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Supplementary Materials for

The rotten apples of Brazil's agribusiness

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Materials and Methods

S§1. Dismantling of Brazil's environmental protection

Brazil's success in reducing deforestation in the Amazon has undergone a tremendous setback that began with the relaxation of the Forest Code (FC) in 2012 (*1*). Since then, attempts to roll back conservation achievements (*14*) had increasingly stimulated the rise of deforestation (*15*). In 2019, with the presidency of Bolsonaro, the dismantling of Brazil's environmental protection has gained momentum. Major actions undertaken by his government include: a) the extinction of secretaries of climate change and of the environment under the ministries of environment and foreign affairs, respectively (*16*); b) transfer of the Forestry Service, responsible for Brazil's environmental registry of rural properties (CAR), to the ministry of agriculture; c) militarization of ICMBio's chief positions (Brazilian institute for the conservation units) (*17*); d) reduction from 96 to 23 members of the civil society participating in the national council for the environment (CONAMA) (*18*); e) blocking through official objections international funding to local socioenvironmental NGOs (*16*, *18*); f) leaving vacant or slow replacement of IBAMA's (the national environmental law enforcement agency) superintends in the 27 states of the union and other key positions with inexperienced nominees (*19*, *20*); g) extinction of the board of advisors of the Amazon fund, triggering the suspension of approximately US$ 1 billion in donations from Norway and Germany to socioenvironmental projects in Amazonia (*16*); h) reduction of environmental field enforcement with a decrease of 37% in environmental fining by IBAMA in the Amazon (*21*); i) confrontation by attempting to discredit deforestation estimates from INPE's monitoring system (the national space agency) alongside the discharge of INPE's chief director (*16*); j) and attempt to pass two congressional bills—one facilitating land titling for squatters (*22*), and another (PL 191/2020) allowing mining inside Indigenous Lands (ILs) that cover 1.2 million km² (23%) of the Legal Amazon and have been pivotal in conserving the forest (*23*).

Those actions were accompanied by personal statements through social media from both Brazil's president and his ministry of environment, Ricardo Salles, proposing to decommissioning protected areas (*20*, *24*), threatening to fire IBAMA personnel in charge of fining illegal deforestation—hence an unprecedented drop of fines in 2019 issued by IBAMA (Fig. S1) (*19*, *20*)—, alongside Salles' personal meetings with illegal loggers, miners and land grabbers, while criticizing and blaming NGOs for setting fire in the Amazon (*25*, *22*). Importantly, industry and rural associations are also held accountable, namely the Brazilian Rural Society (SBR) and the Federation of Industries of the State of São Paulo (FIESP), given that they recommended and continuously supported Ricardo Salles (*26*) as minister of environment. Moreover, Ricardo Salles, who is affiliated to SBR, was a candidate for the Brazilian congress with a large financial support from various CEOs of major Brazilian agribusiness companies (*27*). Ricardo Salles also proposed at a presidential meeting to seize the opportunity provided by Codiv-19 Pandemia to deconstruct the country's environmental laws.

In addition, APROSOJA (Mato Grosso Soybean Producers Association) is demanding the end of the soy moratorium in the Amazon under the pretext of free trade principles (*28*). In the same line, UNICA (the Brazilian Sugarcane Industry Association) has changed drastically its position in relation to the ban on growing sugarcane in the Amazon. Back in 2018, when a senator proposed to lift the ban, UNICA strongly defended the restrictions based on the fact that 98% of its crops are grown outside of the Amazon and the importance of reducing the risk of deforestation linked to ethanol and sugar production since Brazil's is pressing the EU to raise its export quota. However, under a new president, UNICA changed position and successfully helped terminate the ban (*29*, *30*). On top of that, the rural caucus attempted to pass a bill to end the requirement of the Legal Reserve (*31*)—the portion of the rural property that must be set aside with native vegetation. As a result, all those actions sent strong signals that enforcement would be lifted or greatly relaxed, setting in motion a rush to clear-cut forests on private properties as well as on public lands.

It should be noted that some agribusiness associations, NGOs and researchers working under the Brazilian Coalition on Climate, Forests and Agriculture (coalizaobr.com.br) have played an important role in avoiding an even more drastic dismantling of Brazil's environmental policies. Already during the presidential campaign, the Coalition has proposed a series of actions to the different candidates, including ending illegal deforestation alongside land grabbing and securing protected areas (32). Later on, as the newly formed Bolsonaro's government threatened to quit the Paris Agreement and shutdown the Ministry of Environment, the Coalition again played an important role in changing the government's position (33). In the end of 2019, the Coalition did the campaign "Be Legal with the Amazon" in favor of promoting legal agricultural practices in the Amazon, stopping land grabbing and against the further weakening of the Forest Code. As a reaction to the campaign, SRB, UNICA, and Abiove (Brazilian Association of Vegetable Oil Industries) left the Coalition. As of March 2020, ABAG (Brazilian Agribusiness Association), IBA (Brazilian Tree Industry Association) and ABIEC (Brazilian Beef Exporters Association) were the only major association still in the Coalition, indicating the limited ability of the more sustainability-oriented part of the agribusiness sector in opposing the dismantling of Brazil's environmental policies.

S§2. Brazil historical agricultural trading with EU and China and its effects on conservation

In 2010 the European Union (EU) was Brazil´s main trading partner, with a share of 27% of the country's agricultural exports. But with China's growing demand for agricultural products, and especially soybeans for livestock feed, the share of EU exports dropped to 17% with China jumping from 14% to 32% between 2010 and 2019 (*9*) (Fig. S2). This shift was further accelerated in 2018 as a consequence of the tariff war between China and the United States (US). After the US President Donald Trump increased tariffs on imports from China (mostly electronics), China retaliated by imposing a 25% tariff on soybeans and other farm goods from the United States (*34*). This caused a sharp drop in the value of exports from the US to China between 2017 and 2018, from USD 23 to 13 billion, mostly due to a reduction in soybean exports from 31 to 4 million tons (Mt). In the meantime, Brazil filled in the gap by increasing its soybean exports to China from 54 to 68 Mt (*9*, *35, 36*). As a result, China became the destination of 68% of Brazil's soybean exports.

The shift in the destination of Brazil's agricultural exports helps explain the increasing rejection of some of the agribusiness main actors in relation to environmental conservation demands. As the EU was the main destination of Brazilian exports, the sector was forced to accept the soy moratorium, an agreement signed in 2006 between Greenpeace and the world's largest soybean exporters prohibiting expansion of soy crops into forested areas in the Amazon (*37*). As agricultural exports start to shift towards China, the rural caucus successfully lobbied for the weakening of Brazil's Forest Code, leading to an amnesty of 58% of the illegally cleared areas before 2008 (*1*). With the additional push towards China as a result of the tariff war, the soybean production sector started demanding the end of the soy moratorium, feeling confident that the Chinese market would not set the same level of environmental requirements as those of the EU (see also S§1).

The rapid dismantling of Brazil's environmental policies and disregard of consumers' demands from Europe suggest that Brazil's agricultural sector takes for granted a growing demand of agricultural products from China as well as the indifference of China government for issues such as deforestation and biodiversity losses outside its country. Yet, the trade agreement between the US and China to end animosities between them, if implemented, will affect Brazil directly. The agreement establishes that China is expected to buy from the U.S. an additional USD 12.5 and 19.5 billion in the first and second years of the agreement, respectively, in relation to 2017 when China had acquired USD 24 bi (*38*). The fulfilment of the trade agreement will have major repercussion on global trade flows, since Brazil current exports to China, which reached USD 30 billion in 2019, could be overshadowed by that of the US that expect to sell to China in the second year of the agreement USD 43 billion.

It is possible to estimate the impact of the US-China agreement on the profile of Brazil's soybean exports for the second year of the agreement. With that purpose, we assume that: 1) the value of soybean exports from the US to China will represent 52% of the total as in 2017; 2) soybean prices would remain the same as in 2017; 3) US will redirect to China almost all its exports currently going to other countries, except to Mexico due to NAFTA and lower transportation costs; 4) US and China will strive to fulfil the agreement by 2021 by providing economic incentives to each other (i.e. premium price) and/or creating tariff or technical barriers to the imports from other countries, including strict deforestation-free criteria in order to block Brazilian soybeans; and 5) global soybean demand will be at 2018 levels. Under these circumstances, it is likely that soybean exports between the US and China will increase from 19 Mt (2019) to 58 Mt in the second year of the agreement. Likewise, Brazil's exports to China would drop from 58 Mt (2019) to 20 Mt. As a consequence, Brazil will have to redirect its trade towards EU, the world´s second largest buyer of soybeans, increasing exports to EU from 13 Mt (2019) to 22 Mt. This movement is likely to re-establish the EU as Brazil's main trade partner of agricultural goods.

S§3. Modeling approach

We carried out a comprehensive analysis at property level of the Forest Code compliance and deforestation post 2008 to calculate the amount of Brazil´s soy and beef production associated with deforestation (both potentially legal and illegal) in the Amazon and Cerrado, the two major Brazilian biomes with the highest rates of deforestation (*13*). We also looked into the trading of soy and beef from Brazil to EU, aimed at mapping the source and destination of soy and beef contaminated with potentially illegal deforestation as well as the role of traders in supplying EU countries with those products.

To this end, we developed a geospatial database with the best available cartographic data for the Amazon and Cerrado biomes (Table S1). We also developed innovative geoprocessing tools to handle big data by employing PostgreSQL 10.3 (*39*) and PostGIS extension 2.4 (*40*), and Dinamica EGO 5.* freeware (*41*) that takes advantage of full parallel processing. Dinamica EGO parallel execution system uses a variable number of execution threads (called workers) boosted by task-stealing algorithms to provide load balancing and increased flexibility for running parallel tasks. In theory, all model components can run in parallel, including independent operators, loops and map tiles, drastically reducing processing time and hence enabling high-spatial resolution analyses at a continental scale without the need of cloud computing or large servers (*42, 43*). All inputs, scripts, and main outputs are available for download at *csr.ufmg.br/ radiografia_do_car*.

Our analyses begin by applying the rules and definitions of the Forest Code (FC) (*44*) for each private property from our CAR dataset obtained from SICAR—the Online National Rural Environmental Registry System (*6*). In doing so, we provide estimates of the FC level of compliance, *i.e.* landowners' debts and surpluses—areas that must be reforested at the owners' own expenses, or as the latter, exceed the FC conservation requirements. These results per property are integrated into a common database together with annual deforestation maps covering the Amazon and Cerrado biomes (*13*), soy cropping maps (*45*), GTA documents [permit to transport animals (*46*)], and soy and beef trading data (*47, 48*). Our CAR dataset comprising information on roughly 815 thousand rural properties for both biomes allows for mapping potentially legal or illegal post-2008 deforestation—the amnesty deadline year for past-deforesters (*1*)—within compliant and non-compliant properties, respectively, as well as the municipality source, export and import traders, and hence destination of deforestation-contaminated soy and beef shipped to each EU country.

S§4. Estimating Forest Code compliance at property-level

We developed spatially explicit models using Dinamica EGO (*49*) aimed to estimate the FC level of compliance (balance) for each one of the CAR properties of our dataset (Fig. S3). The models consist of two sets: Data preparation and the FC analytical model, itself. The first integrates land use data (Table S1) with the property boundaries and cuts off map subsets for each municipality and its neighborhood (where property boundaries extend beyond the municipality). The second model processes in parallel each municipality subset in order to calculate the FC debt and surplus per property, also summarizing results per municipality.

The FC is the main legislation regulating conservation on private lands. In short, it mandates how and where native vegetation remnants can be suppressed or conserved for natural resource management. Brazil has faced a huge challenge in implementing and enforcing the FC revised in 2012 (*1*). The FC law establishes two types of conservation areas on private land: Areas of Permanent Preservation (APP) along water streams and on steep slopes and hilltops; and the Legal Reserve (LR), a percentage of the property area that must be set aside as native vegetation (ranging from 20% in most of the country to 80% in the Amazon rainforest). The FC also determines the areas to be restored at the owner's own expenses —i.e. LR and APP illegally deforested before 2008.

The FC model applies a set of rules to define the riparian APP width, which depends, in addition to the water stream width, on the property size in terms of the municipality's number of fiscal modules, which vary from 5 ha to 110 ha across Brazil. The law also exempts small landholders (up to 4 fiscal modules) in restoring the LR in addition to other discounts, such as accounting for APP vegetation as a complement to LR's total area (Article 15), and includes other articles and clauses that must be considered to calculate the debts and surpluses, as explained below.

Substantive improvements in our computing capacity and modeling tools enabled fine-scale reanalysis of the FC (*1*, *10*), making it feasible to estimate the FC balance; i.e. level of compliance, throughout the Brazilian territory at the property-level. These advances allowed us to frog-leap from a 60-meter spatial resolution (*1*) to a 5-meter (the narrowest APP width for restoration) by using parallel processing and memory allocation optimization. All processing relied on the computing resources of the Center for Remote Sensing (*50*) of the Federal University of Minas Gerais (Belo Horizonte, Brazil). All calculations can be replicated by downloading the software and opening the FC models (*csr.ufmg.br/radiografia_do_car*) using Dinamica EGO's user-friendly graphical interface.

For the calculation of the FC balance, we first quantified for each property the total area where the FC is applicable, namely the total area of the property, the total area of native vegetation and the total agricultural area in 2008 (also called consolidated areas). Then, based on the presence of watercourses and water bodies, the model generates APP minimum width buffers required for conservation and restoration according to the FC rules, which differ for conservation and restoration purposes (*1*, *44*). To calculate riparian APP buffer width to be restored, the model applies a set of rules so-called "escadinha" (little ladder), which specifies the buffer size to be restored according to the property size (defined in the number of fiscal modules as specified for each municipality) and the river width (Art. 61-A). Next, the LR for conservation is computed as a proportion of the property area—*i.e.* 80% in the Amazon biome, 35% in Cerrado areas in the Legal Amazon and 20% in the remaining regions (Cerrado biome) (Art. 12, I). When a property overlaps different biomes (*i.e.* Cerrado and Amazon), we applied a weighted average of the required percentages.

To calculate LR to be restored, we included fiscal module values and the total area of protected areas (public land) by municipality. LRs in the Amazon biome can be reduced up to 50% in municipalities that have more than 50% of its territory occupied by public conservation areas and indigenous reserves (Art. 12, II - § 4º). The FC exempts small landholders (up to 4 fiscal modules) to restore LR debt (Art. 67). In addition, the FC establishes a maximum percentage of the property for restoring LR (Article 61-B), depending on the total extent of its riparian APPs (Art. 15).

Our Forest Code (FC) algorithm takes into consideration the increase in Legal Reserve (LR) size from 50% to 80% by a provisionary act of 1996 (*Medida Provisória 1.511*) (*51*) and another one of 2001 (*Medida Provisória 2.166-67*) (*52*). The text of 2001 established definitively the LR definition as "the area located inside a rural property or possession, which is not an area of permanent preservation (APP), necessary for the sustainable use of natural resources, conservation and rehabilitation of ecological processes, conservation of biodiversity, through sheltering and protecting native fauna and flora", restricting further possibilities of using these areas. From this year onwards, this definition came in force, mandating 80% of LR in the forest area, 35% in the Cerrado and 20% in other vegetation in the Legal Amazon, and 20% in the rest of the country.

In addition, article 68 of the of FC reviewed in 2012 states that landowners that suppressed native vegetation respecting the legislation in force at the time need not to recover LR to the percentage mandated by the current law, i.e. 80%. Therefore, it corrected conflicting past legislation to bring to legality "farms pushed into illegal status".

The difference in LR definition is the reason that deforestation was separated before 2002 and this year onwards. Deforestation before and after the decree must be analyzed with respect to different specification of LR size. Note that the time of deforestation occurring is also an evidence for article 68 of the 2012's FC as specified in Paragraph 1, as follows:

"Owners of rural properties may prove their history of occupation by documents such as the description of historical facts of the region, commercialization records, data, agricultural activities, contracts and bank documents related to production, and by all other means of evidence permitted by law" (*44*).

The main sequence to obtain the FC balance is depicted in Fig. S4. For each property, the model subtracts the total area required for LRs from the areas of native vegetation remnants in accountable areas of each private property and the areas of native vegetation within the customized APP buffer sizes to arrive at the level of compliance. We define a positive result as an environmental surplus and a negative result as an environmental debt.

The rural properties data originally come from the CAR registry (*6*), a national public database created under the revised FC mandatory for all landowners and meant to support environmental compliance, tackle illegal deforestation, and reduce the cost of monitoring and enforcement by government institutions. Enrollment in the CAR is the first step to obtain the property environmental compliance and includes: property owner data; geo-referenced property boundaries, areas of social interest and restricted use, remnants of native vegetation, consolidated areas, APP and LR delimitations, among others. Yet, these self-reported data must be confirmed through a so-called "CAR validation" process, which has experienced relevant delays by federal and state environmental agencies. Thus, as there are still substantive conflicting or false information not validated, we used a modified CAR registry layer encompassing roughly 4.2 million of properties for the whole country, in which overlaps and duplicate features were resolved (*53*). To do so, a set of algorithms was applied for removing spatial inconsistencies and overlaps before our FC analysis. The following procedures were performed:

1. Validation of the geometry, making it valid;
2. Removal of duplicate geometries;
3. Removal of geometries with the same CAR number, giving priority to the one with the largest area;
4. Removal of features outside Brazil's borders;
5. Separation into “CAR Premium” and “CAR Poor” categories based on the amount of self-overlaps and/or overlaps with the INCRA’s (Instituto Nacional de Colonização e Reforma Agrária) land tenure database:
    i. CAR Premium: overlapping area is less than or equal to 5% of the total area of the property.
    ii. Car Poor: overlapping area is greater than 5% of the total area of the property.
6. Cleaning of self-overlaps in the CAR Poor and CAR Premium categories separately using different priorities (small, large, or random) to create three categories of data that will be preserved until the end of the processing. These three categories have major implications and can interfere directly with later modeling, such as with the calculation of the Brazilian FC balance:
    i. Prioritization of large properties: may overestimate the calculation of FC debts;
    ii. Prioritization of small properties: may underestimate the calculation of FC debts;
    iii. Randomization: creates a normal distribution of errors and generates an intermediate result between the prioritization of large and small properties.
7. Analysis of overlaps between the CAR Poor and CAR Premium categories, giving priority to CAR Premium.
8. Removal of sliver polygons originated in the aforementioned cleaning steps:
    i. For cleaning sliver polygons, all polygons with a circularity index (CI) of less than 0.12 were excluded. The CI calculates how similar a polygon is to the shape of a circle. This index behaves independently of the size of a polygon, unlike the simple form index (area-perimeter ratio). The CI ranges from 0 to 1, with 1 being the exact shape of a circle.

    ii. This value was determined after a series of analyses of the CIs of rural properties included in the CAR database were carried out and it corresponds to the minimum value found for parcels of rural settlements with extremely elongated geometries. The CI (*54*) is calculated as follows:

$$CI = \frac{2\sqrt{\pi A}}{P} \qquad \text{(Eq. S1)}$$

where *CI* is the Circularity Index; *A* the Area; and *P* the perimeter.

As a result, roughly 70% of CAR polygons (2.9 million) were classified as CAR Premium properties. CAR Poor polygons that lost more than 50% (0.4 million) of their original area were aggregated into neighboring properties keeping at least 50% of their area (Fig. S5).

To the CAR property vector layer, we integrated land-use rater data in Albers Conical Equal-Area projection, SIRGAS 2000, which minimizes area error. The composite raster map (Fig. S6) for each municipality integrates (*i*) water bodies; (*ii*) rivers and water streams; (*iii*) consolidated areas in 2008; (*iv*) forest; and (*v*) non-forest (Table S1). This map was resampled to 5x5m to allow the calculation of APP minimum width required for restoration, which is 5 m. Thus, instead of using data on native vegetation, APP, LR, and converted areas from the CAR reports, our modeling approach estimates the FC balance by using open-access cartographic data.

Despite recent progress towards a unified national land-registry database, Brazil still has about 17% of its territory covered by unregistered lands (*55*). Such gap is substantially composed by private lands, which represent 36% of the total 502 million of hectares to be registered. Since the CAR registry is mandatory for obtaining deforestation permits, all properties outside the CAR are thus considered FC non-compliant.

S§5. Integrating the FC balance, deforestation, and agricultural data at property-level

To link environmental compliance and hence potentially legal and illegal deforestation to the soy and beef supply chains, we built a spatial database combining the FC balance, deforestation, soy crop areas, deforestation permits, and embargoed areas per property together with GTA documents (Fig. S7). There are substantial challenges to handle big geospatial data, ranging from heterogeneity of data, such as different spatial resolution, to processing and storage capacity (*56*).

