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Forest conservation in Indigenous territories and protected areas in the Brazilian Amazon

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Yuanwei Qin[1], Xiangming Xiao[1] ✉, Fang Liu[1], Fabio de Sa e Silva[2], Yosio Shimabukuro[3], Egidio Arai[3] & Philip Martin Fearnside[4]

Conflicts between forest conservation and socio-economic development in the Brazilian Legal Amazon (BLA) have persisted for years but the effects of Indigenous territory (ITs) and protected area (PAs) status on deforestation there remain unclear. To address this issue, we analysed time-series satellite images and qualified annual forest area in the BLA under different governance and management regimes. Between 2000 and 2021, areas classified as ITs or PAs increased to cover 52% of forested areas in the BLA while accounting for only 5% of net forest loss and 12% of gross forest loss. In the years (2003–2021) after establishment, gross forest loss fell 48% in PAs subject to 'strict protection' and 11% in PAs subject to 'sustainable use'. However, from 2018 to 2021 the percentage rate of annual gross forest loss in ITs/PAs was twice that of non-designated areas. Our findings reveal the vital role of, and substantial progress achieved by, ITs and PAs in Amazonian forest conservation as well as the dangers of recent weakening of Brazil's forest policies.

The Brazilian Legal Amazon (BLA) has the largest tropical rainforest area, the highest biodiversity and the largest amount of aboveground biomass in the world[1–3]. Since 2000, the Indigenous territories (ITs) and the protected areas (PAs) in the BLA have increased substantially and by 2013 they accounted for 43% of the total land area and covered about half of the total forest area in the region[1]. ITs and PAs have important roles in forest and biodiversity conservation and climate mitigation in the BLA[4,5]. Many studies have investigated the effects of the ITs/PAs in reducing deforestation and strengthening forest conservation in the BLA[1,6–10], but their results differ substantially as different approaches and datasets were used. A comparison of deforestation rates between the PAs and the non-protected areas (non-PAs) showed that the deforestation rates in the PAs were 1.6–2.2 times[6] or ten times[1,7,8] lower than those in the non-PAs, respectively. PAs are usually located in remote areas with small deforestation pressure (Extended Data Fig. 1), whereas the non-PAs often have high deforestation pressure. The strict-protected PAs, located in more remote areas, have more forest cover and less deforestation pressure in comparison to sustainable-use PAs and ITs (Extended Data Fig. 2). The comparison of deforestation rate between PAs and non-PAs may not fully show the effects of the PAs in reducing deforestation. Spatial matching methods were applied to assess the effects of PAs on deforestation in the BLA[9,10]; however, due to extensive deforestation and forest degradation[11], it is challenging to find locations in the non-PAs with conditions similar to those in each PA to serve as the controls for the spatial matching methods. Various studies have assessed the effects of ITs/PAs using the official Brazilian deforestation dataset (PRODES)[6–8], which reports deforestation of primary forests based on the reference forest map in the 1980s and does not include secondary forests that are important for the carbon cycle and biodiversity conservation[12].

The conflicts between forest conservation and socio-economic development in the BLA persist but vary over the years[13–16]. Forest conservation in ITs/PAs has encountered increasing threats from loosened environmental laws and regulations, changing governmental policies and massive economic development[17,18], especially after 2012[19]. About 100×10^6 ha, including at least 20% of the area in strict protection PAs and ITs, have applications pending for mineral prospecting or mining operations[20,21]. The satellite data show that illegal mining in

[1]Department of Microbiology and Plant Biology, Center for Earth Observation and Modeling, University of Oklahoma, Norman, OK, USA. [2]Department of International and Area Studies, University of Oklahoma, Norman, OK, USA. [3]Brazilian National Institute for Space Research, São José dos Campos, São Paulo, Brazil. [4]Department of Environmental Dynamics, National Institute for Research in Amazonia (INPA), Manaus, Brazil. ✉e-mail: xiangming.xiao@ou.edu

the BLA substantially increased from 2000 to 2012 (an average area of 2,500 ha yr^{-1}) and hit a record high area in 2020 (10,000 ha yr^{-1}) amid widespread protests from Indigenous people[22]. Primary forest loss reached a decade high in 2020[23]. Between March and September 2020, Brazil passed 27 legislative acts that weakened environmental protection[24]. Fines for violation of environmental and conservation laws dropped by 72% from March to August 2020, despite an increase in deforestation[24]. Besides, COVID-19 started to spread widely in the Amazon in early 2020, causing high mortality rates among Indigenous groups[25], creating favourable conditions for encroachment of Indigenous lands by illegal loggers and miners.

PAs in the BLA have two types of governance and institution (national versus state PAs) and two types of management objective (strict protection versus sustainable use; Extended Data Figs. 1 and 2). To what degree were deforestation dynamics in the BLA and ITs/PAs under different governance and management affected by the COVID-19 pandemic and changing policies in recent years? Here, we investigate and report on (1) interannual changes in forest areas and deforestation in the BLA, ITs, PAs and non-PAs (that is, non-designated areas) and (2) the effects of ITs, national PAs (nPAs) and state PAs (sPAs) in reducing deforestation from 2000 to 2021 under the changing environmental laws and governance, natural disturbances and COVID-19. We generated annual evergreen forest maps by using daily images acquired by moderate resolution imaging spectroradiometer (MODIS) onboard the Terra satellite from 2000 to 2021 and the forest mapping algorithm[1,2].

Results

Increased areas of ITs/PAs for forest conservation

The number and area of ITs/PAs in the BLA increased from 1980 to 2018 with noticeable characteristics (Fig. 1a). The ITs area rose slowly from 0.2×10^6 ha in 1980 to 4×10^6 ha in 1988 but started to increase rapidly after 1988 and reached 74×10^6 ha in 2000 and 115×10^6 ha in 2016. This large and rapid increase in numbers and areas of ITs was driven by the 1988 Constitution's requirement that the government demarcate all Indigenous lands within 5 years. Although the Constitution's requirement has yet to be fulfilled, it stimulated substantial expansion of ITs, including 40×10^6 ha demarcated with financial support from the G7 Pilot Program to Conserve the Brazilian Rainforest. In 2000, the Brazil's National Protected Areas System was officially established to expand PAs and better manage the PAs for forest conservation. The nPAs area increased from 9×10^6 ha in 1980 to 27×10^6 ha in 2000, 62×10^6 ha in 2008 and 66×10^6 ha in 2018. The sPAs area increased from less than 1×10^6 ha in 1980–1989 to 25×10^6 ha in 2000, 56×10^6 ha in 2007 and 60×10^6 ha in 2018. When lumped together, the total area of ITs/PAs substantially expanded from 10×10^6 ha in 1980 to 126×10^6 ha in 2000 and 241×10^6 ha in 2018. The numbers of ITs, nPAs and sPAs also had similar changes over time and substantially increased from 2, 11 and 2 in 1980 to 227, 70 and 95 in 2000 and 387, 146 and 191 in 2018, respectively.

As most ITs/PAs are covered by forests, the large increase of ITs/PAs strengthens forest conservation substantially in the BLA. Figure 1b shows the interannual change in forest area in ITs, nPAs and sPAs during 2000–2018. Forest area in ITs increased from 67×10^6 ha in 2000 to 105×10^6 ha in 2016, an increase of 55%. Forest area in nPAs increased from 25×10^6 ha in 2000 to 62×10^6 ha in 2018, an increase of 146%. Forest area in sPAs increased from 18×10^6 ha in 2000 to 50×10^6 ha in 2018, an increase of 169%. We overlaid the 2000 annual forest map (a total of 394×10^6 ha of forest) with the 2018 boundary maps of ITs/PAs and these ITs/PAs in 2018 covered 206×10^6 ha forest, accounting for 52% of the total forest area in 2000, which clearly shows the importance of the ITs/PAs for forest conservation.

Interannual change of forest area during 2000–2021

We used our annual forest maps to quantify the interannual changes in forest area during 2000–2021 (Fig. 2a). The total forest area in the BLA decreased substantially from 394×10^6 ha in 2000 to 366×10^6 ha in 2021, a loss of 28×10^6 ha (~7% of the forest area in 2000 or an area loss larger than Brazil's state of Rondônia). The 2018 ITs/PAs boundary maps were overlaid on the annual forest maps to calculate the interannual change of forest area in ITs/PAs during 2000–2021. Total forest area in ITs, nPAs and sPAs decreased from 105.7×10^6 ha, 62.6×10^6 ha and 50.5×10^6 ha in 2000 to 104.9×10^6 ha, 62.2×10^6 ha and 50.0×10^6 ha in 2021, respectively, with the average loss rates of 0.04% yr^{-1}, 0.03% yr^{-1} and 0.10% yr^{-1} over their forest areas in 2000 (Fig. 2b–d). As some of the ITs/PAs overlap each other, we combined the ITs/PAs together; the total forest area in the combined ITs/PAs decreased slightly from 206.4×10^6 ha in 2000 to 204.9×10^6 ha in 2021, an average annual loss rate of 0.08×10^6 ha yr^{-1} (0.04% yr^{-1}). To our surprise, ITs/PAs together had a slightly larger forest area in 2018–2021 (204.6×10^6 ha) than in 2014–2017 (204.1×10^6 ha), which may be related to the recovery of forests after severe damage in 2015/2016 and, to a much lesser extent, from tree-planting projects. In comparison, the forest area in the non-PAs (Fig. 2e) decreased from 187.8×10^6 ha in 2000 to 161.3×10^6 ha in 2021, with an average annual loss rate of 1.3×10^6 ha yr^{-1} (0.7% yr^{-1}), about 14 times more than the ITs/PAs. The loss of 27×10^6 ha forest area during 2000–2021 in the non-PAs accounted for ~95% of the total loss of forest area in the BLA over the same period.

Geographically, the interannual change of forest area in ITs, nPAs and sPAs from 2000 to 2021 had noticeable spatiotemporal patterns. The trend analysis of forest areas (Fig. 2f–i) showed divergent dynamics among ITs/PAs. ITs/PAs in the southern and eastern portions of the BLA (the 'arc of deforestation') had the largest losses of forest area. The ITs/PAs in the northern portion of the BLA either had no significant change in forest area or had increased forest area. In total, 39.8% of nPAs (59 out of 146 nPAs), 40.4% of ITs (154 out of 387 ITs) and 44.0% of sPAs (84 out of 191 sPAs) had significant forest area loss from 2000 to 2021 ($P < 0.1$).

