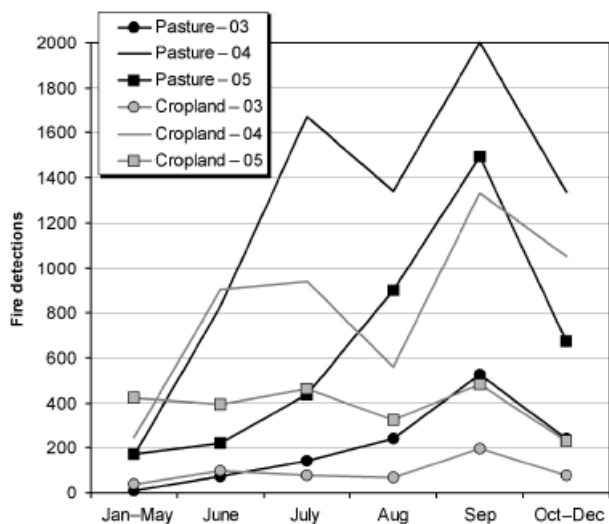
Fig. 3 Seasonality of fire activity during 2003–2005 for pasture and cropland deforestation events > 25 ha in Mato Grosso state from 2004.
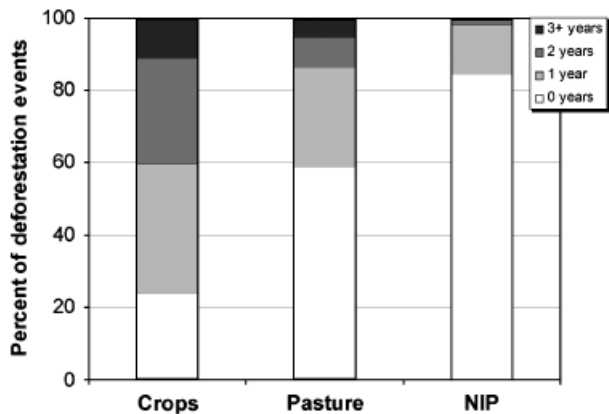

Fig. 4 Years of high-frequency fire activity for three different land uses following deforestation in Mato Grosso state. The typical duration of high-frequency fire activity (> 2 fire days per year) is shown as a percentage of deforestation events during 2003–2005 for each land use. Fire activity was examined for the year before deforestation mapping until 2006.

Fig. 5 Duration of deforestation fire activity following forest clearing highlights the contribution of multiple years of deforestation to fire in any year. Average fire frequency and total deforested area in polygons > 25 ha in size for 2002–2005 are shown separately for cropland (top), pasture (middle), and areas not in production (NIP, bottom). Deforested area for each post-clearing land use is taken from Morton *et al.* (2006, 2007b). Fire data for 2002 are derived only from Terra-MODIS observations.

fires without detections on additional days (fire days, 1) occurred during the late dry season; approximately 30% of the fires for conversion to pasture during September and October were the first fire detection for those deforestation events compared with 11% of all fires for cropland conversion during this period.

High-frequency fire activity may last for several years following initial forest clearing, further increasing the expected combustion completeness of the deforestation process (Fig. 4). Forty percent of the areas deforested for cropland during 2003–2005 had 2 or more years during 2002–2006 with 3 + fire days. The duration of clearing
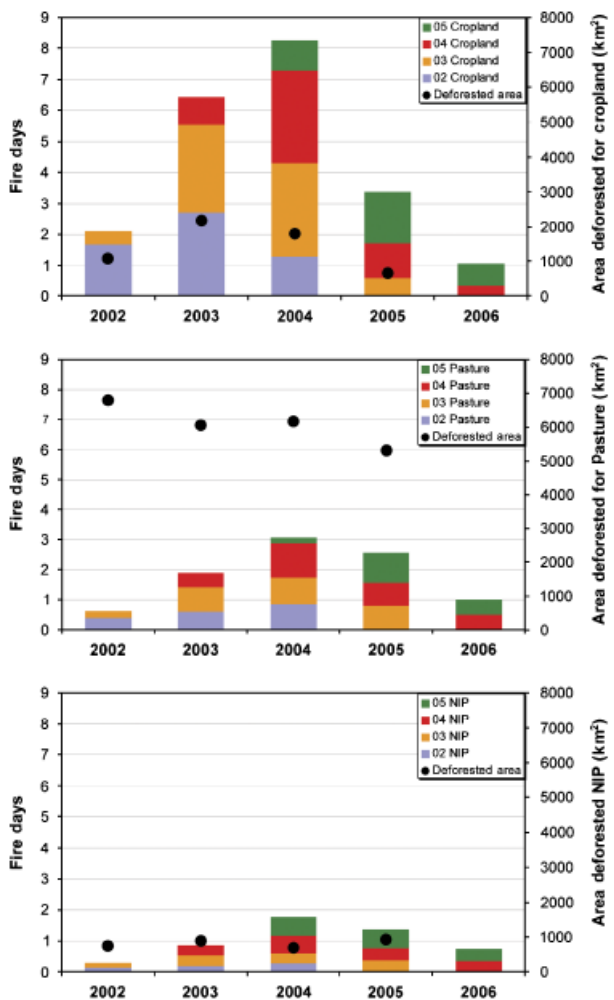
for pasture was more variable. Most areas cleared for pasture had 0–1 years of high-frequency fire usage, although a small portion (14%) had frequent fire detections over 2–3 years typical of mechanized forest clearing.