As PRODES Amazonia and Cerrado projects (*13*) have some overlapping, we built a mosaic integrating both datasets to avoid duplication of deforestation records. To do so, we superimposed PRODES Cerrado classes on the non-forest and clouds mapping classes of PRODES Amazonia. Our analyses cover only private properties from our CAR sample; therefore, we eliminated protected areas, undesignated lands, rural settlements, and lands of maroon communities (quilombolas).

For the calculation of deforestation within each property, we applied a zonal statistic algorithm, namely the Tabulate Area (ArcGIS 10.4). Zonal statistics is a standard procedure that summarizes the values of a raster dataset within a given vector object. In our analysis, the raster dataset consists of annual deforestation maps from PRODES (*13*) and the objects are the properties uniquely identified by a CAR code. Both PRODES projects (Amazon and Cerrado) do not detect deforestation increments smaller than 6.25 hectares. Therefore, we used the minimum detection thresholds of 6.25 and 12.5 hectares to account for intra-property deforestation as well as related mapping uncertainties. This procedure also minimizes the edge effects in accounting for the number of deforestation cells within each property. The results (Figs. S8 to S13) were then integrated into our spatial database with other zonal statistics (soy plantation areas, embargoed areas, and deforestation permits).

According to the FC, landowners need to obtain a deforestation permit to clear-cut the forest or other native vegetation areas within their properties. Only properties with forest surpluses are eligible (except for specific cases specified by law such as national security activities) (*44*). Thus, we define potentially illegal deforestation as post-2008 clearings in properties non-compliant with the FC, i.e. the ones already below LR compliance or that did not contain enough native vegetation remnant above LR requirements (FC surplus) to accommodate additional deforestation, and potentially legal deforestation as a clearing on a property with environmental surplus big enough to accommodate the specific amount of deforestation. Since these property-level classifications are not publicly available, our analyses might point out a property with potentially illegal deforestation even though a permit might have preceded it. Likewise, potentially legal deforestation may has taken place without a permit. However, deforestation permits are too few to allow a comparison with the number of properties with deforestation after 2008 (Table S2).

To pinpoint soy crops within private properties, we used the soy crop layer for the Amazon and Cerrado biomes from AgroSatélite (*45*), which is derived from Landsat-7, Landsat-8, Sentinel-2ª and MODIS time-series imagery (Figs. S14 to S17).

S§6. Validation

We validated our FC modeling exercise by comparing our results with those from the analytical FC models developed by IPAM (*57*) and IMAFLORA (*58*). The intercomparison study between UFMG, IPAM and IMAFLORA aimed firstly to come to a common understanding of the FC (some of its clauses are open to different interpretation) and hence to design a logic model, but with each team developing its own implementation. To this end, we made available a common dataset for three specific municipalities (Table S3). Imaflora uses SQL to call several instances of their FC algorithm on a mainframe supercomputer at Universidade de São Paulo (*59*). IPAM developed its model using R programming language and runs it on the Amazon cloud. In turn, UFMG developed its model using Dinamica EGO version 5 (dinamicaego.com). We used a gaming computer with 32 processors to run the model, which is an updated and improved version from Soares-Filho et al. (2014) (*1*) that employs a new raster dataset at 5-meter spatial resolution and calculates the FC compliance for each one of the CAR properties.

The three institutions performed controlled simulations (*i.e.* using standard input maps) for selected municipalities located in the Amazon and Cerrado biomes within the state of Mato Grosso, Brazil (Figs. S18 and S19). Results from the intercomparison exercise show coefficient of variation (CV) of 6% for the overall estimates of native vegetation and areas required for conservation (APP an LR), and 20% for the FC debts and surpluses (Table S3 and Table S4).

For deforestation and soy area calculation, we validated PRODES (*13*) and Soy mapping (*45*) against visual interpretation of high spatial resolution imagery using Google Earth. Results point out to an overall accuracy of 93% (Table S5).

We also compared the number of embargoed properties and deforestation permits with our resulting properties with legal and illegal deforestation for the Mato Grosso state, where the best data are available (Table S2). While the number of deforestation permits are too low to allow a comparison, 23% properties with illegal deforestation had also embargoes (See fig. S20). This underrepresentation may be due to the inefficiency of the State in fining a large number of lawbreakers, a fact that has worsened over the recent years.

S§7. Estimating exports contaminated with potentially illegal deforestation

Soy export

To estimate the amount of soy contaminated with potentially illegal deforestation (Fig. S21), firstly we identified properties non-compliant with FC that still carried out deforestation post-2008 (Table S6). We used a minimum threshold of 6.25 hectares for soy plantations within each property. We accounted for the entire soy planted area within properties with potentially illegal deforestation — not only soy planted on illegally cleared areas (Table S7)—due to possible displacement of land uses (*60*, *61*), a soy moratorium loophole (*5*).

Next, we traced back a municipality's total exports to EU using TRASE (*47*) (Table S8). TRASE links data on commodity exports from specific ports in Brazil to production data at the municipal level (Table S9). TRASE uses the original database for Aliceweb/Comex Stat, which is just an aggregation offering much less information, but both are identical in volumes per port and country. In addition, TRASE crosses these data with taxation and logistics to identify with very high accuracy the exact volume per logistic hub (with information on exporter, importer, port and country of destination). A logistic hub is a place where soy is stored, crushed, traded, dealt with etc. For example, the towns of Rio Verde and Sorriso are logistic hubs; they are not only producing soy but also are key nodes with multiple companies and infrastructures for processing and transporting soy also produced in neighboring municipalities. Once TRASE accurately identifies the logistic hubs and their volumes, it allocates the soy to the municipalities of production that serve these logistic hubs. TRASE does that by means of using cost optimization techniques, but also considering all facilities per trader in each municipality of production and logistic hub (farms, silos, crushing facilities, wholesale retailing, and so on) (Table S10). The allocation per municipality of production is modeled and therefore not 100% exact, but the volumes at the logistic hub and municipalities serving it are accurate (*47*).

We calculated the level of soy contaminated with illegal deforestation (Figs. S15-S17, S22; Table S11) using two steps: Since, maps of soy crops are available for two harvest seasons (2013/2014 and 2016/2017) (*45*), we firstly derived for each municipality the ratio between areas of soy crops contaminated with potentially illegal deforestation, i.e. soy areas within properties with illegal deforestation post-2008, and total of soy crop areas within that particular municipality. Secondly, we averaged the ratios using the areas of the two soy map dates for each municipality and assumed them constant over the period of analysis. Our assumption that the level of contamination is fixed over time (average between 2013/2014 and 2016/2017) is corroborated by the fact that the levels of contamination in both years are about the same regardless the amount of production (Table S12). Because we used the areal ratio, there was no need to consider varying yields over time and space. We then applied this areal ratio per municipality to the annual soy production exported from the same municipality using TRASE data. This is a bottom-up-approach as denoted below:

$$Ec_j = \sum_{i=1}^{n} P_{ij} * \frac{\bar{A}c_i}{\bar{A}t_{ij}} \quad \text{(Eq. S2)}$$

Where Ec_j is the total soy contaminated with potentially illegal deforestation exported to EU for the period of analysis j, i is the export municipality, P_{ij} is the total soy exported to EU from municipality i over period j, $\bar{A}c_i$ is the average contaminated area of soy within properties with potentially illegal deforestation post-2008 and $\bar{A}t_{ij}$ *is* the average soy area, both using the two harvest seasons (2013-2014, 2016-2017) per municipalities i.

Beef exports

To estimate the number of cattle heads contaminated with potentially illegal deforestation, we analyzed the cattle transaction records using the animal transportation permits (Portuguese acronym GTA) in the states of Pará and Mato Grosso. The GTA is a mandatory document for transporting live animals, thereby allowing for monitoring flows of heads to the slaughterhouses and between cattle ranches (*62*). We used GTA data to identify and trace back the direct and indirect cattle suppliers (*i.e.* intermediate cow-calf and rearing operations before cattle is sent to ranches that fatten and then sell the heads to slaughterhouses). After removing duplicated and canceled records, the GTA records summed up roughly 1 million transactions containing 4.1 million heads traded to abattoirs and slaughterhouses in 2017. Next, we matched the GTAs to CAR codes (nearly 75% of cattle traded directly to slaughterhouses in our sample comes from properties with CAR) and mapped for those properties their level of FC compliance and whether they carried out potentially illegal deforestation (Figs. S23 and S24). As GTA records did not provide unique identification of all animal-moving properties—neither the CAR code nor georeferenced data are required for issuing the GTA—, we applied a sequential matching process to identify all potential unique properties as follows: 1) citizen or company identifier (CPF/CNPJ), 2) municipality name, 3) property name, 4) owner name data from SICAR (National Rural Environmental Registry System) and 5) nearest neighboring municipality (only when location ambiguity still occurs). Thus, when a match is found at the registry-matching level 1, the remaining fields (2 to 5) are used to identify and assign the most likely match between a CAR and a GTA transaction.

The GTA transactions not matched with a CAR code were still considered in the analysis in order to map the flow of cattle in the supply chain. In this case, however, given the impossibility of identifying geographically the property sourcing the cattle, we assumed that no deforestation took place at that property. As a result, we generated about 118 thousand IDs separating properties with CAR from those that did not match CAR codes.

The linkages between the CAR codes with matched GTA transactions, as well as the auxiliary GTA property IDs were used to analyze the contamination of the supply chain with deforestation (legal and illegal). All farms that sell directly to slaughterhouses were considered direct suppliers, while the indirect suppliers were classified according to the number of transactions needed for the cattle to reach the slaughterhouse. If a direct supplier deforests and sells to a slaughterhouse, we consider this a case of direct deforestation. Otherwise, if a ranch does not deforest but buys cattle from a deforesting ranch, we considered this level 1 contamination. Similarly, if a direct supplier to a slaughterhouse buys from a free-deforestation supplier, but who in turn buys from another supplier with potentially illegal deforestation, the direct supplier is contaminated at level 2 (Fig. S25). We repeated this procedure up to level 10 until we could find no more indirect suppliers for each direct supplier (Tables S13). In all cases, based on the monitoring protocol established by the Brazilian Public Attorney's Office (i.e. Ministério Público Federal), we applied a filter removing all ranches that have deforested less than 6.25 ha between 2008 and 2018. A sensitive test was also performed to evaluate the effect of a 12.5 ha threshold. These tolerance levels are required to avoid misclassification of deforestation and other spatial errors that may influence the analysis. As we cannot trace contamination for each individual cattle head, we consider that purchases from a given ranch must contain at least 20% of cattle heads from areas with potentially illegal deforestation to propagate contamination across the supply chain. Also, to be conservative, all transactions with no CAR match are by default deforestation-free. Our results indicate an average contamination level of 12±2% (direct suppliers with deforestation and FC non-compliance) and 60±12% (direct and indirect suppliers with deforestation and FC non-compliance) (Tables S13).

The analysis for Mato Grosso (MT) also enabled an evaluation separating the biomes within this state. Results indicate 13% of direct contamination - direct suppliers with potentially illegal deforestation - in MT portion of Cerrado, while in its Amazon portion this fraction drops to 2%. However, considering both direct and indirect suppliers, both biomes in the State have high rates of contamination by potentially illegal deforestation, tantamount to 44% and 61% in the Amazon and the Cerrado, respectively (Table S14).

Finally, to calculate the potentially contaminated beef exports, we derived for each municipality (Fig. S26), the ratio between total contaminated cattle traded to slaughterhouses and abattoirs (both direct and indirect) and the total of heads sent to slaughterhouses and abattoirs. Then, we applied this contaminated ratio per municipality to beef exports (in equivalent tons of meat) by using TRASE data (*63*) (Table S15) as follows:

$$Ec_j = \sum_{i=1}^{n} P_{ij} * \frac{Hc_i}{Ht_{ij}} \quad \text{(Eq. S3)}$$

where Ec_j is the total beef contaminated with potentially illegal deforestation exported to the EU for the period of analysis *j*, *i* is the municipality of origin for the cattle sent to slaughterhouses, P_{ij} is the total beef exported to the EU from the municipality of origin *i* over period *j*, Hc_i is the total contaminated slaughtered heads with potentially illegal deforestation post-2008 (direct and indirect suppliers) and Ht_{ij} *is* the total heads traded to slaughterhouses per municipality *i*.

S§8. Greenhouse gases emissions from deforestation within properties growing soy

We estimated GHG emissions by superposing a potential carbon biomass map (Fig. S27), which reconstructs the above and below carbon biomass for the original vegetation of the Brazilian biomes (*64*), on the deforestation maps covering the Amazon and Cerrado biomes (*13*). To calculate GHG emissions from deforestation (2009-2018), we multiplied the mean carbon density (Mg/ha) for each private property growing soy (Table S16) with deforestation within it and an emission factor of 0.85 (*65*), which assumes that 85% of the carbon contained in vegetation becomes committed GHG emissions. We then transformed carbon in CO_2 using a factor of 3.67. For calculating EU indirect GHG emissions, we applied the ratio between the annual average soy exports from Amazon and Cerrado biomes (Table S8) with their total annual soy production to derive the share of GHG emissions. Hence, of 318.9 MtCO_2 emitted from deforestation on properties growing soy from 2009 to 2017 (Table S16), roughly 58.3±11.7 MtCO_2 are attributed to the EU imports. Yet this figure is conservative because it does not include 1.5 million tons of soy exported from both biomes not traceable to municipalities (*47*).

S§9. CO_2 removals from required restoration areas

To calculate potential CO_2 removals from restoring APPs in both biomes, we multiplied the properties' mean carbon biomass values (*64*), with their debts of APP and applied a saturation factor of 44% (*64*) (Table S17). To calculate CO_2 removals from restoring LR on low yield pasturelands in both biomes, we overlaid the FC non-compliant properties not growing soy with areas not suitable for cattle raising intensification (Fig. S28) and then applied the above procedure (Table S17).

S§10. The good, the bad and the ugly

Out of 815 thousand properties, 15% deforested after 2008, half of them potentially illegal. However, only 2% (17,557) of all properties in both biomes, which are bigger than 4 FM, are responsible for 62% (1.47 Mha**)** of all potentially illegal deforestation (2% for 55% and 2% for 73% in the Amazon and the Cerrado, respectively), based on the mean between deforestation thresholds of 6.25 ha and 12.5 ha (Table S18). Our analysis also allows a Pareto (*66*) optimization aimed at identifying a fewer number of properties with deforestation (18%) responsible for 80% of all illegal deforestation in both biomes (Fig. S29).

S§11. Uncertainties

Our study aggregates various data sources to delve deeply into the risks posed by illegal deforestation to the soy and beef supply chains and hence exports to EU. Due to the extensive dataset, uncertainties may arise from different sources, including: 1) omission and commission errors from remote sensed data, such as the land-use, deforestation and soy maps, which, in general, show an overall accuracy of 85%, 95% and 82%, respectively (*67-69*); 2) detection thresholds for mapping deforestation and soy areas at the property-level (6.25 and 12.5 ha); 3) parameters and algorithms employed to estimate the FC balance, with resulting coefficient of variation of 20% for the FC debts and surpluses figures (Table S3 and Table S4); 4) Forest biomass estimates, whose uncertainties propagate to 20% (*70*) and carbon removal assumptions, such as a biomass recovery saturation of 44%, 5) export production per municipality modeled by TRASE (i.e. soy exports not traceable to EU) and international trade estimates (Fig. S30), 6) inconsistency and incompleteness of cattle transport permits (GTA), and 7) assumptions to estimate direct and indirect contamination in the cattle supply chain, among other inherent uncertainties in big geospatial data modeling (*71*).

To deal with such uncertainties, we first removed overlapping and inconsistent features from our CAR dataset using spatial queries (section S§3). After cleaning-up, the spatial data were integrated using the CAR code and reprojected to Albers Conical Equal-Area, which minimizes areal errors. For quantitative assessments, we used big data modeling tools (Dinamica EGO) to identify a set of verifiable attributes from remote sensed and official data. Based on these attributes, we estimated potentially illegal deforestation and associated contaminated exports to EU. We also validated our results at property-level using high spatial resolution imagery (Table S5). Finally, we applied sensitivity analysis for deforestation and soy area detection (i.e. detection thresholds of 6.25 and 12.5 ha).

Importantly, due to the aforementioned data limitations and uncertainties, our study does not seek to accurately determine the environmental compliance for each private property together with its agricultural output. Rather, it applies a massive data approach to set the level of potentially illegal deforestation along with its contamination to the beef and soy traded to the EU.

Furthermore, because our property sampling covers about 80% of planted soy in the Amazon and Cerrado biomes, our uncertainty upper bound for contaminated soy may be underestimated. For example, if all left-out properties growing soy would have committed illegal deforestation, which is unlikely, the upper bound would reach 37%, if only half of them, the upper bound would amount to 28%. Therefore, the uncertainty upper bound of exported soy potentially contaminated with illegal deforestation may extend beyond the 22%.

S§12. Analyzing agribusiness environmental compliance and trade agreements

Over the last decade, a growing number of studies have addressed the risk of deforestation embedded in commodities, such as soy, palm oil, beef, leather, and cocoa. One line of research has focused on zero-deforestation commitments (ZDCs), whereby a company pledges to reduce or eliminate deforestation associated with the commodities it produces, trades, and/or sells (*37*, *72*, *73*). In this respect, broader private-public and public initiatives, such as the New York Declaration on Forests (*74*) and the Amsterdam Declaration (*75*), have gained momentum by setting ambitious ZDC (Zero Deforestation Commitment) goals, including efforts to reduce or eliminate tropical deforestation (legal and illegal) from the supply chains of agricultural commodities by no later than 2020.

Most ZDCs aimed to cover every node of the supply chain requiring traceability to the farm (direct and indirect suppliers) (*72*). This is a more stringent monitoring than other deforestation-control mechanisms, which generally work at the municipal level and thus are unable to link properties with deforestation and the commodities produced there. While direct deforestation at farm-level can be monitored by remote sensing data (*i.e.* soy replacing forested areas), indirect deforestation (*5*), mainly in the beef supply chain, poses challenges (*4*). In parallel, another set of studies has endeavored to compare and analyze forest policies in different countries. It includes top agricultural production countries with mandatory rules to protect native vegetation within private properties such as the USA, China, Canada, Russia, Argentina, and Brazil. Despite the diversity of requirements, most national legislations impose restrictions and obligations regarding riparian areas (*76-78*) and legal reserves (*1*). Following the signature of the EU-Mercosur trade agreement (EUMTA) (*79*), this body of literature is likely to become increasingly central. While ZDCs are private agreements between buyers and sellers, international trade agreements set the rules between states and as such as are grounded in national legislations. EUMTA makes it explicit that countries can establish their own environmental sustainability regulations. At the same time, EUMTA establishes that the agreement would be breached if a country, in order to obtain commercial advantages, does not enforce systematically its own laws.

Our study provides the basis to build a transparent systems of compliance and verification for all beef and soy suppliers using official and national tools, thus, contributing to property-level ZDCs and to the Mercosur's environmental safeguards. Therefore, by developing tools and integrating both standards of ZDCs and environment compliance at property-level, our work provides the first comprehensive analysis of illegality level in the main export-oriented agricultural commodities from the Cerrado and the Amazon, Brazil's largest biomes with highest rates of deforestation.

Acknowledgments: Supported by the Climate and Land Use Alliance, the Gordon and Moore Foundation, Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) e Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG). Britaldo Soares-Filho and Jan Börner received support from the Alexander von Humboldt Foundation, and Jan Börner received support from the German Federal Ministry of Education and Research. Dataset, model, and results are available at csr.ufmg.br/radiografia_do_car.

Fig. S1. Comparison between annual deforestation in the Amazon biome (*80*) and fines in the states of the Legal Amazon for crimes against the flora issued by IBAMA (Brazilian agency for the Environment) (*81*).

