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LETTER

Marked non-compliance with deforestation embargoes in the Brazilian Amazon

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Abstract

Advances in monitoring capacity and strengthened law enforcement have helped to reduce deforestation in the Brazilian Amazon since the early 2000s. Embargoes imposed on the use of deforested land are important instruments for deterring deforestation and enabling forest recovery. However, the extent to which landowners respect embargoes in the Brazilian Amazon is unknown. In this study, we evaluated the current recovery status of embargoes due to deforestation imposed between 2008 and 2017 to conduct the first large-scale assessment of compliance with embargo regulations. We observed forest recovery in only 13.1% (±1.1%) of embargoed polygons, while agriculture and pasture activities were maintained in 86.9% (±1.8%) of embargoed polygons. Thus, landowners openly continue to disrespect environmental legislation in the majority of embargoed areas. We attribute the marked non-compliance observed to limited monitoring of embargoed areas, as environmental agents seldom return to verify the status of embargoed lands after they have been imposed. Recent advances in remote sensing provide low-cost ways to monitor compliance and should form the basis of concerted efforts to ensure that the law is observed and that those responsible for illegal deforestation do not benefit from it.

1. Introduction

Until recently, Brazil had been considered a global example in terms of its environmental policies, being recognized for its dedicated programs to reduce deforestation, particularly in the Amazon forest (Gibbs *et al* 2015, 2016, Carvalho *et al* 2019). Foremost among these was the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm). This plan aimed to reduce deforestation rates in the Brazilian Amazon through a set of integrated actions related to land planning, monitoring and control as well as fostering sustainable productive activities (IPEA *et al* 2011, Assunção *et al* 2015). Its implementation led to a drop in deforestation from 27 800 km^2 in 2004 to 4600 km^2 in 2012, due in part to enhanced command and control capability (Assunção *et al* 2013, 2015). Since 2012, deforestation in the Brazilian Amazon has increased steadily, although it is still substantially lower than peak deforestation rates in the early and mid-2000s. The rise in deforestation observed since then (INPE 2021) indicates a loss of efficiency of the PPCDAm and may be due to the weakening of enforcement measures, which include fining and incarceration of perpetrators of environmental crimes (Vale *et al* 2021).

The Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) is the main agency responsible for applying environmental legislation in Brazil. Upon confirmation of illegal deforestation, IBAMA can fine the landowner or embargo the deforested area (Moraes *et al* 2018). The embargo is an administrative measure that aims to prevent the beginning or continuation of productive activity (for example, pasture/agriculture) on illegally cleared land. It aims to promote forest regrowth to recover the deforested or degraded area (Brasil 2008). If an embargo is disrespected, the infringer is fined again. Whoever acquires, handles, transports or commercializes goods produced in an embargoed area may also be fined and the goods confiscated (Schmitt 2015). Despite the legislation in place, the extent to which landowners comply with deforestation embargo restrictions across the Brazilian Amazon is unknown. The only study to date on this issue was conducted by Moraes *et al* (2018) in four municipalities in the eastern part of Pará, from 2004 to 2016. Of the 144 embargoes considered in that study, 60% continued to be used for pasture, 10% for agriculture, and only 30% were found to be under natural regeneration. However, to truly understand the effectiveness of embargo measures, scaled-up studies which consider the broader Brazilian Amazon are necessary.

In this study, we consider 6972 embargoes imposed due to deforestation in the Brazilian Amazon between 2008 and 2017 which met the minimal area requirements for remote sensing analysis (6.25 ha, equivalent to the area threshold used for national deforestation estimates (INPE 2021)). Of this total number, we sampled 1289 embargoes spanning four strata corresponding to different area thresholds (see section 2) and used available Landsat satellite imagery to discriminate the land cover of embargoed areas between 2017 and 2019 to evaluate compliance with embargo legislation across the Brazilian Amazon. We selected these 3 years to analyze because most of the deforestation embargoes happened before 2017 and thus they provide a full picture of current compliance.