The carryover of fire activity from forest clearing into subsequent years is a cumulative process, such that total high-frequency fire activity in any year represents burning for multiple years of forest loss (Fig. 5). For example, elevated fire activity during 2004 in Mato Grosso (Table 2) is the product of deforestation rates during 2002–2005 and high fire frequencies in 2004 for cropland and pasture deforestation. In general, fire

frequency is highest for the year in which the deforestation was mapped. For cropland deforestation, fire frequency is similar in the year before $(n-1)$ and following $(n+1)$ deforestation mapping. For pasture deforestation, fire frequency is consistently higher in the year following deforestation mapping than the year before detection of deforestation. Deforestation NIP contributes little to the fire activity or deforested area during this period.

Discussion

Deforestation fires in Amazonia

The number of days on which fires are detected at the same ground location is higher for areas undergoing deforestation than for other fire types in Amazonia, and fires on 3 or more days at the same ground location are almost exclusively linked with forest conversion. During 2003–2007, more than 40% of all high-confidence MODIS fire detections within Amazonia were associated with deforestation. Within this subset of repeated fire detections, variations in fire frequency suggest that carbon losses from deforestation vary with postclearing land use. Deforestation for cropland may involve burning on as many as 15 days during the same dry season as woody fuels are piled and re-burned to prepare the land for mechanized agricultural production. Forest conversion for pasture is characterized by fewer days of burning during the dry season, on average, and fewer years of high-frequency fire detections than conversion to cropland. Forests without evidence for cropland or pasture usage following deforestation detection have the lowest fire activity.

Higher fire frequency associated with mechanized deforestation suggests greater combustion completeness of the deforestation process compared with less intensive clearing methods. Whereas the first fire following deforestation may consume 20–62% of the forest biomass depending on fuel moisture conditions (Fearnside et al., 1993; Kauffman et al., 1995; Carvalho et al., 1998; Guild et al., 1998; Araujo et al., 1999; Carvalho et al., 2001), piling and burning trunks, branches, and woody roots many times in the same dry season may increase the combustion completeness of the deforestation process to near 100% (Fig. 6). Based on published combustion completeness estimates of 20% or 62% per fire, repeated burning during the deforestation process could eliminate initial forest biomass after 5–22 fire events.

Combustion completeness and fire emissions from recent deforestation may be higher than previous estimates for deforestation carbon losses. Mechanized equipment can remove stumps and woody roots in
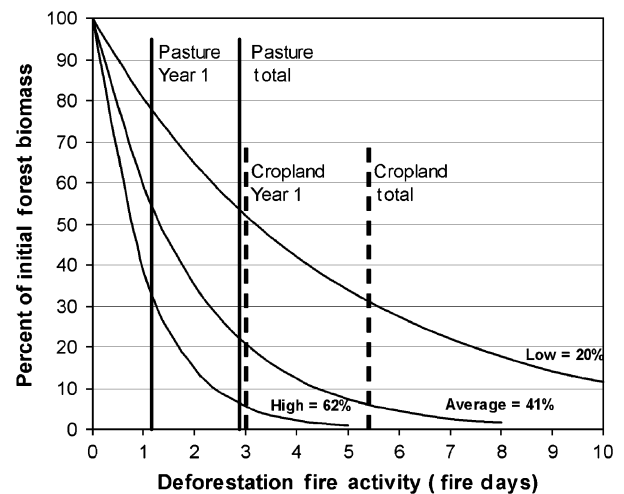

