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Massive soybean expansion in South America since 2000 and implications for conservation

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Abstract

A prominent goal of policies mitigating climate change and biodiversity loss is to achieve zero-deforestation in the global supply chain of key commodities, such as palm oil and soybean. However, the extent and dynamics of deforestation driven by commodity expansion are largely unknown. Here we mapped annual soybean expansion in South America between 2000 and 2019 by combining satellite observations and sample field data. From 2000–2019, the area cultivated with soybean more than doubled from 26.4 Mha to 55.1 Mha. Most soybean expansion occurred on pastures originally converted from natural vegetation for cattle production. The most rapid expansion occurred in the Brazilian Amazon, where soybean area increased more than 10-fold,

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Data Availability: The annual soybean maps generated in this study can be viewed and downloaded at: https://glad.earthengine.app/view/south-america-soybean and https://glad.umd.edu/projects/commodity-crop-mapping-and-monitoring-south-america. Forest change maps are available at: https://earthenginepartners.appspot.com/science-2013-global-forest

Code Availability: Satellite-based soybean classification was carried out using the GLAD Landsat Analysis Ready Data and Tools[52], available at: https://glad.geog.umd.edu/ard/home. Custom code for analyzing soybean-driven deforestation is available from corresponding authors upon reasonable request.

from 0.4 Mha to 4.6 Mha. Across the continent, 9% of forest loss was converted to soybean by 2016. Soy-driven deforestation was concentrated at the active frontiers, nearly half located in the Brazilian Cerrado. Efforts to limit future deforestation must consider how soybean expansion may drive deforestation indirectly by displacing pasture or other land uses. Holistic approaches that track land use across all commodities coupled with vegetation monitoring are required to maintain critical ecosystem services.

To feed a growing population, global food production needs to increase by 70–100% by 2050[1]. The rising demand for food has caused massive deforestation across the tropics, leading to greenhouse gas emissions, loss of terrestrial biodiversity and deterioration of ecosystem services[2–6]. Land used to produce soybean is rapidly expanding in the agricultural frontiers of South America, replacing natural vegetation, pastures, and other cropland[7,8]. Soybean, a major oil crop that originated from China, is the world's largest source of protein for animal feed and the second largest source of vegetable oil after palm. Global production of soybean has more than doubled since 2000 and more than quadrupled since 1980[9]. About 70% of the production increase was from expansion of harvested area and 30% from yield gain[10]. More than half of the world's soybean production currently resides in South America, where soybean harvested area has increased since 2000 by 160% in Brazil and by 57% in Argentina with relatively smaller yield growth (< 30%) in both countries[9]. Over the same period, China's soybean import from Brazil has surged by 2000%[9], mostly for providing animal feed to meet the increasing meat consumption in China. The escalating trade tensions between the U.S. and China are expected to motivate China to seek more imports from South America, incentivizing deforestation, especially at the frontiers[11]. To fill the U.S. shortfall, as much as 13 million hectares of additional soybean land are needed[11].

Meanwhile, many regional and international initiatives are being developed to remove deforestation from commodity supply chains[12]. A successful example is the Amazon Soy Moratorium, a voluntary agreement signed by traders who committed not to buy soybeans sowed on deforested lands in the Brazilian Amazon after 2008[13]. A number of studies have investigated the role of soybean in driving deforestation in Brazil as well as the effectiveness of forest-protection policies[14–22]. For example, Gibbs *et al.* (2015) analyzed satellite data from before and after the Amazon Soy Moratorium and demonstrated that it was effective in reducing deforestation[14]. Soterroni *et al.* (2019) applied a land use model and evaluated the potential deforestation-reduction effect of extending the soy moratorium to the Cerrado biome[20]. The soy moratorium for the Amazon was renewed indefinitely in 2016, but the Cerrado biome was only recently covered by a voluntary manifesto signed by civil society organizations in 2017 without legal enforcement[23]. Protection policies for other biomes lag even further behind the Amazon and Cerrado. These previous studies have generated valuable scientific insights in regional dynamics of commodity-driven deforestation. However, a long-term, continental perspective does not exist, primarily due to lack of spatially explicit data on commodity expansion. Mapping post-deforestation land uses for commodity production is critical for designing and implementing commodity-specific conservation policies. Ideally, such data should be derived at a high spatial resolution to match the scale of land use, over a long temporal span to establish a baseline, and over a large geographical extent to allow for the assessment of the potential issue of land-use displacement[24].

In our study we mapped annual soybean extent at 30-meter spatial resolution over the southern hemisphere of South America from 2000 to 2019. Our study area encompasses all major biomes where soybeans are cultivated: Amazonia, Atlantic Forest, Cerrado, Chaco, Chiquitania, Pampas, and more recently, Pantanal and Caatinga biomes. Our maps were produced using wall-to-wall Landsat and Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data, a stratified random sample of Sentinel 2 satellite data, and three years of continent-wide field observations. We assessed the accuracy of the maps using data collected from field visits obtained at sample pixels selected by a stratified two-stage cluster sampling design. The soybean classification map was then tailored so that the area of mapped soybean was constrained to match the field-based sample area estimates over South America. Our analysis revealed the extent and expansion of soybeans over the past two decades in South America with unprecedented precision. The high-resolution, annual soybean maps we generated provide valuable spatial information, which is absent in government statistics, for monitoring commodity crop growth. More importantly, complementary to the operational annual forest change mapping[3,25], these soybean maps provide key historical baseline information for tracking commodity-driven deforestation.

To better understand the shifting dynamics of land-use change in South America in the 21st century we quantified the amount of primary forests, non-primary forests, non-forest natural vegetation, pre-existing croplands and pastures that were replaced by soybean. We also integrated the annual soybean maps with annual forest loss maps, and quantified deforestation caused by soybean as a direct and latent driver, highlighting emerging hotspots of soybean expansion as a direct driver of deforestation. For simplicity in reporting subsequent results, we refer to a cropping year by the harvest year. For example, year 2001 indicates the 2000/2001 cropping year.

Continental and regional patterns of soybean expansion

Based on satellite observations, soybean area in South America increased from 26.4 Mha in 2001 to 55.1 Mha in 2019 (Fig. 1). This doubling of soybean cultivated area was mainly contributed by the two largest producing countries, Brazil and Argentina. Soybean area in Brazil increased by a factor of 2.6, from 13.4 Mha in 2001 to 34.2 Mha in 2019 (average growth rate 1.2 Mha/year). Soybean area in Argentina increased by a factor of 1.7, from 11.4 Mha in 2001 to 19.9 Mha in 2015 (average growth rate 0.6 Mha/year), which then gradually declined to 16.3 Mha in 2019.