1.1. Results

The vast majority (73%) of deforestation embargoes applied during our study period were located in what is known as the Brazilian Arch of Deforestation (figure 1), reflecting the distribution of deforestation in the Brazilian Amazon. This region extends from the state of Maranhão in the eastern Amazon along the southern rim of Amazonia to the state of Acre in the Western Amazon. Although embargoes can be found distributed across all states in Brazilian Amazonia (figure 1(a)), the majority (>80%) are located in the states of Mato Grosso (2346 embargoes, 33.6% of all embargoes), Pará (1843 embargoes, 26.4% of all embargoes) and Rondônia (1467, 21.0% of all embargoes). Moreover, almost all large (>600 ha in area) embargoes have been applied in these three states, which have historically been responsible for most of the deforestation in the Brazilian Amazon (INPE 2021).

The number of deforestation-related embargoes applied annually has changed markedly over time. Following a decline in embargoes applied between 2008 and 2009, the number of deforestation-related embargoes increased steadily, reaching a peak in 2012 and 2013 (figure 1(b)). Over 40% (2819/6972) of all embargoes considered in this study period were imposed in those 2 years. Since 2013, the number of deforestation embargoes applied fell markedly. In 2014, the number of embargoes applied corresponded to only a third of the number applied in the previous year. The last 3 years considered in this study were characterized by very low application of deforestation-related embargoes. In these years, only 82 embargoes were applied, representing only 1.2% of all embargoes imposed over the entire study period (2008–2017). The declines over time in number of embargoes applied occurred across all size classes considered—i.e. the declines were not linked to embargoes being applied preferentially to large land areas over time. This corroborates other findings (Vale *et al* 2021) that have demonstrated a weakening of environmental protection efforts over time.

Embargoes are imposed to prevent or stop damage to the forest and allow forest recovery in deforested or degraded areas. However, we find that only 13.1% of the embargoes sampled comply with the legislation. In >85% of embargoed areas, non-forest land uses are observed well after the embargoes are imposed, with 80.9% of embargoes identified as pasture and a further 6.0% as agriculture between 2017 and 2019. Extensive cattle ranching is the major vector for deforestation in the Amazon (Almeida *et al* 2016) due is its low cost and low economic risk (Rivero *et al* 2009) and our results suggest that the application of embargoes is of little effect in deterring illegal deforestation for pasture. Our results show that non-compliance with deforestation embargoes in the Brazilian Amazon is markedly worse than reported by Moraes *et al* for a small number of municipalities in the state of Pará (Moraes *et al* 2018). We found that this general pattern was consistent across sampled years—e.g. 14.9 $\pm$ 1.1% of embargoes sampled in 2017 were under forest regrowth compared to 13.1 $\pm$ 1.1% in 2019. Furthermore, we find little evidence of changes in the degree of compliance with deforestation-related embargoes over time. We compared sampled polygons embargoed before 2010 ($n = 418$) with those embargoed post-2010 ($n = 871$) and found that the proportion of polygons exhibiting forest recovery was very similar in both periods, 12.3% and 14.8% respectively, indicating that low compliance is a long-term historical problem.

The degree of compliance with environmental legislation did not vary markedly across Amazonian states indicating that non-compliance is a widespread and generalized problem. Across almost all Amazonian states, most (>75%) embargoed areas were found to be under pasture (figure 2), reflecting its importance as a driver of deforestation across the Amazon. In Mato Grosso, a substantially greater proportion of embargoes (20%) were found to be under

