Marked non-compliance with deforestation embargoes in the Brazilian Amazon

Verissimo César Sousa da Silva*, Ima Celia Guimaraes Vieira, David Galbraith, Peter Potapov, Sérgio Luiz de Medeiros Rivero, Aline Maria Meiguins de Lima, Marcia Aparecida da Silva Pimentel and Marcos Adami

Environmental Science Graduate Program, Universidade Federal do Pará, Belém, PA, Brazil
Museu Paraense Emilio Goeldi, Belém, PA, Brazil
School of Geography, University of Leeds, Leeds, WY, United Kingdom
Department of Geographical Sciences, University of Maryland, College Park, MD, United States of America
Universidade Federal de Campina Grande, Campina Grande, PB, Brazil
Divisão de Observação da Terra e Geoinformática, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, SP, Brazil

* Author to whom any correspondence should be addressed.
E-mail: marcos.adami@inpe.br

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 km² in 2004 to 4600 km² 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

© 2022 The Author(s). Published by IOP Publishing Ltd
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 1a), 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 1b). 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 embargoed areas 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 to 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 ± 1.1% of embargoes sampled in 2017 were under forest regrowth compared to 13.1 ± 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...
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
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

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]).
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 amnesty 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. Clearing of forests or other natural formations, outside the legal reserve, without authorization from the competent authority. | 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. 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$ 1000.00 per hectare or fraction.                 |
| Logging or other types of harvesting in forest in legal reserve areas (RL). | 53      | 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. | 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
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:

$$\text{NDVI} = \frac{\text{NIR} - R}{\text{NIR} + R}$$

$$\text{NDWI} = \frac{\text{NIR} - \text{SWIR}}{\text{NIR} + \text{SWIR}}$$

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 embargoed 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.

Acknowledgments

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES)—Finance Code 001. I C G V was supported by CNPq (National Council for Scientific and Technological Development) Grant 314215/2021-2. D G acknowledges support from the NERC-funded ARBOLES project (NE/S011811/1). M A thanks CNPq (Grant 306334/2020-8) and Royal Society Newton Advanced Fellowship (NRF/180405).

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.

ORCID iDs

Ima Celia Guimaraes Vieira
https://orcid.org/0000-0003-1233-318X
David Galbraith
https://orcid.org/0000-0002-5555-4823
Peter Potapov
https://orcid.org/0000-0003-3977-0021
Sérgio Luiz de Medeiros Rivero
https://orcid.org/0000-0002-7723-2497
Aline Maria Meiguins de Lima
https://orcid.org/0000-0002-0594-0187
Marcia Aparecida da Silva Pimentel
https://orcid.org/0000-0001-9893-9777
Marcos Adami
https://orcid.org/0000-0003-4247-4477