The spatial extent of soybeans has been expanding from traditional cultivation regions in all directions across the continent (Fig. 1). In South Brazil (the states of Paraná, Santa Catarina and Rio Grande do Sul), soybeans have been expanding into surrounding regions, most notably onto higher slopes. In the traditional breadbasket of Argentina (the provinces of Buenos Aires, Córdoba, Santa Fe and Entre Ríos), new soybean fields have been spreading to the south. However, in the agricultural frontiers in Brazil's center-west and northeastern states, the principal direction of soybean development is towards the equator (Fig. 2a and

2b). In northwest Argentina, soybeans have been encroaching into Chaco ecosystems from both the western and eastern sides (Fig. 2c). In eastern Paraguay, an established agricultural landscape, the area of land under soybean cultivation continues to grow, threatening to replace remnant Atlantic forests (Fig. 2d), whereas in the western Paraguayan Chaco, soybean fields have just started to emerge. In central Bolivia, soybeans are rapidly replacing the Chiquitania forests, and in southwest Uruguay, vast areas of Campos pasture/grassland are being transformed for soybean production.

Land source attribution of new soybean fields

To attribute and quantify the original land source of new soybean fields, we first constructed a 30-m resolution, circa-2001 land-cover map, consisting of primary humid forests[26], non-primary forests[3], cropland[8] and other land (mostly pasture/grassland). We then overlaid 2002–2019 annual soybean maps on the 2001 land-cover map, identified the 2001 land source of soybean pixels for each subsequent year, and summarized results for every biome. We found that the rates of conversion of forests, pasture/grassland, and pre-existing cropland to soybean varied substantially among biomes (Fig. 3). The conversion of primary humid forests to soybean was apparent in the Brazilian Amazon and Chiquitania. Soybean area in the Brazilian Amazon increased more than 10-fold from 0.4 Mha in 2001 to 4.6 Mha in 2019 with 32% of the 4.2 Mha added soybean sourced from year 2001 primary forests, 17% from non-primary forests and 51% from previously cleared pastures[8] (Fig. 3). Soybean expansion in the Chiquitania in Bolivia followed similar trends as those in the Brazilian Amazon with 25% of new soybean fields in 2019 sourced from year 2001 primary humid tropical forests, 37% from other forests, and 38% from pasture/grassland.

Soybean cultivated areas in the Pampas, Cerrado and Atlantic Forest, the three biomes with the largest soybean cultivation, all nearly doubled over the past two decades (Fig. 3). While 18% (1.7 Mha) of new soybean fields in the Cerrado and 20% (1.0 Mha) of new soybean fields in the Atlantic Forest were sourced from dry forests and non-primary humid forests, respectively, almost all new soybean fields in the Pampas were converted from non-forest lands. Forest cover and forest loss in the Pampas were relatively low compared to the Cerrado and Atlantic Forest (Supplementary Table 1 and Supplementary Fig. 1). Our results for the Cerrado are consistent with previous studies[17–19]. Soybean cultivation has been rapidly developing in the Caatinga and Pantanal since 2013, albeit at smaller magnitudes than in other biomes (Fig. 3). The main land source (87%, 16 Kha) for new soybean fields in the Caatinga was semi-arid woodlands, whereas the main land source (76%, 11 Kha) for new soybean fields in the Pantanal was pasture/grassland.

Our map-based attribution analysis indicated that substantial areas of both forest and non-forest vegetation were converted to soybean. To further distinguish conversion of native vegetation from conversion of pastures within non-forest vegetation, we conducted a sample-based attribution analysis using a time-series of satellite data and high-resolution images in Google Earth (see details in Methods). Of soybean area established on non-forest vegetation, 6% was converted from native vegetation and 94% replaced land uses such as pasturelands. Much of the converted pasturelands resulted from clearing of forest and non-forest natural vegetation that predated the study period[8].

Soybean expansion as a direct vs. latent driver of deforestation

To characterize the role of soybean expansion in driving deforestation, we combined our annual soybean data layers and the annual forest loss dataset[3] over 2001–2019, focusing on distinguishing direct versus latent drivers. We defined new soybean as any pixel that was mapped as soybean for two consecutive years for the first time after 2001. The time difference between forest loss and the first soybean appearance is a key metric indicating soybean as a direct or latent driver of deforestation. For soybean as a direct driver, the interval from clearing of forests to mechanized soybean cultivation is three years or less, depending on the market price, road accessibility, land clearing status and soil preparation (Supplementary Fig. 2)[13,14]. For soybean as a latent driver, defined as new soybean that appeared more than three years following forest loss, cattle ranching prior to soybean is the most common land-use pathway[13]. For each 30 m pixel, we calculated the time lag between forest loss and the new appearance of soybean, and then computed the 25th percentile (Q_1), the median, and the 75th percentile (Q_3) by biome. In the Cerrado, the median time lag was estimated to be 3 years (Q_1=2 years, Q_3=5 years), considerably shorter than the median of 5 years in the Brazilian Amazon (Q_1=3 years, Q_3=9 years) and the median of 4 years in the Chaco (Q_1=2 years, Q_3=6 years). The shorter time lag in the Cerrado suggests that soybean cultivation was a direct driver of clearing forests in this biome more often than it was in the Brazilian Amazon.

Direct soybean-driven deforestation reached a total of 3.4 Mha between 2001 and 2016. This dynamic accounted for 5% of the 71.9 Mha of total forest loss during this period. Of the 3.4 Mha directly converted from forest to soybean, 1.5 Mha (44%) was located in the Cerrado, 0.7 Mha in the Brazilian Amazon and 0.5 Mha in the Chaco (Table 1). The area of deforested land that experienced latent soybean cultivation (>3 years after clearing) amounted to 2.9 Mha between 2001 and 2016, accounting for 4% of total forest loss. This relatively low total reinforces the fact of soybean largely replacing long established pasture land uses. Of the latent driven deforestation, 1.0 Mha (34%) was located in the Brazilian Amazon, 0.9 Mha in the Cerrado and 0.5 Mha in the Chaco (Table 1). In addition, from 2001 to 2016, new soybean fields directly converted from forests accounted for 13% of the total soybean gain over the continent and soybean indirectly converted from forests accounted for 11% of total soybean gain. Relative to the total soybean gain within a biome, the majority of soybean gain in the Chiquitania (62%) and Caatinga (57%) and about half of soybean gain in Chaco (48%) was from direct deforestation (Table 1).

Temporally, direct soybean-driven deforestation in the Brazilian Amazon increased from 2001 to 2003, declined in 2004 and 2005, totaling 356 Kha during 2001–2005, and remained relatively low thereafter, totaling 336 Kha during 2006–2016 (Fig. 4). In the Cerrado, soybean-driven deforestation also increased before 2004 and declined in 2005, totaling 637 Kha during 2001–2005, but stayed relatively high thereafter, totaling 856 Kha during 2006–2016. A declining trend after an initial increase was also found in the Chaco, but annual soybean-driven deforestation stayed relatively flat in the Atlantic Forest and Chiquitania, albeit at smaller magnitudes.