Fig. 6 Percentage of initial forest biomass remaining following repeated deforestation fire activity. The range of combustion completeness for each fire is shown as low (19.5%; Carvalho et al., 2001), average of published figures for Amazonia (40.6%; Fearnside et al., 1993; Kauffman et al., 1995; Carvalho et al., 1998; Guild et al., 1998; Araujo et al., 1999; Carvalho et al., 2001), and high (61.5%; Carvalho et al., 2001). Curves end once initial forest biomass drops below 1% (5–22 fires). Vertical lines show the mean number of fire days for 2004 deforestation in Mato Grosso for pasture and cropland in 2004 (year 1) and during 2003–2006 (total).

preparation for cropland (Morton et al., 2006) such that both above and belowground forest biomass are burned. Burning woody roots may increase the fire-affected biomass by as much as 20% (Houghton et al., 2001). Fires that burn piled wood are likely to be at the high end of the published range for combustion completeness, given field measurements of high fire temperature and longer duration of flaming and smoldering stages of combustion in piled fuels compared with pasture or initial deforestation fires (Schroeder et al., 2008). High fire frequency for recent deforestation also generates higher total fire emissions compared with previous estimates that assume that a majority of carbon is lost as CO_2 from heterotrophic respiration of unburned biomass (e.g. Houghton et al., 2000).

These attributes of fire use for mechanized deforestation in Amazonia challenge the basic assumptions that monitoring deforested area and estimating aboveground biomass of tropical forests are sufficient to estimate carbon emissions from deforestation (DeFries et al., 2007; Gullison et al., 2007). Failure to consider the evolving roles of postclearing land use on combustion completeness could introduce substantial uncertainty into calculated reductions in carbon emissions from declines in deforestation rates. Findings in this study

suggest that average combustion completeness for recent deforestation may be two to four times greater than that estimated for deforestation during 1989–1998 (Houghton *et al.*, 2000), increasing per-area gross fire emissions for the current decade by a similar magnitude in regions where mechanized deforestation is common. Deforestation for highly capitalized, intensive agricultural production may also reduce the rates of land abandonment to secondary forest compared with previous periods of Amazon colonization, reducing the offset of gross fire emissions from regrowing forests (Ramankutty *et al.*, 2007). In addition to further field measurements, we are currently developing a detailed model representing variations in forest biomass, combustion completeness of new deforestation, and offset of fire emissions from regrowing vegetation to more accurately quantify the influence of agricultural intensification on carbon emissions in the region.

The use of heavy equipment to manage forest biomass may also change the nature of trace-gas emissions from deforestation. Emissions factors for CO_2 are relatively similar for flaming and smoldering phase combustion, but emissions of CH_4, CO, and some VOCs from the smoldering stage of deforestation fires are nearly double than that during the flaming phase (Guild *et al.*, 2004). The balance between flaming and smoldering phase combustion for 2nd–*N*th fires during the forest conversion process is unknown. If emissions ratios do change during the course of the deforestation process as a function of the size or moisture content of woody fuels, the frequency of satellite-based fire detections provides one method to characterize time-varying trace gas emissions for Amazonia. Combining daytime and night-time observations from multiple sensors may better characterize the duration of individual fires to allow more direct interpretation of satellite data for trace gas emissions.

Spatial and temporal dynamics of fire activity

Interannual differences in total and high-frequency fire activity highlight trends in both economic and climate conditions across Amazonia. Concentrated fire activity in Mato Grosso state during 2003–2004 is consistent with peak deforestation for cropland, driven, in part, by high prices for soybean exports (Morton *et al.*, 2006). Carryover of fire activity from previous years' deforestation also contributes to high fire detections during 2003–2005 in Mato Grosso. Thus, reductions in fire-intensive cropland deforestation during 2005 (Morton *et al.*, 2007b) do not result in a shift in fire intensity away from central Mato Grosso state until 2006.