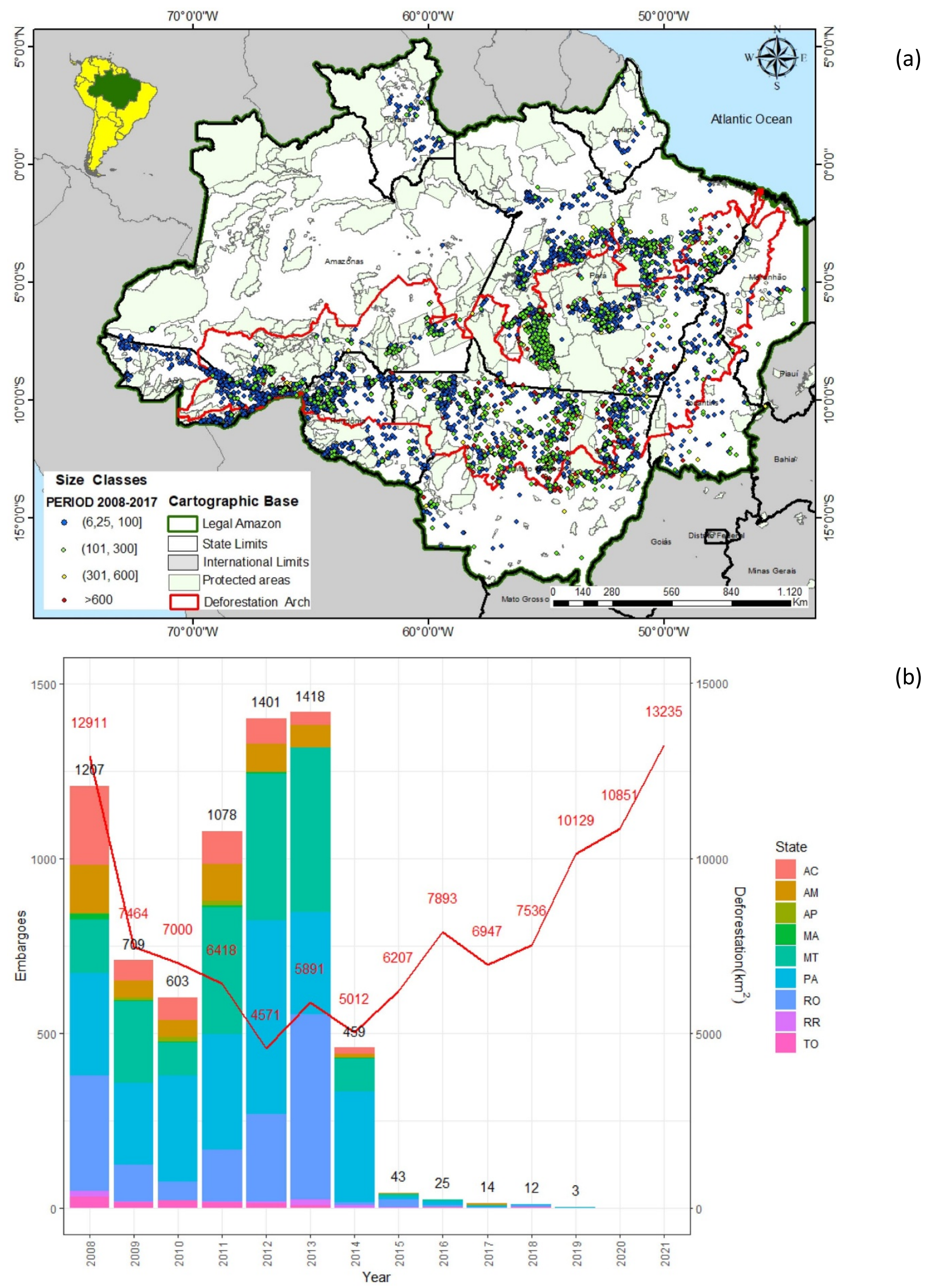

Figure 1. Deforestation-related embargoes. (a) Spatial distribution of deforestation-related embargoes imposed between 2008 and 2017 in the Brazilian Legal Amazon. The solid red outline denotes the boundaries of the arch of deforestation, which most of the embargoes were issued. (B) Temporal distribution of deforestation-related embargoes imposed between 2008 and 2017 per state (Acre [AC], Amazonas [AM], Amapá [AP], Maranhão [MA], Pará [PA], Rondônia [RO], Roraima [RR], and Tocantins [TO]) and deforestation rate (km^2) estimated by PRODES between 2008 and 2021.
Data source: (IBAMA 2020, IBGE 2021, INPE 2021)

agriculture compared to other states (5%). This state is Brazil's largest soy producer and the higher number of embargoed lands found to be under agricultural use reflects this.