Spatiotemporal dynamics of primary forest area loss

We used the 2001 forest map as the reference map and identified the first year the forest pixels in 2001 were classified as non-forest pixels during 2002–2021 (Fig. 3a,b) and we counted the number of pixels with a change from forest to non-forest (forest loss) in a year as annual gross forest area loss over the BLA, ITs, PAs and non-PAs from 2002 to 2021 (Fig. 3c–g). The cumulative gross forest area losses during 2002–2021 were 49×10^6 ha for the BLA, including 2.1×10^6 ha for ITs, 1.2×10^6 ha for nPAs, 2.8×10^6 ha for sPAs and 43.1×10^6 ha for non-PAs. The combined ITs/PAs had a 5.9×10^6 ha gross forest area loss from 2002 to 2021, accounting for ~12% of total gross forest area loss in the BLA, which clearly indicates the critical role of the ITs/PAs in forest conservation.

The interannual change of gross forest area loss in the BLA (Fig. 3c) during 2002–2021 reveals three interesting results. First, annual gross forest area losses in 2005, 2007, 2010 and 2015 were substantially larger than those in previous and subsequent years. Years 2005, 2007, 2010 and 2015 were characterized by strong El Niño events (Extended Data Fig. 3), high air temperature or severe drought[26]. Second, annual gross forest area loss in 2013 was least during 2000–2021. Year 2013 was a year with high air temperature without an El Niño or Atlantic Multidecadal Oscillation event. Third, when those years (2005, 2007, 2010, 2013 and 2015) are taken out, the temporal dynamics of annual gross forest area loss show five noticeable phases and each of these phases lasted a few years: (1) increased forest area loss in 2002–2004, (2) reduced forest loss in 2006–2009, (3) increased forest area loss in 2011–2014, (4) decreased forest area loss in 2016–2018 and (5) increased forest area loss in 2019–2021. In 2018–2021, the annual gross forest area loss rates increased 3.6 times in ITs/PAs, larger than the increase in non-PAs (1.6 times), indicating increasing deforestation pressure and an alarming signal in ITs/PAs.

Varying effects of ITs/PAs on annual forest area loss

To investigate the effect of ITs/PAs on reducing forest area loss after they were established, we selected those ITs/PAs that were established

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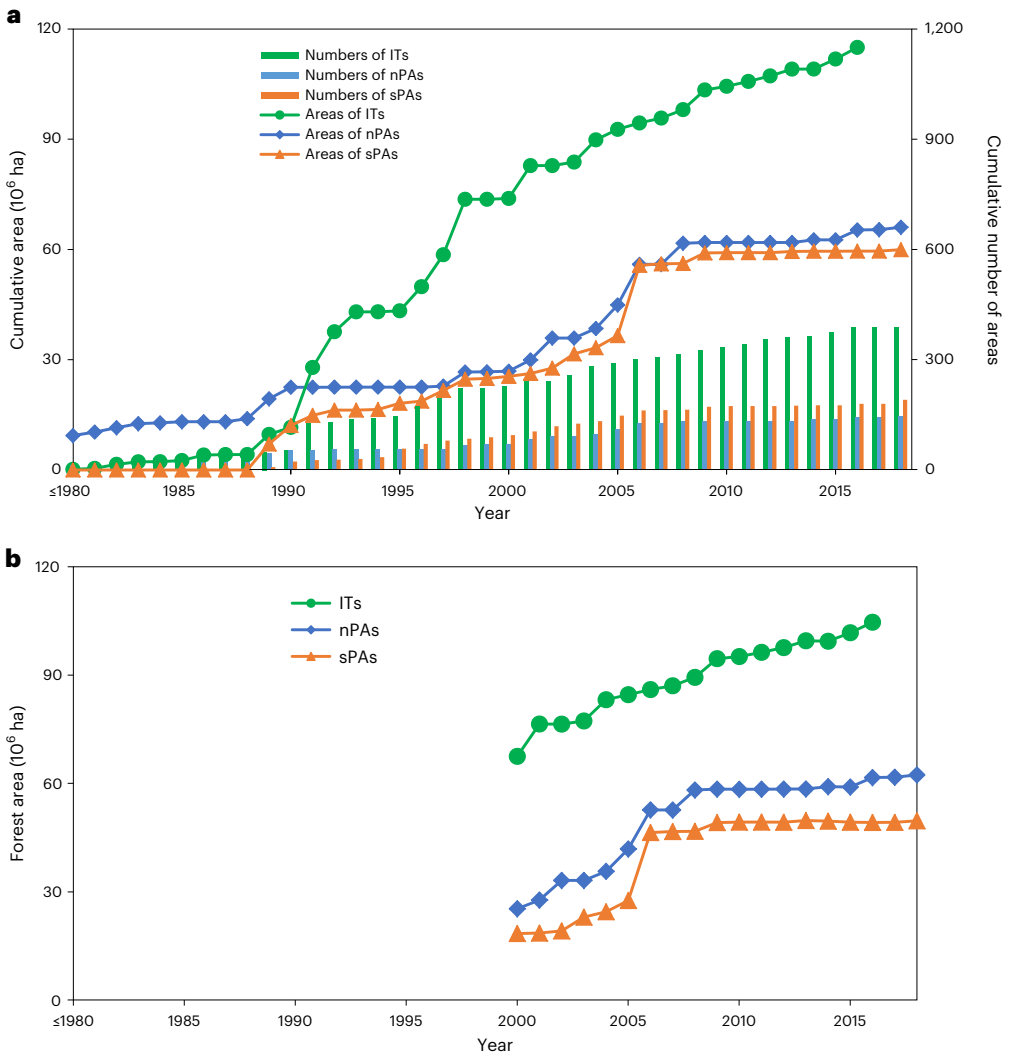

Fig. 1 | Cumulative areas and numbers of ITs and PAs and cumulative forest areas in ITs/PAs in the BLA. a, Cumulative areas and numbers of ITs, nPAs and sPAs from 1980 to 2018. ITs data in 2017 and 2018 are not available. **b**, Cumulative forest areas in ITs, nPAs and sPAs from 2000 to 2018.

after 2002 and analysed the average annual gross forest area loss rates before and after their establishment years (Fig. 4). The results show that 72 ITs, 32 nPAs and 38 sPAs had substantially reduced annual forest area loss rates but 49 ITs, 21 nPAs and 27 sPAs still had small to moderate increases in annual forest area loss rates; the other 24 ITs, 2 nPAs and 7 sPAs had no change in forest area loss rates as they had little or no forest area loss (Fig. 4a–c). There was no clear geographical cluster among those ITs/PAs with reduced or increased forest loss rates (Fig. 4d–f). Most of the sPAs in the northern and western BLA had small increases in annual forest area loss rates. In terms of institution and governance, the average annual gross forest area loss rates were reduced substantially for the nPAs (36%, 13.7×10^3 ha) and the ITs (30%, 10.7×10^3 ha) but only slightly for the sPAs (5%, 2.7×10^3 ha; Fig. 4g and Extended Data Fig. 4a). In terms of management objectives, the average annual gross forest area loss rates were reduced substantially for the strict-protection PAs (48%, 8.6×10^3 ha) and the ITs (30%, 10.7×10^3 ha) but only moderately for the sustainable-use PAs (11%, 7.7×10^3 ha; Fig. 4h and Extended Data Fig. 4b).

Different deforestation dynamics inside different PA types

Forest area in nPAs with the strict-protection objective (Fig. 5a) varied slightly during 2000–2013 but decreased moderately in 2014–2016, with a net loss of 0.14×10^6 ha (0.45%) from 2000 to 2021. Forest area in the nPAs with the sustainable-use objective (Fig. 5a) decreased continuously from 2000 (31.7×10^6 ha) to 2021 (31.5×10^6 ha), a net loss of 0.22×10^6 ha (0.7%). Forest area in sPAs with the strict-protection objective (Fig. 5b) decreased from 5.91×10^6 ha in 2000 to 5.88×10^6 ha in 2021, a net loss of 0.03×10^6 ha (0.51%). Forest area in sPAs with the sustainable-use objective (Fig. 5b) decreased from 44.65×10^6 ha in 2000 to 43.53×10^6 ha in 2016, a net loss of 1.12×10^6 ha (2.5%) but it had a modest recovery by 2021 (44.19×10^6 ha), thus a net loss of 0.46×10^6 ha (1.0%) from 2000 to 2021.

Differences in annual gross forest area loss rates were small and not significant between the PAs with different governance and management (Fig. 5c,d). The sPAs with the sustainable-use objective had the highest average gross forest area loss rate ($0.31 \pm 0.14\%$ yr^{-1} of the forest area in 2001), followed by nPAs with the strict-protection objective ($0.11 \pm 0.05\%$ yr^{-1}) and nPAs with the sustainable-use objective ($0.09 \pm 0.04\%$ yr^{-1}). The sPAs with the strict-protection objective had the lowest average gross forest area loss rate ($0.04 \pm 0.04\%$ yr^{-1}) due to these PAs being far away from the 'arc of deforestation' and therefore were under little deforestation pressure (Fig. 4f). The gross forest area loss rates increased from 2018 to 2021; these losses were probably related to the loosened forest conservation policies during the Bolsonaro presidential administration that began in January 2019[17,18,27]. Gross forest area loss from 2018 to 2021 increased 1.5 times in nPAs with the strict-protection objective and 5 times in nPAs with the sustainable-use