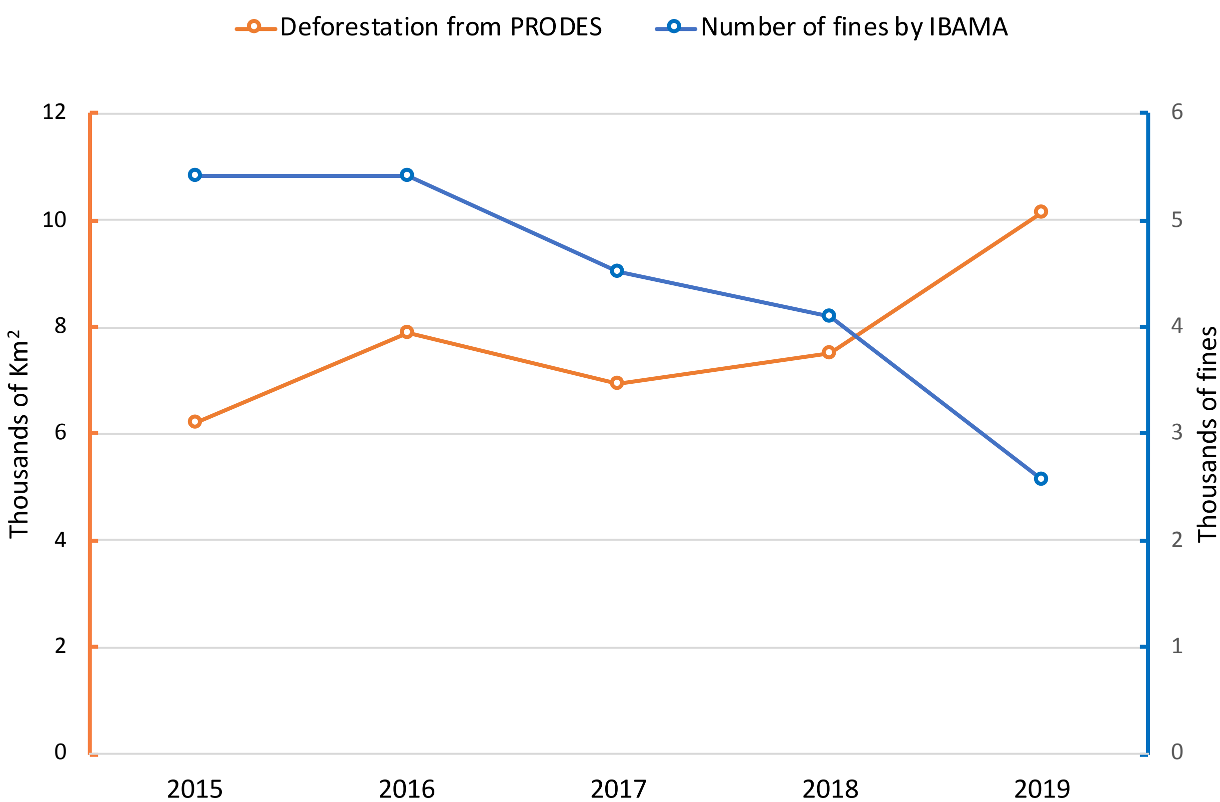


Fig. S2. Country shares of Brazil's agricultural exports (*9*).

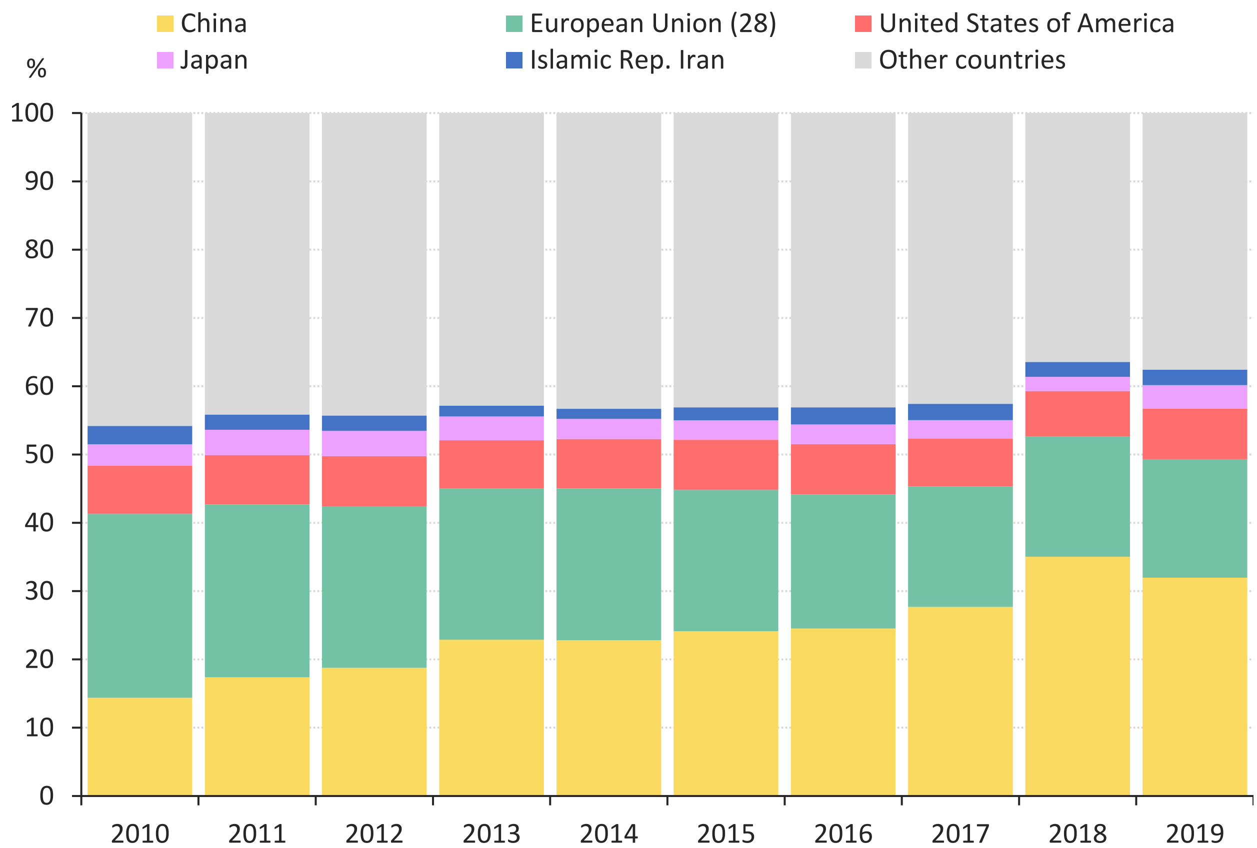


Fig. S3. Rural properties registered in SICAR in the Amazon and Cerrado biomes.

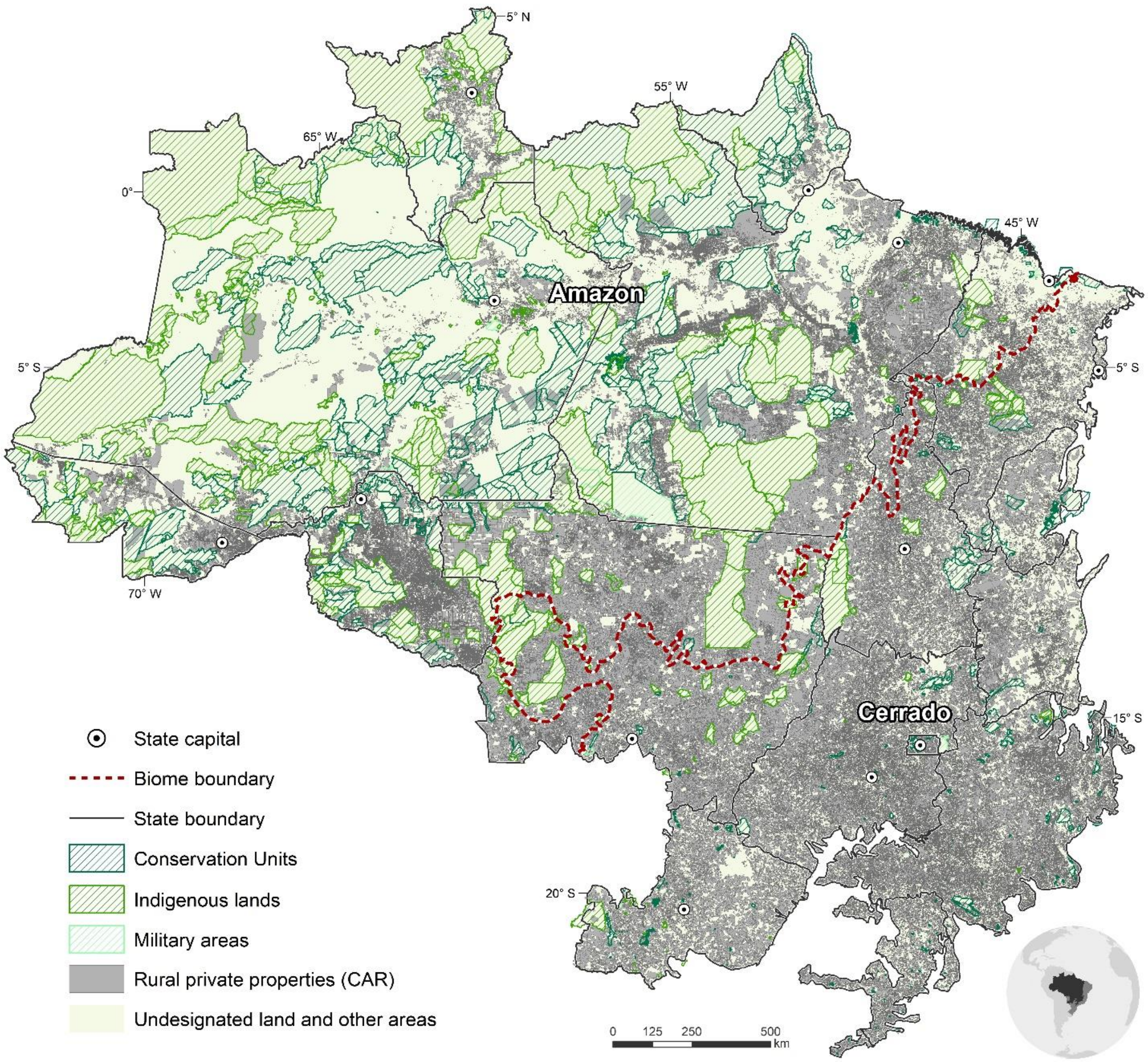


Fig. S4. The FC model flowchart with main processing steps**.**

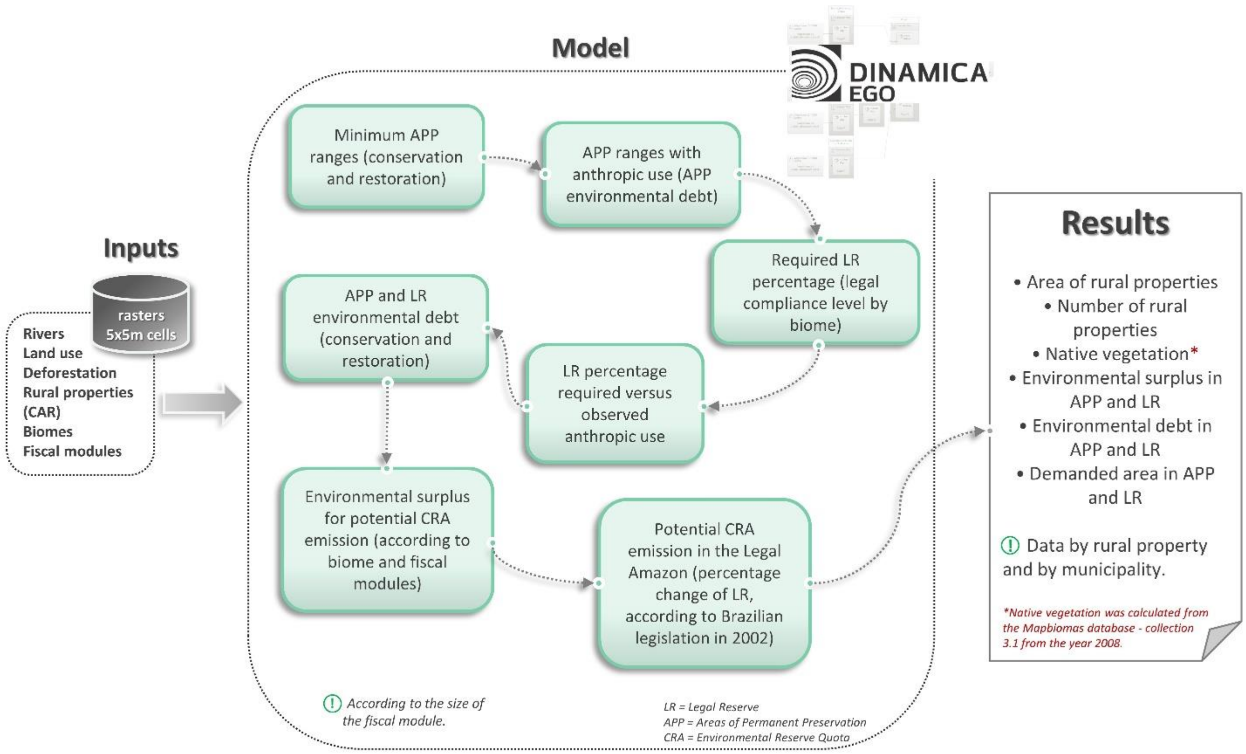


Fig. S5. Examples of CAR polygons cleaned up and classified into CAR Premium and CAR Poor classes. A) Overlap identified. B) Overlap treated by prioritizing CAR Premium within the same CAR class (*59*).

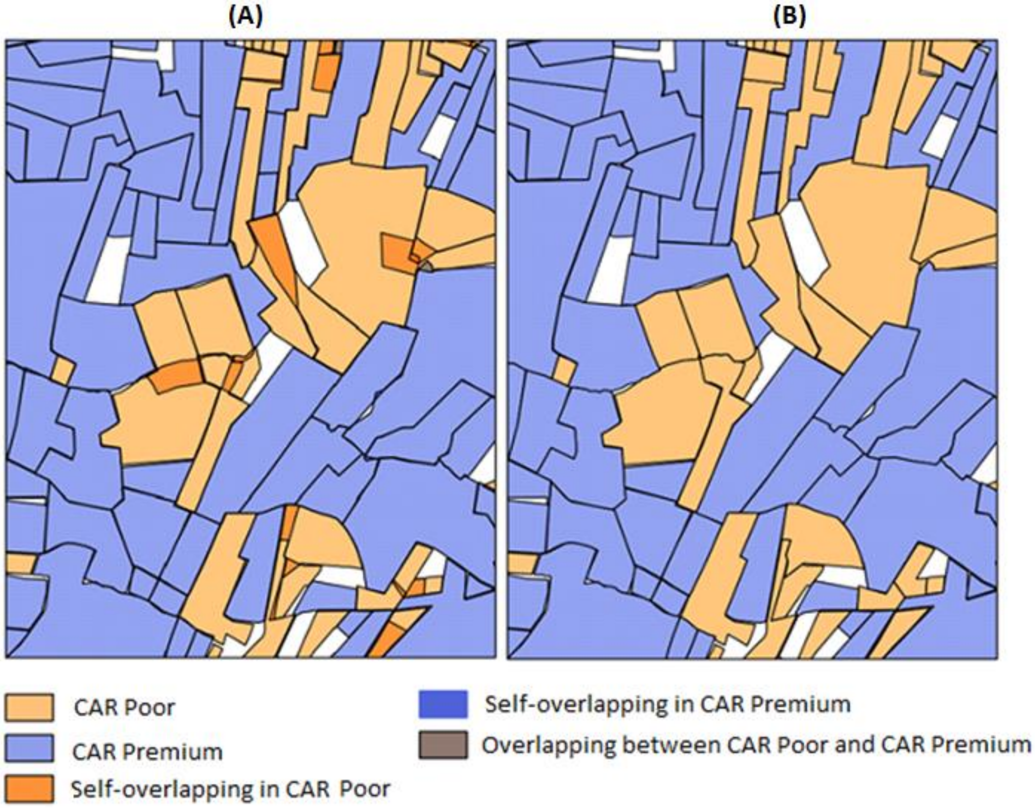


Fig. S6. Geospatial data processing to compose a unique land use map for each municipality.

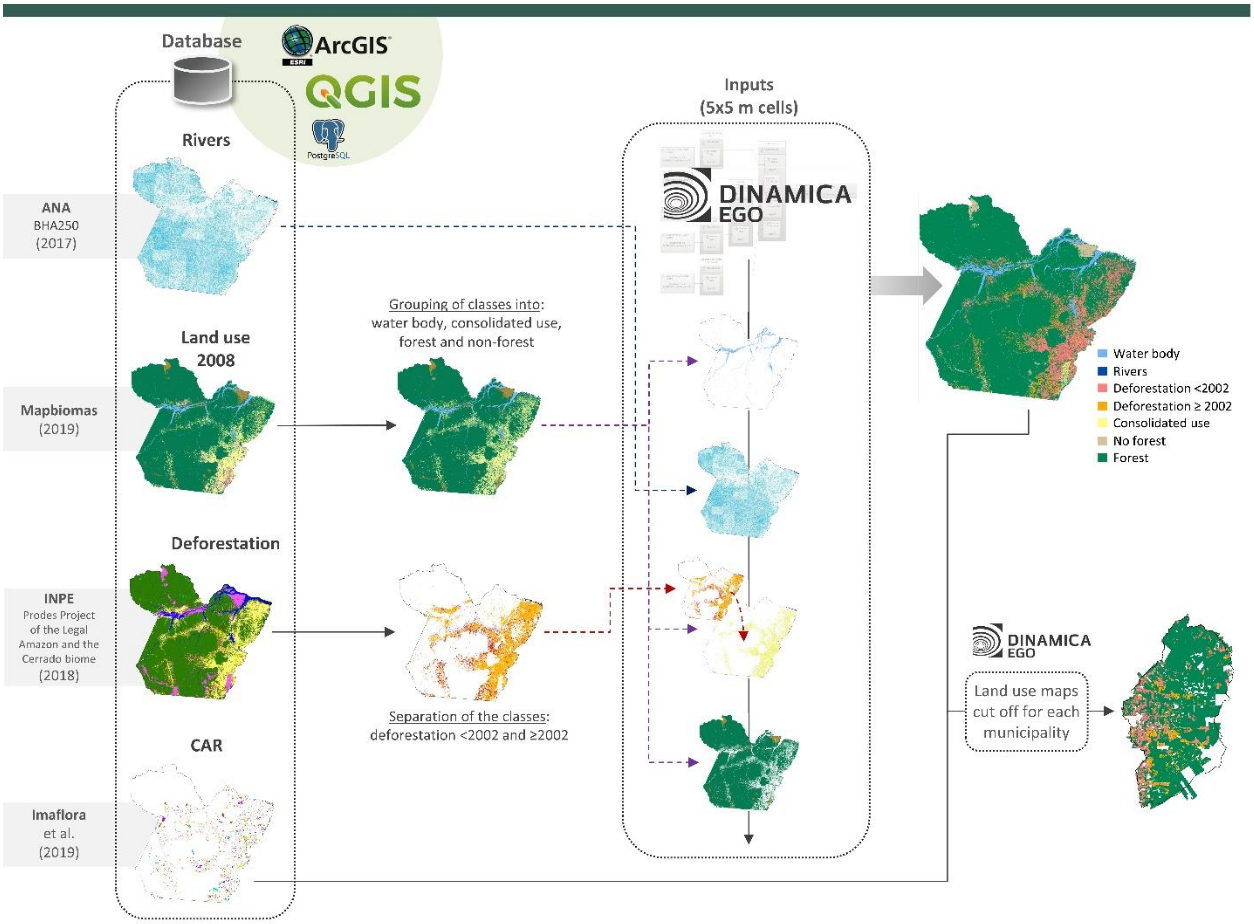


Fig. S7. Spatial database framework including main inputs and data analysis modules.

