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Understorey fire frequency and the fate of burned forests in southern Amazonia

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Recent drought events underscore the vulnerability of Amazon forests to understorey fires. The long-term impact of fires on biodiversity and forest carbon stocks depends on the frequency of fire damages and deforestation rates of burned forests. Here, we characterized the spatial and temporal dynamics of understorey fires (1999–2010) and deforestation (2001–2010) in southern Amazonia using new satellite-based estimates of annual fire activity (greater than 50 ha) and deforestation (greater than 10 ha). Understorey forest fires burned more than 85 500 km^2 between 1999 and 2010 (2.8% of all forests). Forests that burned more than once accounted for 16 per cent of all understorey fires. Repeated fire activity was concentrated in Mato Grosso and eastern Pará, whereas single fires were widespread across the arc of deforestation. Routine fire activity in Mato Grosso coincided with annual periods of low night-time relative humidity, suggesting a strong climate control on both single and repeated fires. Understorey fires occurred in regions with active deforestation, yet the interannual variability of fire and deforestation were uncorrelated, and only 2.6 per cent of forests that burned between 1999 and 2008 were deforested for agricultural use by 2010. Evidence from the past decade suggests that future projections of frontier landscapes in Amazonia should separately consider economic drivers to project future deforestation and climate to project fire risk.

1. Introduction

The dynamics of recent Amazon deforestation and forest degradation illustrate that regional changes in forest cover increasingly reflect distant teleconnections in both the global marketplace and the climate system. During 2000–2005, the Amazon arc of deforestation was the most active tropical land use frontier [1]. Large, export-oriented enterprises played an unprecedented role in the rise and fall of Amazon deforestation between 2000 and 2009 [2–5]. Climate-driven fire risk in Amazonia during the past decade also responded to large-scale climate modes, such as the El Niño Southern Oscillation (ENSO) and Atlantic Multi-decadal Oscillation (AMO). All fires, including understorey forest fires, were more common in years with positive (warm) phases of both ENSO and AMO in the three to six months prior to the fire season [6]. Combined, emissions from deforestation and forest degradation in Amazonia accounted for 37 per cent ($0.16\,\mathrm{Pg\,C\,yr^{-1}}$) of all fire emissions from tropical forests and peatlands during 2000–2009 [7]. The strength of the future Amazon carbon–climate feedbacks depends, in part, on the synergies among deforestation, fire and climate change [8–10], including the frequency and fate of burned forests.

What controls the frequency of fires in Amazon forests? Fuels, ignitions and suitable climate are necessary for all fires, and each of these elements could limit the location and frequency of repeated fires in Amazon forests. First, fire may initiate a positive feedback in which canopy gaps from fire-killed trees alter the forest microclimate, drying leaf litter and accumulated woody fuels, thereby making future fires more likely [11,12]. Recurrent fires could be more common under average climate conditions if fuel abundance and fuel moisture respond to local forest structure in a positive fire feedback [11,13]. Second, the regional distribution of human fire ignitions may influence the likelihood of repeated fires in Amazon forests, such that active land use frontiers with fire-driven deforestation and fire-dependent land uses may be important loci for repeated burning. Third, interannual variability in understorey burned area is strongly linked to large-scale climate modes and synoptic fire weather conditions [6,14]. The recurrence of fire weather conditions, rather than fuels or ignitions, may control repeated fire activity if climate is the driving mechanism behind both initial and repeated fires in Amazon forests. To date, knowledge of the frequency of understorey fires in Amazonia is limited to localized remote sensing [14] and field studies [11,15,16]. Regional data on understorey fire frequency are critical to evaluate the role of these mechanisms for repeated understorey forest fires in Amazonia.

Frequent understorey forest fires may accelerate long-term changes in Amazon forest structure and carbon stocks. Fires in previously burned forests further reduce above-ground biomass [11,12,15,17], facilitating the growth of pioneer tree species with lower fire tolerance [15,18]. Repeated exposure to fire may eventually convert tropical forests into fire-adapted grasslands or woodlands, a process described as savannization or secondarization [15], with dramatic consequences for carbon storage and biodiversity [11,12,16–18]. The long-term impact of frequent fires on Amazon forest carbon stocks also depends on whether burned forests are subsequently deforested.