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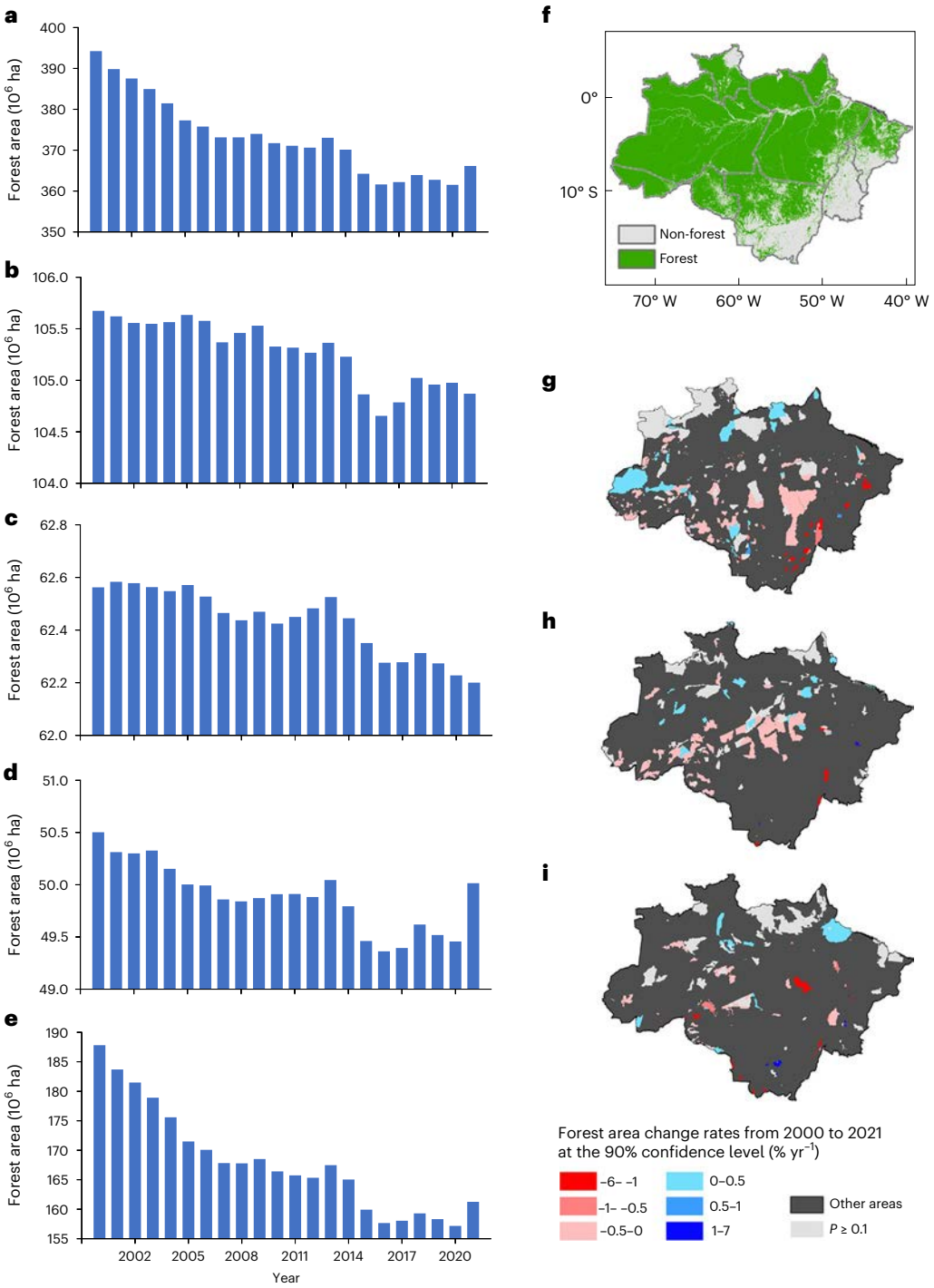

Fig. 2 | Interannual changes of forest areas in the BLA from 2000 to 2021. a–e, Forest areas in the BLA (**a**), ITs (**b**), nPAs (**c**), sPAs (**d**) and non-PAs (**e**). **f**, Forest area map in 2000. **g–i**, Forest area change rates in ITs (**g**), nPAs (**h**) and sPAs (**i**). Forest area change rates are calculated from annual forest areas between 2000 and 2021 on the basis of linear regression analysis at the 90% confidence level.

objective. Gross forest area loss from 2018 to 2021 increased 12.4 times in the sPAs with the strict-protection objective and 4.3 times in sPAs with the sustainable-use objective.

Discussion

Interannual change of forest area and deforestation

Annual forest maps from our mapping tools, PRODES[28] and Global Forest Watch (GFW)[29] were evaluated for South America[30] and the BLA[1], showing higher accuracy in our annual forest maps. The interannual changes of forest area and deforestation during 2000–2017 from these datasets were reported[1]. Here, we extended the data record from 2017 to 2021 (Fig. 6). We compared our forest area with the newly developed MapBiomas[31] forest area and they had similar interannual change trends in forest area in the BLA (Extended Data Figs. 5 and 6). During 2000–2020, the average annual forest area from our dataset is ~4% lower than the MapBiomas and our forest area declined by 8% (32.7×10^6 ha), close to the MapBiomas (7%, 27.9×10^6 ha). As the MapBiomas dataset has not provided annual gross forest area loss data to the public yet, it was not

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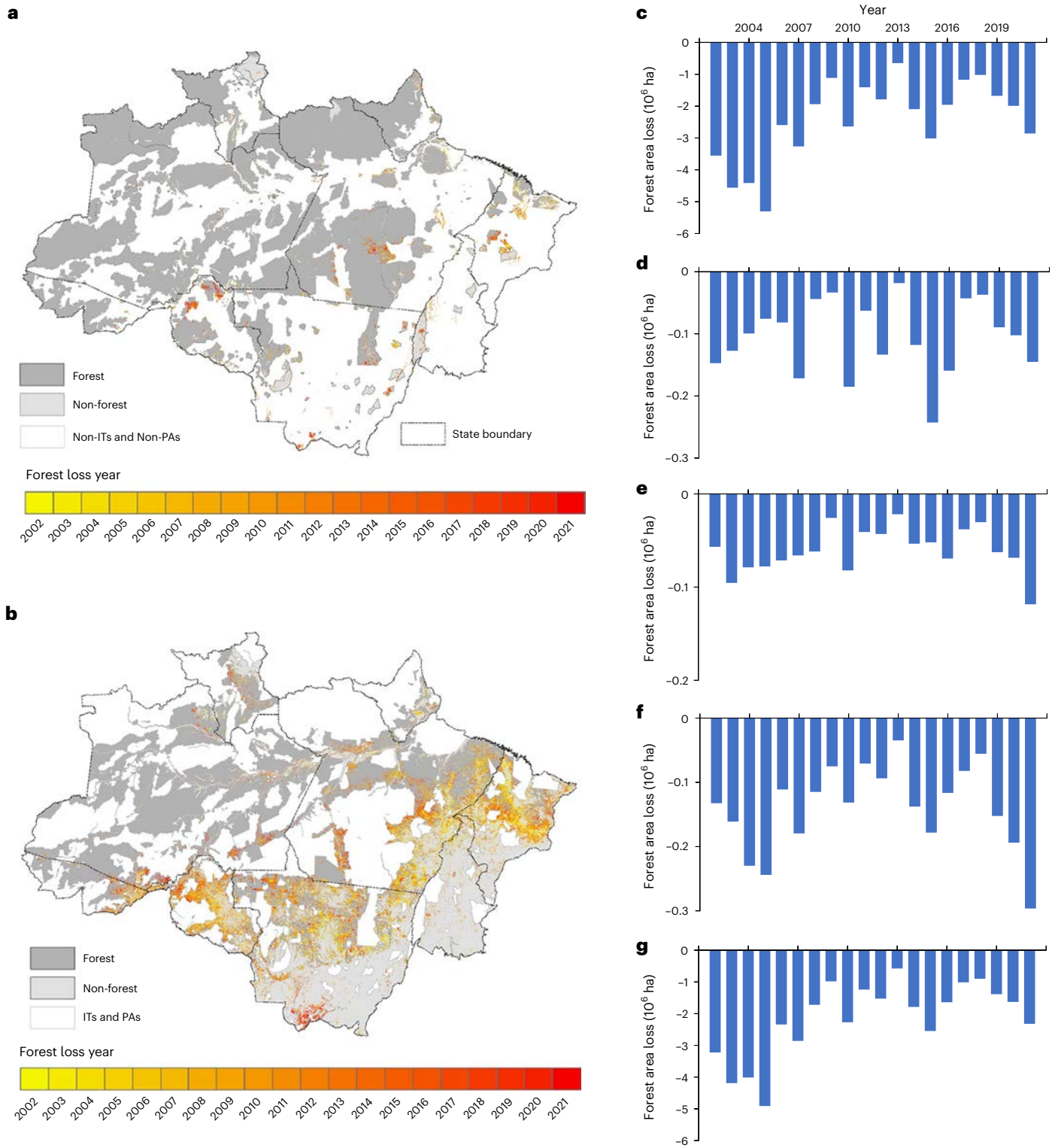

Fig. 3 | Annual gross forest area losses in the BLA from 2002 to 2021. a, Spatial distribution of the year a forest pixel in 2001 was classified from forest to non-forest (forest loss) in the ITs/PAs. **b**, Spatial distribution of the year a forest pixel in 2001 was classified from forest to non-forest (forest loss) outside ITs/PAs. **c**–**g**, Annual gross forest area loss in the BLA (**c**), ITs (**d**), nPAs (**e**), sPAs (**f**) and non-PAs (**g**). We used the 2001 forest map as the reference and identified the first year that forest pixels became non-forest pixels during 2002–2021. The dark grey pixels in **a** and **b** are forest in 2001.

used for detailed analysis in this study. Annual gross forest area loss from our dataset was 1.0×10^6 ha in 2018 and increased to 2.9×10^6 ha in 2021 (Fig. 6a). Annual gross forest area loss from the PRODES deforestation dataset was 0.8×10^6 ha in 2018 and increased to 1.3×10^6 ha in 2021 (Fig. 6b). Compared to the PRODES dataset, annual gross forest area loss from our dataset was higher but had a similar temporal trend. Our previous study explained the differences in forest area loss estimates between the PRODES dataset and our forest map, using annual forest maps in the BLA from 2002 to 2016[1]. Annual gross forest area losses from the GFW dataset in 2018–2020 were slightly higher than

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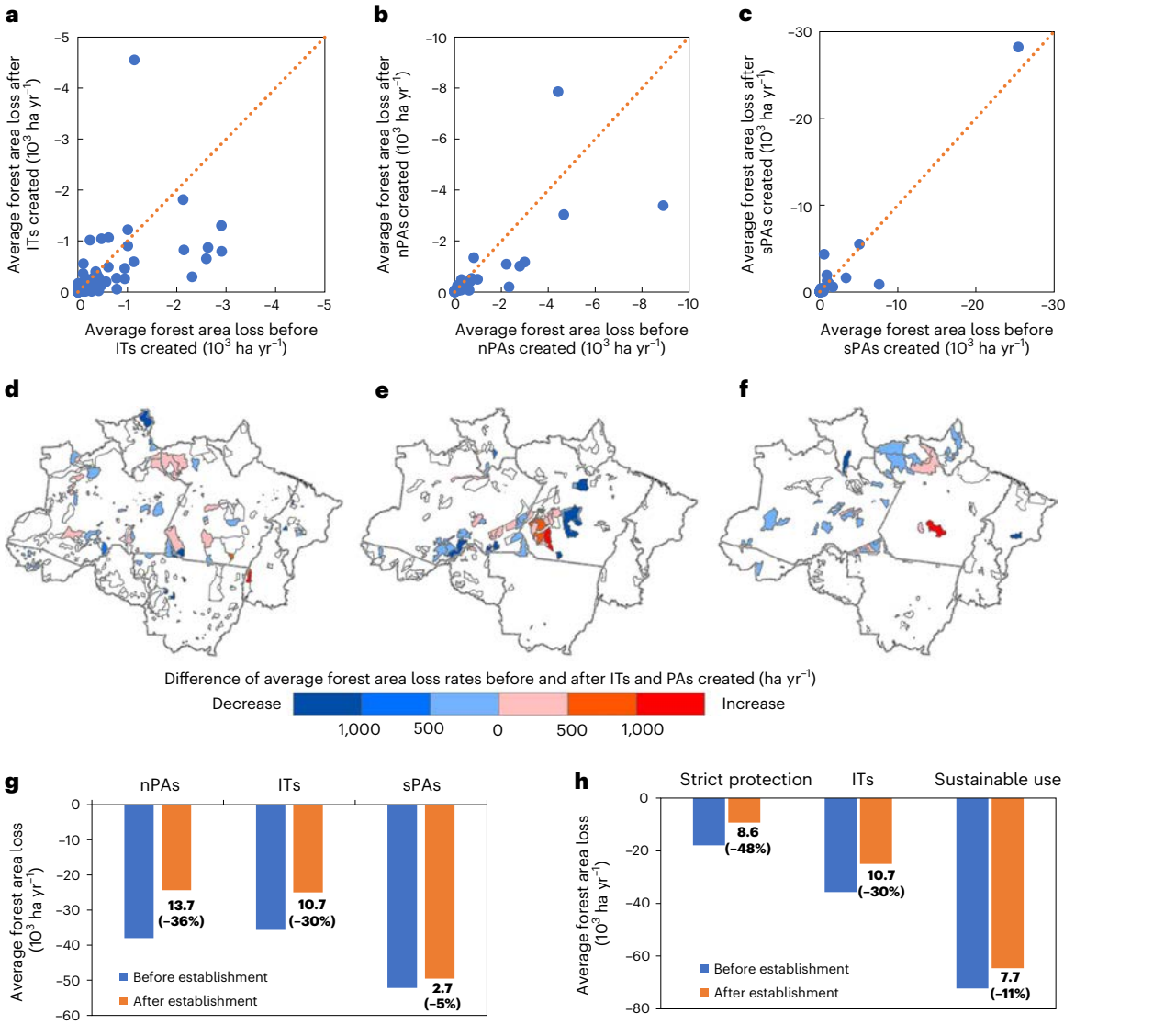