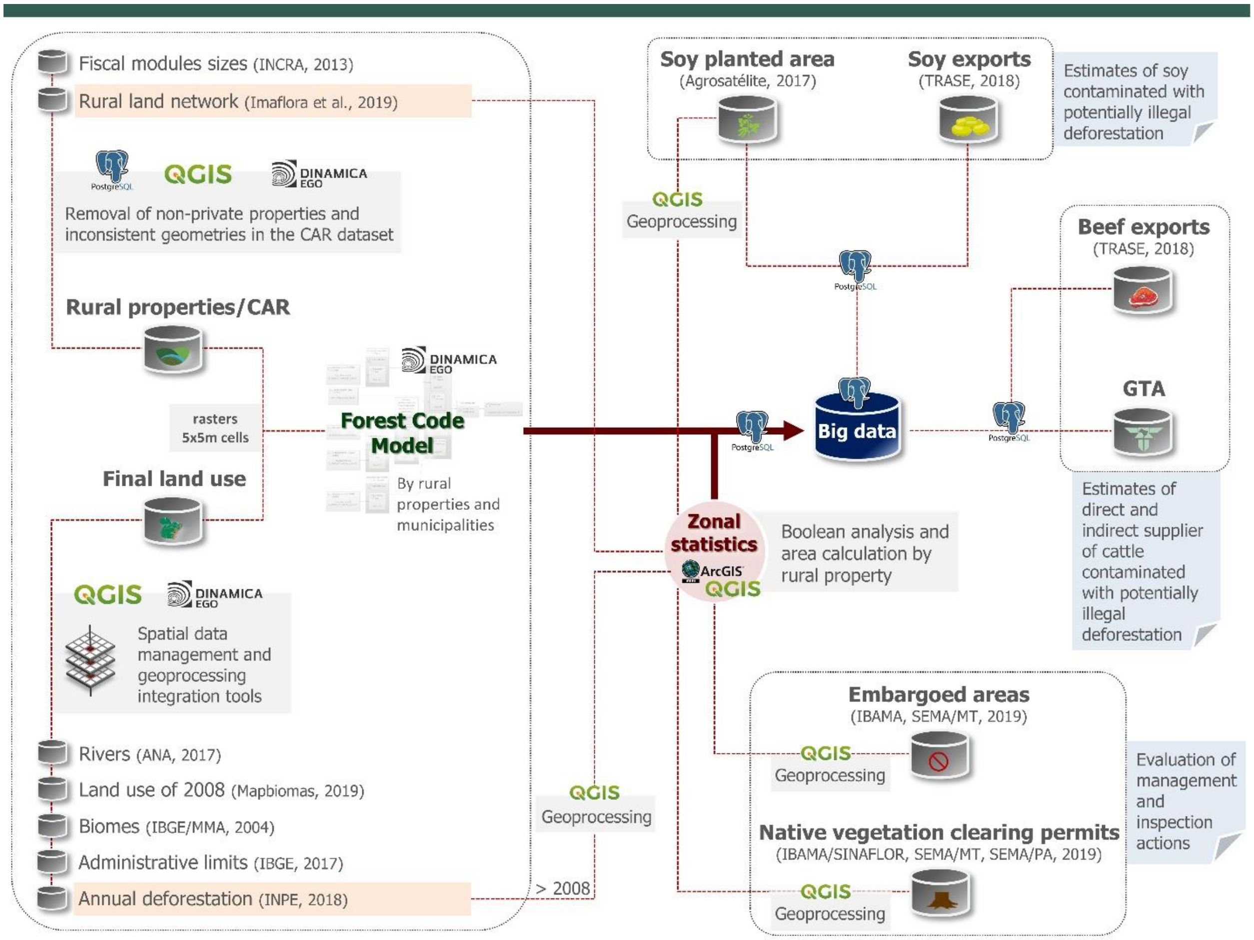


Fig. S8. Potentially legal and illegal deforestation within CAR properties between 2009 and 2018 in the Amazon biome.

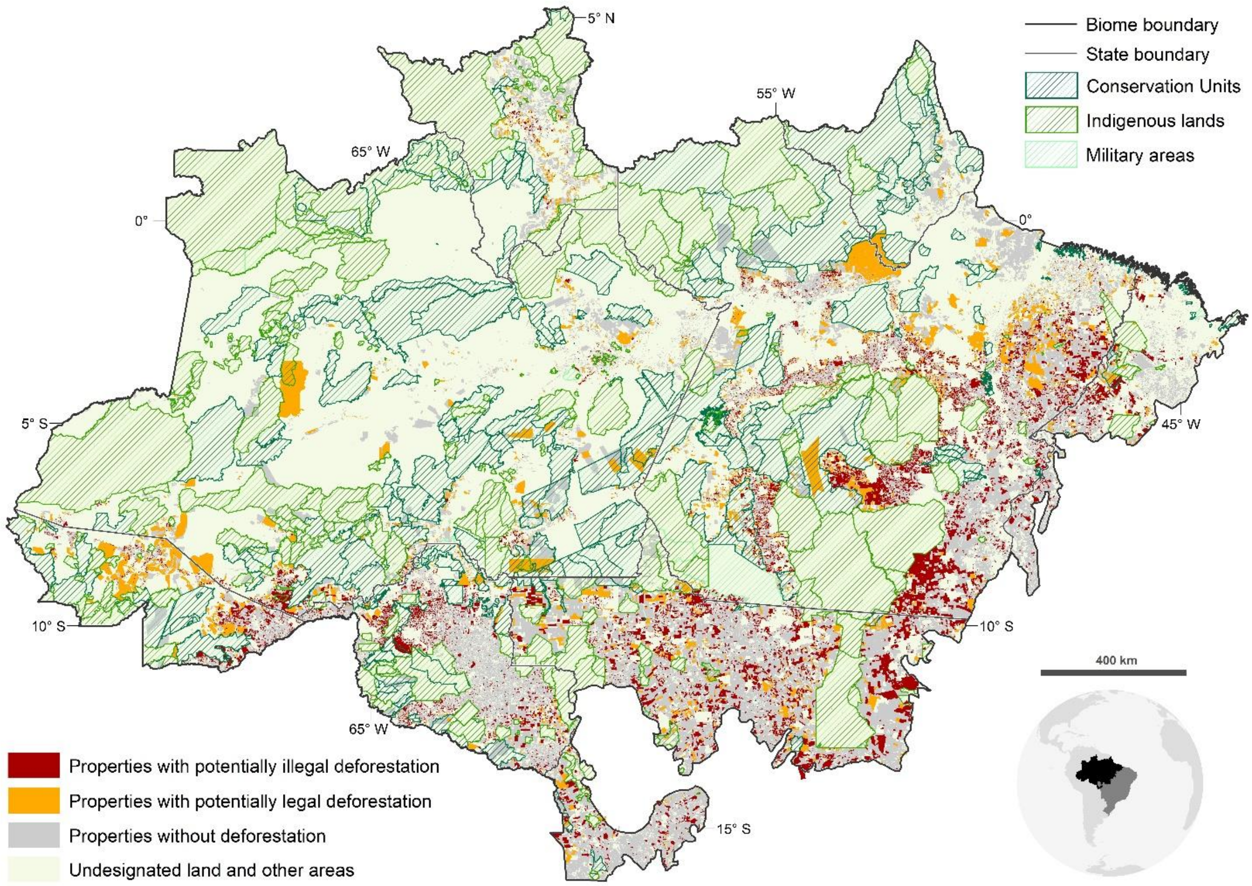


Fig. S9. Potentially legal and illegal deforestation within CAR properties between 2009 and 2018 in the Cerrado biome.

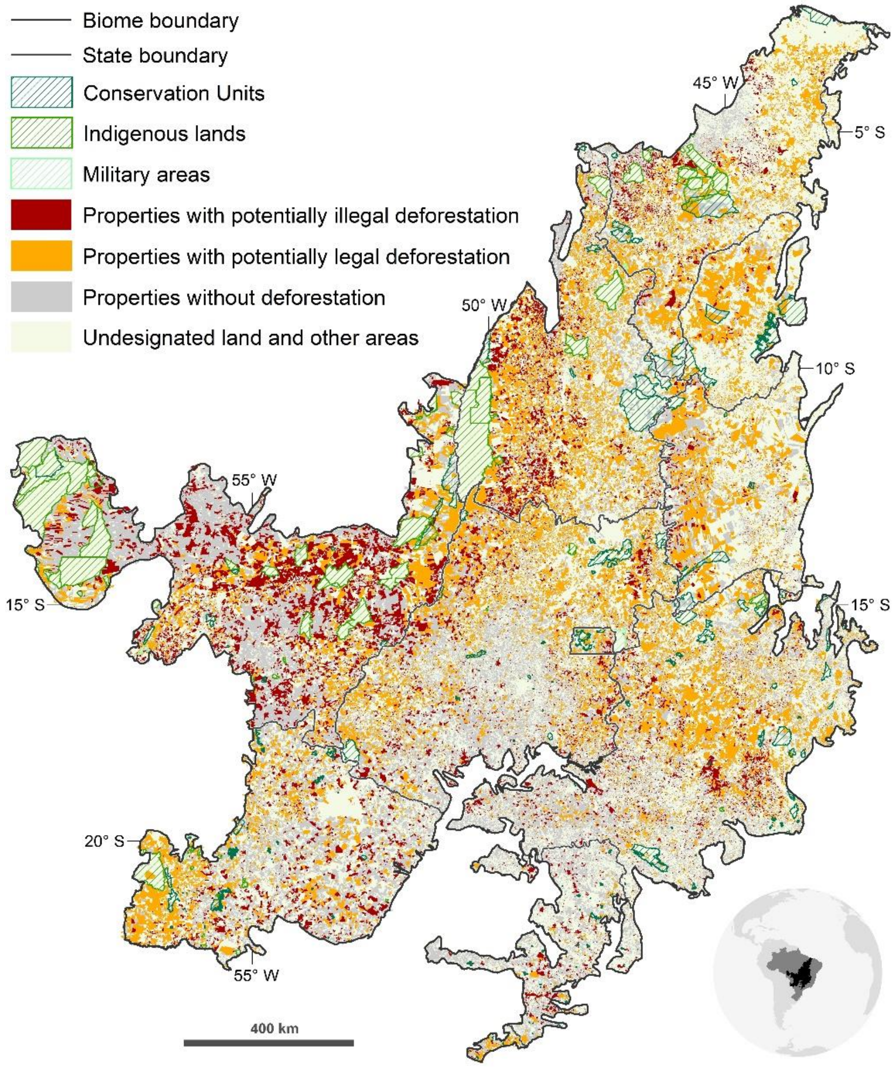


Fig. S10. FC compliance at property-level. Positive results indicate environmental surplus and negative results debts, *i.e.* above and below compliance.

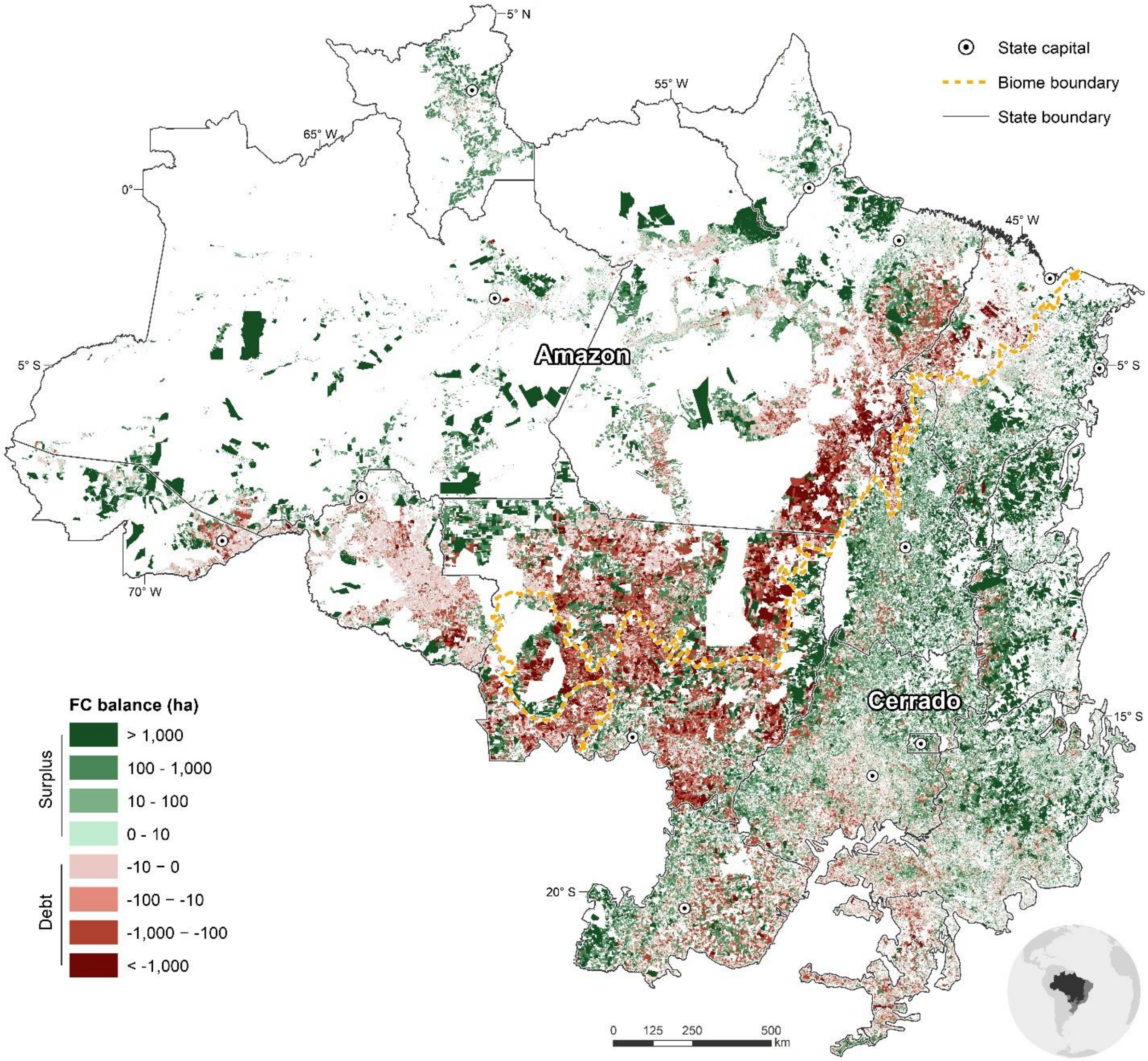


Fig. S11. Private rural properties with potentially legal and illegal deforestation in the Amazon and Cerrado biomes. a) APP and LR compliance; b) total number of properties with deforestation and non-compliant and compliant properties with deforestation using a deforestation minimum threshold of detection of 6.25 hectares; c) and using a deforestation minimum threshold of detection of 12.5 hectares.

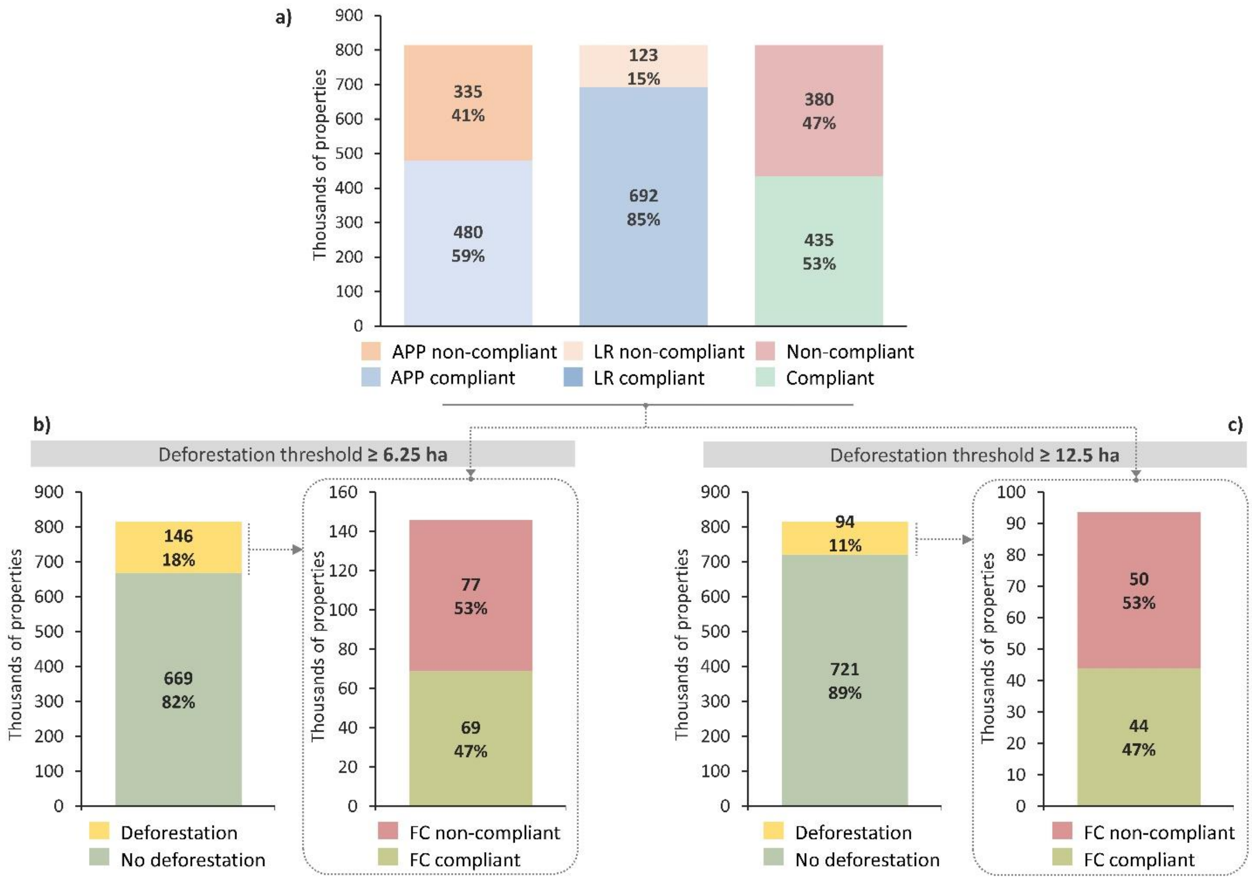


Fig. S12. Private rural properties with potentially legal and illegal deforestation in the Amazon biome. a) APP and LR compliance; b) total number of properties with deforestation and non-compliant and compliant properties with deforestation using a deforestation minimum threshold of detection of 6.25 hectares; c) and using a deforestation minimum threshold of detection of 12.5 hectares; d) total area of potentially legal and illegal deforestation using threshold of 6.25 hectares; e) and threshold of 12.5 hectares.

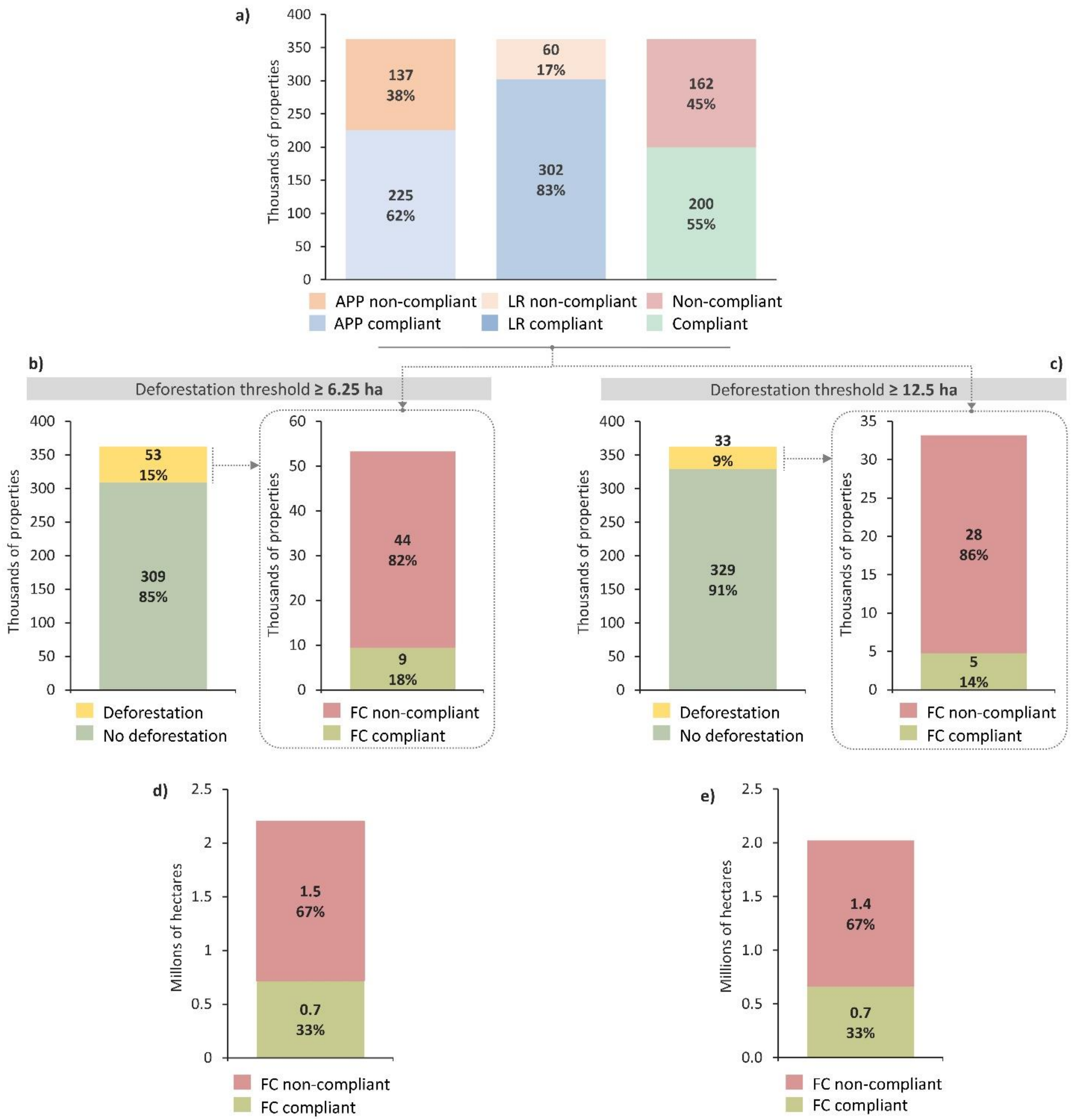


Fig. S13. Private rural properties with potentially legal and illegal deforestation in the Cerrado biome. a) APP and LR compliance; b) total number of properties with deforestation and non-compliant and compliant properties with deforestation using a deforestation minimum threshold of detection of 6.25 hectares; c) and using a deforestation minimum threshold of detection of 12.5 hectares; d) total area of potentially legal and illegal deforestation using threshold of 6.25 hectares; e) and threshold of 12.5 hectares.