1.2. Discussion and conclusions

We carried out the first large-scale assessment of embargoes related to deforestation in the Brazilian Amazon and found that: (a) the number of

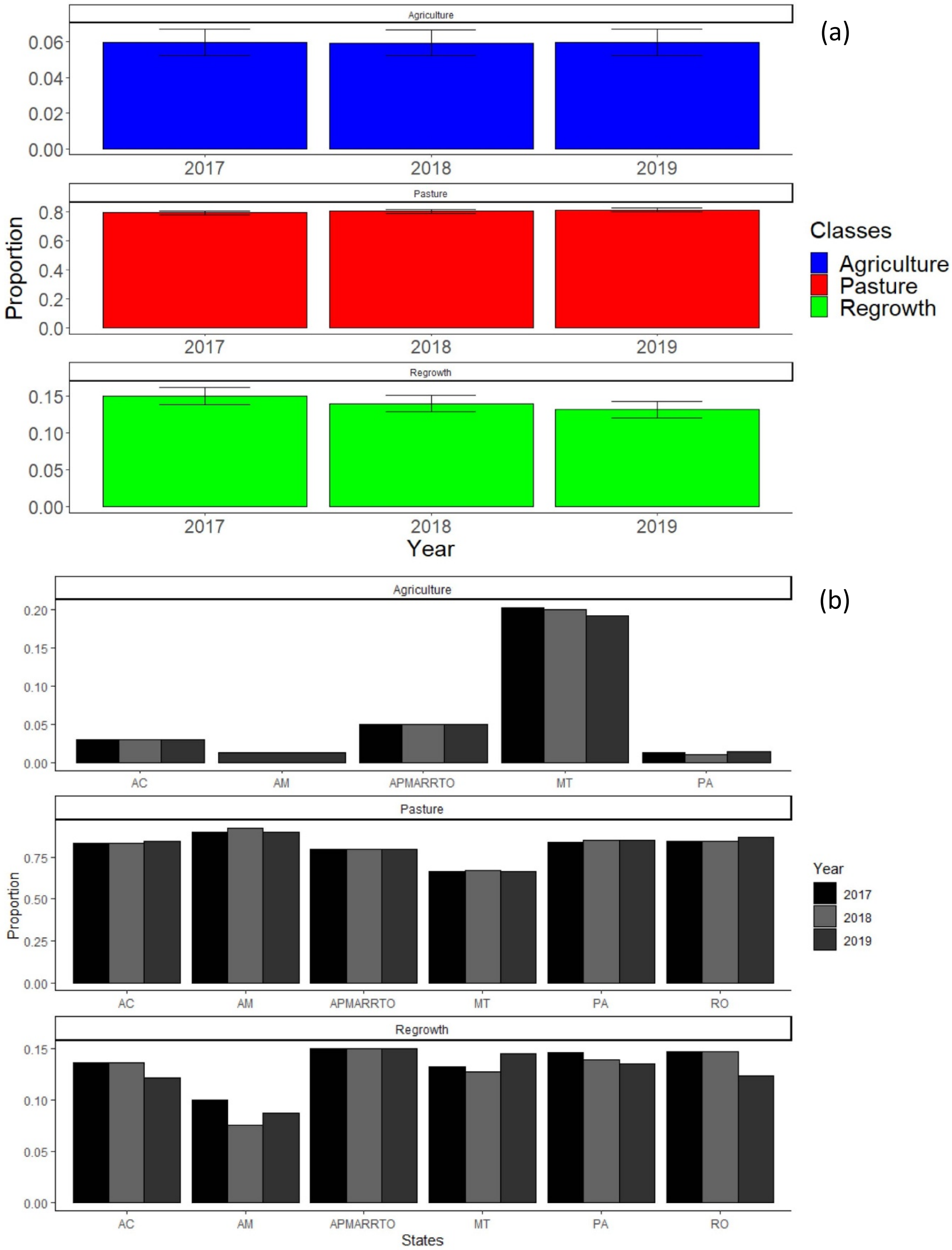

Figure 2. Proportion of embargoed areas classified as agriculture, pasture, and regrowth between 2017 and 2019; (a) for all sampled embargoes; (b) per state (Acre [AC], Amazonas [AM], Amapá, Maranhão, Roraima, and Tocantins [APMARRTO], Pará [PA], and Rondônia [RO]).

embargoes issued has declined sharply since 2013 and (b) the level of compliance with embargo legislation is very low (<13%). The first point, the reduction of embargoes, may be associated with an overall weakening of environment monitoring capacity, resulting in increasing levels of illegal activities such as clandestine gold mining, animal trafficking, land grabbing, biopiracy, and violence in rural areas (Barbosa *et al* 2021, Hochstetler 2021, Simões Agapito *et al* 2022). Previous work has shown that levels of field surveillance and monitoring are strongly related to deforestation. Notably, the number of embargoes applied was greatest when field surveillance operations were greatest (2004–2014) (Assunção *et al* *2013*). The marked decline in issued embargoes may therefore directly reflect reduced levels of field surveillance over time by IBAMA. Also, it may reflect a change in IBAMA's *modus operandi*, which has shifted towards targeting major sources of pressure, with regard to the most sensitive links in the production chains that used deforestation, such as livestock and soy (Rajão *et al* 2020). This may be due to an increasing strain on IBAMA's human resources. For example, the number of Environmental Inspection Agents (Agentes Ambientais Federais), civil servants deployed in the field to evaluate the occurrence of environmental crimes, suffered a 43% reduction from 2010 to 2019, from 1311 to 743 agents (Borges 2020). There have also been changes in key management posts responsible for national law enforcement efforts (Schmitt 2015). Ultimately, the reduced application of embargoes means that offending landowners have been increasingly able to avoid economic sanctions arising from deforestation and have been allowed to keep using the land where the environmental damage occurred.