These temporal trends were also apparent at the municipal scale. Between 2001 and 2016, 14 municipalities had more than 50 Kha deforestation directly driven by soybean expansion, with Tapurah (137 Kha) of Mato Grosso, Brazil leading the list (Supplementary Fig. 3a). Of the top 14 municipalities, five were in Mato Grosso, Brazil, five in the Cerrado and Amazon transition states – Maranhão, Tocantins, Piauí and Bahia – collectively known as "MATOPIBA", two in Santa Cruz, Bolivia, one in Salta and one in Santiago del Estero, Argentina. These municipalities represent the active frontiers of agricultural expansion in the 21st century. As the deforestation wave moved towards the Amazon interior and with the onset of enforcement of the Amazon Soy Moratorium in 2008, soybean-driven deforestation in most municipalities in central Mato Grosso has been decreasing or stagnating (Supplementary Fig. 3b). We also observed decreasing soybean-driven deforestation in the Argentine Chaco. Soybean planted area in Argentina has stagnated after 2015 as farmers have switched from soybean to corn in response to a larger reduction in export taxes on grains[27]. However, soybean-driven deforestation has been increasing in municipalities in MATOPIBA and eastern Pará. The largest increase occurred in Paragominas in the Brazilian State of Pará, from an average of 1000 ha/year between 2006 and 2008 to an average of 3300 ha/year between 2014 and 2016. Nevertheless, regardless of soybean as a direct or latent driver of deforestation, our results show that soybeans have been progressively encroaching onto previously forested lands at the active frontiers over the past two decades (Supplementary Fig. 4).

Implications for conservation policy

Quantification of soybean expansion as a direct driver of deforestation can facilitate commodity-specific conservation policy design, implementation and monitoring. The decline of soybean-driven deforestation in the Brazilian Amazon has been widely attributed to the implementation of the Amazon Soy Moratorium[13–16,22]. To augment the voluntary moratorium, the Ministry of Environment and the Central Bank of Brazil eliminated agricultural credits to farmers and ranchers within counties with the highest deforestation rates[28]. These measures along with The Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) played a key role in the success of reduced deforestation in the Brazilian Amazon[28,29]. Our results confirmed these trends in central Mato Grosso. However, our results also revealed increasing trends in some municipalities in the Amazon (e.g. eastern Pará), indicating that these policies have met with varying success between regions (Supplementary Fig. 3b).

Single commodity policies aimed at mitigating deforestation face the challenge of land-use displacement, which can occur over broad scale as well as on the property level, creating leakages of deforestation[16,30,31]. Risk of leakage of these emerging zero-deforestation commitments requires great traceability and transparency along commodity supply chains[12]. Our high-resolution, long-term annual soybean maps provide data to improve our understanding of the pathways of commodity expansion and thus help to address the issue of leakage[24]. Supply chain monitoring in practice will depend on several factors beyond the technical features of our current dataset, including the availability and acceptance of official deforestation and soybean extent data, rules defined and enforced through specific policies, and political considerations that may compromise maintenance of monitoring and enforcement activities. Efforts to limit future deforestation will need to take into consideration other direct drivers of forest clearing to account for the latent conversion to commodity crops[32,33]. Since pasture extensification is the leading direct driver of deforestation in South America[34,35], achieving a deforestation-free soybean commodity chain requires consideration of how expanding its production area may indirectly drive deforestation by increasing land demand for pasture or other land uses[16,36,37].

The most significant finding of our study concerns the attribution of soybean as the proximate cause of forest clearing in the context of overall forest loss across South America. Between 2000 and 2019, total forest loss amounted to 84 Mha within the study area with less than 10% of these deforested lands converted to soybean, including both direct and latent drivers. Although the proportion is relatively small, these lands are highly concentrated in the active deforestation frontiers. More commonly, soybean replaces pasture land uses[7,8,38], and this dynamic may be expected to continue. Future soybean production is projected to increase by 50% by 2050, requiring an additional 20 Mha of soybean cultivation, and much of the growth is expected to occur in South America[39]. In the Brazilian Legal Amazon, 22 Mha of forest were cleared from 1988 to 2000[25], providing potential areas for further soybean expansion or reforestation[40,41]. Recent research has also shown that by 2015, 23 Mha of cleared land in the Cerrado are considered highly suitable for potential soybean expansion[17]. Our analysis further suggests that the frontier regions such as Mato Grosso, Pará and Rondônia in Brazil, Santa Cruz in Bolivia, Boquerón and Alto Paraguay in Paraguay, and Salta and Santiago del Estero in Argentina possess vast potential for continued soybean expansion to fulfill the projected need without incurring new deforestation (Fig. 5).

Our results quantified the large areas of pasture that have and continue to be converted to soybean cultivation. While deforestation has well-documented environmental impacts, the conversion of pasture to intensive row cropping also deleteriously impacts the environment. The increased use of machinery, agrochemicals and fertilizer can substantially alter the physical and chemical properties of terrestrial and aquatic systems, leading to soil erosion and water pollution with implications for long-term agricultural productivity and human health[42]. Converting pasture to cropland can also modify seasonal water balance, elevate water-table level and increase the risk of regional flooding in flat plains[43]. Although current policy discussion overwhelmingly focuses on protecting forests, protecting non-forest ecosystems, such as downstream aquatic systems, is essential for the maintenance of critical ecosystem services. Our results show that soybean cultivation is rapidly developing in the Pantanal (Fig. 3), which may change the regional hydrological cycle and water quality, and cause biodiversity loss in the world’s largest freshwater wetland[44]. Moreover, soybean expansion can cause severe environmental and social impacts beyond the direct conversion area, as the massive infrastructure development required for soybean transportation paves way for other land-use activities[36,45]. Comprehensive land use monitoring, including tracking of all commodities and the extent and loss of natural land cover, is required. The targeting of single commodities and single geographies for monitoring omits leakage effects, inter-commodity transitions, and land banking, all of which may result in concurrent increased forest loss and increased soybean cultivated area.