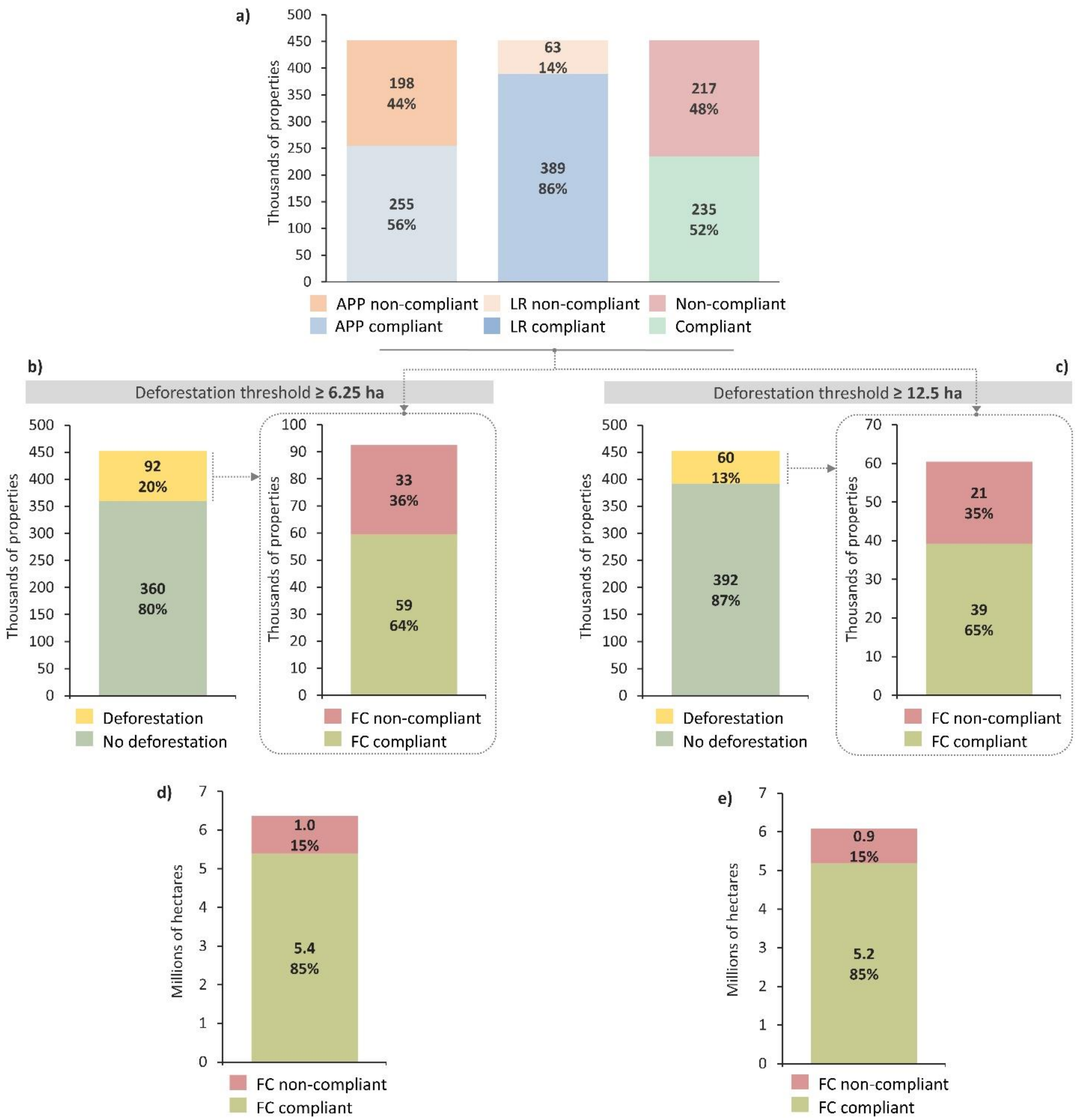


Fig. S14. Potentially legal and illegal deforestation within CAR properties growing soy in the Amazon and Cerrado biomes.

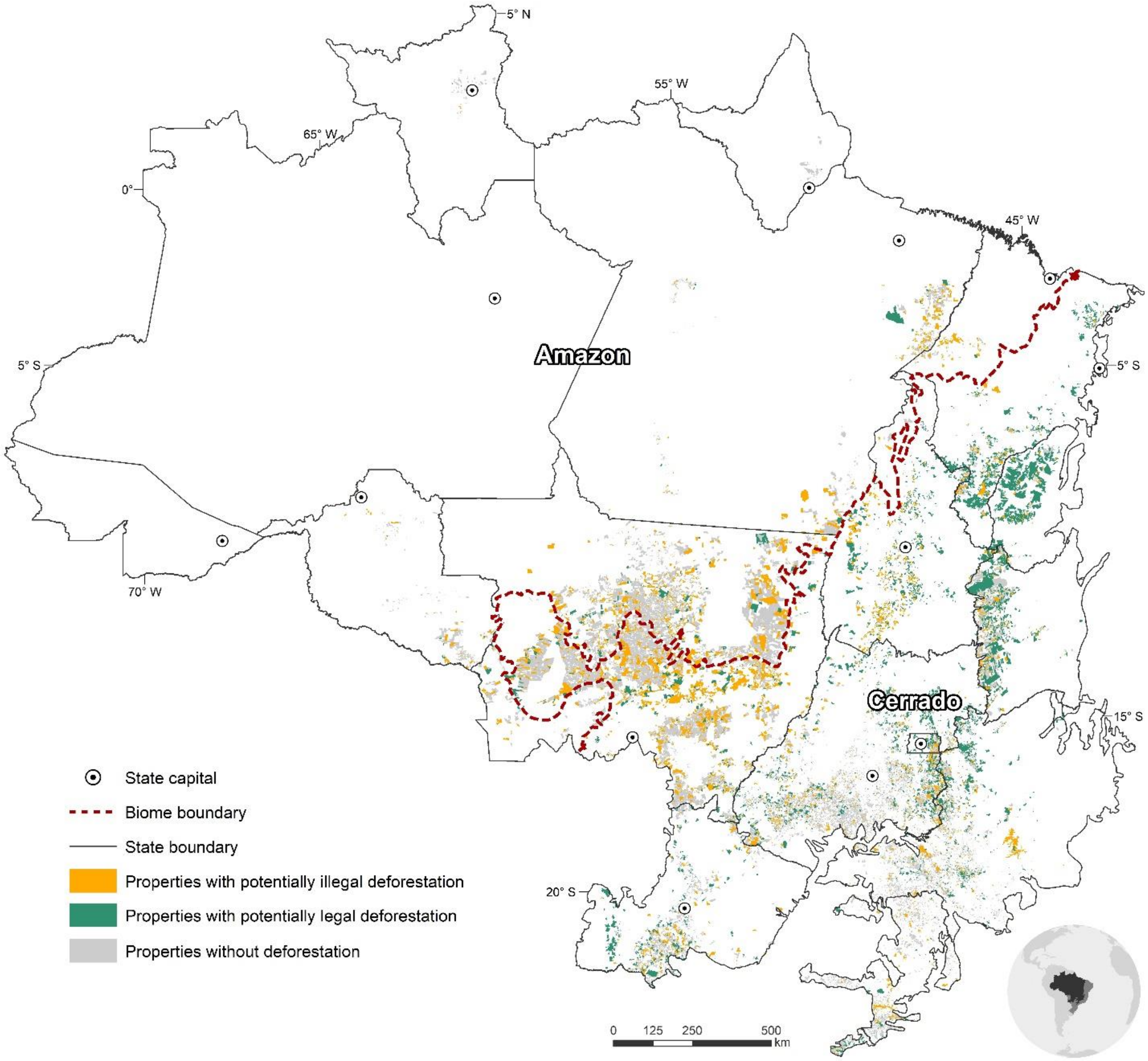


Fig. S15. Private rural properties growing soy with potentially legal and illegal deforestation in the Amazon and Cerrado biomes. a) APP and LR compliance; b) total number of properties with deforestation and non-compliant and compliant properties with deforestation using a minimum threshold of 6.25 hectares; c) and using a minimum threshold of 12.5 hectares; d) potentially legal and illegal deforestation and soy area contaminated with potentially illegal deforestation using a minimum threshold of 6.25 hectares; e) and using a threshold of 12.5 hectares.

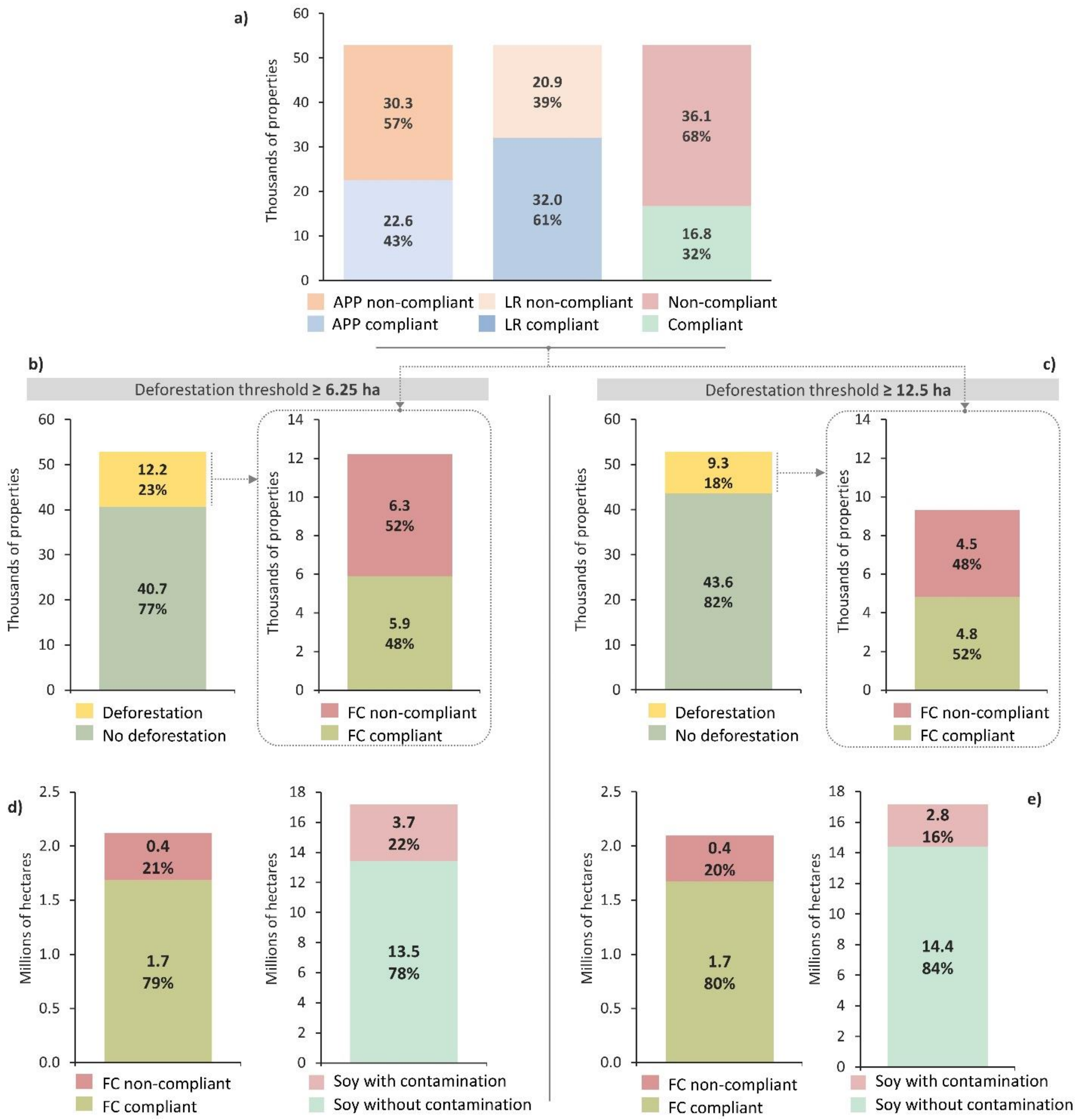


Fig. S16. Private rural properties growing soy with potentially legal and illegal deforestation in the Amazon biome. a) APP and LR compliance; b) total number of properties with deforestation and non-compliant and compliant properties with deforestation using a minimum threshold of 6.25 hectares; c) and using a minimum threshold of 12.5 hectares.

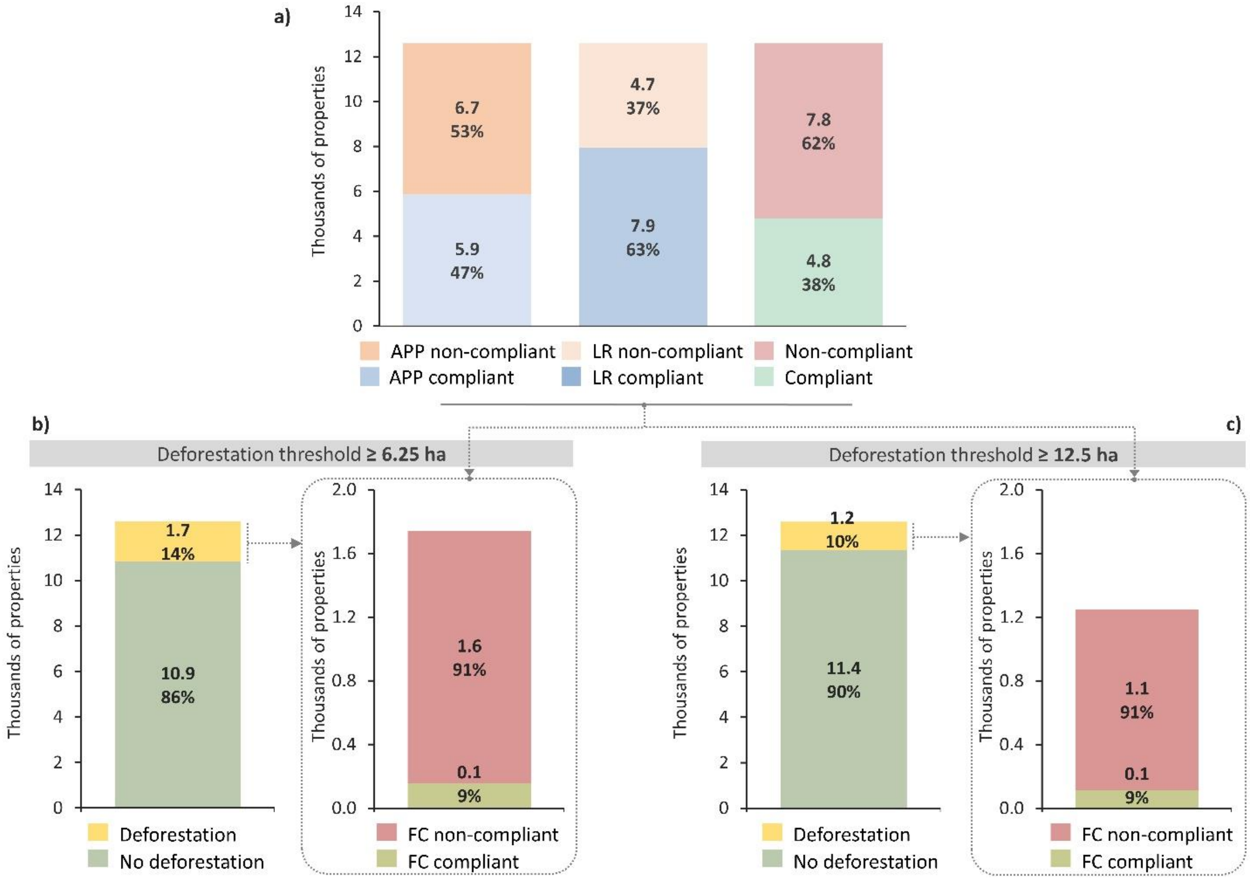


Fig. S17. Private rural properties growing soy with potentially legal and illegal deforestation in the Cerrado biome. a) APP and LR compliance; b) total number of properties with deforestation and non-compliant and compliant properties with deforestation using a minimum threshold of 6.25 hectares; c) and using a minimum threshold of 12.5 hectares.

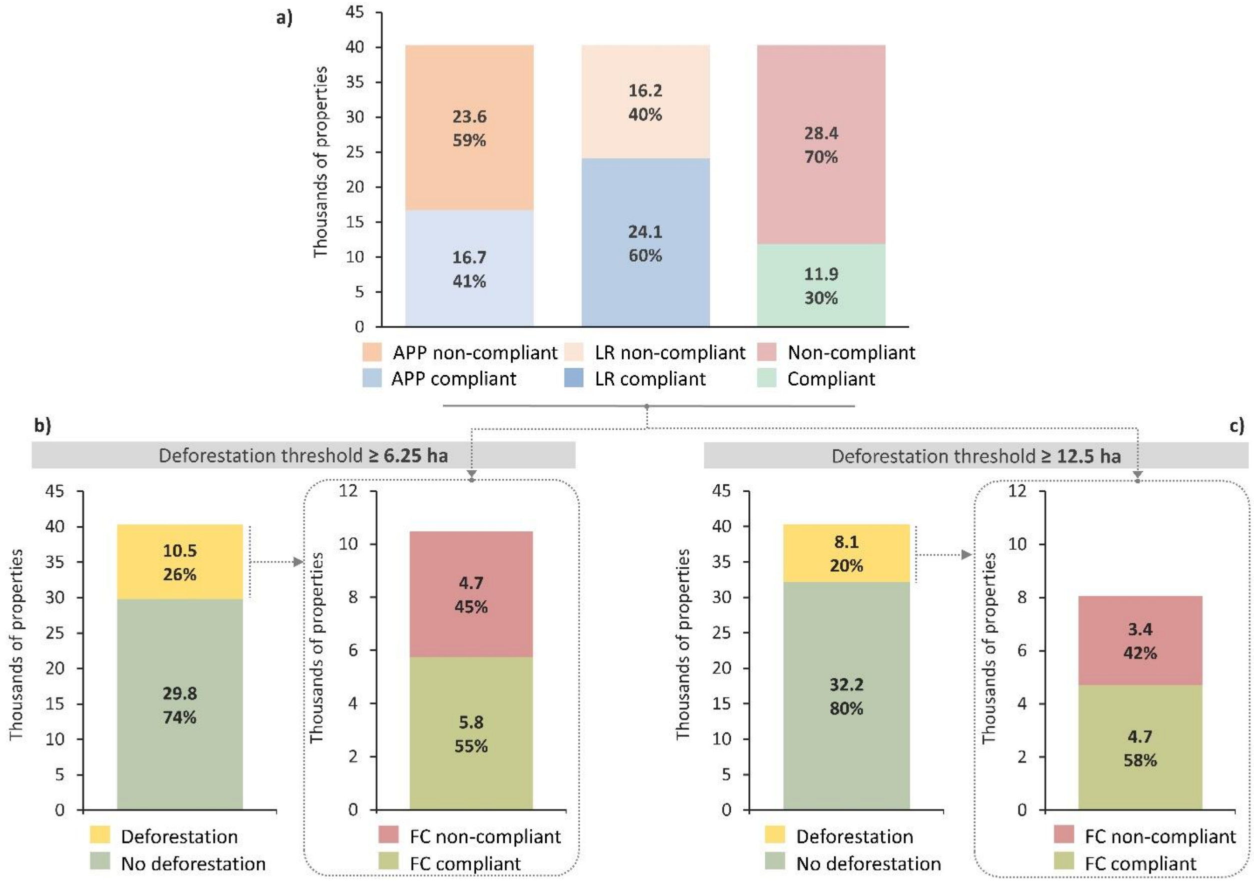


Fig. S18. Example of the FC modeling at the property level. The intercomparison exercise analyzed areas of native vegetation, required areas for conservation and the FC balance results (*i.e.* environmental debts and surpluses).