The second finding (low compliance with embargo law) is likely due to limited monitoring of compliance following application of embargoes. The large reduction in IBAMA field agents in recent years (55% decline over a 10 years period (Borges 2020)) has made this task even more difficult. Even though landowners who choose not to comply with embargoes imposed upon them may face the prospect of further penalties, the low likelihood of further punishment means that the embargoes are ultimately inefficient in deterring deforestation in the Brazilian Amazon. The difficulty in enforcing payment of fines and in implementing market restrictions for products extracted illegally from embargoed areas contributes to the increase of impunity and reduction of the effect of the accumulated work of the inspection in the last decade (Schmitt 2015). The lack of compliance may also be facilitated by a perception by landowners of weakening government environmental policy. In recent times, the pressure on Congress to change regulatory legislation such as the Federal Forest Law (1965), environmental licensing, reduction of indigenous lands and other protected areas, including amnestied fines for deforestation (Soares-Filho *et al* 2014, Barbosa *et al* 2021) has intensified. This may have created a conducive environment to disrespecting environmental law (Simões Agapito *et al* 2022) including compliance with embargoes.

The relationship between land use and land cover change in the Amazon and how landowners respond to the global commodities market has been well documented (Morton *et al* 2006, Barona *et al* 2010, Latawiec *et al* 2017, Arvor *et al* 2018, Garrett *et al* 2018, Zu Ermgassen *et al* 2020) and it may be that these markets may also influence degree of compliance with embargo legislation. Despite our observation of reduction in the regrowth proportion over time, our results do not allow direct evaluation of the relationship between commodity prices and the degree of compliance with embargo legislation.