More broadly, agricultural production and environmental conservation are two distinctive objectives with inherent trade-offs as both involve the use of land resources. Our results showed how such trade-offs were clearly unfolding in South America. While the expansion of soybean area in South America has boosted global food production, raised living standards and improved social wellbeing for the producing countries[46,47], it also depleted natural ecosystems and caused environmental damage from local to global scales. Balancing society's short-term need with long-term sustainability requires innovation from both the conservation and agricultural sectors. Sustainable intensification, a process where crop yields are increased without adverse environmental impact and without the conversion of non-agricultural land, is being advocated as a viable solution to address these trade-offs[10]. In the Brazilian state of Mato Grosso, the traditional single-cropping system is being intensified to double-cropping systems, partially driven by conservation restrictions, and has, in turn, reduced local deforestation in the short term[48]. Enhanced dialogue and coordination between conservation and agricultural sectors is necessary to devise and implement comprehensive policies that will achieve sustainable use of limited land resources.

Methods

Field data-based soybean area estimation, satellite-based annual soybean mapping, land source attribution and deforestation driver analysis are described as follows.

Field data collection and soybean area estimation

We implemented a stratified random sampling design for field data collection during the growing years of 2017, 2018, and 2019, following methodology implemented by Song *et al.* (2017)[49]. The land area of the southern hemisphere of South America was divided into 20 × 20 km^2 equal-area blocks. For each year of field sampling, we mapped soybean coverage for South America using Landsat and MODIS observations of the year prior to the field visit. Each block was assigned to a high, medium or low stratum based on the mapped area of soybean in the block. We randomly selected 25 blocks from each stratum as the primary sampling units (PSUs). Within each PSU, we randomly selected twenty 30 × 30 m^2 pixels as the secondary sampling units (SSUs). Therefore, the sample set in each year consisted of 75 PSUs and 1,500 SSUs. This sampling design was implemented independently for each of the three field visit years. In total, we sampled 225 PSUs and 4,500 SSUs (Supplementary Fig. 5). For each sample pixel in each year, we conducted field visits and collected crop type information. Based on the field sample data, we applied a survey sampling regression estimator to estimate soybean area for 2017, 2018 and 2019[50]. These area estimates were used to constrain the total soybean area when generating the soybean classification maps (see next section). The field data from this continentally distributed, probability sample were also used to assess the accuracy of the annual soybean maps for 2017, 2018 and 2019. While collecting data over the probability sample in the field, we also recorded a large number of data points via a windshield survey, independent to the validation sample, as training data for soybean classification.

Satellite data processing and soybean mapping

The annual 30 m resolution soybean maps were derived using all Landsat and MODIS observations acquired between November 1st and April 30th in each growing year. The MODIS surface reflectance (SR) data was obtained from the 16-day MOD44C product. We applied an automated Landsat processing system to convert Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) observations from top-of-atmosphere reflectance to normalized surface reflectance (NSR). The system consists of a series of steps, including at-sensor radiance calculation, cloud, shadow and haze masking, reflectance normalization and anisotropy correction using MODIS SR as normalization target. The Landsat NSR was then processed to 16-day composites similar to the MODIS product. Both Landsat NSR and MODIS SR 16-day time-series were used to create annual phenological metrics for land cover and land use mapping. For a complete description of the methodology, readers are referred to Potapov *et al.* (2019)[51] and Potapov *et al.* (2020)[52].

An effective strategy for mapping crop type across a continent must be capable of dealing with local crop diversity, varying crop phenology, and changing environmental conditions (e.g. latitudinal gradient). Capturing such variability requires accurate training data with sufficient spatial and temporal coverage. We applied a multi-scale, multi-temporal approach for mapping soybean over South America. First, we classified each of the 225 sampled PSUs using field training data and all Landsat and Sentinel 2 images. Each PSU was mapped into binary soybean and non-soybean classes using a decision tree classifier trained with locally collected in-season field data and additional training data based on visual interpretation of satellite imagery. Although the method was labor intensive, highly accurate results could be achieved and were ensured by experienced image analysts through an iterative fine-tuning procedure (PSU-level average accuracy 96%). We then pooled all 225 classified PSUs together and randomly selected 5% of the pixels as training for the continental classification (Supplementary Fig. 6). Since the training data were located in sampled PSUs, their random nature ensured that the training set contained representative signatures of soybeans over the continent. Moreover, as the training data were accumulated over three consecutive years, they captured the various spectral responses of soybean fields under different management practices as affected by local weather variation that occurred during those three years. The spatial and temporal coverage of the training data, therefore, enhanced the temporal generalization capability of the trained machine learning model.

We trained a decision tree ensemble model using phenological metrics derived from both Landsat and MODIS, in addition to SRTM-based topographic features including elevation, slope and aspect. We applied this decision tree model to each growing year from 2001 to 2019 and generated 19 annual soybean probability maps at 30 m spatial resolution. Following the method reported in Song *et al.* (2017)[49] we identified the empirical probability thresholds (instead of the default threshold of 0.5) that produced a match between the map-derived soybean area and the sample-based area estimates. These probability thresholds were determined for the years of 2017, 2018 and 2019, where we have sample-based area estimates. We applied the average threshold values of the three years to all years prior to 2017 to create binary soybean/non-soybean classifications. The classification maps were used to derive annual soybean area statistics (Supplementary Fig. 7). We also applied the lower and upper thresholds of the three years to the entire time series to derive the uncertainty range of annual area estimates (error bars in Supplementary Fig. 7).

For the most recent years 2017, 2018 and 2019, we validated the maps using field sample data as a reference. The overall accuracies were 96%, 94% and 96%, respectively, with high and balanced producer's and user's accuracies (Supplementary Table 2). For the years prior to 2017, we do not have field sample data for validation. Consequently, we compared our map-based annual soybean area estimates to annual harvest area statistics reported by the United States Department of Agriculture Foreign Agricultural Service (USDA FAS) (Supplementary Fig. 7). The mean absolute deviation of the two time series was 5.3 Mha, 3.0 Mha, and 1.2 Mha for South America, Brazil and Argentina, respectively. The root-mean-square-deviation was 6.1 Mha, 3.3 Mha and 1.9 Mha, and the r^2 values were 0.90, 0.95 and 0.66 for South America, Brazil and Argentina, respectively. As our maps were based on satellite observations and field surveys, they provided objective and consistent area estimates independent of government reports.

Land source attribution

As a type of agricultural land use, soybeans can be planted on existing cropland or on land converted from non-crop land uses. To attribute the original land source at the beginning of the study period, we constructed a 30 m resolution land-cover map circa year 2001, consisting of primary humid forest, non-primary forest, cropland and other land (mostly pasture/grassland). The primary humid forest class was derived from Turubanova *et al.* (2018)[26]. Non-primary forest was derived based on a percentage tree canopy cover layer[3]. We applied a 10% threshold to convert tree canopy cover to a binary forest/non-forest map. This 10% threshold was chosen to match the official definition of forest by the United Nations Food and Agriculture Organization[53] and Brazil's submission of forest emission reference level to the United Nations Framework Convention on Climate Change[54]. The cropland class was derived from Zalles *et al.* (2019)[8]. We overlaid the 2002–2019 annual soybean maps on the 2001 land-cover map to compute the area of soybean sourced from primary forest, non-primary forest, cropland and pasture/grassland at the biome scale. Biome boundaries were produced by combining Brazil's biome polygon file (available at http://data.globalforestwatch.org/) for those biomes inside Brazil and the Terrestrial Ecoregions of the World[55] (available at https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world) for those outside of Brazil.