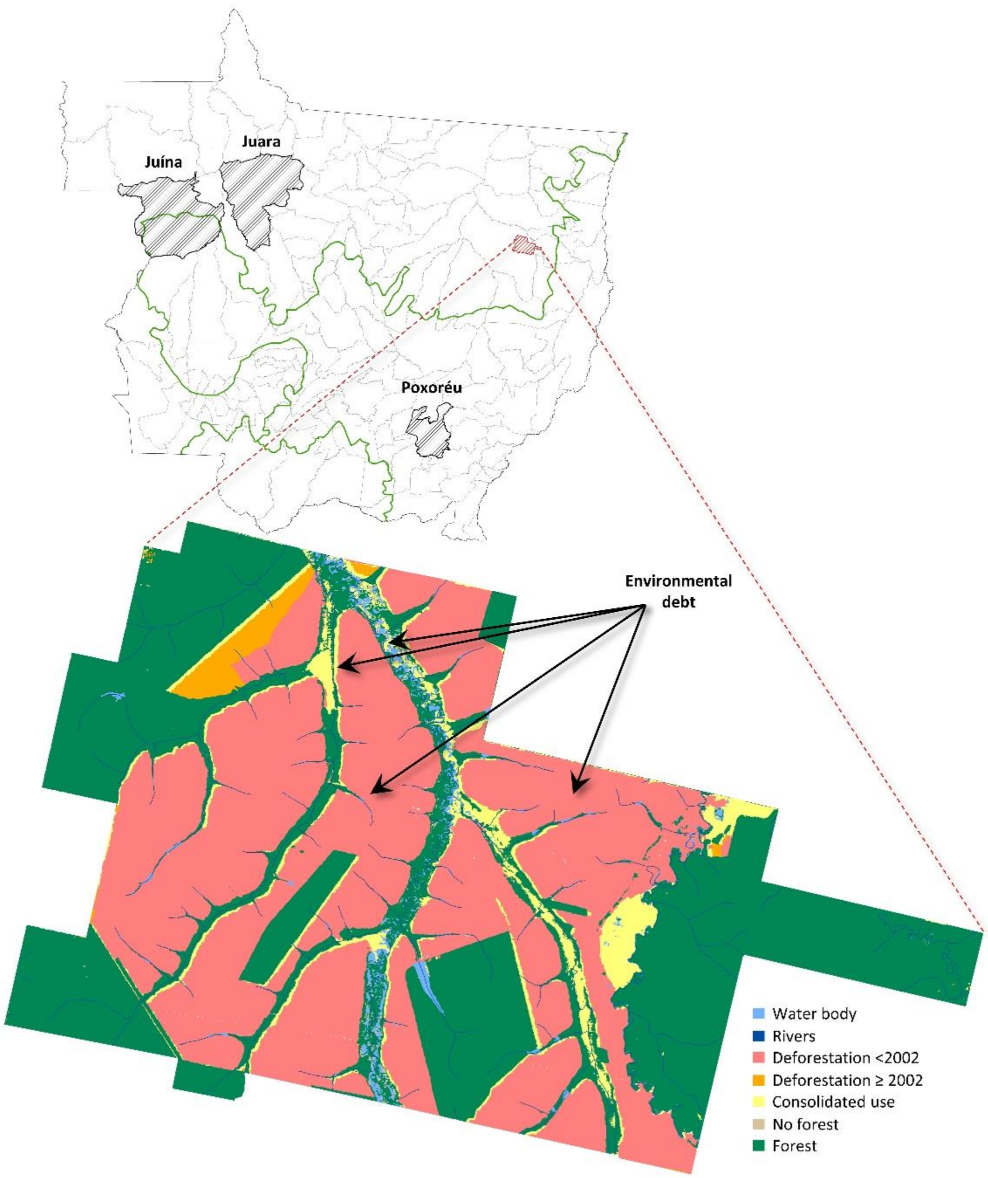
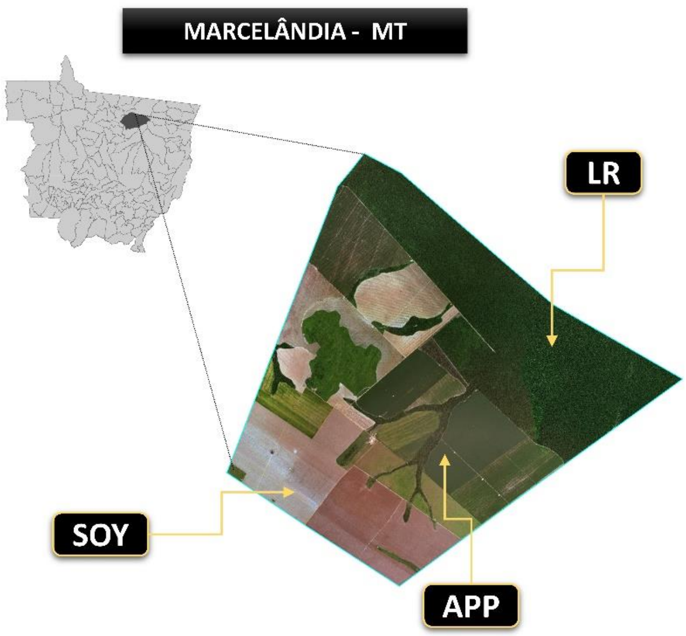
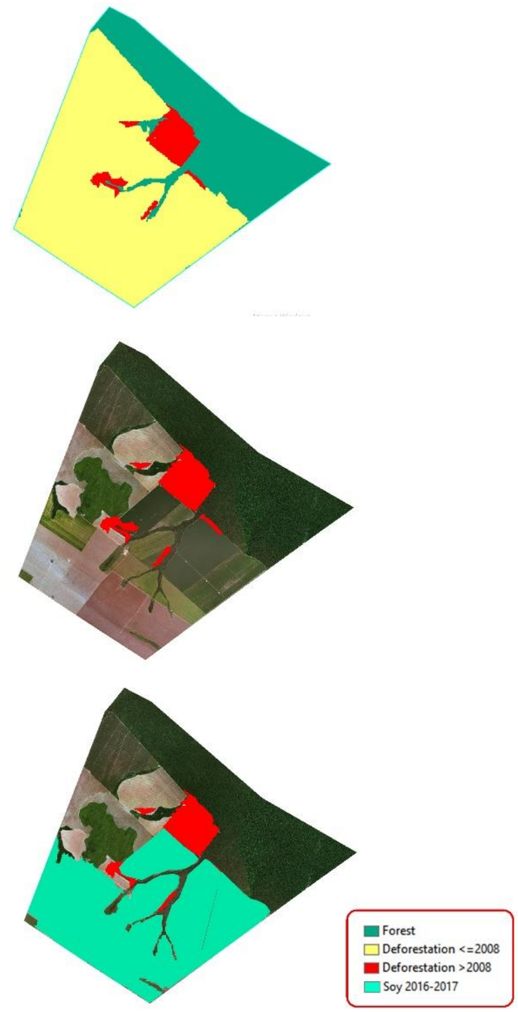


Fig. S19. Validation using high-resolution imagery to identify deforestation, soy crops, and verify estimates of the FC compliance at property-level.





Remnants of native vegetation	2704.2
Areas of Permanent Preservation (APP) debt	-13
Legal Reserve (LR) debt	-1092.0
Legal Reserve (LR) surplus	0

Fig. S20. Overlapping of potentially illegal deforestation within CAR properties with embargoes in the state of Mato Grosso, Brazil (*82*).

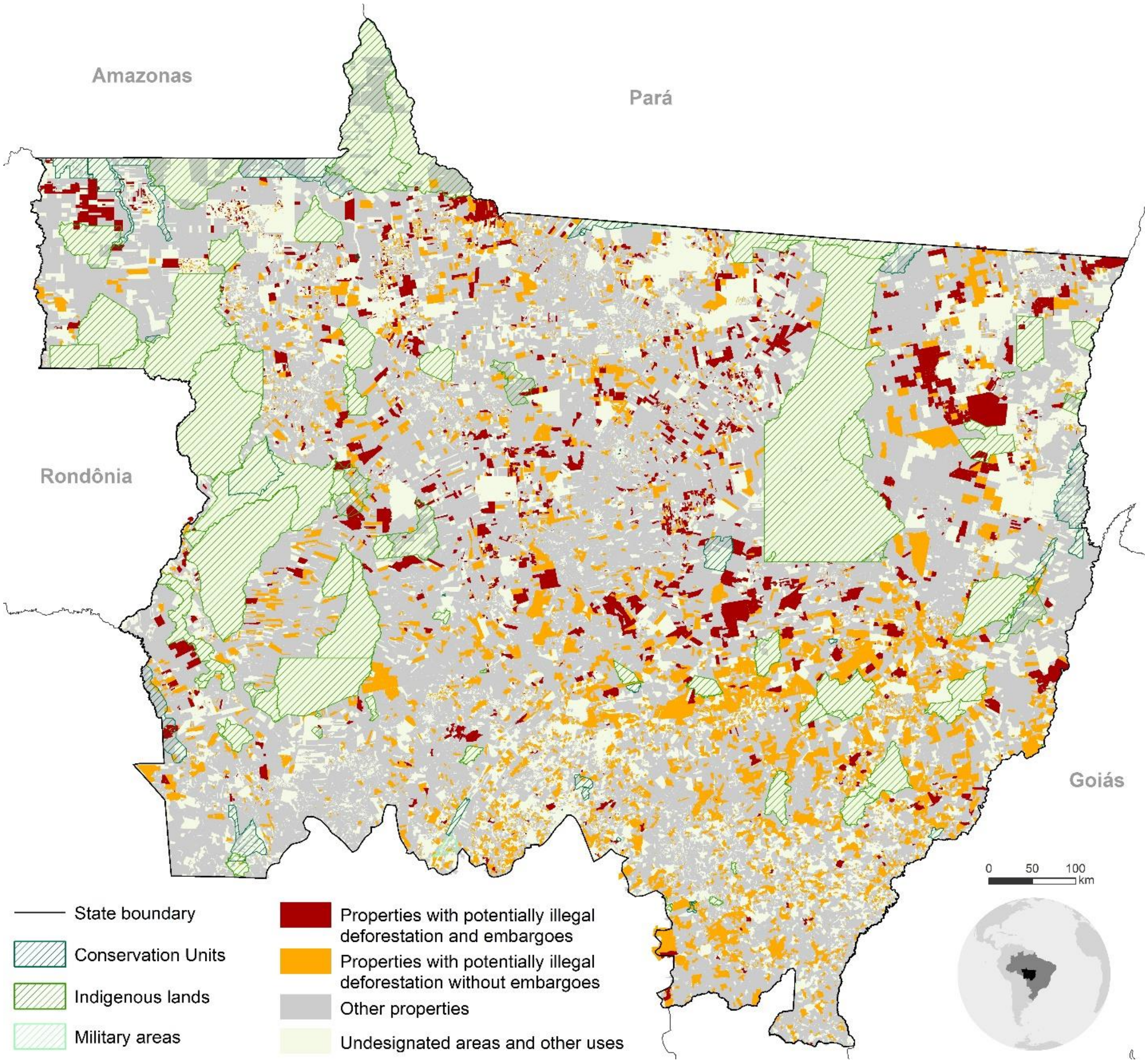


Fig. S21. Source and country destinations of soy potentially contaminated with potentially illegal deforestation. Estimated annual average between 2009 and 2017 from TRASE (47).

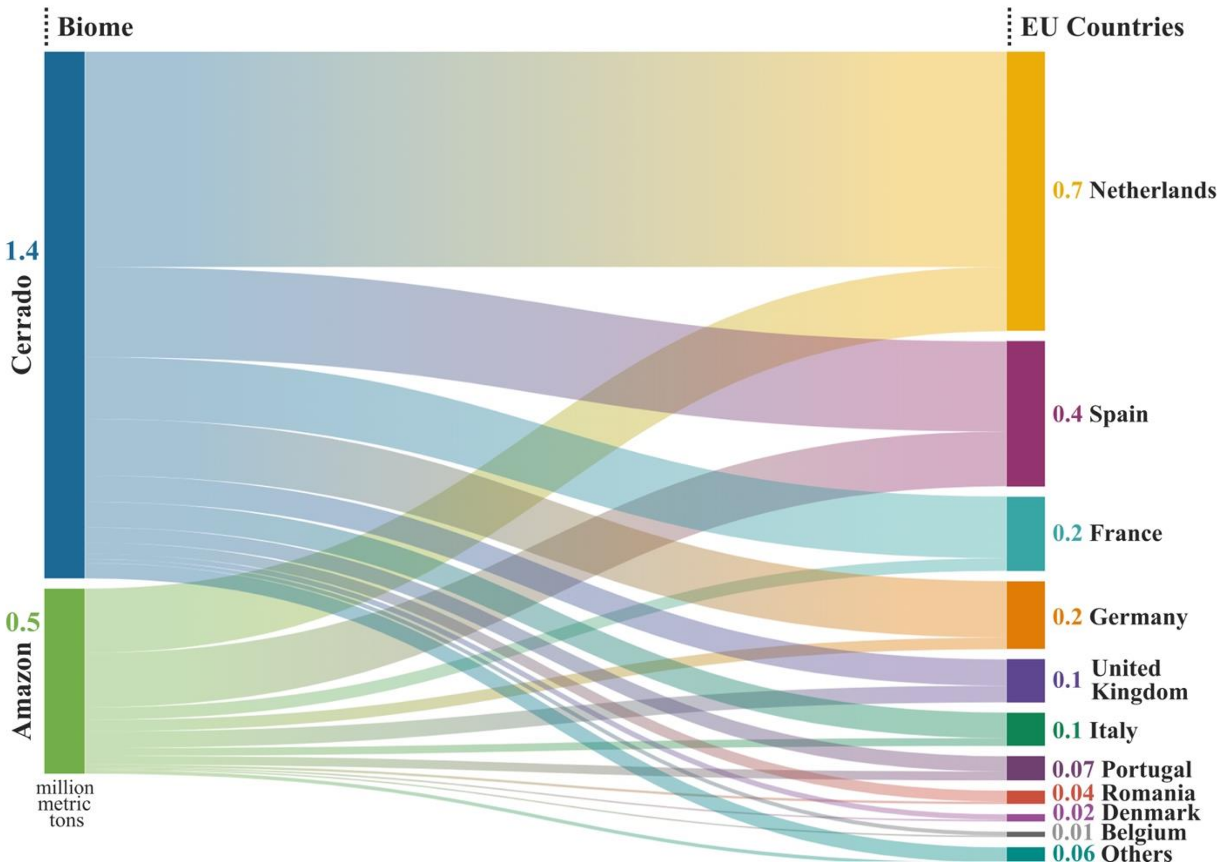


Fig. S22. Potentially illegal deforestation and deforestation-contaminated soy per municipality.

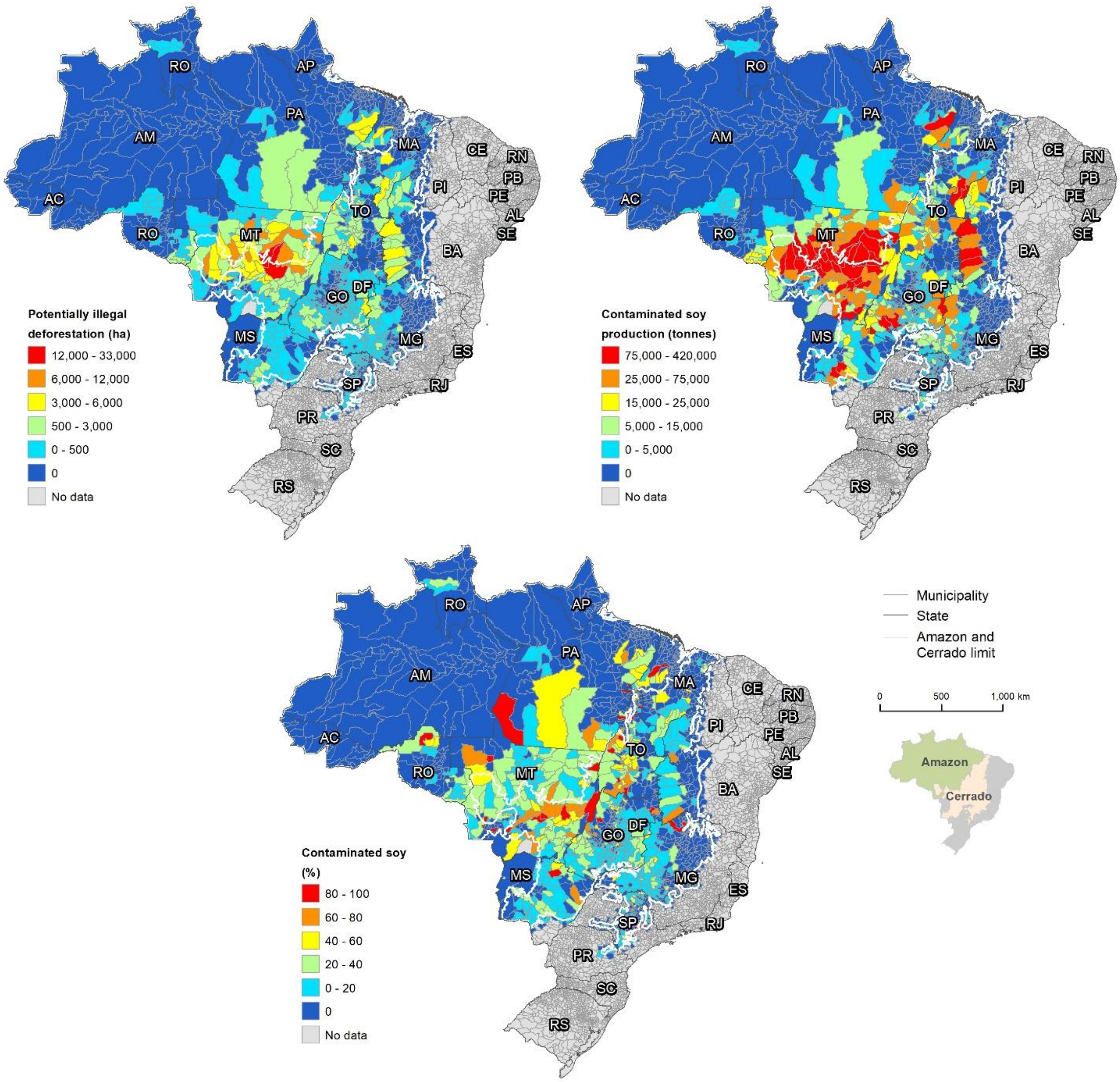


Fig. S23. Potentially legal and illegal deforestation within cattle ranches with CAR code identified by our analysis in the states of Pará and Mato Grosso, Brazil.