Although other instruments exist for deterring deforestation, including prohibition of the commercialization of products arising from illegal deforestation (e.g. SEMAS decree IN 01/2008 (SEMAS-PA 2008)), restricted access to credit to companies commercializing beef arising from deforested areas (e.g. TAC da Carne (Gibbs *et al* 2016)) and agreements such as the soy moratorium whereby companies agree not to buy products from deforested areas (Rudorff *et al* 2011, Gibbs *et al* 2015), embargoes constitute an important mechanism for curbing deforestation. While the legal framework is in place (Federal Decree 6514/2008 (Brasil 2008)), improvements in the efficiency of the implementation of embargoes are needed. Better implementation would afford Brazil a greater chance of meeting its deforestation and climate change mitigation targets, including its pledge to end illegal deforestation by 2030 (Brazil 2016). Remote sensing tools can assist in monitoring embargoed areas and can even be incorporated into near real-time monitoring systems such as near real-time deforestation detection system (DETER) (Diniz *et al* 2015), facilitating the work of IBAMA's agents in monitoring embargoes, setting up operations, and establishing appropriate penalties for those who do not respect the embargoes.

2. Methods

2.1. Selection of embargoes for analysis

The coordinates of embargoed polygons were obtained from the IBAMA public database (IBAMA 2020). As our goal was to evaluate forest recovery in embargoed areas, we applied an area filter such that embargoed polygons were only included in the analysis if they were >6.25 ha in area. This is the area threshold that is used in Brazil's PRODES deforestation monitoring system for a patch of land to be counted as deforestation and is considered to be a minimal viable area for the photointerpretation of land cover. As our focus was on assessing compliance with legislation passed in 2008 (Decree No. 6514, published in 23 July 2008 (Brasil 2008)), we further only considered embargoes imposed post-2008 in our analysis. This law describes a host of environmental crimes as well as the penalties associated with them. Consequently, the filter makes it possible to compare embargoes, as they are all associated with the same legislation. As embargoes can be issued for a host of environmental crimes (e.g. illegal fishing), we restricted our analysis to embargoes directly associated with deforestation or forest degradation (table 1).

Filtering out non-deforestation related embargoes resulted in a total of 6989 embargoed polygons >6.25 ha. However, geographical positional errors meant that some of the embargoes could not be used in the study, resulting in a total of 6972 embargoes. In order to estimate the degree of compliance with environmental legislation we used a stratified sampling for proportions following the recommendation of Cochran (1977). These were divided into four area

Table 1. Environmental infractions related to illegal deforestation outlined in Federal Decree 6514 which form the basis of embargoes considered in this study.

Summary infringement	Article	Description	Fine value
Deforestation in areas of permanent preservation	43	Destruction or damage to forests or natural vegetation in an area considered to be of permanent preservation, without government authorization, when required, or in disagreement with that obtained.	R$ 5000.00–50 000.00 per hectare or fraction.
Deforestation in an unauthorized area	49	Destruction or damage to forests or any type of natural vegetation, subject to special preservation, not subject to authorization for harvesting or suppression.	R$ 6000.00 per hectare or fraction.
Deforestation without authorization	50	Destruction or damage to forests or any type of natural vegetation or planted native species, subject to special preservation, without authorization or license from the competent environmental authority.	R$ 5000.00 per hectare or fraction.
Deforestation in legal reserve areas (RL)	51	Destruction, deforestation, damage or harvesting of forest or any type of natural vegetation or planted native species, in a legal reserve or forest easement area, in the public or private domain, without prior authorization from the competent environmental agency or in disagreement with the one granted.	R$ 5000.00 per hectare or fraction.
Deforestation without authorization outside RL	52	Clearing of forests or other natural formations, outside the legal reserve, without authorization from the competent authority.	R$ 1000.00 per hectare or fraction.
Logging or other types of harvesting in forest in legal reserve areas (RL).	53, and sole paragraph	Logging, harvesting or other damage of forests on any type of natural vegetation or planted native species, located outside a registered legal reserve area, in the public or private domain, without prior approval from the competent environmental agency or in disagreement with the one granted. The same penalties apply to those who fail to comply with mandatory forest regeneration.	R$ 3000.00 per hectare or fraction, or per unit, stereo, kilo, mdc or cubic meter.