We designed a sample-based attribution analysis to supplement map-based attribution analysis, focusing on distinguishing new soybeans converted from non-forest native vegetation versus soybeans converted from managed vegetation. We created a 30 m spatial layer of soybeans developed on non-forest lands and randomly selected 50 pixels. We created annual, monthly and bi-weekly Landsat composites from 2000 to 2019 over each sample pixel, and extracted 16-day time-series of red, near-infrared (NIR), shortwave infrared (SWIR) reflectance as well as normalized difference vegetation index (NDVI) and normalized difference water index (NDWI) from MODIS over 2000 to 2019. We also employed high-resolution images in Google Earth and visually interpreted the land-cover type of the pixel before it was converted to soybean. Based on these sample data, we estimated the percentage of soybeans converted from non-forest native vegetation.

Deforestation driver analysis

Beef and soybean are the two major commodities driving deforestation in South America[28]. However, the pathways of land-use change have been changing. Direct conversion from forests to cropland was common in Mato Grosso during 2001–2004, peaking at 23% of 2003 deforestation[56]. From 2006 to 2010, cropland expansion in Mato Grosso increasingly occurred on previously cleared pastures, accounting for only 2% of deforestation during this period[38]. A recent sample-based national analysis reported that 20% of new cropland in Brazil between 2000 and 2014 had been converted from natural vegetation, while the majority, 80%, had been converted from pastures[8].

Since multiple land-use change pathways could lead to eventual conversion of forest to soybean [13,14,28], we quantified both direct and indirect conversions of forest to soybean. We defined “new soybean” as any pixel that was mapped as soybean for two consecutive years for the first time after 2001. We defined “soybean-driven deforestation”, with soybean as a direct driver, as a pixel that was classified as new soybean that appeared within 3 years following forest loss (Supplementary Fig. 2). New soybean that appeared after 3 years of forest loss was labeled as a latent driver. Information on the year of forest loss was obtained from the global forest change data[3]. We produced two annual deforestation layers, with soybean as the direct and latent driver, respectively, by integrating the annual soybean layers and annual forest loss layers.

We conducted a sample analysis to evaluate the uncertainty of these two change layers, focusing on the timing component. We randomly selected 50 pixels from each of the two change layers and created annual, monthly and bi-weekly Landsat composites from 2000 to 2019 over each sample pixel. We then extracted 16-day time-series of red, near-infrared, shortwave infrared reflectance as well as NDVI and NDWI from MODIS over 2000 to 2019. We also employed high-resolution images in Google Earth to aid visual interpretation. From these various datasets, we recorded the year of forest loss and the year when the pixel was converted to crop cultivation, and computed the time lag from forest loss to crop cultivation (Supplementary Fig. 8). The forest loss data is based on V1.7 of the global forest change dataset (earthenginepartners.appspot.com/science-2013-global-forest), which has known issues with temporal consistency. Identifying the years of forest loss and crop cultivation and computing the time lag allowed us to address the uncertainties in both the forest loss map and the soybean map. For a random location without in-situ data, only crop versus non-crop can be reliably identified based on satellite data, and discrimination of soybean versus non-soybean based on satellite data alone is tenuous. Therefore, although our uncertainty analysis addressed the critical timing component of change, it did not encompass the full range of uncertainty due to a lack of in-situ data for the random sample locations. Based on the sample, the mean time lag of direct soybean-driven deforestation was 2.6 years, and the mean time lag of deforestation with soybean as a latent driver was 4.7 years, consistent with the two definitions of the change maps.

We summarized the area of deforestation that was converted to soybean cultivation at the biome and municipal/county scales. Municipal boundaries were derived from the GADM database (v3.6; available at: https://gadm.org). For each biome and each municipality, we computed the annual areas of deforestation that were eventually converted to soybean from 2001 to 2019. We computed the annual areas of soybean-driven deforestation, with soybean as a direct driver, from 2001 to 2016. At the municipal scale, we also computed changes in soybean-driven deforestation from 2008 to 2016, with 2008 chosen as the starting year because of its critical importance from a policy perspective. The Amazon Soy Moratorium was initially designed with a cutoff date in 2006, which was subsequently revised to 2008. We calculated average annual soybean-driven deforestation between 2006 and 2008 as the beginning deforestation rate of the study period. In the case of the Amazon Soy Moratorium, this represents the pre-moratorium deforestation rate. We calculated average annual soybean-driven deforestation between 2014 and 2016 as the ending deforestation rate. The difference between mean 2006–2008 deforestation and mean 2014–2016 deforestation was calculated as the annual change in soybean-driven deforestation area from 2008 to 2016 (Supplementary Fig. 3b).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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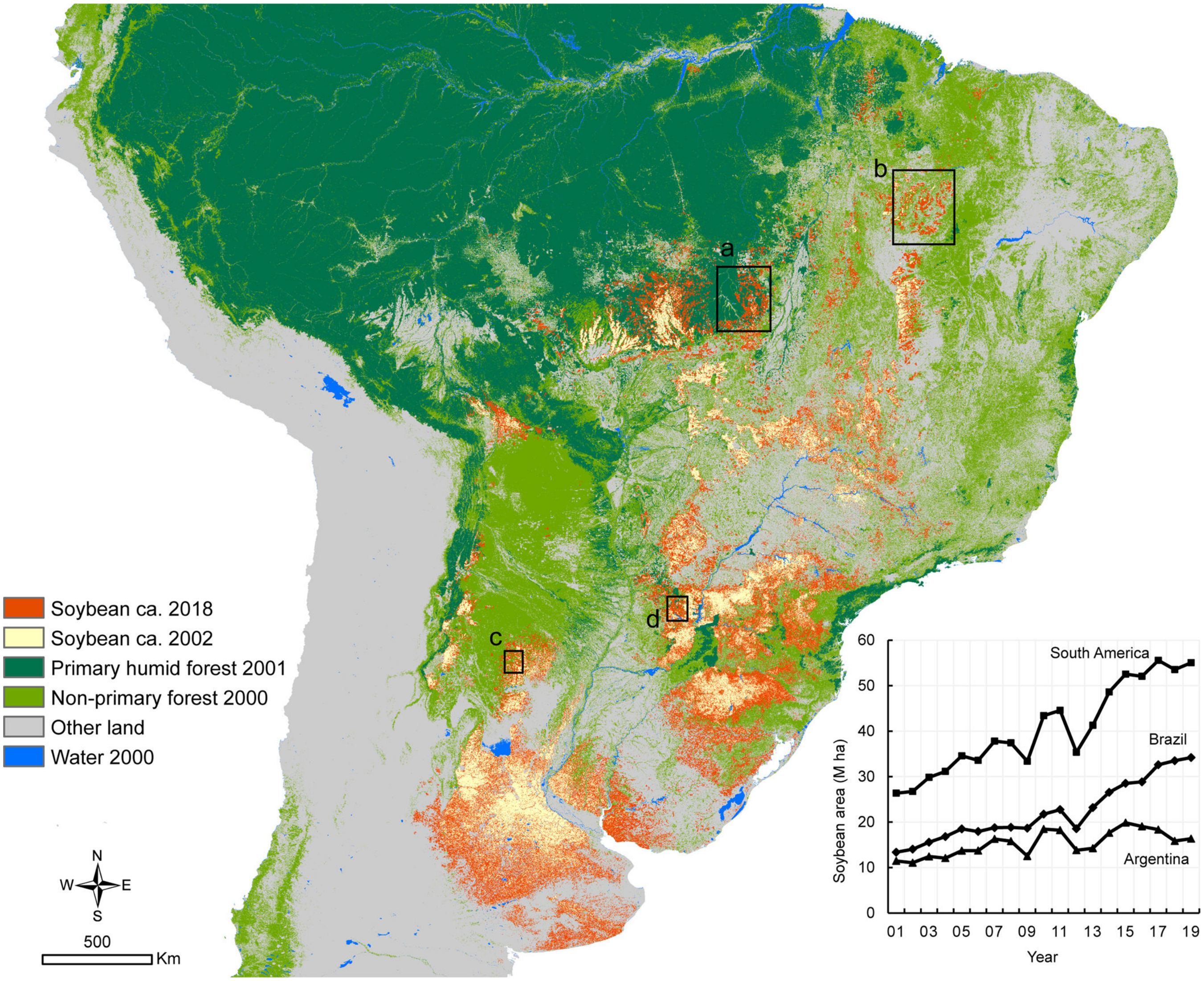