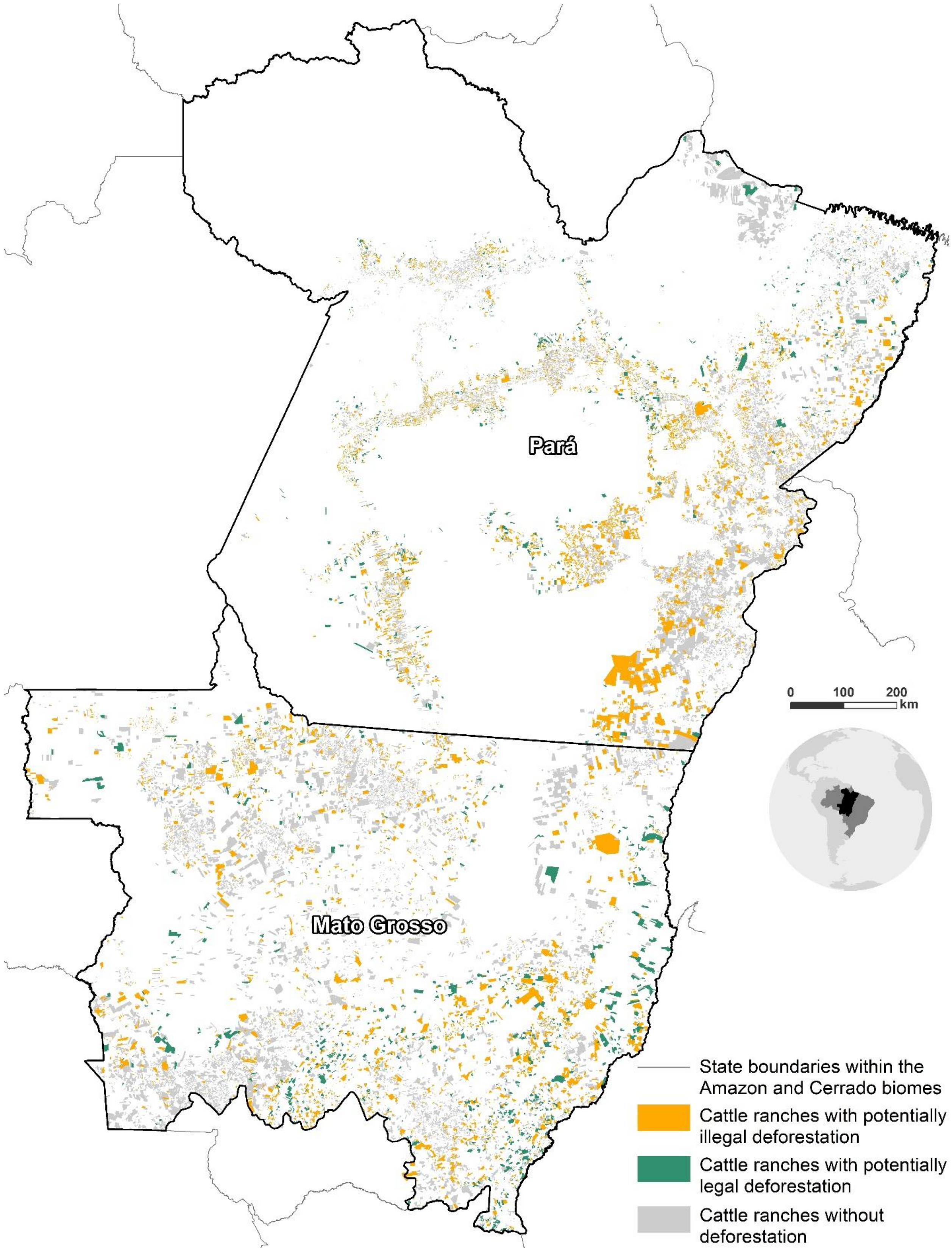


Fig. S24. Cattle-suppliers contaminated with potentially illegal deforestation identified by our analysis in the state of Pará and Mato Grosso, Brazil.

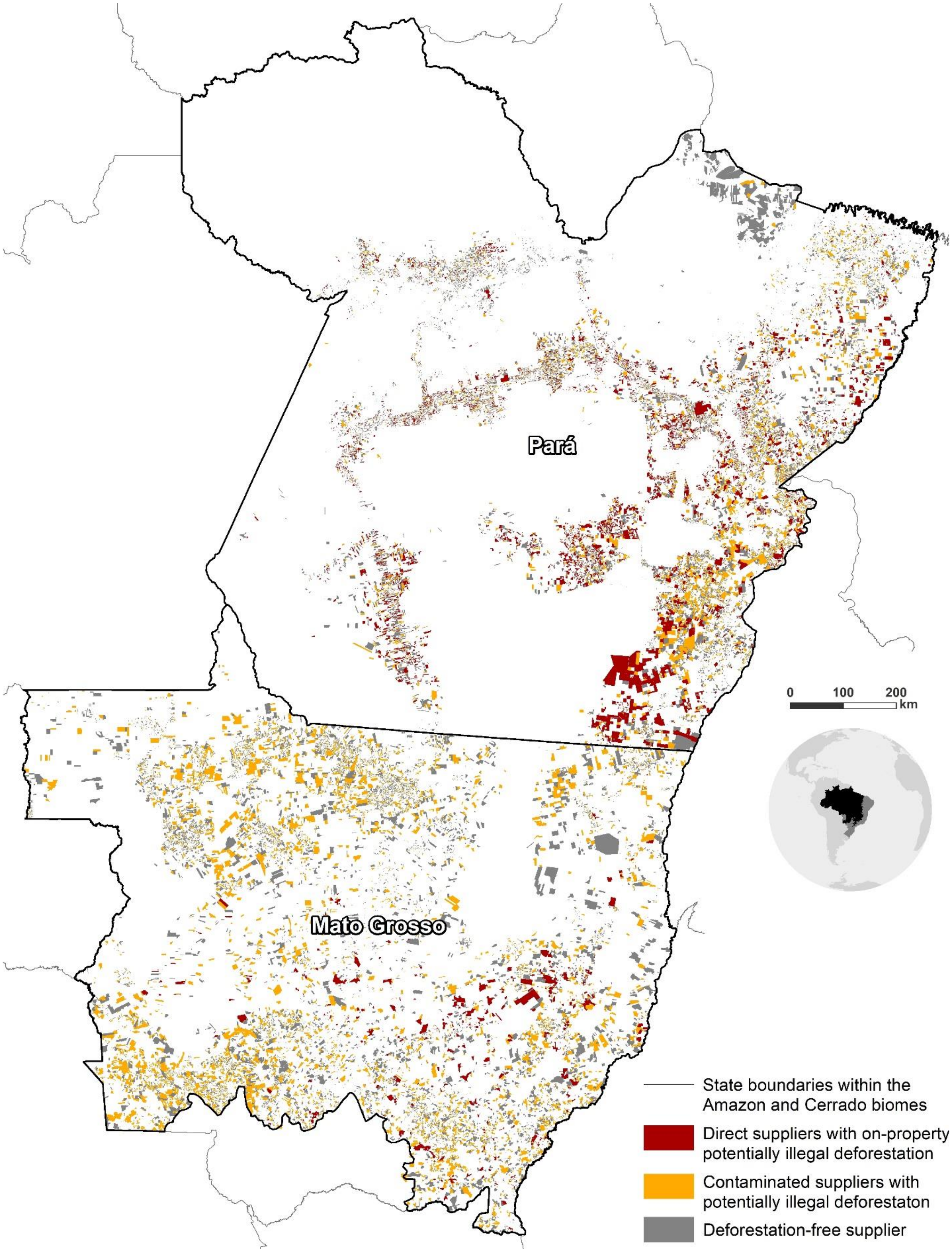


Fig. S25. Levels of deforestation contamination. Cattle ranch contamination based on deforestation thresholds (6.25 and 12.5 ha) and purchase from one property, whose sold lots contain at least 20% contaminated heads.

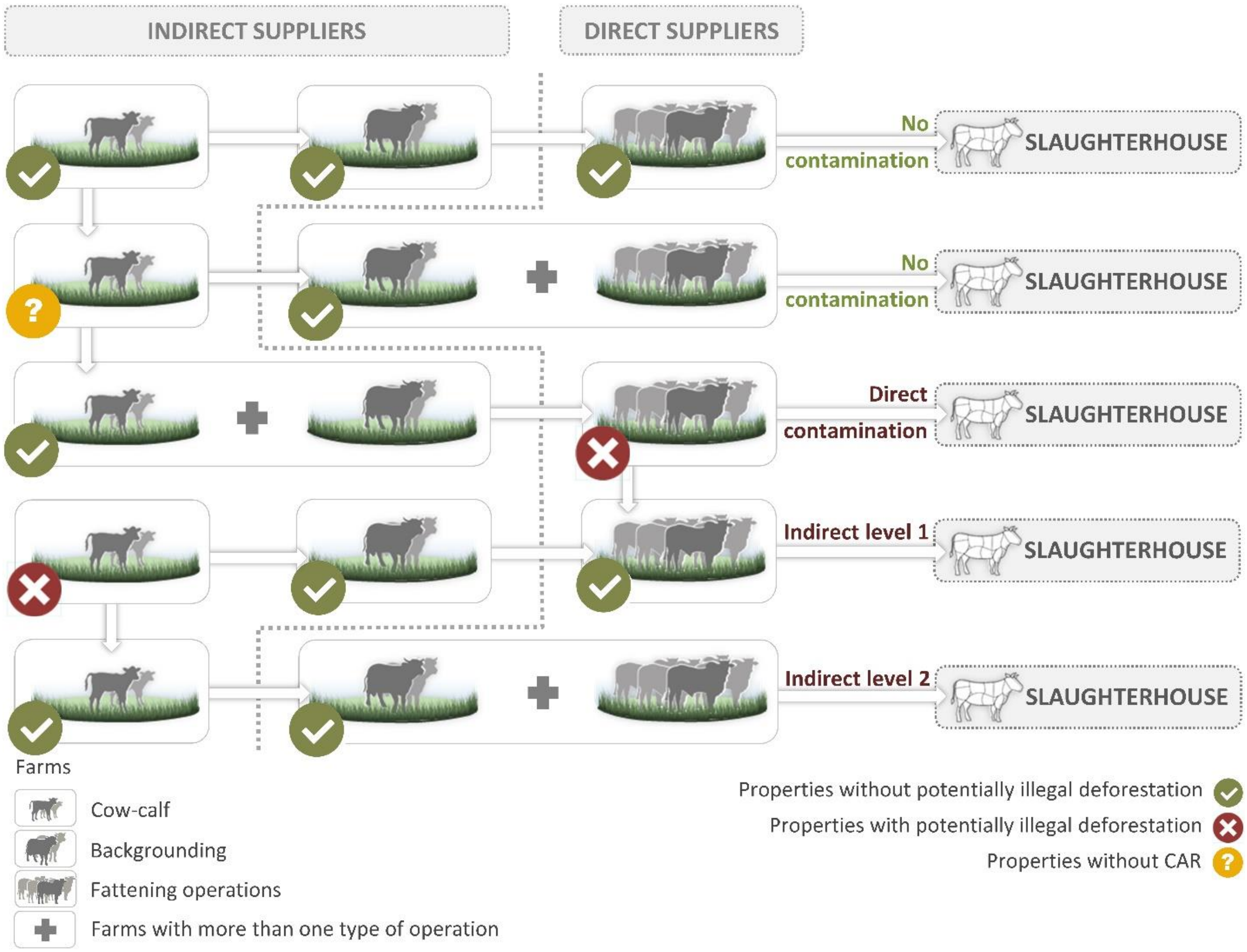
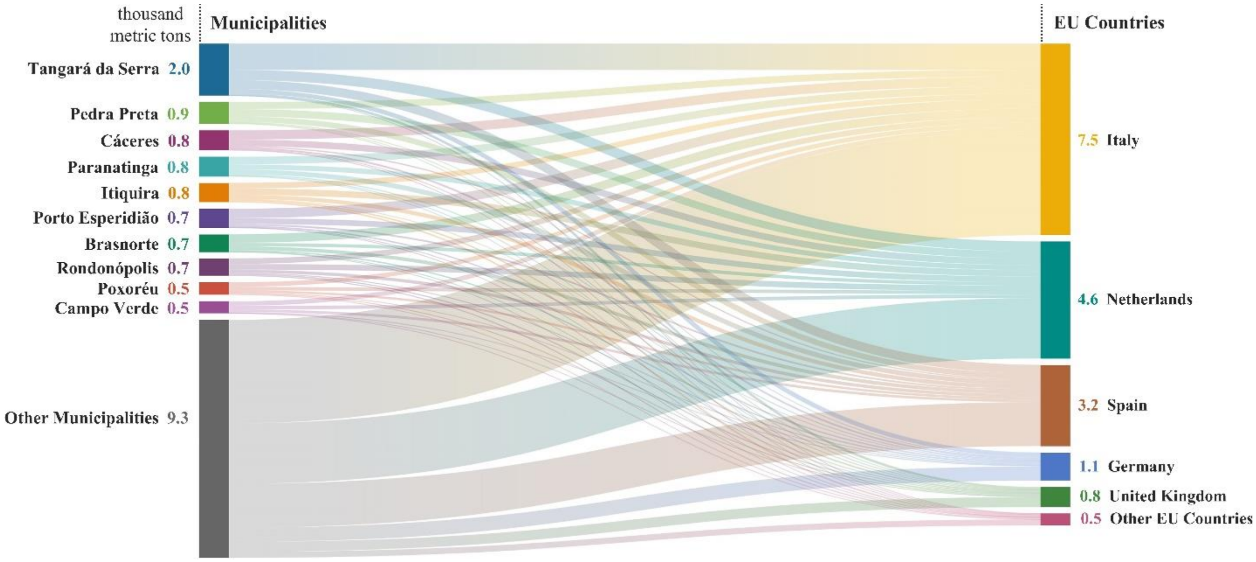


Fig. S26. Exports of beef potentially contaminated with illegal deforestation from municipalities of Mato Grosso and Pará state to the European Union in 2017. Total of 17.7±1.2 thousand metric tons*. Source: TRASE (*48*).



*Uncertainty calculated from non-traceable exports.

Fig. S27. Average aboveground and belowground potential carbon biomass in soy farms from MCTIC (*64*).

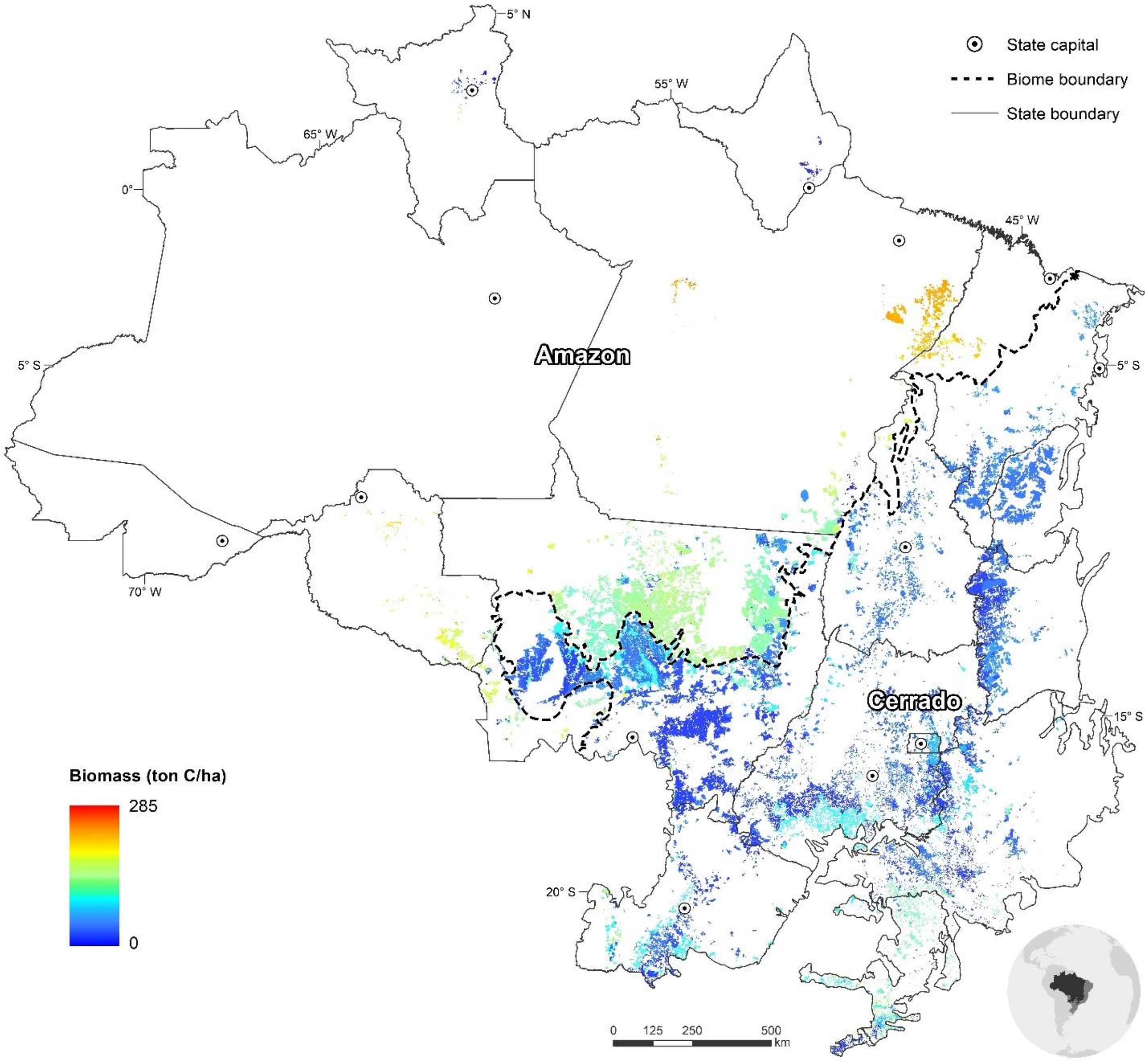


Fig. S28. Priority areas for cattle herd intensification in Brazil from Barbosa et al. (*83*).

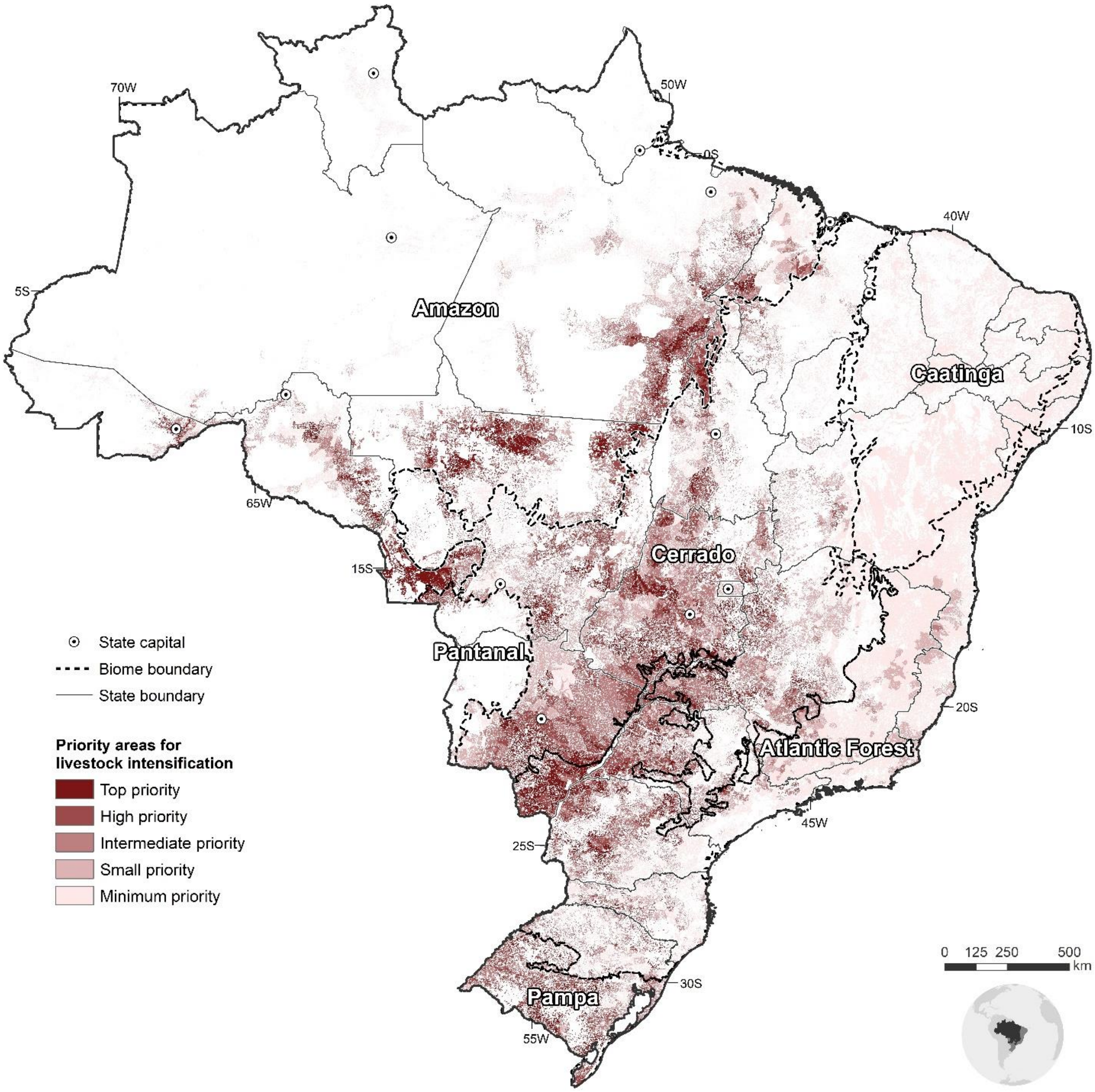


Fig. S29. Pareto principle applied to potentially illegal deforestation in the Amazon and Cerrado biomes. Roughly 20% of properties are responsible for 80% of potentially illegal deforestation (*66*). a) Both biomes, b) the Amazon biome, c) the Cerrado biome.