Source: (Brasil 2008)

Table 2. Sub-sampling of deforestation embargoes: total number of polygons (N), sampled polygons (n), total embargoed area, and total sampled area, both in hectares (ha).

Strata	N	n	Total area (ha)	Sampled area (ha)
(6.25, 100]	5391	543	175 035.8	16 548.3
(100, 300]	924	270	159 385.3	53 200.7
(300, 600]	339	170	142 189.7	71 179.7
>600 ha	317	306	456 032.5	431 097.7
Total	6972	1289	932 643.3	572 026.1

classes (6.25, 100 ha]; (100, 300 ha]; (300, 600 ha]; >600 ha. For each stratum, we randomly sampled the following proportions of embargoed polygons: 10%, 30%, 50%, and 90% randomly (table 2) for subsequent photointerpretation.

2.2. Land use and land cover of embargoed polygons

After sampling the filtered embargo polygons, we calculate the centroid for each polygon. The centroid of each embargoed polygon was individually photointerpreted using the time series of Landsat satellite images and high spatial resolution images available on the Google Earth platform as reference data, the result of the interpretation of this centroid was extrapolated to the embargo polygon. The integration of high-resolution and Landsat data provided valuable information and allowed the direct assessment of changes in land cover in each sample.

To simplify the application of Landsat data, we employ the Landsat Analysis Ready Data (ARD) products produced by the automated image processing system Global Land Analysis and Discovery (GLAD). The essence of the GLAD ARD approach is to convert individual Landsat images into a time series of 16 d normalized surface reflection composites with minimal atmospheric contamination. The Landsat data processing algorithms have been described at length in several previous studies (Hansen *et al* 2008, Potapov *et al* 2019, 2020).

We extracted Landsat ARD time series information using two complementary methods. First, we