The spatial and temporal relationships between deforestation and forest fires in Amazonia remain uncertain. Reliable projections of land use and forest carbon stocks in Amazonia depend on understanding whether deforestation increases the risk of fires in adjacent forests, understorey fires alter the likelihood of future deforestation as in the case of selective logging [19], or deforestation and understorey fires are unrelated. Previous studies have independently quantified regional deforestation [1,20] or understorey forest fires [6,21]. However, these independent estimates frequently overlap, confounding efforts to characterize the associations between deforestation and understorey fires (and overestimating total changes in forest cover) [21]. Time series of annual data on deforestation and understorey fires are, therefore, necessary to characterize the spatial and temporal relationships between forest conversion and understorey fires in standing forests. The nature of these relationships can inform efforts to Reduce Emissions from Deforestation and Forest Degradation plus enhance forest carbon stocks (REDD+) [22,23], including whether understorey fires are an independent source of carbon emissions or a regional driver of deforestation.

Here, we examined the frequency of understorey forest fires and the fate of burned forests across the southern Amazon in Brazil, Bolivia and Peru. Our analysis used estimates of large (greater than 50 ha) understorey forest fires (1999–2010) and deforestation events greater than 10 ha (2001–2010) derived from annual satellite data. The study had two primary aims: (i) to quantify the frequency of recurrent forest fires across southern Amazonia and (ii) to assess the spatial and temporal relationships between deforestation and forest fires, including adjacency, edge effects at varying spatial scales and post-fire deforestation. In combination with previous studies of climate-driven fire risk in Amazonia [6], these analyses provide additional insights regarding the mechanisms for repeated burning in Amazon forests, and the relative importance of deforestation and forest degradation in southern Amazonia over the past decade.

2. Data and methods

Understorey forest fires in southern Amazonia were mapped using the Burn Damage and Recovery (BDR) algorithm, a time-series approach to distinguish fire-related canopy damages from deforestation and selective logging [21]. The BDR algorithm uses up to 4 years of satellite data from the early dry season (June–August) to identify the trajectory of damage and recovery of burned forests over time [21]. We used annual estimates of large (greater than 50 ha) understorey forest fires from 1999 to 2010 to estimate the frequency and fate of burned forests in southern Amazonia during this period (data available at http://forest.gsfc.nasa.gov). The study area included more than 3×10^6 km^2 of closed-canopy Amazon forests in 2000.

A new time-series approach was used to identify annual deforestation between 2001 and 2010 for the entire southern Amazon study region. Forest areas converted for cropland or pasture have distinct non-forest phenology in the years following deforestation [2,5,21]. Based on these previous studies, a threshold (0.65) in dry season Normalized Difference Vegetation Index (NDVI) was used to identify forest to non-forest transitions in annual time series of 250 m satellite data from NASA's moderate resolution imaging spectroradiometer (MODIS) [21]. Forests converted to non-forest cover types for a minimum of two consecutive years were considered new deforestation events. Time-series trajectories for deforestation and understorey fires are mutually exclusive, avoiding potential misclassification issues that can arise from deforestation mapping or monitoring approaches based on observations of forest cover change from a single season [20,24]. Only deforestation events greater than 10 ha (at least 2 MODIS pixels) were used to assess total deforestation and deforestation of previously burned forests, based on a prior validation of deforestation monitoring with MODIS data [25]. Annual deforestation data were also used to update a map of remaining forest cover in order to estimate the distribution of understorey fires according to the distance from the forest edge. Finally, MODIS-based deforestation estimates for the Brazilian Amazon were compared with deforestation estimates derived from annual Landsat data at 30 m resolution to assess the contribution of smaller deforestation events not detected with the MODIS approach [20].

Dry season climate conditions were estimated using night-time relative humidity estimates from NASA's Atmospheric Infrared Sounder (AIRS) instrument onboard the Aqua satellite. Given the slow spread rates of understorey fires (0.1–0.5 m min^{-1} [12,26]), extended periods with low night-time relative humidity may allow fires to damage large areas by burning over multiple days. The AIRS level 3 8-day standard physical retrieval product v. 5 [27] was acquired for 12 composite periods during the Amazon dry season (18 July–21 October). AIRS retrievals for surface (1000 hPa) relative humidity were used to estimate seasonal variability in night-time conditions (approx. 01.30 local overpass time) for each composite period during 2003–2010.