Regional differences in concentrated fire activity also highlight the role of climate in mediating human-

caused fires. Roraima, Acre, and Tocantins states in Brazil show dramatic differences in fire activity during 2003, 2005, and 2007. During drought periods in 2003 and 2005, Roraima and Acre had approximately seven and four times as many fires as under normal climate conditions, respectively. The fraction of high-frequency fires was also highest during these drought years, supporting the results from recent studies showing anomalous fire activity (Aragão *et al.*, 2007) and large areas of burned agricultural land and forest in drought-affected areas (Shimabukuro *et al.*, 2006). Future work to verify the detection of active forest burning by satellites is needed to quantify the contribution of forest fires to the regional patterns of high-frequency fire in drought years. In 2007, anomalous fire activity was driven primarily by low-frequency fires concentrated in southeastern Amazonia and a return to 2004 levels of deforestation fire activity in southeastern Bolivia and the Brazilian states of Mato Grosso and Pará. These examples suggest that even localized drought conditions can spur anomalous fire activity in the presence of anthropogenic ignition sources for deforestation and agricultural land management with important consequences for gross fire emissions.

The timing of fires for forest conversion may influence the likelihood of fires escaping their intended boundaries and burning neighboring forest and Cerrado vegetation. Deforestation for pasture contributes more fires during the late dry season when forests in Mato Grosso state may be most flammable after 3–5 months with little rainfall. More even distribution of fires for cropland clearing throughout the dry season may reduce the risk of forest fires. Different timing for cropland and pasture deforestation fires is consistent with management practices for intensive agriculture; mechanized crop production with chemical fertilizers is less reliant on the ash layer from deforestation fires for soil fertility than cattle pasture or smallholder agriculture land uses. However, deforestation fires for both cropland and pasture in Mato Grosso state were common during July and August of 2003–2005 despite local regulations prohibiting fires during these months to minimize the risk of unintended forest fires (Schroeder *et al.*, in press).

Because the most frequent fire detections are indicative of mechanized deforestation and postclearing land use for intensive agricultural production, monitoring cumulative fire frequency could aid the rapid detection of mechanized forest clearing. Improved geolocation and fire detection capabilities of the MODIS sensors compared with previous satellite instruments enable a higher resolution investigation of these patterns of repeated fire activity. Despite the moderate resolution of the MODIS sensors, information on fire frequency

at 1-km resolution is commensurate with clearing sizes for mechanized crop production in Amazonia that average 3.3 km^2 (Morton *et al.*, 2006). Active fire information has not previously been merged with land cover change estimates for deforestation monitoring.

Uncertainties

Our approach to quantify the contribution of deforestation to satellite-based fire activity and characterize individual forest conversions in terms of fire frequency is intentionally conservative. Because of issues of both omission and commission of fires by the MODIS sensors, it is not possible to determine the exact timing or frequency of all fires for the conversion process. We begin with a high-confidence subset of active fire detections to reduce data errors from spurious fire detections over tropical forest (Schroeder *et al.*, 2008). Next, we link deforestation fire activity to high-frequency fire detections, such that fires must be detected at the same ground location on 2 or more days, despite omission of fires from MODIS attributable to fire size (Cardoso *et al.*, 2005), orbital coverage (Schroeder *et al.*, 2005), and the diurnal cycle of fire activity (Giglio, 2007). Despite well-defined changes in land cover, 12% of cropland and 27% of pasture deforestation events in 2004 showed no fire activity in the high-confidence subset of fire detections. Therefore, low-frequency and omitted fires likely increase the fraction of total fire activity in Amazonia linked to deforestation. Because of omission of active fires by MODIS, a more robust method to estimate combustion completeness of the deforestation process may be to combine active fire detections from multiple sensors with other satellite data on deforestation or vegetation phenology to follow the fate of cleared areas over time.

Conclusions

The spatial and temporal patterns of fire activity in Amazonia characterize the differences in fire frequency for deforestation and agricultural maintenance. We present the fraction of MODIS fire detections associated with forest conversion, quantifying the disproportionate contribution of high-frequency burning for conversion of forest to mechanized cropland in satellite-based fire detections. Patterns of high-frequency fire use for deforestation compared with agricultural maintenance highlight the fact that postclearing land use is more important than clearing size for determining the intensity of fire use during deforestation. Fire activity for both cropland and pasture deforestation may continue over multiple years, contributing to higher combustion completeness compared with previous estimates of carbon losses from deforestation. Because deforestation from multiple years may contribute to fire activity in any given year, a decrease in deforestation may not reduce fire activity in that year.

The trend toward more intensive land management in Amazonia is clearly linked with an increase in the frequency of fire usage for deforestation. Proper characterization of related changes in fire emissions will, therefore, depend on the ability to separate fires from repeated burning of deforested areas from other fire types in Amazonia, as demonstrated here. In addition, combining the frequency of active fire detections with existing deforestation monitoring approaches could assist in the identification of mechanized forest clearing typical of intensive agricultural production.

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