Fig. 4 | The effects of ITs/PAs on annual forest area loss rates in the BLA (2001–2021). a–**c**, Comparison of average annual gross forest area loss rates before and after ITs/PAs establishment (after the year 2002) by ITs (**a**), nPAs (**b**) and sPAs (**c**). **d**–**f**, Spatial distribution of the changes in annual gross forest area loss rates before and after ITs/PAs establishment by ITs (**d**), nPAs (**e**) and sPAs (**f**). **g**,**h**, The changes in average annual gross forest loss rates before and after the ITs/PAs establishment by governance (nPAs, ITs and sPAs) (**g**) and management (strict protection and sustainable use) (**h**). All ITs/PAs established before and during 2002 are white polygons.

those from our dataset (Fig. 6c). Annual forest area loss from the GFW dataset has been modified in numerous ways and these forest area loss data may not be comparable in those years[32]. Despite their differences in forest definition, in the satellite image data used and, in the forest mapping algorithms, all three datasets report that annual forest area loss in the BLA increased from 2018 to 2021. Together these results provide strong satellite-based evidence of increased forest area loss in 2020/2021.

Effects of ITs/PAs on forest conservation

Several studies analysed the PRODES deforestation datasets and assessed the effects of the ITs/PAs on forest conservation under changing laws, policies and climate change[9,33,34]. One study found that during 2000–2008 ITs/PAs in the states outside of the 'arc of deforestation' had little impact on deforestation within their boundaries but ITs and nPAs in the 'arc of deforestation' were more effective in reducing deforestation than were sPAs[9]. Another study reported that 91 sPAs established between 2005 and 2016 reduced deforestation both within their boundaries and in their adjacent surroundings during 2005–2017[33]. The third study also reported that ITs/PAs reduced deforestation during 2000–2010 in the BLA[34]. The PAs with the strict-protection objective reduced deforestation more than PAs with the sustainable-use objective and the ITs were particularly effective at reducing deforestation in locations with high deforestation pressure[34].

Our study uses a longer (2000–2021) and updated dataset to assess the effects of the ITs/PAs for forest conservation in the BLA. Our results over the 2000–2013 period agree with the findings from these previous publications and showed that ITs/PAs reduced deforestation within their boundaries. PAs with the strict-protection objective had small forest area losses in 2000–2013 but large forest area losses in 2013–2021 (Fig. 5). ITs/PAs in the states outside of the 'arc of deforestation' reduced deforestation within their borders (Fig. 4), which differs from that of ref. [9], possibly due to the different study periods or to limited data availability in PRODES caused by cloud cover[1]. Deforestation fronts also reached or encroached into some ITs/PAs (Fig. 3a and Extended Data Fig. 7). Those PAs with large deforestation areas were more likely

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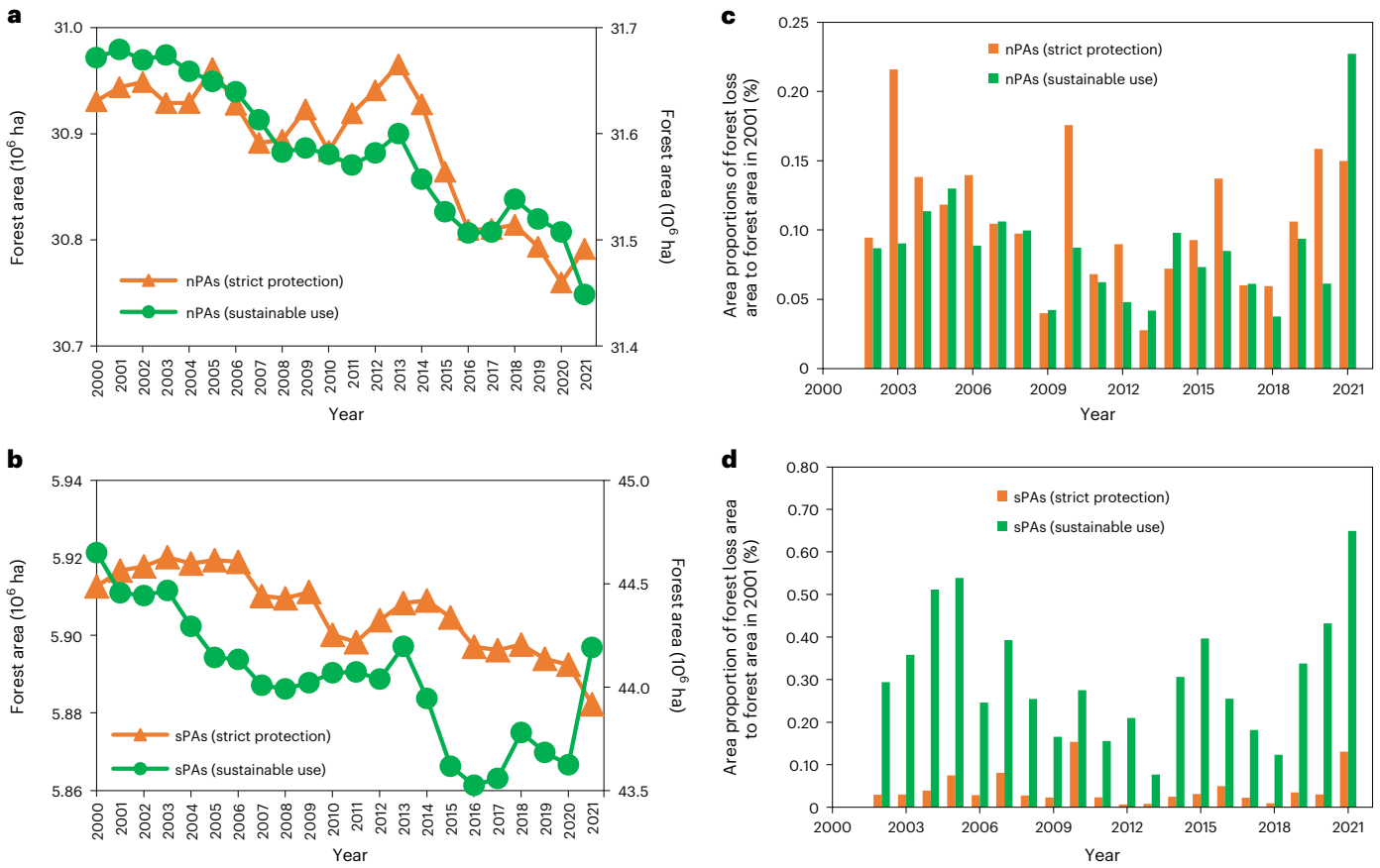

Fig. 5 | Annual forest areas and gross forest area loss rates in PAs with different governance and management regimes from 2000 to 2021. **a**, Annual forest areas in nPAs (strict protection, left Y-axis, and sustainable use, right Y-axis). **b**, Annual forest areas in sPAs (strict protection, left Y-axis, and sustainable use, right Y-axis). **c**, Area proportion of annual gross forest area loss to forest area in 2001 in nPAs (strict protection and sustainable use). **d**, Area proportion of annual gross forest area loss to forest area in 2001 in sPAs (strict protection and sustainable use).

to experience downgrading, downsizing and degazettement[35]. To avoid deforestation and reconcile the conflicts between forest conservation and socio-economic development, both intensive agriculture production in the deforested areas and forest restoration projects need to be fully explored. While these measures are important for environmental quality and for generating employment, they cannot be expected to have a 'land sparing' effect in reducing gross deforestation rates[19]. PAs with the sustainable-use objective, where small resident populations have low-impact uses of natural resources[36], are designed to promote conservation. They have been demonstrated to offer a win–win solution for biodiversity conservation and socio-economic development[37]; however, substantial deviations from the intended low-impact uses have sometimes occurred[38].

Investigation of various driving factors and development of models that predict the effects of ITs/PAs on reducing deforestation is important for stake-holders and decision-makers. Several studies identified a few driving factors (for example, Indigenous land rights, institutional context and property rights of ITs) and different methods (spatial matching and regression discontinuity model)[39–42]. Our exploratory data analyses (Supplementary Information) reveal the importance and limitation of the governance (ITs, nPAs and sPAs), management (strict protection and sustainable use), sizes and locations of the ITs/PAs and forest areas within the ITs/PAs for reducing deforestation. Our preliminary study also highlights the need for casual analysis and more efforts by the research community, stake-holders and decision-makers, more data collection (for example, politics[43], social-economic conditions and management practices in individual ITs/PAs), integrated analytics and models across multiple spatial and temporal scales.