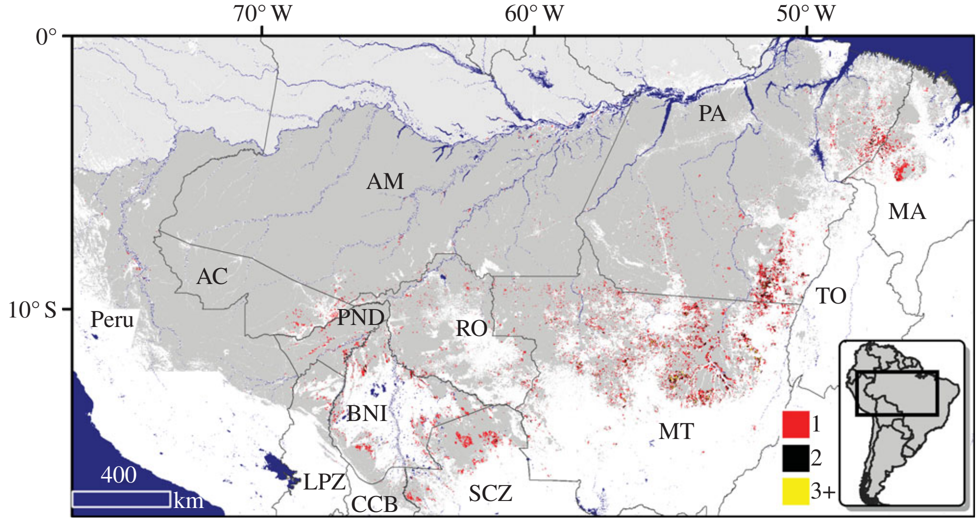

Figure 1. Extent of understorey forest fires across southern Amazonia based on the frequency of fire damages during 1999–2010. Forests in the southern Amazon study region (3 × 10^6 km^2) appear grey. In Brazil and Bolivia, state and department names are abbreviated as: Acre (AC), Amazonas (AM), Maranhão (MA), Mato Grosso (MT), Pará (PA), Rondônia (RO), and Tocantins (TO); Beni (BNI), Cochabamba (CCB), La Paz (LPZ), Pando (PND), and Santa Cruz (SCZ).

Table 1. Area of understorey forest fires (km^2) during 1999–2010 by fire frequency. Numbers in parentheses indicate the fraction (0–100%) of repeated understorey forest fires in the Brazilian states of Mato Grosso and Pará, respectively.

year	1st	2nd	3rd	4th	5th	% repeated
1999	6188.5					—
2000	840.9					—
2001	1564.5					—
2002	2430.1	542.5 (99.8, 0.2)				18.2
2003	2284.0	240.8 (99.4, 0.2)				9.5
2004	4864.9	693.2 (95.9, 3.6)	130.3 (100, 0)			14.5
2005	13 557.2	720.4 (82.4, 11.1)	98.9 (100, 0)			5.7
2006	2482.6	465.4 (94.3, 4.5)	176.6 (100, 0)	32.3 (100, 0)		21.4
2007	21 902.5	3228.1 (57.8, 35.6)	491.6 (90.7, 8.2)	61.3 (100, 0)		14.7
2008	2253.6	333.8 (50.0, 37.0)	68.2 (88.4, 6.7)	11.8 (100, 0)	2.5 (100, 0)	15.6
2009	1199.0	148.3 (42.9, 42.0)	21.7 (88.6, 11.4)	7.2 (100, 0)	1.7 (100, 0)	13.0
2010	13 570.2	4303.1 (52.7, 31.6)	530.7 (74.9, 21.4)	88.1 (97.4, 1.0)	7.6 (100, 0)	26.6