References

Adami M, Rudorff B F T B F T, Freitas R M, Aguiar D A D A, Sugawara L M I M and Mello M P M P 2012 Remote sensing time series to evaluate direct land use change of recent expanded sugarcane crop in Brazil Sustainable 4 574–85
Arvor D, Daugard M, Tritsch I, de Lello-thery N A, Thery H and Dubreuil V 2018 Combining socioeconomic development with environmental governance in the Brazilian Amazon: the Mato Grosso agricultural frontier at a tipping point Environ. Dev. Sustain. 20 1–22
Assunção J, Gandour C and Rocha R 2013 DETERstring deforestation in the Brazilian Amazon: environmental monitoring and law enforcement Climate Policy Initiative CPI Report p 34 CPI (available at: https://climatepolicyinitiative.org/wp-content/uploads/2013/05/DETERstring-Deforestation-in-the-Brazilian-Amazon-Environmental-Monitoring-and-Law-Enforcement-Technical-Paper.pdf)
Assunção J, Gandour C, Rocha R, Assunção J, Gandour C and Rocha R 2015 Deforestation slowdown in the Brazilian Amazon: prices or policies? Environ. Dev. Econ. 20 697–722
Barbosa L G, Alves M A S and Grell E C E V 2021 Actions against sustainability: dismantling of the environmental policies in Brazil Land Use Policy 104 105384
Barona E, Ramankutty N, Hyman G and Coomes O T 2010 The role of pasture and soybean in deforestation of the Brazilian Amazon Environ. Res. Lett. 5 24002
Borges A 2020 Ibarra perde 55% dos fiscais em 10 anos—Sustentabilidade—Estadão O Estado de São Paulo (available at: https://sustentabilidade.estadao.com.br/noticia/s/geral,ibarra-perde-55-dos-fiscais-em-10-anos,70003397998 (accessed 20 November 2021))
Brazil 2008 DECRETO No. 6.514, DE 22 DE JULHO DE 2008 (Brasília) (available at: https://legislacao.presidencia.gov.br/ato/tipo—DEC%26numero—6514%26ano—2008%26ato =a87%2CXR501dVPWtd6 (retrieved 13 July 2020))
Brazil 2016 Federal Republic of Brazil intended nationally determined contribution towards achieving the objective of the intended Nationally Determined Contribution (INDC) (available at: www4.unfccc.int/sites/mdstaging/PublishedDocuments/Brazil%20First/BRAZIL%20INDC_20english%20FINAL.pdf (retrieved 20 November 2021))
Carvalho W D, Mustin K, Hilário R R, Vasconcelos I M, Eilers V and Fearnside P M 2019 Deforestation control in the Brazilian Amazon: a conservation struggle being lost as agreements and regulations are subverted and bypassed Perspect. Ecol. Conserv. 17 122–30
Cochran W G 1977 Sampling Techniques (New York: Wiley) de Almeida C A, Coutinho A C, Esquedo J C D M, Adami M, Venturieri A, Diniz C G, Dessay N, Durieux L and Gomes A R 2016 High spatial resolution land use and land cover mapping of the Brazilian Legal Amazon in 2008 using Landsat-5/TM and MODIS data Acta Amazon. 46 291–302
Diniz C G et al 2015 DETER-B: the new Amazon near real-time deforestation detection system IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens. 8 3619–28
Garrett R D, Koh L, Lambin E F, le Polain de Waroux Y, Kastens J H and Brown J C 2018 Intensification in agriculture-forest frontiers: land use responses to development and conservation policies in Brazil Glob. Environ. Change 53 233–43
Gibbs H K, Mungier J, L’Roe J, Barreto P, Pereira R, Christie M, Amaral T and Walker N F 2016 Did ranchers and slaughterhouses respond to zero-deforestation agreements in the Brazilian Amazon? Conser. Lett. 9 32–42
Gibbs H K, Rausch L, Mungier J, Schelly I, Morton D C, Noojipady P, Soares-Filho B, Barreto P, Micol I and Walker N F 2015 Brazil’s soy moratorium Science 347 377–8
Hansen M C, Roy D P, Loveland T R, Ver decomposition of recent expanded sugarcane crop in Brazil Sustainability 4 574–85
IBAMA 2020 Consulta de Autuaçoes Ambientais e Embargos (available at: https://servicos.ibama.gov.br/ctf/publico/areasembargadas/ConsultaPublicaAreasEmbargadas.php (accessed 05 May 2019))
IBGE 2021 Downloads (IBGE) (available at: www.ibge.gov.br/ibgeociencias/downloads-geociencias.html (retrieved 20 November 2021))
IBGE 2013 Consulta de Autuaçoes Ambientais e Embargos (available at: https://servicos.ibama.gov.br/ctf/publico/areasembargadas/ConsultaPublicaAreasEmbargadas.php (accessed 05 May 2019))
IBGE 2020 Consulta Publica Areas Embargadas (available at: https://servicos.ibama.gov.br/ctf/publico/areasembargadas/ConsultaPublicaAreasEmbargadas.php (accessed 05 May 2019))
INPE 2021 Deforestation TerraBrasilis (available at: http://terrahtp://terrabrabrasilis.dpi.inpe.br/app/dashboard/deforestation/biomes/legal_amazon/rates (retrieved 19 November 2021))