Fig. 1.

Soybean expansion across South America in the 21st century. Annual soybean classification maps were generated at 30 m spatial resolution from 2001 to 2019. Data from the beginning and ending years are used in this visualization to show soybean expansion. To reduce the effect of annual crop rotation on data visualization, for this map we applied a 3-year majority filter for the beginning and ending years to derive soybean layers circa (ca.) 2002 and 2018. The inset at the lower bottom corner shows annual soybean area statistics over South America, Brazil and Argentina, derived from the annual maps without filtering. Black boxes and labels on the map indicate the spatial extents of regional examples shown in Fig. 2.

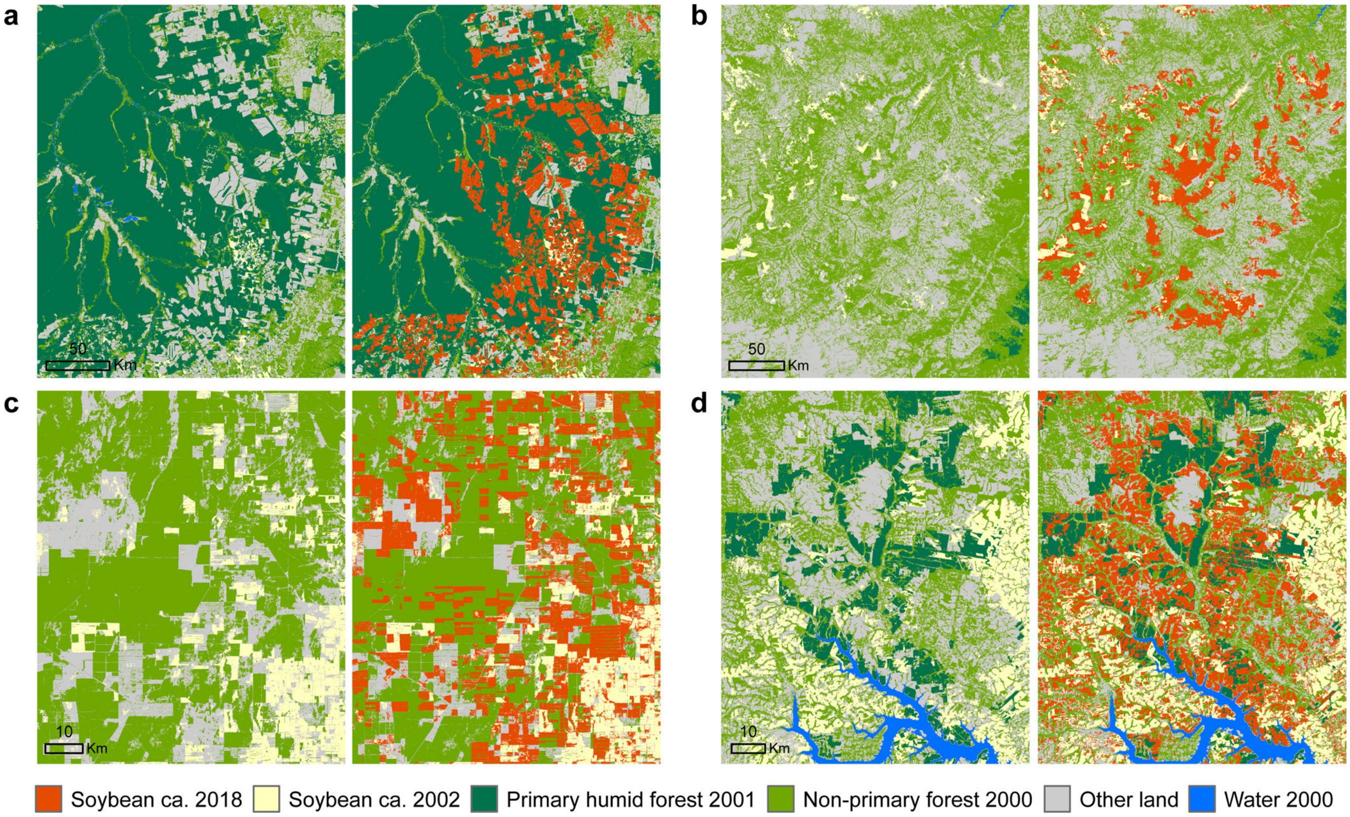

Fig. 2.

Selected regional examples of soybean expansion in South America. **a**. Eastern side of the Xingu river basin in Mato Grosso, Brazil. **b**. Southern part of Maranhão and Piauí, Brazil. **c**. Northeastern part of Santiago del Estero, Argentina. **d**. Caaguazú and Alto Paraná, Paraguay. The extents of these examples are marked as black boxes on Fig. 1.