3. Results

(a) Fire frequency

Understorey forest fires were widespread across the arc of deforestation during 1999–2010 (figure 1). In contrast, repeated understorey fire activity during this period was largely concentrated along the eastern extent of Amazon forests in Brazil. Forests with two or more fires during this period were common in three frontier areas: the upper Xingu River Basin in Mato Grosso, southeastern Pará and the border between Pará and Maranhão states. Thrice-burned forests were limited to the upper Xingu watershed and adjacent areas of central Mato Grosso (figure 1), where the maximum frequency of repeated burning was five fires in the past 12 years. The mean fire return interval (FRI) for forests with multiple fires was 3.7 years. This spatially explicit FRI, directly calculated using satellite data, reflects a human-dominated fire regime along the deforestation frontier. A standard FRI calculation of the biome-wide fraction of annual fire activity masks this increase in fire frequency from the combination of land use and climate in frontier forests; the FRI of edge forests (less than 5 km from non-forest in 2000) was 245 years and the FRI of all forests in the study region was 422 years.

Repeated fire activity accounted for 16 per cent of all understorey forest fires during 2002–2010 (table 1). In Mato Grosso, where recurrent fires were most common, repeated burning contributed 24 per cent of all understorey fires during this period. Extensive understorey fires in 2005 in southwestern Amazonia did not generate repeated fire activity in subsequent years; less than 10 per cent of forests that burned in 2005 in Pando, Acre, Amazonas and near the city of Pucallpa (Peru) burned again by 2010. The fraction of repeated fires varied interannually, yet patterns of repeated fire activity were similar for low (10–21%) and high-fire years (6–27%, table 1). Even by 2010, 73 per cent of all forests

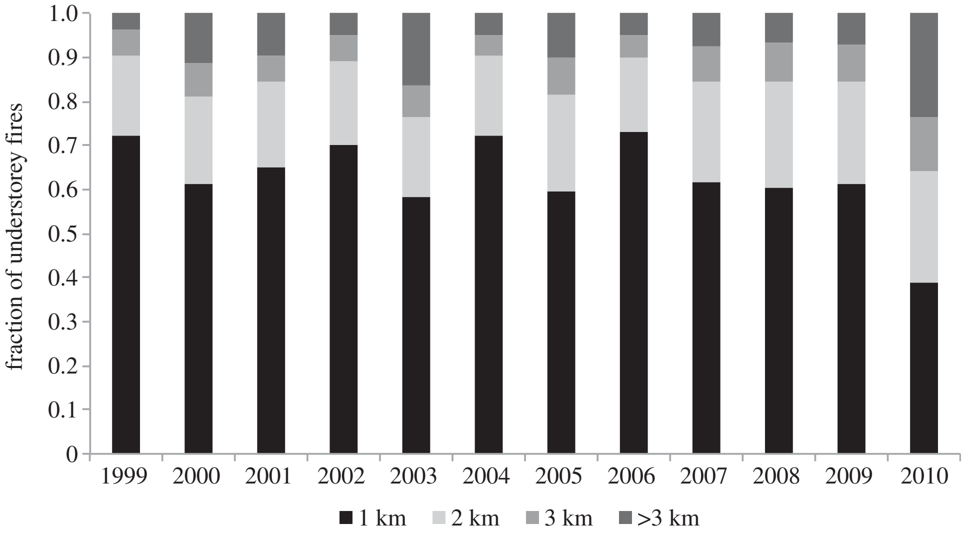

Figure 2. Fraction of understorey forest fires (1999–2010) based on the distance from the forest edge (km).

damaged by understorey fires had not burned previously (1999–2009).

Understorey fires were an edge effect at both small and large scales. The majority of burned forests were 1 km or less from the forest edge in all years except 2010 (figure 2). Forest areas farther from the forest edge (more than 2 km) also burned each year, accounting for an average of 16 per cent of annual fire activity. Owing to the slow spread rate of understorey fires, fires more than 2 km from the edge may have burned continuously for more than a week. Repeated burning was more clustered along the forest edge than single fire damages (see the electronic supplementary material, figure S1). On average, 74 per cent of repeated fires each year during 2002–2010 were less than 1 km from the forest boundary.