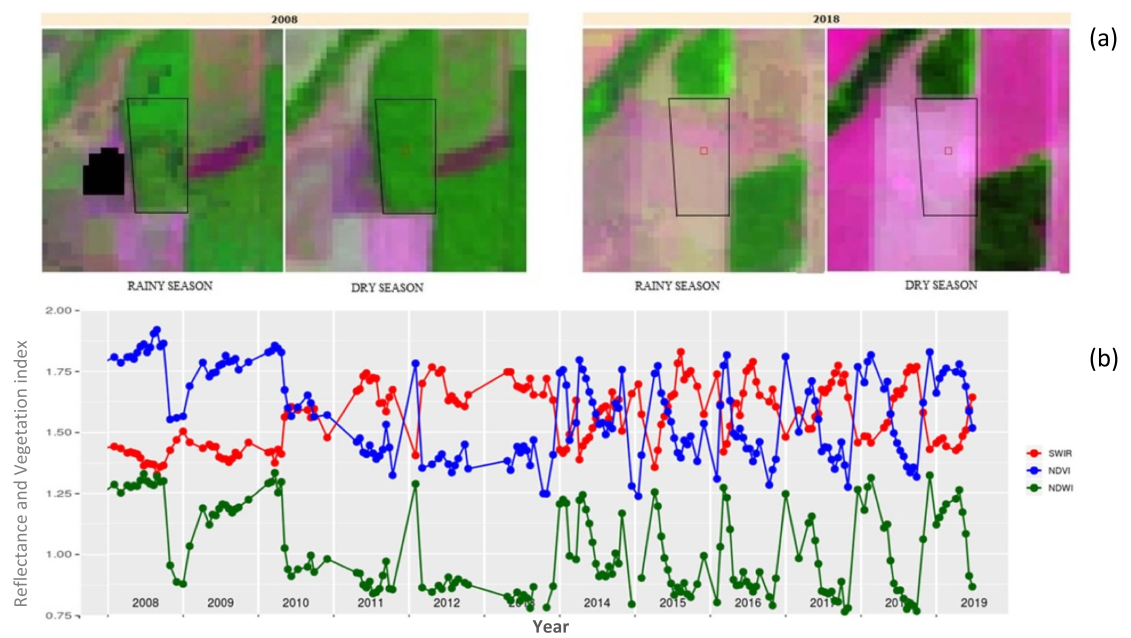

Figure 3. (a) Landsat-5 image for 2008 (left) and Landsat-8 image for 2018, with the black polygon depicting the embargoed area. (b) Vegetation index and reflectance (added 1) time series profile of the center of a selected polygon that was deforested in 2008 and subsequently converted to agriculture.

extracted and visualized the dynamics of the surface reflectance for a selected sample (which corresponds to a single pixel of Landsat data). For that, we used all the reflectance values of the surface in 16 d of the year 2008 to present for each sample. Using the ARD data quality layer, all observations with clouds or cloud shadows were removed. From the remaining observations in a clear sky, we extracted the reflectance value from the normalized surface of the medium infrared band and calculated two indices: the normalized difference vegetation index (NDVI) and the normalized difference water index (NDWI). We added the NDWI, and shortwave infrared (SWIR) profiles because it provides complementary information about vegetation water stress (NDWI) and percentage of soil (SWIR) in the area. The joint analysis of NDVI, NDWI, and SWIR helped to better differentiate pasture from regeneration. These are calculated as follows:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - R}{\mathrm{NIR} + R} \tag{1}$$

$$\mathrm{NDWI} = \frac{\mathrm{NIR} - \mathrm{SWIR}}{\mathrm{NIR} + \mathrm{SWIR}} \tag{2}$$

where NIR, R and SWIR are band reflectances in the near infrared, red, and shortwave infrared respectively. NDVI and NDWI values range from -1 to $+1$. Negative values of NDVI represent clouds and around zero they represent bare soil or without vegetation while positive values denote vegetation.

The second method of data extraction involved creating a time series of multispectral composites that exhibit soil cover properties for each year, from 2008 to 2019. In addition to a sample, each composite includes information about the landscape (within the 1.2×1.2 km window) to facilitate image interpretation. For each year, the rainy season was defined from October of the year prior to March of the current year and the dry season from April to September of the current year. These compositions were made by obtaining the best pixel, according to the methodology described by (Potapov *et al* 2012, 2019).

The visual interpretation of the polygons using the time profiles of vegetation indices was performed based on prior knowledge of the time patterns of the main targets studied in the deforested polygons, which are pasture, agriculture and regeneration. The three classes analyzed in this study were interpreted taking into account satellite images and graphical inspection of NDVI, NDWI, and SWIR behavior following approaches used in other studies (Adami *et al* 2012, Almeida *et al* 2016, Spera *et al* 2014). Figure 3, is an illustrative embargoed polygon analyzed in the state of Mato Grosso. The satellite image shows an area that had forest in 2008 (left) and on the right shows the embargoed polygon with the vegetation completely removed for application in agriculture. Figure 3(b) shows the historical series of the sample, in which NDVI values decrease from 2008, indicating a significant loss of forest canopy due to the deforestation process, showing an agricultural land cover in 2019.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

The embargoes data can be accessed at https://servicos.ibama.gov.br/ctf/publico/areasembargadas/ConsultaPublicaAreasEmbargadas.php.

The remote sensing data can be accessed at https://glad.umd.edu/ard/home.

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Conflict of interest

The authors have no conflicts of interest to declare.

Ethics statement

All authors have seen and agreed with the contents of the manuscript and there is no financial interest to report.

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