Challenges for forest conservation in ITs/PAs

The changes in laws, policies, agriculture (soybean and beef cattle) and climate strongly affect forest conservation[44,45] and recent changes in those factors suggest that forest conservation in the ITs/PAs and non-PAs could face increasing challenges in the coming years. As shown in Extended Data Fig. 8, the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm)[23,46], which reduced deforestation, had been implemented since 2004 but was interrupted in 2019 by the Bolsonaro's administration. The Forest Code and the credit restrictions to owners of deforested lands implemented by the Brazil's Central Bank as of 2008[19], which also reduced deforestation, had also been weaken since 2012[47]. The Bolsonaro's administration is well known for its proximity to agribusiness[18,48] and since 2019 has implemented various measures that weaken forest policies and laws and impede their enforcement. In 2021, there was an even stronger push-back against the Brazilian legal framework governing the PAs: five draft bills (PL 490/2007, PL 191/2020, PL 2633/2020, PL 2159/2021 and PLS 510/2021) would further loosen constraints to the economic activities in the ITs, reduce government authority over PAs and provide incentives for agricultural expansion in these areas. The Brazilian Supreme Court is currently trying a case (RE 1017365) that could restrict the constitutional provisions that favoured the demarcation of Indigenous lands and could result in only areas effectively possessed by Indigenous peoples in 1988 being granted demarcation as Indigenous lands.

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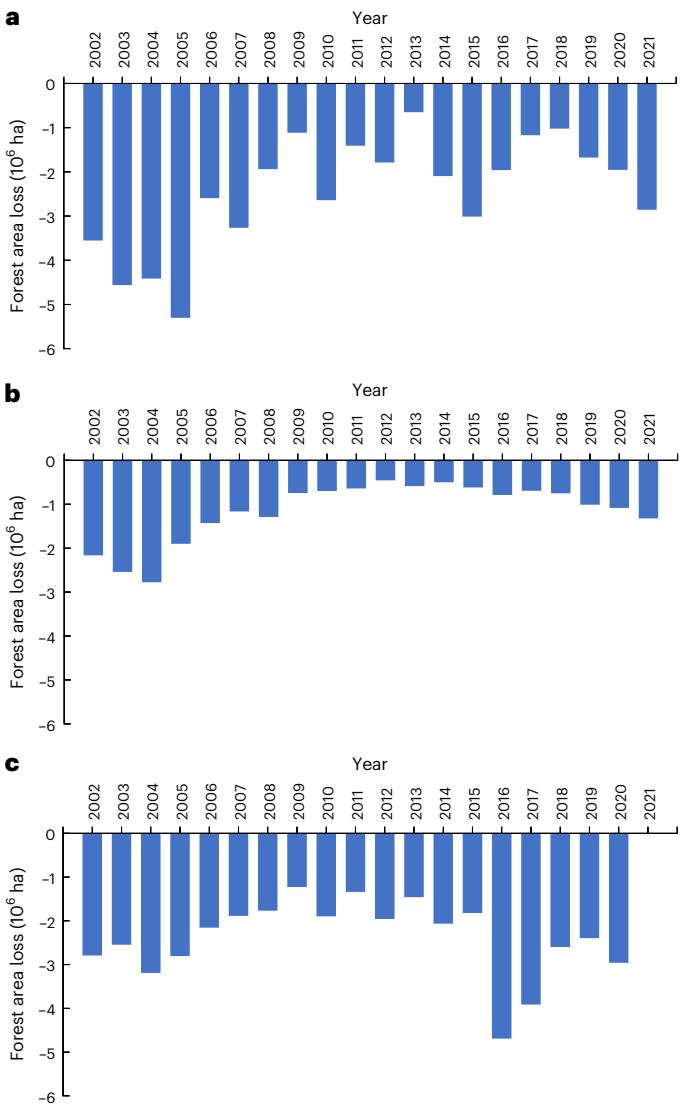

Fig. 6 | Comparison of annual gross forest area loss rates from this study, the official Brazilian deforestation dataset PRODES and GFW in the BLA from 2002 to 2021. a, Annual gross forest area loss rates from this study. **b**, Annual gross forest area loss rates from PRODES. **c**, Annual gross forest area loss rates from GFW.

In addition, as the prices of soybeans and beef increased substantially in 2021 (Extended Data Fig. 9), more deforestation for agriculture expansion is likely to continue.

Our study also reveals that annual gross forest area loss rates were high in the El Niño and tropical Atlantic dipole drought years, such as 2005, 2007, 2010 and 2015 (Fig. 3), which may be related to the extensive tree mortality caused by the drought–fire interactions[45]. Over the period 2002–2021, a total of 10.4×10^6 ha forest was burned in ITs/PAs and 55.1×10^6 ha forest in non-PAs and out of these burned forest areas deforestation occurred in 31% for ITs/PAs and 48% for non-PAs (Extended Data Fig. 10). As the Amazon is projected to have more frequent and severe droughts in the future[49], how to manage and protect the remaining intact forests in the ITs/PAs continues to be a major concern.

Summary

The results of this study confirm the critical role of ITs/PAs in forest conservation and raise serious concerns about increased deforestation in the BLA in 2018–2021, especially in the ITs/PAs. The large infrastructure projects[50] and the severe COVID-19 pandemic could further increase deforestation and forest degradation in the ITs/PAs. Both deforestation and forest degradation had severe potential impacts on biodiversity and carbon stock in the BLA[2,51,52]. More attention is urgently needed to strengthen the environmental policies and laws, uphold the existing legal protections and resist the changes being staged in Brazil's National Congress. More investments from the Brazilian government, private companies and international organizations for the expansion and management of ITs/PAs are also critically needed[53]. Further reducing deforestation and forest degradation and supporting forest conservation and Indigenous people could prevent passing the tipping point for the Amazon forest ecosystems to flip into savanna ecosystems[54].

Methods

Annual forest cover data from MODIS forest mapping tool

We published annual forest maps in the BLA during 2000–2017, which were generated by using the time-series MOD09A1 data product (8 d temporal resolution, 500 m spatial resolution) and the forest mapping algorithm[1,2,55]. The MOD09A1 8 d composite selects the best-quality observation within each 8 d period. We used cloud-free MOD09A1 observations based on the quality layer. The forest mapping algorithm is mainly based on the unique features of evergreen forest in terms of vegetation greenness, land surface water content and phenology[1,2,55], specifically, all good-quality observations for an evergreen forest pixel in a year have the enhanced vegetation index (EVI) ≥ 0.2 and the land surface water index (LSWI) ≥ 0. Our annual MODIS forest maps in the BLA had high overall accuracy (>97%) when they were validated by three independent ground reference datasets[1]: (1) 18 5 × 5 km^2 sample blocks from the Global Land Cover Validation Reference Dataset, which was produced from analyses of very high spatial resolution images at 2 m spatial resolution (a total of 1,268 pixels at the 500 m spatial resolution); (2) 416 10 × 10 km^2 sample blocks from the TREES-3 forest and non-forest dataset at 30 m spatial resolution (a total of 262,514 pixels at the 500 m spatial resolution); and (3) 1,991 stratified random sample pixels at 500 m spatial resolution for forest changes generated by visual interpretation of time-series Landsat-5 TM, Landsat 7 ETM+ and Landsat 8 OLI images at 30 m spatial resolution. Our annual forest maps have area and spatial distribution similar to the forest maps derived from microwave images[1], which are less affected by frequent clouds in the Amazon.

In this study, we made a minor improvement to the forest mapping algorithm, as a few pixels were contaminated by clouds or aerosols but may not be detected by the quality layer, which resulted in the EVI values dropping substantially although LSWI and the normalized difference vegetation index (NDVI) did not change much. Thus, we added another criterion to identify evergreen forest, that is, we classified a pixel as evergreen forest when it had >90% cloud-free observations that met the criteria of EVI ≥ 0.2 and LSWI ≥ 0 and had annual minimum LSWI ≥ 0. We analysed MOD091 data from February 2000 to December 2021 and we generated the annual evergreen forest maps from 2000 to 2021. We applied a 3 yr consistency check procedure to reduce the potential error in the annual maps of evergreen forest. We used the annual evergreen forest maps to generate two reports. One report is on forest area by year. In this report, we counted primary forest and secondary forest together as forest (no separation into these two categories). The second report is on 'primary forest' (used 2001 as the reference year) and primary forest area loss. Here, we tracked which year deforestation first occurred for individual pixels. It is possible that some of forest pixels in 2001 were 'reforested or recovered forest'. As we have no data before 2000, we do not know how many pixels there were for this case, thus we kept this caveat during our data analysis and result interpretation.

Annual forest area data from the MapBiomas project

The MapBiomas project was launched in 2015 and generates annual land-cover and land-use maps in Brazil[31]. The algorithm theoretical

basis document (ATBD) of MapBiomas presents the cross-reference of the MapBiomas land-cover and land-use classes with classes from other classification systems, including Food and Agriculture Organization of the United Nations (FAO), Brazilian Institute of Geography and Statistics (IBGE) and National Greenhouse Gas Emissions Inventory. The MapBiomas project (Collection 6) uses six steps to generate the annual land-cover and land-use maps by analyses of surface reflectance data from Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+) and the Operational Land Imager and Thermal Infrared Sensor (OLI-TIRS). The first step is to generate annual Landsat mosaics for specific temporal windows. The second step is to derive the spectral and temporal attributes from Landsat spectral bands to train the Random Forest classifier. The third step is to generate annual land-cover and land-use maps in each biome and cross-cutting theme using the random Forest algorithm (the classification of aquaculture, mining, irrigation, rice and citrus is based on the U-Net convolutional neural network classifier) and training samples. The fourth step is to apply spatiotemporal filters to reduce noise, including gap fill, spatial filter, a 3–5 yr temporal filter, frequency filter and incident filter. The fifth step is to merge the filtered land-cover and land-use maps of each biome and cross-cutting themes and apply the spatiotemporal filters again. The sixth step is the accuracy assessment based on the 75,000 independent samples per year from 1985 to 2018. At the level-1 (forest, non-forest natural formation, farming, non vegetation area and water) classes, the land-cover and land-use maps have 91% global accuracy. We used the level-1 class of forest from the MapBiomas land-cover and land-use maps in this study. For more information about the MapBiomas project see https://mapbiomas-br-site.s3.amazonaws.com/Metodologia/ATBD_Collection_6_v1_January_2022.pdf.

Annual forest cover loss data from the GFW

The 30 m GFW (v.1.8) annual forest cover loss in 2001–2020 was generated by using the decision-tree algorithms and time-series Landsat images acquired during the growing season[29]. In terms of the year in which a pixel experienced forest loss, the data producers reported that they are 75% confident that the forest loss occurred within the stated year and 97% confident that it occurred within the period from 1 yr before to 1 yr after the stated year.

Annual deforestation data from PRODES

The PRODES dataset[28] is generated by Brazil's National Institute for Space Research (INPE) and is the official Brazilian deforestation dataset. PRODES selected high spatial resolution images (tens of metres) from Landsat-5/7/8, China–Brazil Earth Resources Satellite (CBERS-2/2B), Indian Remote Sensing Satellites (IRS-1) and United Kingdom-Disaster Monitoring Constellation-2 (UK-DMC-2) with two criteria: (1) acquisition dates close to the reference date (1 August) and (2) cloud cover as low as possible. Both visual interpretation and digital image classification were used to identify forest and non-forest pixels.