Understorey fire activity also appeared as an edge effect at the basin scale (figure 3). The number of years with high-fire activity (greater than 10 $\text{km}^2\ \text{yr}^{-1}$ burned forest per 1° grid cell) highlights the routine impact of understorey fires in the eastern Amazon. Over the past decade, northern Mato Grosso state experienced high-fire activity in at least 7 years (figure 3*a*). The maximum frequency of repeated fires in each 1° grid cell showed a similar pattern (figure 3*b*). The fraction of repeated fires in each 1° grid cell increased linearly with additional years of high-fire activity ($R^2 = 0.27$; electronic supplementary material, figure S2), implying that the frequency of all understorey fire activity influences the likelihood of repeated burning.

Dry season climate may facilitate initial and repeated fire activity in eastern Amazonia. The eastern arc of deforestation experienced low (less than 60%) night-time relative humidity in 6+ years during 2003–2010 (figure 3*c*). This large-scale edge effect, where conditions frequently permit understorey fires in southeastern Amazonia, is consistent with climatic control over the location and frequency of repeated understorey forest fires. Dry air covered the entire arc of deforestation in 2010, and the larger area and longer duration of consecutive dry conditions in 2010 (see the electronic supplementary material, figure S3) may partially explain evidence for burned forests further from the forest edge that year (figure 2).

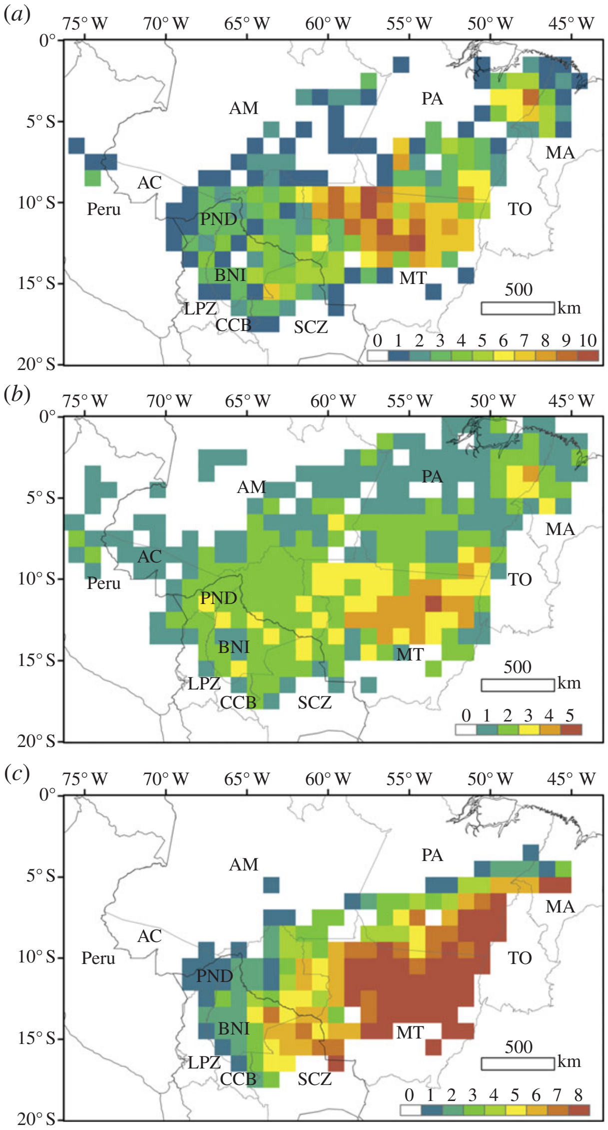

Figure 3. For each 1° grid cell, maps indicate (*a*) number of years with greater than 10 km^2 of understorey fires during 2001–2010, (*b*) maximum frequency of repeated understorey fires 2001–2010, and (*c*) number of years during 2003–2010 with AIRS 8-day average night-time relative humidity less than 60%.

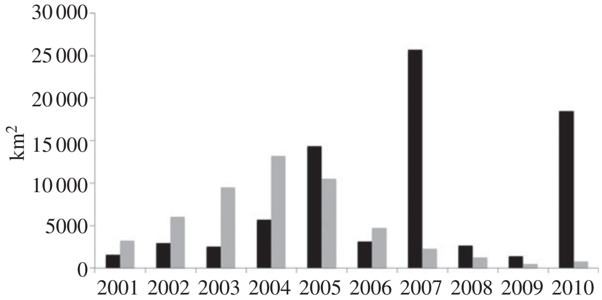

Figure 4. MODIS-based estimates of deforestation (grey bars) and understorey forest fires (black bars) (in km^2) across Southern Amazonia during 2001–2010.