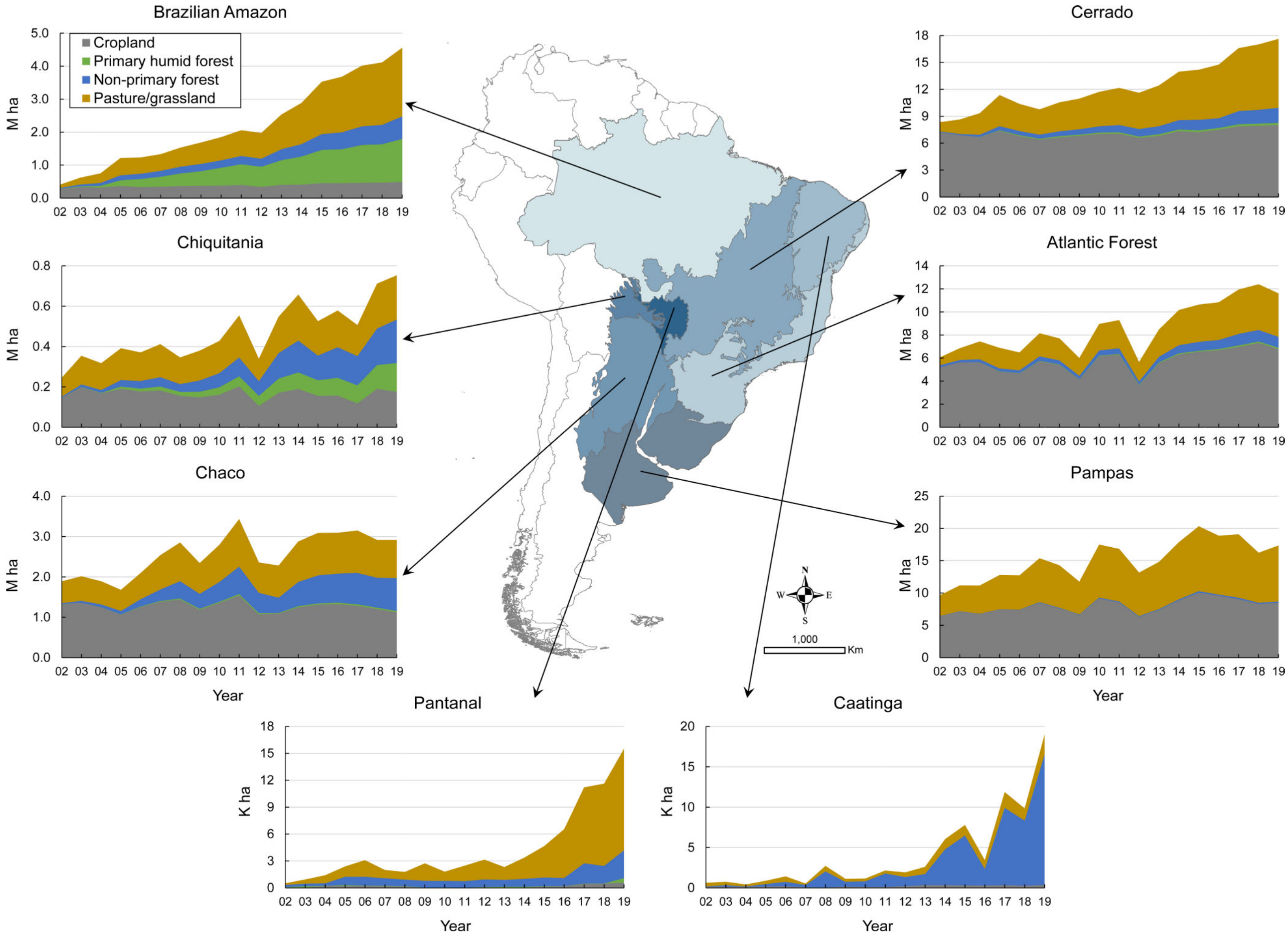

Fig. 3.

Year 2001 land source of annual soybean between 2002 and 2019 in major biomes in South America.