Active fire data during 2002–2021

We used the MODIS active fire data product: MODIS/Terra Thermal Anomalies/Fire 8-Day L3 Global 1 km SIN Grid. We only used nominal and high-confidence observations.

The ITs and PAs data

We downloaded the data for ITs and PAs from the Amazonian Network for Socio-environmental Information (RAISG)[56]. The dataset covers the 1980–2018 period and its attributes include the boundary maps (shapefiles) of individual ITs/PAs, names, years of establishment, governance (by national or state government agency) and management objectives (strict protection or sustainable use; Extended Data Figs. 1 and 2). There are 387 ITs, 146 nPAs and 191 sPAs within the BLA in this study, including the establishment of 145 ITs, 55 nPAs and 72 sPAs after 2002.

The boundary map of BLA

BLA includes nine states: Amazonas, Pará, Mato Grosso, Amapá, Roraima, Acre, Rondônia, Tocantins and Maranhão.

Geospatial data analyses

We used the resultant annual evergreen forest maps, the boundary maps for the BLA, individual ITs/PAs in ArcGIS software to calculate annual forest area by the BLA, ITs and PAs. We also used the evergreen forest map for 2001 as the reference map and calculated the annual gross forest area loss from 2002 to 2021. We grouped individual PAs first by governance—(1) nPAs and (2) sPAs—and second by management objectives—(1) strict protection and (2) sustainable use. We then compared the forest area and deforestation dynamics among these four types of PA.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

MODIS evergreen forest maps are available at Figshare: https://figshare.com/articles/dataset/Annual_evergreen_forest_cover_maps_in_the_Brazilian_Amazon_from_2000_to_2021/21298497. MOD09A1 and MOD14A2 products are available at the US Geological Survey Land Processes Distributed Active Archive Center (LP DAAC): https://lpdaac.usgs.gov/. The PRODES project data are available from INPE: http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes. The GFW product is available from the University of Maryland: https://glad.earthengine.app/view/global-forest-change#dl=1;old=off;bl=off;lon=20;lat=10;zoom=3. The MapBiomas data are available from https://mapbiomas.org/en. The ITs/PAs boundary maps are available from RAISG: https://www.amazoniasocioambiental.org/en/.

Code availability

The Google Earth Engine code for evergreen forest mapping is available at Figshare: https://figshare.com/articles/software/Code_for_evergreen_forest_cover_mapping_in_the_Brazilian_Amazon_version_2_/21298725. Other code for data analysis in R x64 3.4.2, ENVI/IDL 5.2 and Matlab R2017a should be addressed to X.X. (xiangming.xiao@ou.edu).

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Author contributions
X.X. and Y.Q. designed the overall study plan. Y.Q. and X.X. prepared the annual evergreen forest maps. Y.Q., X.X. and F.L. carried out data processing and analysis. X.X., Y.Q. and F.L. interpreted the results. Y.Q. and X.X. drafted the manuscript and F.L., F.S.S., Y.S., E.A. and P.M.F. contributed to the writing and revision of the manuscript.

Competing interests
The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to Xiangming Xiao.

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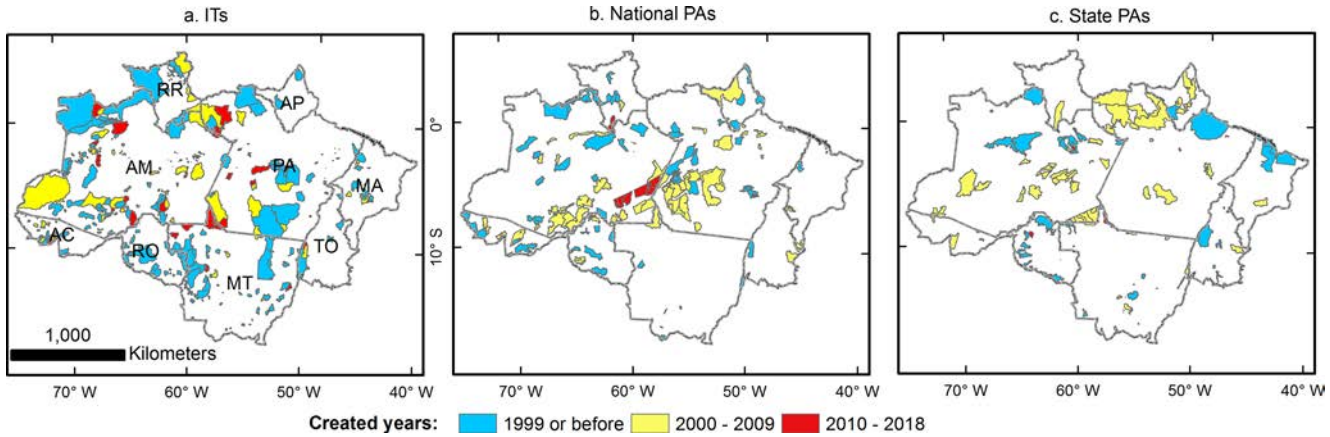

Extended Data Fig. 1 | Spatial distribution of created years for ITs, national PAs and state PAs. (**a**) ITs. (**b**) National protected areas (nPAs). (**c**) State protected areas (sPAs). States in the Brazilian Amazon: PA (Pará), AM (Amazonas), RR (Roraima), MT (Mato Grosso), MA (Maranhão), RO (Rondônia), TO (Tocantins), AC (Acre) and AP (Amapá).

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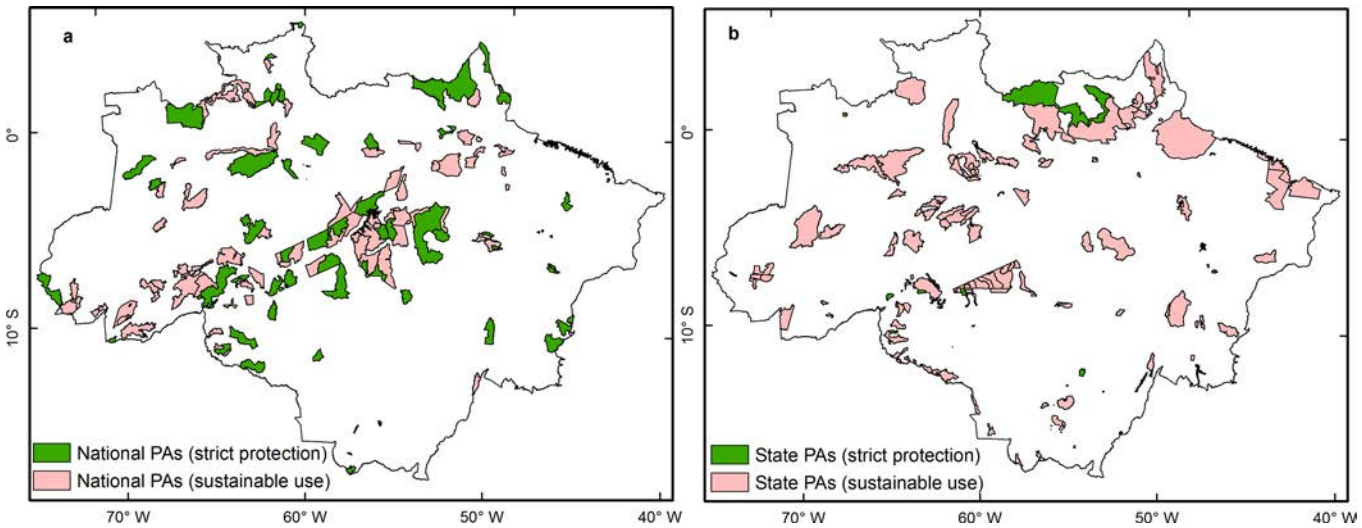

Extended Data Fig. 2 | Spatial distribution of national PAs (strict protection, sustainable use) and state PAs (strict protection, sustainable use). (**a**) National PAs (strict protection, sustainable use). (**b**) State PAs (strict protection, sustainable use).

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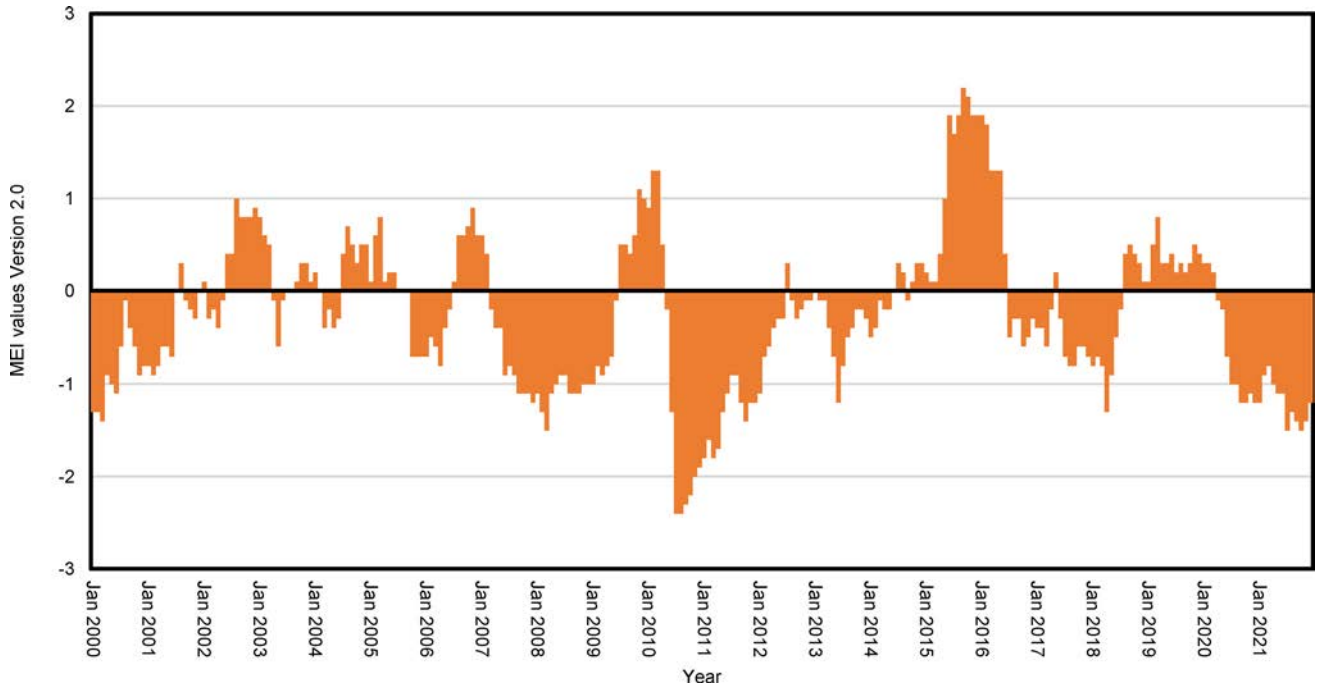

Extended Data Fig. 3 | Multivariate El Niño–Southern Oscillation (ENSO) Index Version 2 (MEI). ENSO index values are provided by the National Oceanic and Atmospheric Administration (NOAA) Physical Sciences Laboratory (PSL).