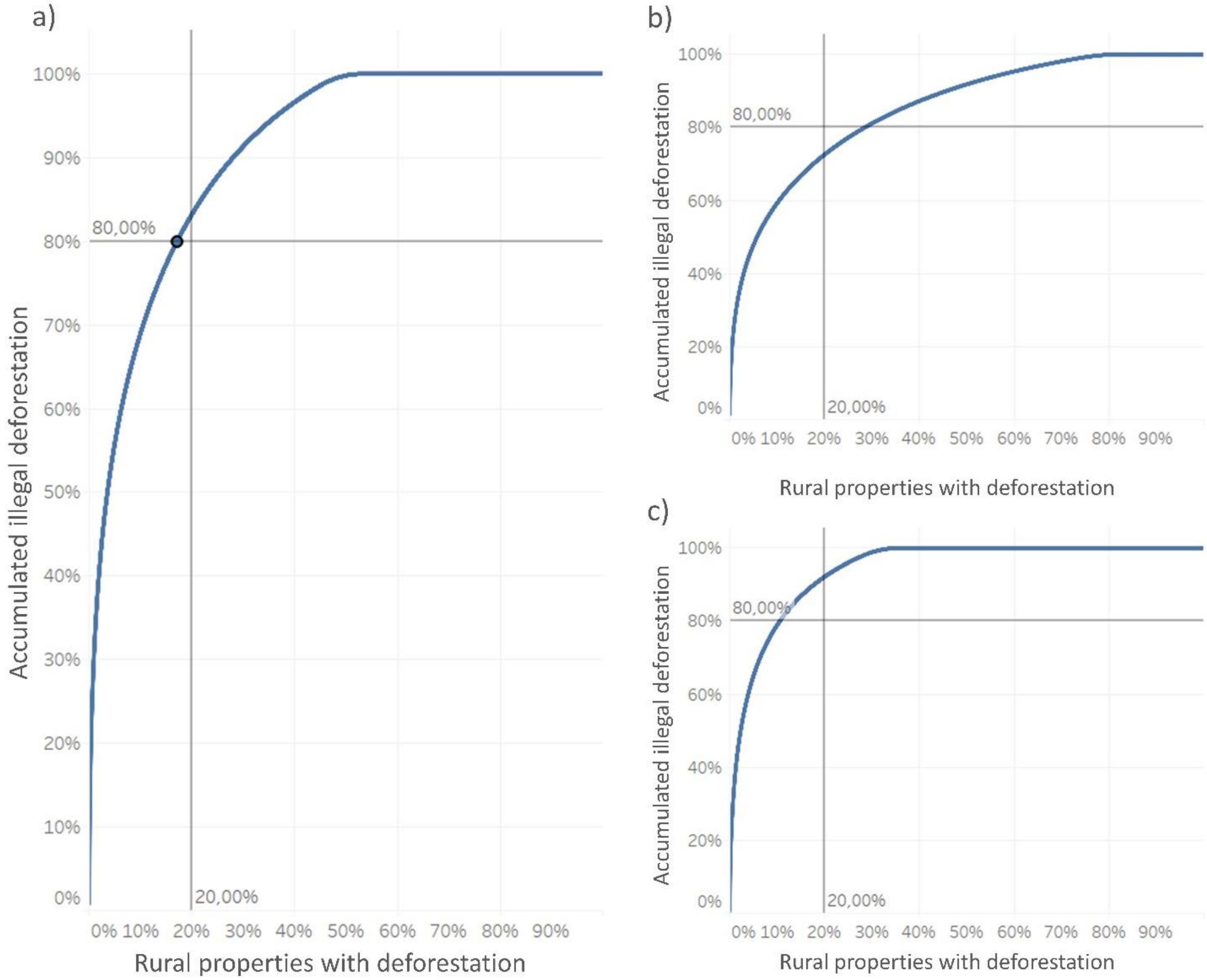


Fig. S30. Annual average of EU beef imports from Brazilian states between 2016 and 2017 (thousand metric tons). Source: TRASE (*84*).

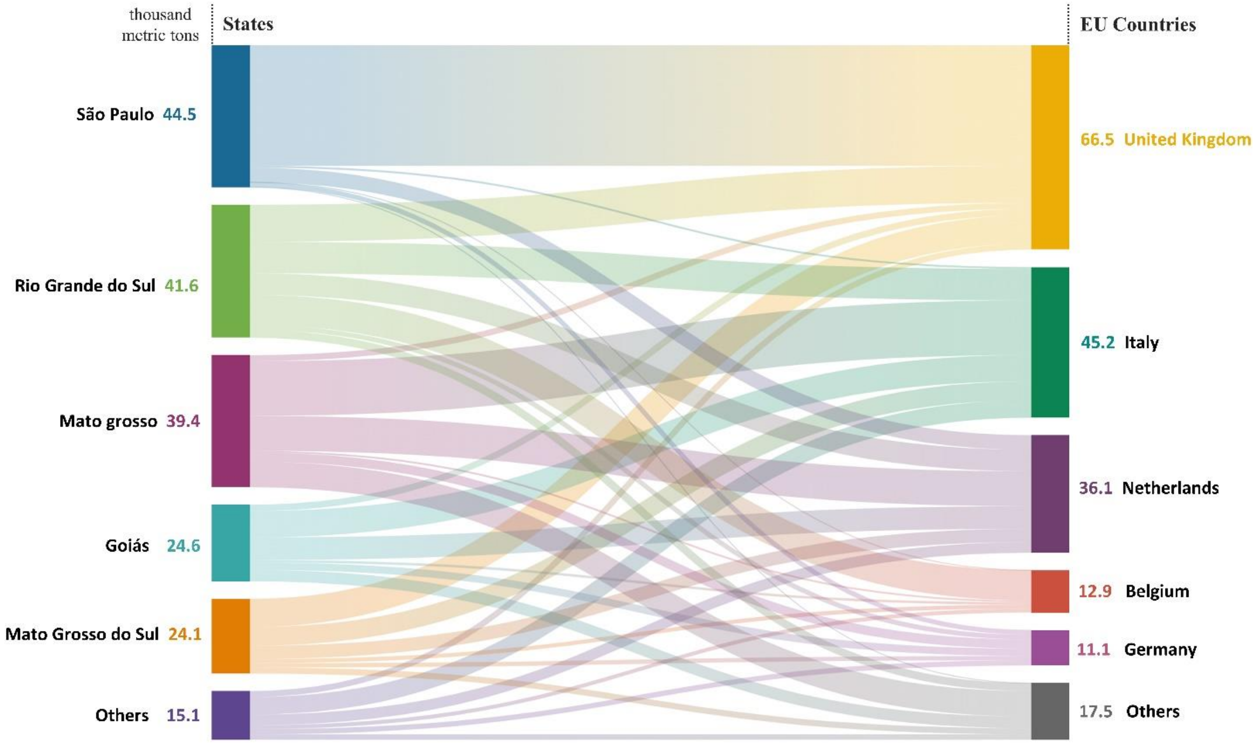


Table S1. Dataset.

Theme	Description	Source	Date of acquisition	Period covered	Reference
CAR	Brazil's national environmental registry of rural properties (CAR)	Imaflora	13/03/2019	2019	*53*
Land use	Land cover and land use in Brazil	Mapbiomas	03/2019	2008	*85*
Rivers	Rivers in Brazil	ANA	06/02/2019	2017	*86*
Deforestation	Annual deforestation in the Legal Amazon	INPE	07/08/2019	2007-2018	*13*
	Annual deforestation in the Cerrado biome		07/08/2019	2000-2018	
Vegetation Suppression Authorization	Authorization of vegetation suppression in the state of Mato Grosso	SEMA/MT	23/10/2019	2000-2019	*87*
Embargoed areas	Embargoed areas in the state of Mato Grosso.	SEMA/MT	24/10/2019	2011-2019	*82*
Planted area of soy	Planted area of soy in Amazon and Cerrado biomes	Agrosatélite Applied Geotechnology Ltd	01/11/2018	2016-2017	*45*
			24/05/2016	2013-2014	
Soybean exports	Quantity of soy exported between 2009 and 2017	TRASE	09/10/2019	2003-2017	*47*
Beef exports	Quantity of beef exported between 2016 and 2017	TRASE	16/03/2020	2015-2017	*48*
Administrative	Municipality boundaries	IBGE	27/04/2018	2017	*88*
	State boundaries	IBGE	27/04/2018	2017	*89*
Biomes	Amazon and Cerrado biomes	IBGE/MMA	22/05/2017	2004	*90*
Environmental Fines	Environmental fines applied	IBAMA	20/02/2020	1977-2020	*81*
Fiscal modules	Fiscal module sizes by municipality	INCRA	02/2016	2013	*91*
Animal Transportation Permits	Animal transportation permits (Portuguese acronym GTA)	GTA	03/03/2020	2017	-

Table S2. Potentially legal and illegal deforestation and available command-and-control data in the state of Mato Grosso/Brazil.

	Number of rural properties				
	Potentially legal deforestation	**Potentially illegal deforestation**	**No deforestation**	**Permits**	**Embargoes**
Potentially legal deforestation	3,670			125	586
Potentially illegal deforestation		10,661		192	2,501
No deforestation			76,979	263	2,716
Totals			**91,310**	**580**	**5,803**
% Properties with permits	3%	2%	0%		
% Embargoed properties	16%	23%	4%		

For period 2009-2018.

Table S3. Intercomparison of the Forest Code modeling exercises for the municipalities of Juará (Amazon), Juína (Amazon and Cerrado) and Poxoréu (Cerrado). Native vegetation remnants and areas required for conservation (APP an LR) in millions of hectares (Mha).

FC Model	Juará (Amazon)		Juína (Amazon and Cerrado)		Poxoréu (Cerrado)		Total
	Native vegetation remnants	Areas required for conservation	Native vegetation remnants	Areas required for conservation	Native vegetation remnants	Areas required for conservation	
	(Mha)		(Mha)		(Mha)		(Mha)
Imaflora	1.02	1.72	0.50	1.11	0.21	0.32	3.85
IPAM	1.03	2.47	0.51	0.95	0.21	0.36	4.51
CSR/UFMG	1.04	2.15	0.51	0.98	0.21	0.45	4.30
Average	1.03	2.11	0.51	1.01	0.21	0.38	4.22
Standard deviation	0.01	0.31	0.00	0.07	0.00	0.05	0.27
Coefficient of variation (CV)	1%	15%	1%	7%	1%	14%	6%

Table S4. Intercomparison of the Forest Code modeling exercises for the municipalities of Juará (Amazon), Juína (Amazon and Cerrado) and Poxoréu (Cerrado). Sum of debts and surplus.

FC model	Amazon Juará (Thousands ha)	Mix Juína (Thousands ha)	Cerrado Poxoréu (Thousands ha)	Total (Thousands ha)
CSR/UFMG	210	61	75	346
Imaflora	362	70	90	522
Average	286	65	83	434
Standard deviation	76	4	7	88
Coefficient of variation (CV)	26.6%	6.5%	8.9%	20.2%

Table S5. Validation of deforestation* and soy mapping** stratified per fiscal modules.

Fiscal modules	Number of properties	Mapping		High spatial resolution imagery		
		Deforestation*	Soy areas**	Deforestation	Soy areas	Accuracy
<= 2	113	113	113	104	113	**92%**
> 2 and <= 4	109	109	109	100	109	**92%**
> 4	99	99	99	93	99	**94%**
Total	321	321	321	297	321	**93%**

*PRODES (*13*) and **Soy mapping (*45*).

Table S6. Sample of properties growing soy in the Amazon and Cerrado biomes.

Properties with soy plantations	Number of properties	Area (Mha)
Total area	52,874	44.4
Planted soy area [a]	52,874	17.2
Legal Reserve debt	20,848	4.1
Deforestation post-2008 [b]	10,761	2.1
Potentially legal deforestation	5,363	1.7
Potentially illegal deforestation	5,399	0.4
Contaminated soy area [c]	5,399	3.7

[a] Soy production estimated at 51.7 million of metric tons yearly based on the 2016/2017 harvest season.
[b] Threshold of 6.25 hectares for soy plantations and 6.25 and 12.5 hectares for deforestation within each property.
[c] Soy production estimated at 11.3±1.1 million of metric tons yearly based on the 2016/2017 harvest season.

Table S7. Sample of properties growing soy and forest-clearings replacing forests with soy.

Sample of properties growing soy	Amazon	Cerrado	Total
		(Mha)	
Total soy planted area	4.48	17.1	21.6
Soy planted area within private properties	3.98	13.3	17.3
Soy planted area in deforested areas after 2008[a]	0.05	0.82	0.87
Direct deforestation	1%	5%	4%

[a] Estimates using a spatially-explicit approach.

Table S8. Mean annual soy imports by EU and Brazil's soy exports from 2009 to 2017.

EU soy imports (2009-2017)	Mtons	%
World[a]	33.3	-
Brazil	13.6	40.8
Brazil soy exports to EU per biome[b]		
Cerrado	7.18	52.9
Atlantic Forest	3.33	24.5
Amazon	2.20	16.2
Pampa	0.84	6.2
Pantanal	0.02	0.2
Caatinga	0.00	0

[a] World imports from EUROSTAT (*92*) and Brazil exports from TRASE (*47*). Brazilian soy imports from EUROSTAT are about 2% higher than TRASE data.

[b] 1.5 million tons not traceable by biome. Of this total, 48% comes from the state of Mato Grosso, while 29% comes from states with municipalities in the Amazon or Cerrado.

Table S9. Main agricultural commodities exported from Brazil to the world in 2019 (*93*).

Ranking*	Value FOB (billion US$)	Product
1º	26.1	Soy
4º	7.43	Meat of bovine animals, frozen, chilled and edible offal
5º	7.29	Corn
6º	6.49	Meat and edible offal of poultry
7º	5.18	Cane or beet sugar
8º	4.58	Coffee

*The ranking refers to all Brazilian commodities.

Table S10. Traceable exports of agricultural commodities from Brazil to the European Union.

Agricultural commodity	Traceable exports to EU (annual average)**	Non-traceable exports to EU (annual average)**	Share of non-traceable exports (%)
Soy*	15.7 Mtons	1.6 Mtons	11
Meat*	189 ktons	13.4 ktons	7

*Annual average soy exports between 2009 and 2017; annual average meat exports over the period 2016-2017.
**Source: TRASE (*47*).

Table S11. Annual average export of deforestation-contaminated soy to the EU by biome (2009/2017).

Biome	Soy contaminated with potentially illegal deforestation (Mtons)	Percentage	Total soy exported (Mtons)	Percentage
Cerrado	1.42±0.15	74%	7.18	77%
Amazon	0.49±0.05	26%	2.20	23%
Total	**1.91**±0.20	**100%**	**9.38**	**100%**

*Source: TRASE (*47*).

**Uncertainty calculated from non-traceable exports.

Table S12. Municipalities exporting soy contaminated with potentially illegal deforestation per harvest season.

	Soy harvest	
	2013/2014	**2016/2017**
Nº municipalities with contaminated soy	430	583
Nº municipalities exporting contaminated soy (TRASE)	422	553
Total contaminated in municipalities (Mha)	2.6	3.7
Total area of soy in municipalities (Mha)	11.7	16.7
Average contamination	22%	22%
Mean municipality contamination**	27.5%	27.5%
Standard deviation	25.3%	24.6%
Percentage of contaminated soy exported to EU	21.2%	20.8%

**Averaging the fraction of each municipality contamination.

Table S13. Levels of potentially illegal deforestation contamination in the states of Pará and Mato Grosso in 2017. Sample of cattle transported to slaughterhouses and abattoirs in 2017.

Levels of contamination	Million slaughtered cattle heads	%
No contamination	1.6±0.7	38±17
Direct	0.5±0.1	12±2
Indirect 1	1.2±0.4	30±9
Indirect 2	0.4±0.1	10±2
Indirect >= 3	0.3±0.1	8±3

*Estimated based on the average and standard deviations of contamination (deforestation thresholds and purchase from one property, whose sold lots contain at least 20% contaminated heads).

Table S14. Levels of potentially illegal deforestation contamination of slaughtered cattle in Mato Grosso state in 2017.

Levels of contamination	Amazon		Cerrado	
	Thousands of slaughtered cattle heads	%	Thousands of slaughtered cattle heads	%
No contamination	161.5	56%	56.1	39%
Direct	5.8	2%	18.7	13%
Indirect	121.1	42%	69.1	48%

*Estimated based on the average of contamination (deforestation thresholds and purchase from one property, whose sold lots contain at least 20% contaminated heads).

Table S15. Mean annual beef imports by EU and Brazil's exports per biome.

EU beef imports (2016-2017)	**Thousands metric tons**	**Percentage**
Total	480	
Brazil	189	39%
Brazil beef exports to EU per biome		
Cerrado	90.8	48%
Amazon	13.1	7%

*Total beef imports from EUROSTAT (*92*) and Brazil beef exports from TRASE (*48*). Brazilian beef imports from EUROSTAT about 15% higher than TRASE data.

Table S16. Deforestation-associated emissions from properties growing soy and the share of emissions embedded in soy imports from the European Union.

Biome	**Number of properties (thousands)**	**Annual soy production (Mtons)**	**EU annual soy imports (Mtons)[a]**	**Deforestation Post-2008 (Mha)**	**Deforestation-associated emissions ($MtCO_2$)**	**EU Share of emissions embedded in soy imports ($MtCO_2$)[b]**
Amazon	12.6	11.7±1.1	2.2±0.2	0.2	68.4±13.7	12.5±2.5
Cerrado	40.3	39.7±3.8	7.2±0.7	1.9	250.5±50.1	45.8±9.2
Total	52.9	51.4±5.0	9.4±0.9	2.1	318.9±63.8	58.3±11.7

[a] Estimated based on EU mean annual Brazil´s soy imports from 2009 to 2017 (*47*).
[b] Estimated based on the ratio between the annual average soy exports from Amazon and Cerrado biomes with their total annual soy production.

Table S17. Areas to be restored (LR and APP debts) according to the Forest Code within private properties and associated GHG removals estimates.

Properties	Biome	LR debt (Mha)	APP debt (Mha)	GEE removals ($GtCO_2$)
Properties growing soy	Amazon	1.62	0.07	0.32±0.06
	Cerrado	2.49	0.10	0.18±0.04
	Total	4.11	0.17	0.50±0.10
Properties raising cattle	Amazon	2.79	0.24	0.73±0.15
	Cerrado	1.55	0.22	0.14±0.03
	Total	4.34	0.46	0.87±0.17
Total		**8.45**	**0.63**	**1.37±0.27**

Table S18. Potentially legal and illegal deforestation per rural properties stratified by fiscal module from SICAR dataset in the Amazon and Cerrado biomes. Average of the thresholds of 6.25ha and 12.5ha.

Biome	Properties	Number of rural properties		
		<= 4 FM	> 4 FM	Total
Both biomes	No deforestation	591,107	104,188	695,294
	Potentially legal deforestation	26,655	29,809	56,463
	Potentially illegal deforestation	45,681	17,557	63,238
	Total	**663,442**	**151,553**	**814,995**
Amazon	No deforestation	285,755	33,619	319,374
	Potentially legal deforestation	3,378	3,713	7,091
	Potentially illegal deforestation	28,968	7,178	36,146
	Total	**318,101**	**44,509**	**362,610**
Cerrado	No deforestation	305,352	70,569	375,920
	Potentially legal deforestation	23,277	26,096	49,373
	Potentially illegal deforestation	16,713	10,380	27,093
	Total	**345,341**	**107,044**	**452,385**
Biome	**Properties**	**Area (millions of hectares)**		
		<= 4 FM	**> 4 FM**	**Total**
Both biomes	Potentially legal deforestation	0.97	5.01	5.98
	Potentially illegal deforestation	0.89	1.47	2.36
	Total	1.86	6.48	8.34
Amazon	Potentially legal deforestation	0.19	0.50	0.69
	Potentially illegal deforestation	0.64	0.78	1.42
	Total	0.83	1.28	2.11
Cerrado	Potentially legal deforestation	0.77	4.51	5.29
	Potentially illegal deforestation	0.25	0.69	0.94
	Total	1.02	5.20	6.23

*****2% of all properties (> 4 FM) are responsible for 62% of the total potentially illegal deforestation area.

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