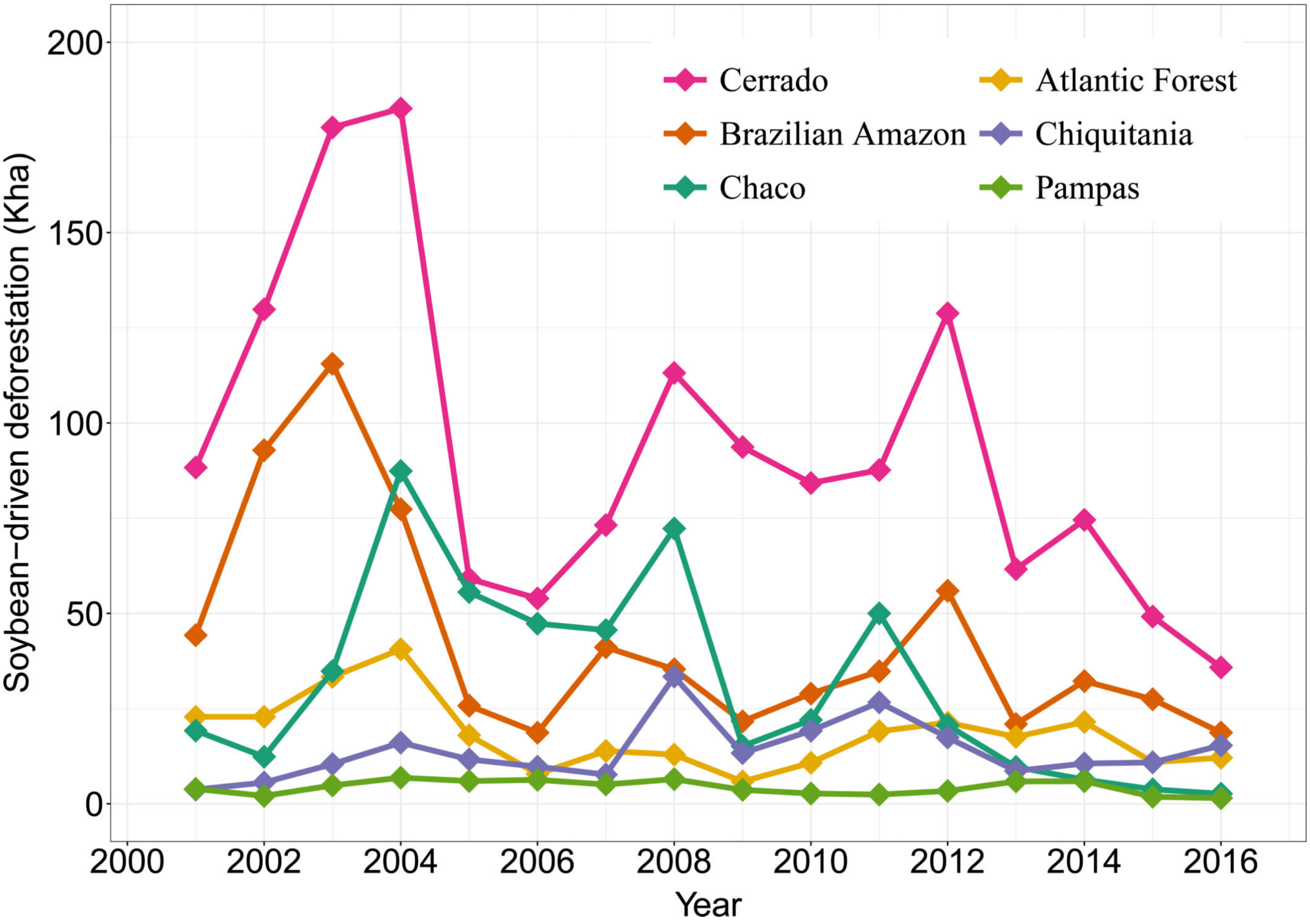

Fig. 4.

Annual area of soybean-driven deforestation per biome 2001–2016. Soybean-driven deforestation is defined as conversion of forest to soybean cultivation within 3 years after forest clearing.

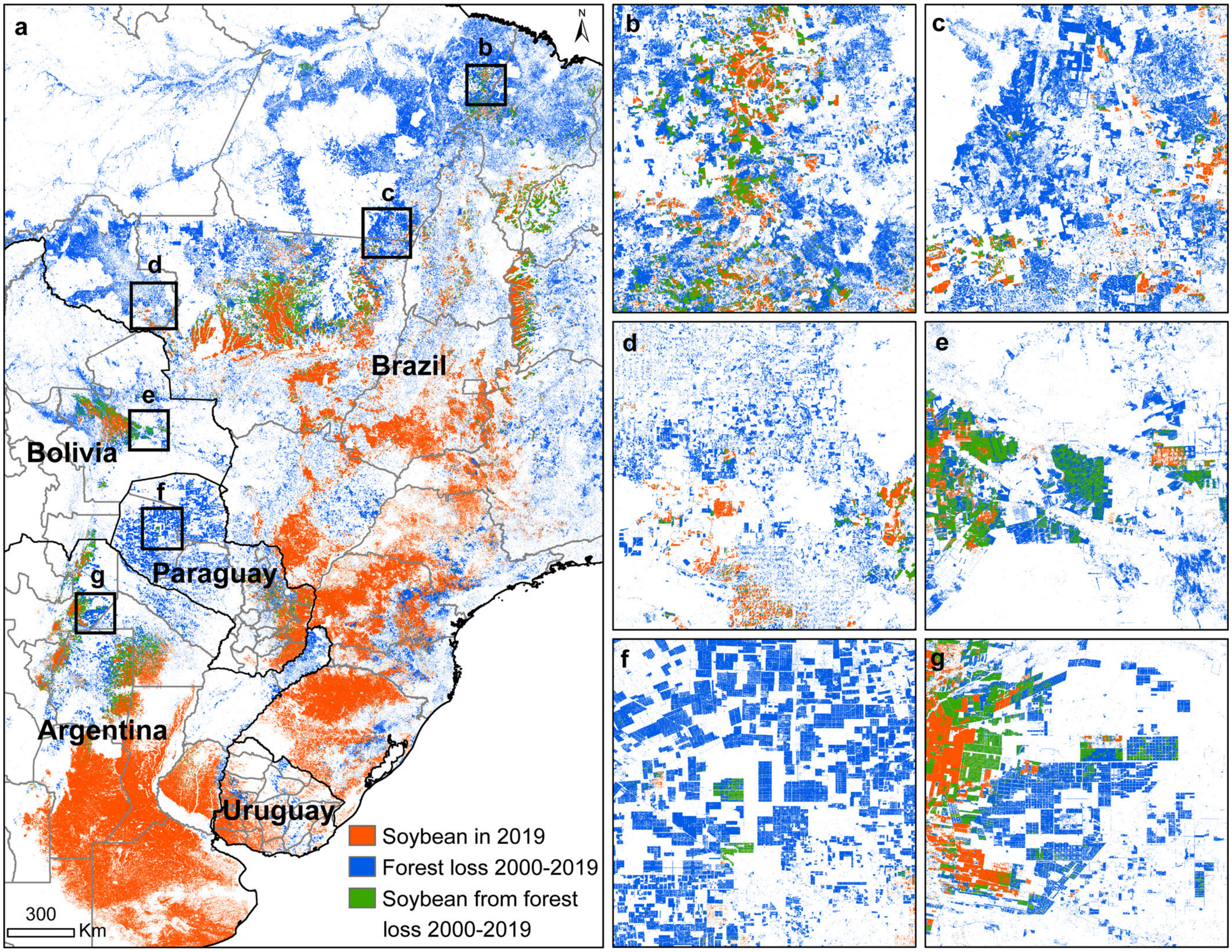

Fig. 5.

Potential of future soybean expansion onto lands with recent forest loss. Soybeans in year 2019 are shown in orange, with soybeans converted from forest loss between 2000 and 2019 shown in green. Forest loss between 2000 and 2019 that is not converted to soybean cultivation is shown in blue, and represents area where there may be future soybean expansion. The area of soybean directly converted from forest accounts for less than 5% the area of total forest loss. **a**. Overview of the continent. **b-g**. Regional zooms showing details at active frontiers.

Table 1.

Forest loss, soybean gain, and deforestation driven by soybean cultivation from 2001 to 2016 (unit: Kha).

Biome	**Total forest loss (a)**	**Total soybean gain**	**Soybean gain as a direct driver of deforestation (time lag ≤ 3 years) (b)**	**Soybean gain as a latent driver of deforestation (time lag > 3 years) (c)**	**Proportion of forest loss converted to soybean ((b+c)/a)**
Brazilian Amazon*	27766	3294	692	982	6.0%
Atlantic Forest	6935	4689	291	250	7.8%
Caatinga	2759	7	4	1	0.2%
Cerrado	14316	7536	1493	885	16.6%
Chaco	9837	1061	505	529	10.5%
Chiquitania	1724	354	220	104	18.8%
Pampas	1243	8669	69	83	12.2%
Pantanal	626	6	1	0	0.2%

*Brazilian Amazon covers the Southern Hemisphere portion of the Amazon in this study.