IPEA, IPEA and IPEA 2011 Avaliação do plano de ação para prevenção e controle do desmatamento na Amazônia legal: PPCDAm 2007–2010 (available at: www.cepal.org/dmaah/publicaciones/sinsigla/xml/7/45887/IPEA_GIZ_Cepal_2011_Avaliacao_PPCDAm_2007-2011_web.pdf (retrieved 20 November 2021))

Latawiec A E et al. 2017 Improving land management in Brazil: a perspective from producers Agric. Ecosyst. Environ. 240 276–86

Moraes D R D, Neto L C, Costa M D, de Lima A M, Vieira I C, Lisboa Filho J and Adami M 2018 Monitoramento de áreas embargadas por desmatamento ilegal Rev. Bras. Cartogr. 70 1593–617

Morton D C, DeFries R S, Shimabukuro Y E, Anderson L O, Arai E, Espirito-Santo F D, Freitas R and Morisette J 2006 Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon Proc. Natl Acad. Sci. USA 103 14637–41

Potapov A M, Klarner B, Sandmann D, Widyastuti R and Schuë S 2019 Linking size spectrum, energy flux and trophic multifunctionality in soil food webs of tropical land-use systems J. Anim. Ecol. 88 1845–59

Potapov P V, Turubanova S A, Hansen M C, Adusei B, Broich M, Altstatt A, Mane I and Justice C O 2012 Quantifying forest cover loss in Democratic Republic of the Congo, 2000–2010, with Landsat ETM + data Remote Sens. Environ. 122 106–16

Potapov P, Hansen M C, Kommareddy I, Kommareddy A, Turubanova S, Pickens A, Adusei B, Tyukavina A and Ying Q 2020 Landsat analysis ready data for global land cover and land cover change mapping Remote Sens. 12 426

Rajão R et al. 2020 The rotten apples of Brazil’s agribusiness Science 369 246–8

Rivero S, Almeida O, Ávila S and Oliveira W 2009 Pecuária e desmatamento: uma análise das principais causas diretas do desmatamento na Amazônia Nova Econ. 19 41–66

Rudorff B F T B F T, Adami M, Aguiar D A D A, Moreira M A M A, Mello M P M P, Fabiani L, Amaral D F D F and Pires B M B M 2011 The soy moratorium in the Amazon biome monitored by remote sensing images Remote Sens. 3 185–202

Schmitt J 2015 Crime sem castigo: a efetividade da fiscalização ambiental para o controle do desmatamento ilegal na Amazônia (Brasília: Universidade de Brasília)

SEMAS-PA 2008 Instrução Normativa No.: 1/2008 (Belém) (available at: www.semas.pa.gov.br/2008/03/10/10925/ (retrieved 20 November 2021))

Simões Agapito L, de Alencar E Miranda M and Xavier January 2022 A political agenda in conflict with environmental protection: a critical policy essay from Brazil Int. Criminal. (accepted) (https://doi.org/10.1007/s43576-021-00041-y)

Soares-Filho B, Rajão R, Macedo M, Carneiro A, Costa W, Coe M, Rodrigues H and Alencar A 2014 Cracking Brazil’s forest code Science 344 363–4

Spera S A S A, Cohn A S A S, Vanwey L K L K, Mustard J F J F, Rudorff B F B F, Risso J and Adami M 2014 Recent cropping frequency, expansion, and abandonment in Mato Grosso, Brazil had selective land characteristics Environ. Res. Lett. 9 64010

Vale M M, Berenguer E, de Menezes M A, de Castro E B, de Siqueira L P and Rita de Cássia Q P 2021 The COVID-19 pandemic as an opportunity to weaken environmental protection in Brazil Biol. Conserv. 255 108994

Zu Ermgassen E K H J, Godar J, Lathuillière M J, Löfgren P, Gardner T, Vasconcelos A and Meyfroidt P 2020 The origin, supply chain, and deforestation risk of Brazil’s beef exports Proc. Natl Acad. Sci. 117 31770–9