Table 2. Temporal and spatial relationships between understorey forest fires and deforestation in southern Amazonia.

year	deforested by 2010 (%)	500 m or less from deforestation (%)
1999	9.0	—
2000	16.1	—
2001	15.3	24.5
2002	11.0	38.0
2003	6.4	41.9
2004	3.3	46.1
2005	0.5	43.5
2006	0.5	27.2
2007	0.1	52.2
2008	0	16.3
2009	—	2.0
2010	—	5.6

(b) Fire and deforestation

The interannual variability of understorey fires and deforestation in southern Amazonia were uncorrelated ($R^2 = 0.02$, figure 4). Large-scale deforestation activity in southern Amazonia peaked in 2004 before declining sharply between 2005 and 2010. The two years with highest understorey burned area (2007, 2010) coincided with very low annual deforestation estimates. Trends in large-scale deforestation and understorey fire activity in Mato Grosso state were similar to patterns for the entire southern Amazon (see the electronic supplementary material, figure S4).

MODIS-based deforestation estimates for the Brazilian portion of the study area were expectedly lower than estimates from Landsat data [20]. However, MODIS results captured the interannual variability of deforestation during 2001–2010 ($y = 0.57x - 4019$, $R^2 = 0.81$), especially for the states of Mato Grosso and Pará ($y = 0.66x - 3492$, $R^2 = 0.84$) (see the electronic supplementary material, figure S5). Small deforestation events below the detection limit with MODIS data (less than 10 ha) may partially explain the difference between Landsat and MODIS-based deforestation estimates.

Forest degradation from fire extended the influence of human activity beyond the deforestation frontier, as few burned forest areas were cleared for agricultural use in the past decade (table 2). Only 1 per cent of understorey burned area in 1999–2007 was deforested within 3 years, and 3.8 per cent of forests burned between 1999 and 2005 were deforested within 5 years. Overall, understorey fires between 1999 and 2010 impacted more than 85 500 km^2 of forest (table 1), or 2.8 per cent of all forests in the study region, of which approximately 83 800 km^2 remained forested in 2011.

Human access, whether by road or river, is an important factor for the distribution of understorey fires in southern Amazonia. Deforestation may be one of several important ignition sources for understorey fires (figure 5). Understorey fires were frequently adjacent to deforestation activity during 2001–2005 (table 2), estimated as any portion of the burn scar less than or equal to 500 m from a deforestation event in the same year. Adjacency in this context does not confirm deforestation as the source of fire ignitions. In subsequent years, as deforestation activity declined, the spatial relationship between understorey fires and deforestation was more variable. Only 5.6 per cent of all understorey burned area was less than or equal to 500 m of a deforestation event in 2010, the year with the second highest understorey fire damages (figure 4) and active fire detections from human ignitions (July–October [6]) despite low deforestation rates.

4. Discussion

This study provides the first estimate of the frequency of understorey forest fires across the entire Amazon arc of deforestation. Repeated understorey fires were primarily concentrated in northern Mato Grosso and southeastern Pará. These two states also accounted for the majority of single-year understorey fire damages and deforestation during this period, highlighting the co-location of deforestation and forest degradation at the forest frontier. Routine damages from understorey fires in Mato Grosso and Pará underscore the uniqueness of the southeastern Amazon region in terms of fire risk. Whereas the leading edge of the deforestation frontier experienced understorey fires in 1–3 years during the past decade, large understorey fires occurred nearly every year during 2001–2010 in Mato Grosso, with some forests burning five times. The intrusion of dry air during the fire season may partially explain routine large fire activity in the southeastern Amazon region. The area of frontier forests at risk of repeated fire activity could, therefore, increase in coming decades, irrespective of declines in deforestation, based on projections of warmer and drier conditions in central and eastern Amazonia [9,28].

The location and frequency of repeated fires suggest that climate was the dominant control on repeated burning of Amazon forests. Recurrent fires were most extensive in 2007 and 2010, when climate anomalies also promoted widespread understorey fires in unburned forests, suggesting a climate trigger for initial and repeated fires. The slow spread of understorey fires typically restricted initial and repeated understorey fires to forests within 1–2 km of the deforestation frontier, as extended fire weather conditions are needed to burn long distances from the edge source of anthropogenic ignitions (e.g. 2010). The edge area at risk of fire may, therefore, be predictable based on the duration of fire weather conditions and the distance from the forest edge.

The results of this study provide less evidence for a positive fire feedback in the absence of climate anomalies. In particular, the fraction of repeated burning did not increase in years with low fire activity, and repeated burning was rare in interior forests of central and southwestern Amazonia

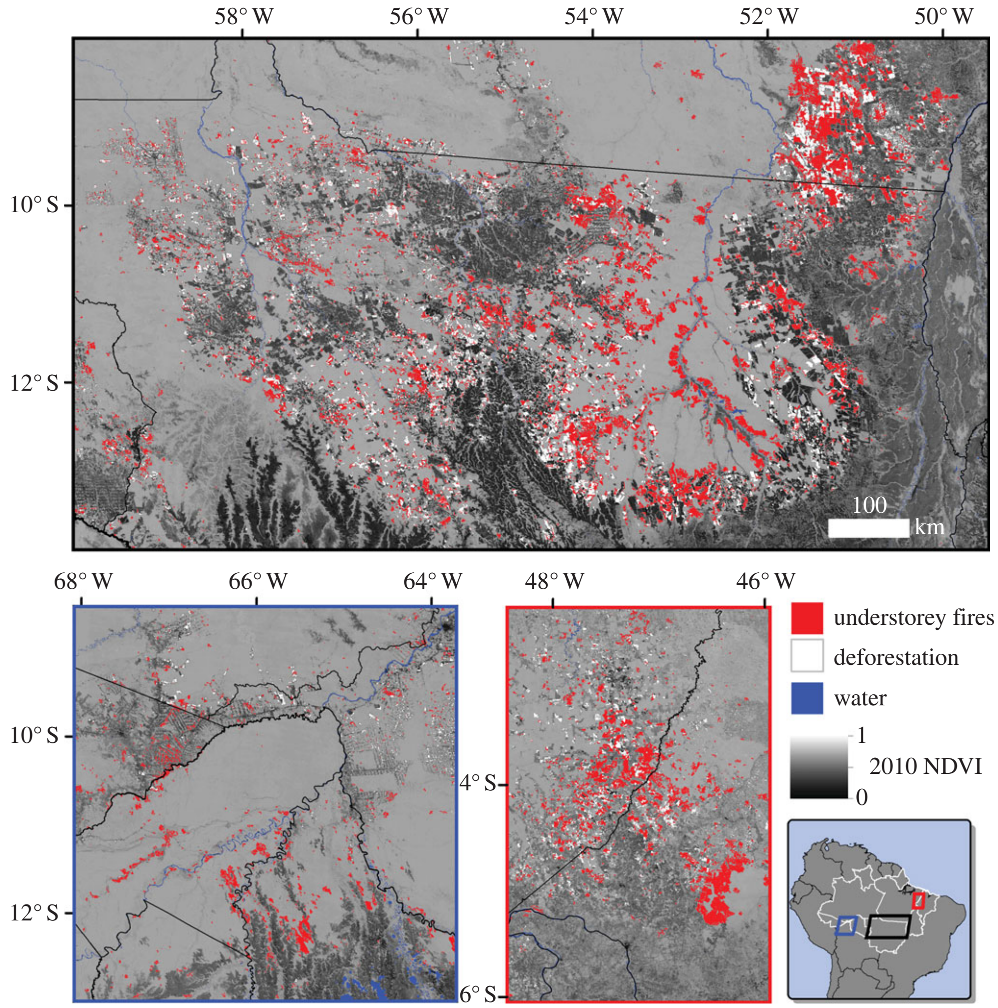

Figure 5. Deforestation and understorey forest fires during 2001–2010 for three frontier regions in southern Amazonia. Coloured frames indicate subset extents on the map of South America.

following fire damages in 2005. These two patterns contradict the expected increase in fire activity following initial fire exposure under a positive fire feedback [10–13,15,26,29]. The spatially explicit FRI for forests with multiple fires (3.7 years) was also consistent with evidence for lower risk of repeated fires on short (1–2 year) time scales [26]. We note the advantages of satellite data for assessing the dynamics of human-dominated fire regimes.

Human ignitions are a prerequisite for understorey fires, but ignitions alone were insufficient to spark widespread forest fires without suitable climate conditions. Satellite-based fire detections suggest an abundance of ignition sources from deforestation and agricultural management in the past decade [6,30]. However, understorey fire extent or frequency did not increase with rising deforestation (2001–2004), and widespread understorey fire damages in 2007 and 2010 occurred as deforestation rates in the Brazilian Amazon were the lowest since satellite-based estimates began [20]. Thus, eliminating deforestation will not stop understorey fires without a concurrent move towards fire-free land uses along the forest frontier.

Burned forests are an extensive and long-term component of the frontier landscape in Amazonia. In the context of REDD+, forest degradation from fire constituted an independent source of forest carbon emissions from Amazonia during 1999–2010, as few burned forests were deforested for agricultural use during this timeframe. Three factors may have contributed to the low rates of deforestation in burned forest areas. First, large fires occurred in regions such as indigenous reserves with lower risk of deforestation. In Mato Grosso, where property sizes are large [3], restricted use of forests in legal reserves may also maintain extensive areas of burned forest. Second, declining deforestation rates in Brazil after the implementation of new monitoring and enforcement programmes [5,24] probably slowed deforestation of both burned and unburned forests. Finally, burned forests were concentrated along the forest edge where small deforestation events may be difficult to identify with the MODIS approach in this study.

Several elements of this regional study could be improved or extended with more targeted analyses of fine-scale processes along the forest frontier. Small fires and deforestation events were not included in this study, based on the resolution of the MODIS time series [25]. Small fires [21] and deforestation events [3] are a minor component of forest cover changes in Mato Grosso, but the scale of forest cover changes may differ in other portions of the basin. Landsat or other high-resolution satellite data may improve estimates of fire frequency in this study and further elucidate the relationships between specific land uses and routine fire risk in adjacent forests. Deforestation estimates in this study were designed to be mutually exclusive with burned forests, but MODIS-based estimates were conservative compared with Projeto PRODES [20]. In addition to small clearings, the deforestation detection approach in this study excluded the possible influence of speculative deforestation, where areas are cleared but not immediately put into production [2,5]. The relationship between deforestation and fire could also be evaluated using finer temporal resolution satellite data, especially to confirm the role of deforestation events as the ignition source for understorey fires. Finally, fire frequency in this study was based on 12 years of satellite data. Estimates of repeated burning would benefit from a longer time series of satellite data, including coverage of the 1997–1998 ENSO [14,21], especially for regions of southern Amazonia where climate conditions rarely promote understorey fires.

The twenty-first century Amazon frontier presents unique challenges for efforts to reduce carbon emissions and minimize the human impacts on standing forests. Efforts to model future deforestation and fire activity could separate the economic [2,5] and climate drivers [6] of future changes in forest cover, respectively, as deforestation and understorey fires were largely independent pathways of forest changes and related emissions in the past decade. A new generation of economic land use projections [31], using representative concentration pathways (RCPs) developed for the Intergovernmental Panel on Climate Change 5th Assessment Report [32], highlights the potential for additional forest fragmentation from agricultural expansion in coming decades. Such a model would also need to track the unique elements of understorey forest fires to estimate the net carbon impacts from fire over a range of spatial and temporal scales, including size and species-dependent mortality of canopy trees [15,17,18,29] and multi-day fire spread based on the duration of climate anomalies in Amazonia. Ideally, sub-grid cell information on fire-dependent land uses and forest fragmentation would be shared between submodels for land use and understorey fires to update the location and frequency of human ignitions and the area of edge forests at risk of fire. Multiple realizations of combined land use and climate scenarios could provide a more robust assessment of the synergy between climate change and human ignitions along the forest frontier, including the relative importance of future deforestation and climate anomalies for forest carbon emissions from Amazonia [8,33].

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