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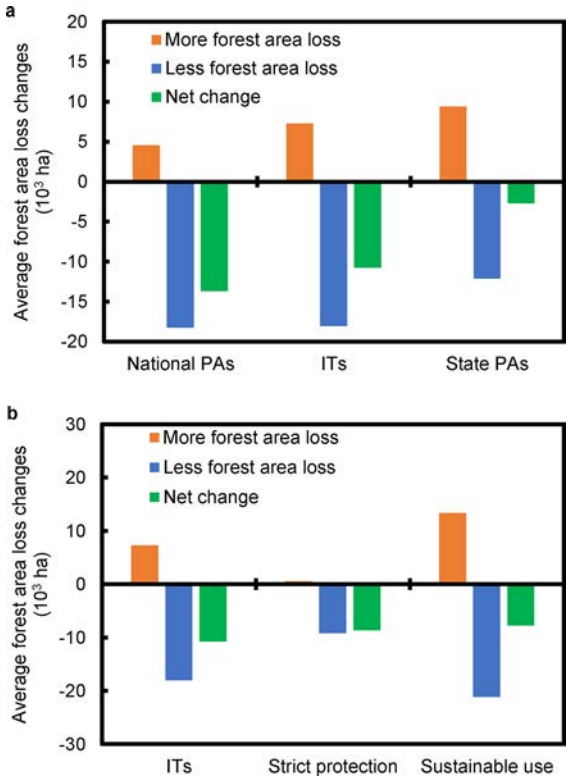

Extended Data Fig. 4 | Changes in average annual forest area loss rates before and after the ITs and PAs establishment. (**a**) The types of ITs and PAs. (**b**) The management categories of ITs and PAs.

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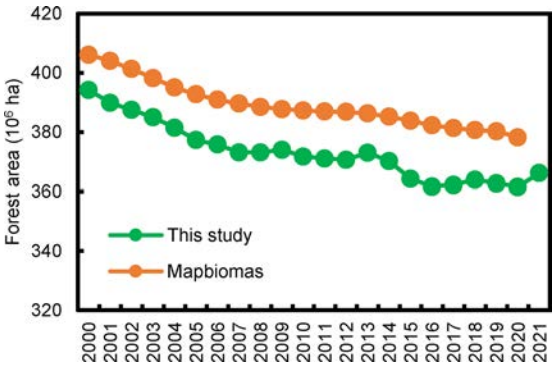

Extended Data Fig. 5 | Interannual changes of forest area estimates in the BLA from 2000 to 2021 by this study and the MapBiomas dataset. The forest area data in 2020 from the MapBiomas dataset is the newest dataset.

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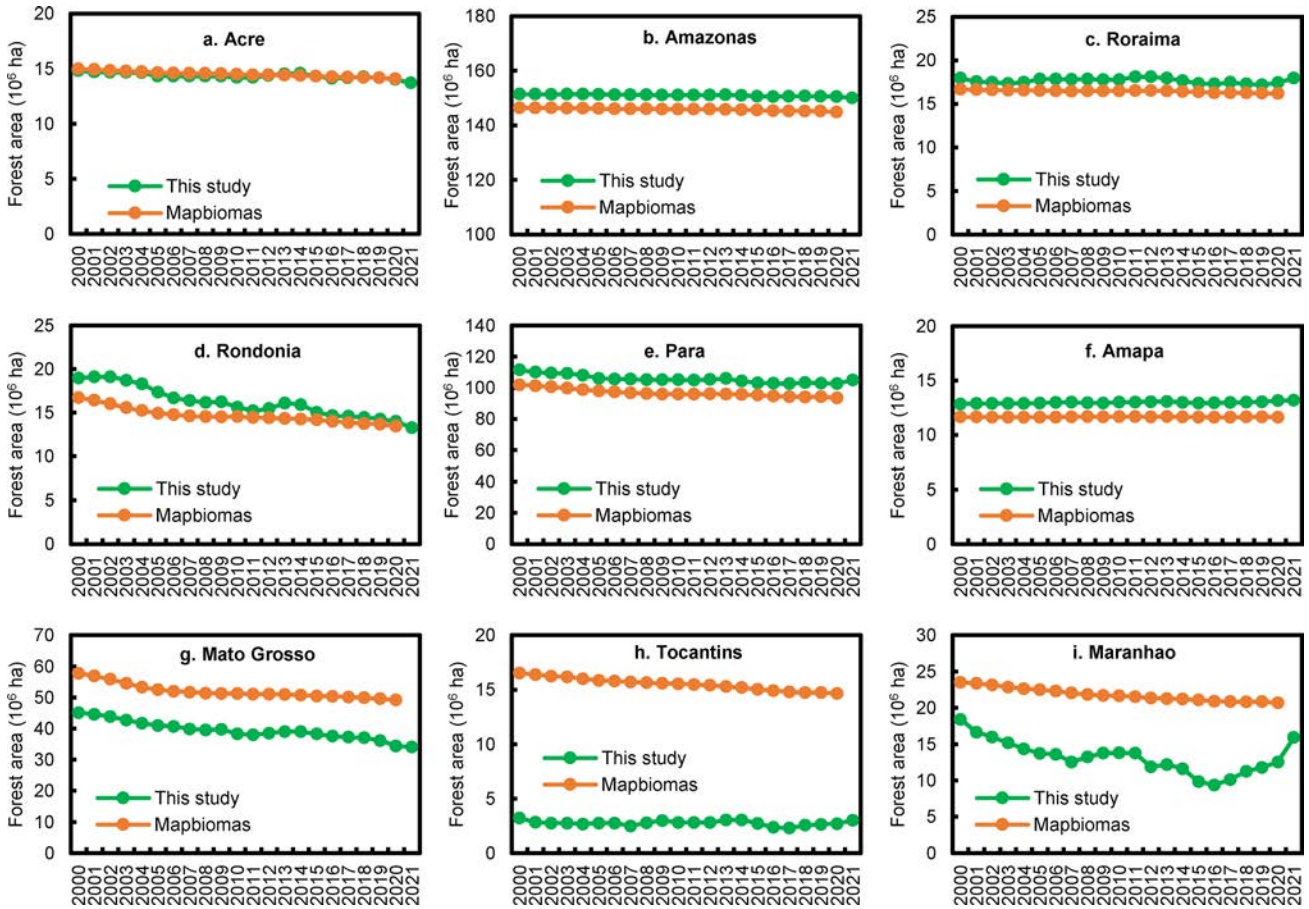

Extended Data Fig. 6 | Interannual changes of forest area estimates in the nine states in the BLA from 2000 to 2021 by this study and the MapBiomas dataset. (**a**) Acre. (**b**) Amazonas. (**c**) Roraima. (**d**) Rondonia. (**e**) Para. (**f**) Amapa. (**g**) Mato Grosso. (**h**) Tocantins. (**i**) Maranhao.

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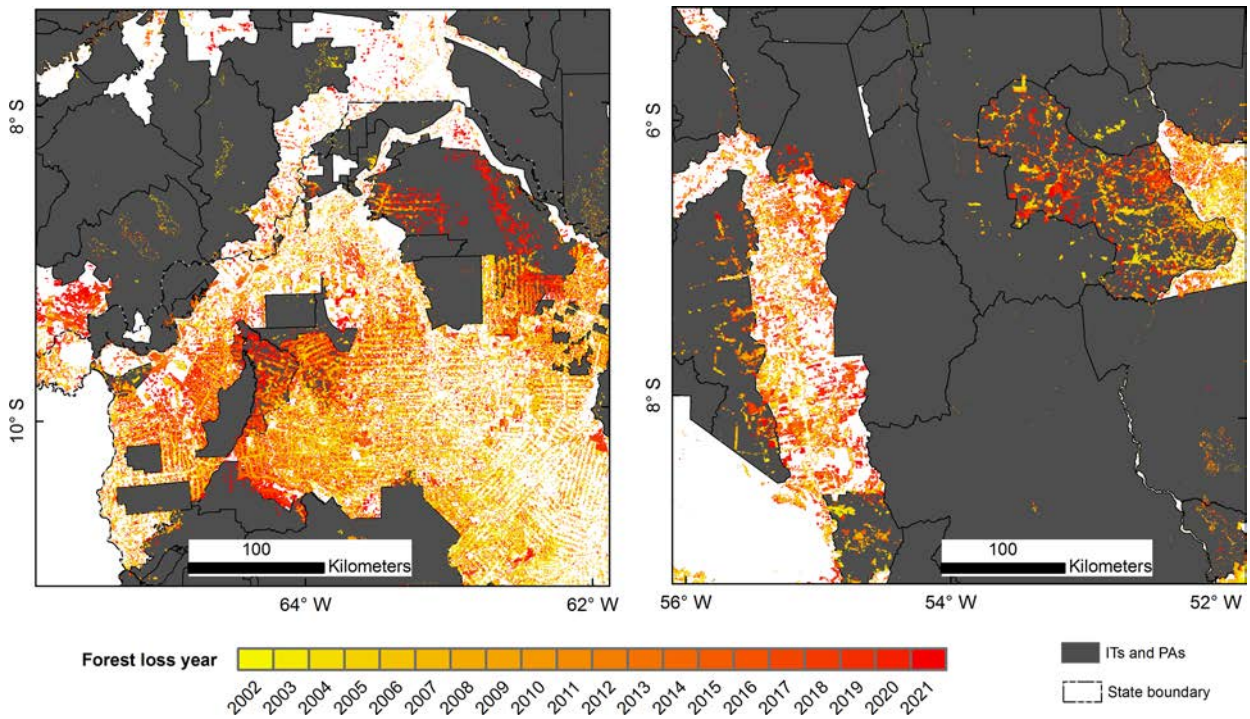

Extended Data Fig. 7 | Two hotspot regions of annual gross forest area losses in the ITs and PAs from 2002 to 2021. Each region covers an area of ~400 km × 400 km.

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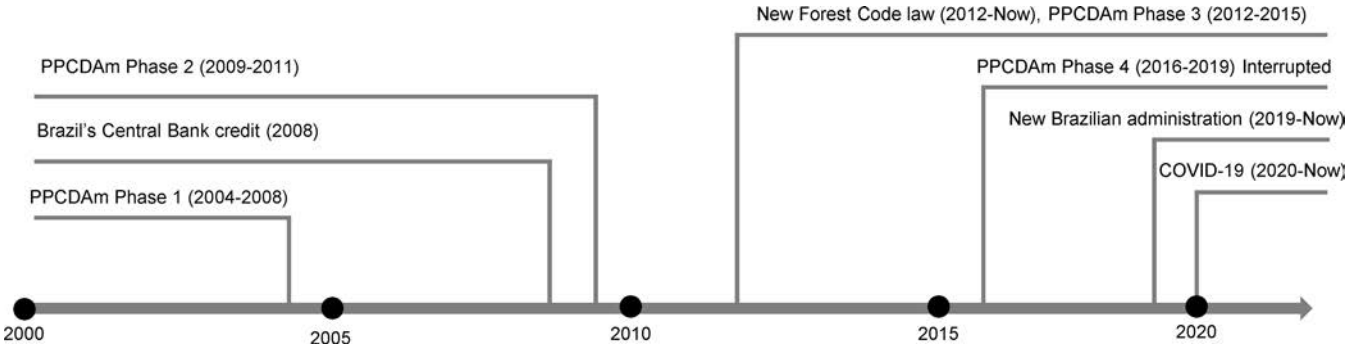

Extended Data Fig. 8 | Major events in laws, policies, governance and COVID-19 from 2000 to 2021, which are related to forest conservation in the BLA. PPCDAm means the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon.

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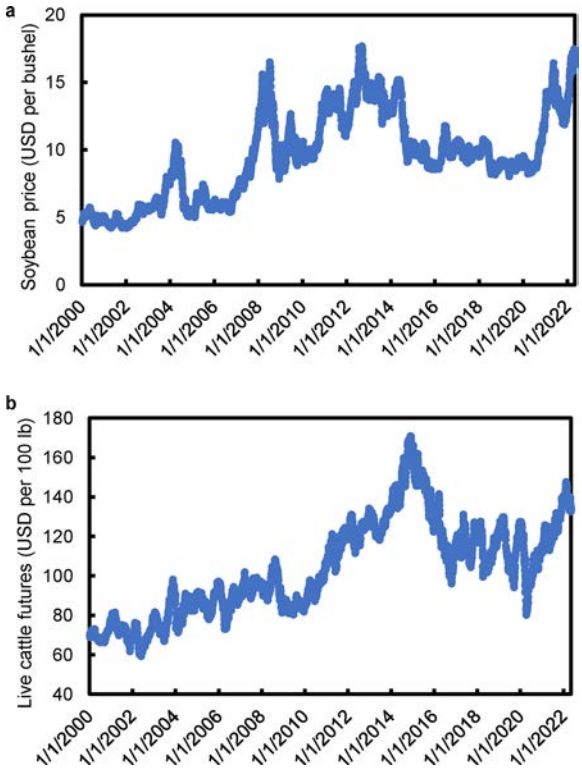

Extended Data Fig. 9 | Interannual changes of soybean price and live cattle futures. (**a**) Soybean price. (**b**) Live cattle futures. The data are provided from https://www.macrotrends.net/.

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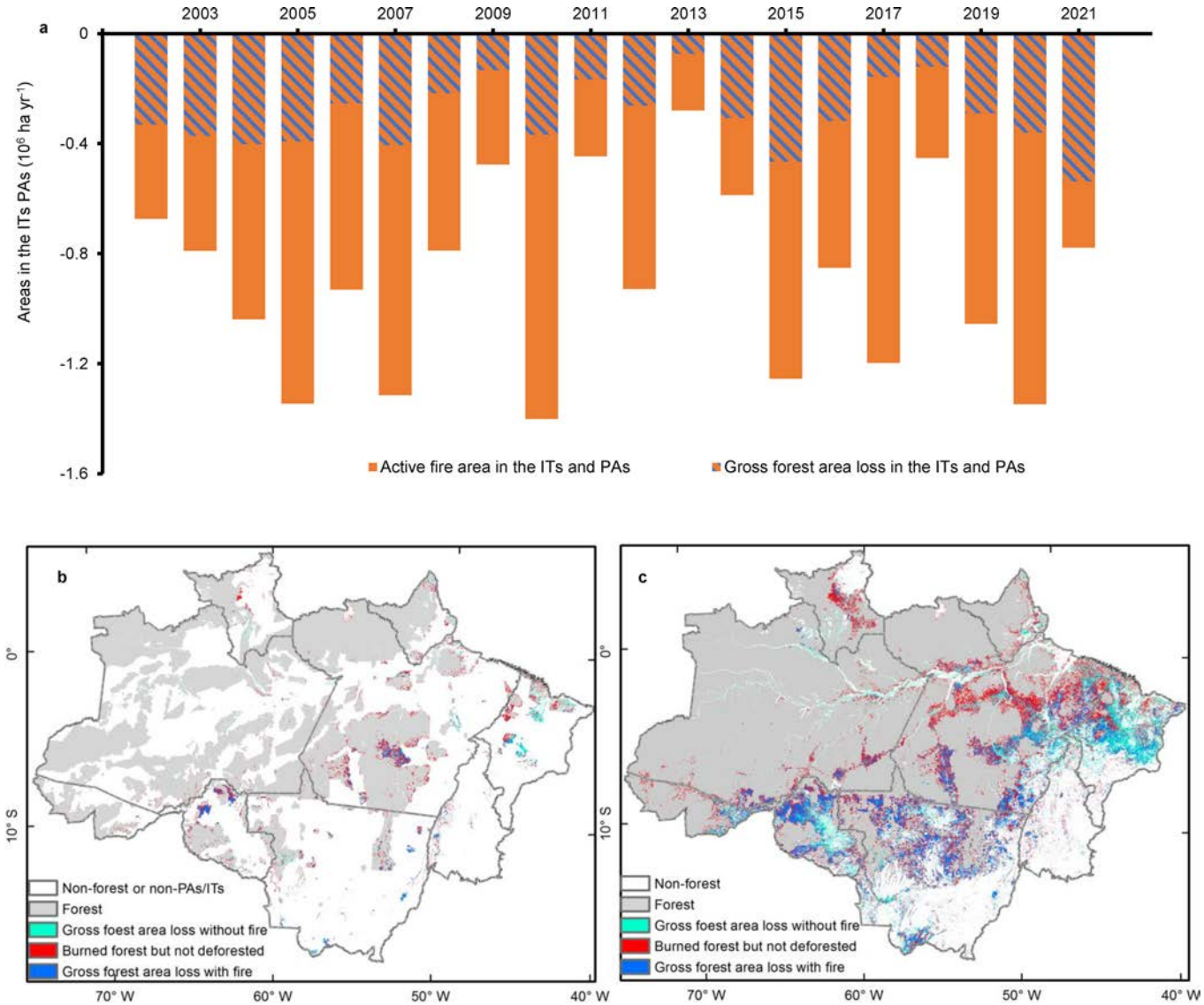

Extended Data Fig. 10 | Forest fire area and gross forest area loss in the ITs/PAs and BLA from 2002 to 2021. (**a**) Interannual changes of forest fire areas and gross forest area loss with fire in the ITs and PAs. (**b**) Forest fire area, gross forest area loss with fire and gross forest area loss without fire in the ITs and PAs. (**c**) Forest fire area, gross forest area loss to fire and gross forest area loss without fire in the BLA.

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Corresponding author(s): Xiangming Xiao

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Reporting Summary

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For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
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☐	☒	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☐	☒	A description of all covariates tested
☐	☒	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☐	☒	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☐	☒	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	The annual forest maps (DOI: 10.6084/m9.figshare.21298497) are generated using Google Earth Engine and MOD09A1 surface reflectance product provided by the United States Geological Survey (https://lpdaac.usgs.gov/products/mod09a1v006/).
Data analysis	We use ArcGIS 10.1 (https://www.arcgis.com/index.html), R x64 3.4.2 (https://www.r-project.org/), ENVI/IDL 5.2 (https://www.harrisgeospatial.com/), and Matlab R2017a (https://www.mathworks.com/products/matlab.html) to carry out data analysis.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

All the data used in this study are freely available to the public. The evergreen forest maps generated in this study are available in the Figshare (DOI: 10.6084/m9.figshare.21298497). MOD09A1 surface reflectance product (https://lpdaac.usgs.gov/products/mod09a1v006/) and MOD14A2 fire data (https://lpdaac.usgs.gov/products/mod14a2v006/) are provided by the United States Geological Survey. The PRODES project data are available from the Instituto Nacional de Pesquisas Espaciais, Brazil (INPE, http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes). The Global Forest Watch forest cover loss product is available from the University of Maryland (https://glad.earthengine.app/view/global-forest-change#dl=1;old=off;bl=off;lon=20;lat=10;zoom=3;). The MapBiomas data is available from

https://mapbiomas.org/en. The boundary maps of protected areas and indigenous territories are available from the Amazonian Network for Socio-environmental Information (RAISG, https://www.amazoniasocioambiental.org/en/).

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	The conflicts between forest conservation and socio-economic development in the Brazilian Legal Amazon (BLA) have persisted for years. Previous studies reported inconsistent results on the effects of the indigenous territories (ITs) and protected areas (PAs) in reducing deforestation. Here we analyzed time-series satellite images and qualified annual forest area from 2000 to 2021 in the BLA, ITs, and PAs with different governance and management. We find that the areas classified as ITs/PAs had increased substantially since 2001 and covered 52% of forest area in the BLA by 2021. ITs/PAs accounted for only 5% of the total net forest area loss during 2000-2021 and 12% of the total gross forest area loss during 2001-2021. In terms of institution and governance, annual gross forest area loss rate after the years of establishment was reduced by 36% for national PAs, 30% for ITs, and 5% for state PAs. In terms of management objectives, annual gross forest area loss rate after the years of establishment was reduced by 48% for the PAs with "strict protection" and 11% for the PAs with "sustainable use". ITs/PAs had increased gross forest area loss in 2018-2021, and the increased rate was two times of the non-protected areas. Our findings reveal the substantial progress and the critical role of ITs/PAs in forest conservation and call for urgent actions and investment to strengthen ITs/PAs, reverse Brazil's weakened forest policies, and tackle the negative impacts of COVID-19 pandemic in the ITs/PAs.
Research sample	This study uses satellite image data covering the entire study area.
Sampling strategy	This study uses satellite image data covering the entire study area.
Data collection	This study uses MOD09A1 surface reflectance data product and MOD14A1 fire data product.
Timing and spatial scale	This study uses satellite image data at 500-m spatial resolution over the period of 2000-2021 in the Brazilian Legal Amazon.
Data exclusions	This study uses all satellite images and identifies good-quality observations.
Reproducibility	This study can be readily reproduced, as (1) satellite images are available to the public and (2) all the mapping algorithms are published.
Randomization	This study uses all the satellite images in the study area and over the study period.
Blinding	This study analyzes satellite images, thus blinding is not needed.

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Human research participants
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging