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Safeguarding Brazilian soy and beef supply chains: vegetation loss, climate risks, and implications for trade with China

Ana Beatriz dos Santos, John James Loomis, Karoline Silva, Emily Ane Dionizio, Rodrigo Bellezoni, Virginia Antonioli, Argemiro Teixeira Leite-Filho, Julia Faro, Mariana Oliveira

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Highlights

- The scale of Brazil–China soy and beef trade, reliant on predominantly rainfed production systems in Brazil, creates a shared dependence on the climatic stability of Brazilian production landscapes.
- Across the Amazon and Cerrado, native vegetation loss is associated with shifting rainfall patterns, increasing extreme heat, and shorter rainy seasons, potentially undermining Brazilian soy and beef production and exports to China.
- Between 1993 and 2023, rainy season duration declined by up to 75 days in some parts of the Amazon and 45 days in parts of the Cerrado, reducing the agricultural window for rainfed systems.
- Extreme heat exposure is widespread: 82% of mapped soybean areas and 62.9% of mapped pasture areas within municipalities exporting to China show increasing frequency of days above 35°C.
- Approximately 1.4 million hectares of mapped soy and pasture areas within municipalities exporting to China face overlapping climate stressors, concentrated in the Cerrado and southern Amazon transition zone.
- Climate trends associated with vegetation loss can create risks for production, finance, insurance, and supply chain stability. Stronger land-use governance in Brazil, combined with Brazil–China cooperation on data sharing, sustainable procurement, and finance, can help reduce climate-related supply chain risks and support more resilient bilateral trade.

Executive Summary

Introduction

Brazil–China agricultural trade in soy and beef relies on production from Brazilian landscapes that are predominantly rainfed and increasingly exposed to shifting rainfall patterns, rising temperatures, and more frequent extreme heat, particularly in the Amazon and Cerrado (Leite-Filho et al., 2021, 2025; Marengo et al., 2022). A growing body of evidence shows that land-use change and native vegetation loss can intensify these climatic stresses, with implications for crop yields, pasture productivity, and the long-term reliability of agricultural supply chains (Lawrence and Vandecar, 2015; Spracklen and Garcia-Carreras, 2015; Leite-Filho et al., 2021). The climatic resilience of Brazilian production landscapes is therefore increasingly relevant to the stability of soy and beef exports to China.

In this context, the study first examines climate trends in the Amazon and Cerrado and their statistical relationship with native vegetation loss. It then assesses how these trends overlap spatially with mapped soy and pasture areas within municipalities exporting these commodities to China, identifying important regions for Brazil–China agricultural trade where production is increasingly exposed to climate-related risks. The study also evaluates Brazil's policy and governance framework for deforestation control, land restoration, and supply chain traceability, and discusses how complementary Brazil–China cooperation — through data sharing, sustainable procurement, and financial mechanisms — can help strengthen supply chain resilience and support more sustainable long-term trade.

Methodology

The analysis begins with a 30-year assessment of climate trends (1993–2023) in the Amazon and Cerrado biomes and examines their statistical relationship with native vegetation loss, following the methodological framework proposed by Leite-Filho et al. (2021, 2024). This first component identifies where climatic conditions have changed and assesses how these trends relate to vegetation loss over the same period.

The second component overlays observed climate trends with mapped soy and pasture areas within municipalities exporting these commodities to China, identifying where export-relevant production areas are exposed to changing rainfall, shorter rainy seasons, and increasing extreme heat. It does not attribute vegetation loss or climate change to trade or Chinese demand, but assesses the spatial exposure of production areas important to Brazil–China agricultural trade. This diagnosis provides the basis for the policy assessment.

The third component evaluates whether Brazil's regulatory and institutional framework supports more climate-resilient, low-deforestation, and restoration-oriented supply chains. While the climate analysis identifies the geography of exposure, the policy assessment examines how governance arrangements address these risks through deforestation control, restoration, traceability, and risk-aligned finance. Integrating both analyses, the study identifies governance and implementation gaps and discusses how stronger domestic action and complementary Brazil–China cooperation on data sharing, sustainable procurement, and finance could strengthen the resilience and long-term stability of bilateral agricultural trade.

Results

The results show statistically significant shifts in rainfall patterns, rainy-season duration, and extreme heat exposure across the Amazon and Cerrado between 1993 and 2023. The rainy season shortened by up to 75 days in parts of the Amazon and 45 days in parts of the Cerrado, narrowing the window for rainfed agriculture (Leite-Filho et al., 2025; Commar et al., 2023, 2024). The analysis also finds a statistically significant relationship between native vegetation loss and regional climate conditions. In the Amazon, this relationship is non-linear, with climate effects intensifying beyond critical levels of vegetation loss, while the Cerrado shows a predominantly linear and cumulative response. Full regression results are provided in Appendix A.

These climate trends overlap substantially with mapped production areas in municipalities exporting soy and beef to China. Together, the municipalities analyzed accounted for approximately 34% of Brazil's soy exports and 45% of its beef exports to China over the study period. Within these municipalities, 82% of mapped soybean areas and 62.9% of mapped pasture areas — more than 37 million hectares combined — show an increasing frequency of days above 35°C, a threshold particularly relevant to soybean productivity during critical reproductive stages (Silva et al., 2023). Approximately 1.4 million hectares of mapped soy and pasture areas are located where multiple climate stressors overlap, particularly in the Cerrado and the transition zone with the southern Amazon. These findings indicate substantial climate exposure in Brazilian production landscapes that are important to bilateral agricultural trade.

The policy assessment finds that Brazil's regulatory framework — including the Forest Code, Rural Environmental Registry (CAR), Brazil's national plan for Low Carbon Agriculture (ABC+), Action Plan for Deforestation Prevention and Control in the Legal Amazon (PPCDAm) and Brazilian National Plan for Native Vegetation Recovery (PLANAVEG) — is broadly aligned with more climate-resilient, low-deforestation supply chains when effectively implemented (Reis and Corazza, 2025; MAPA, 2021). However, three implementation gaps limit its effectiveness: CAR compliance analysis covered only 7.2% of registered properties as of March 2026 (SFB, 2026); fragmentation between CAR and Animal Transit Record (GTA) systems enables cattle laundering through indirect suppliers, which account for approximately 37% of deforestation in key states (Loomis et al., 2026; Choquet, 2025); and most financial instruments still treat climate and deforestation risks as exogenous, limiting capital flows toward verified, climate-resilient production (Carreira et al., 2024; Hänggli et al., 2023; Rajão et al., 2020).

Conclusion

The findings indicate that climate trends and land-use dynamics are becoming material considerations for the resilience of Brazilian soy and beef production and the stability of trade with China. Shorter rainy seasons, increasing extreme heat, and shifting rainfall patterns can affect productivity, while their observed relationship with native vegetation loss reinforces the importance of land-use governance in key agricultural regions.

Deforestation control and land restoration should therefore be understood not only as environmental or compliance objectives, but as strategic measures to support rainfall regulation, reduce thermal stress, and sustain agricultural productivity, strengthening the long-term resilience and competitiveness of Brazil's agricultural sector.

Brazil already has a comprehensive policy framework, including the Forest Code, CAR, ABC+, and restoration programs, such as PLANAVEG and the Caminho Verde Program, implementation gaps remain the binding constraint. Priorities include accelerating CAR validation, strengthening enforcement and traceability, integrating monitoring systems, and expanding incentives for restoration and sustainable intensification. Complementary Brazil–China cooperation through data sharing, sustainable procurement, financial mechanisms, and restoration initiatives can support these domestic efforts while contributing to more resilient supply chains and more stable long-term trade.

Introduction

Brazil and China are deeply interconnected through agricultural trade, forming one of the world's most consequential South–South agri-food relationships. China has been Brazil's largest importer of agricultural products for four consecutive years, reflecting a partnership built through trade liberalization, complementary economic structures, and growing Chinese demand for protein and feed commodities (Zhang, 2021; Brasil de Fato, 2025). China is the destination for roughly 70% of Brazil's soybean exports and more than 50% of its beef exports, representing approximately US$30 billion per year in trade flows (Comexstat, 2025; USDA, 2025). China is the destination for roughly 70% of Brazil's soybean exports and more than 50% of its beef exports, representing approximately US$30 billion per year in trade flows (Comexstat, 2025; USDA, 2025). The scale of this relationship creates important interdependencies: China is a critical market for Brazilian producers, while Brazilian soy and beef contribute substantially to China's food and livestock-feed supply. The climatic resilience of Brazilian production landscapes is therefore increasingly relevant to the long-term stability of bilateral agricultural trade (Gavoni et al., 2026).

Agricultural production in Brazil—particularly in the Amazon and Cerrado biomes—is highly dependent on climatic conditions, including the timing and distribution of rainfall and the occurrence of extreme heat events (Rattis et al.,2021; Marengo et al., 2022). These biomes also host exceptional biodiversity and support critical climate and hydrological processes, including moisture recycling and rainfall generation across South America (Lovejoy and Nobre, 2018; Strassburg et al., 2017). This dependence is especially important in predominantly rainfed production systems: more than 90% of soybean and beef production in the Amazon and Cerrado relies on rainfall, while irrigated agriculture represents less than 2% of Brazil's total planted area (Global Yield Gap Atlas, 2023; Conab, 2025). Changes in rainfall volume and timing, shorter wet seasons, and more frequent extreme heat can therefore constrain planting cycles, crop development, pasture productivity, and production stability.

Recent observations reinforce these concerns. The year 2025 ranked among the warmest years globally, while 2015–2025 was the warmest eleven-year period recorded for global mean temperature since 1850 (WMO, 2026). In Brazil, warming has been particularly pronounced in the North and Center-West, where absolute maximum temperatures increased by approximately 4°C over the past two decades (Curado et al., 2023). Decreasing rainfall volumes, delayed rainy-season onset, and shorter rainy seasons have also been documented across several major agricultural regions (Commar et al., 2023, 2024; Pousa and Costa, 2023; Lawrence and Vandecar, 2015; Spracklen and Garcia-Carreras, 2015; Leite-Filho

et al., 2021, 2024). Together, these trends indicate that the climatic conditions underpinning Brazilian agricultural production are shifting.

Native vegetation loss can interact with broader climatic changes, particularly in the Amazon and Cerrado. Both biomes are globally significant for biodiversity conservation and climate regulation but have also experienced substantial agricultural expansion (Rodrigues et al., 2022; Flores et al., 2024). In the Amazon, much of the recent deforestation has been associated with pasture expansion, while agriculture, particularly soybean cultivation, has become a major land use in the Cerrado (MapBiomas, 2024). A growing body of literature shows that native vegetation loss can influence local and regional temperatures, rainfall patterns, and moisture recycling (Lawrence and Vandecar, 2015; Spracklen and Garcia-Carreras, 2015; Leite-Filho et al., 2021, 2024). These changes can have material consequences for production: higher temperatures may reduce soybean yields by approximately 6% for each 1°C increase (Silva et al., 2023), while climate change is projected to reduce pasture biomass under some warming scenarios, affecting forage availability and livestock-system resilience (Vaiknoras et al., 2024). This creates a growing challenge for major Brazilian soy-and beef-producing regions and, by extension, for export supply chains that depend on them.

In Brazil, a set of complementary policy instruments addresses both deforestation[1] and climate change. The country's National Policy on Climate Change (PNMC) and its updated Nationally Determined Contribution (NDC) under the Paris Agreement establish national targets for reducing greenhouse gas emissions, while sectoral and territorial policies—such as the Action Plans for the Prevention and Control of Deforestation[2] (PPCDAm and PPCerrado)—focus more directly on curbing native vegetation loss and strengthening land-use governance. In China, the Ecological Civilization framework and recent policy agendas have emphasized greener supply chains, improved environmental governance, and more sustainable overseas sourcing (MOFCOM and MEE 2021; NDRC 2022). Although these agendas arise from distinct domestic responsibilities and priorities, they create potential areas of cooperation around more sustainable and resilient agricultural trade.

Against this background, this study assesses climate trends relevant to Brazilian agricultural production and their implications for areas participating in export-oriented supply chains. It analyzes changes in annual precipitation, rainy-season onset, and the frequency of days above 35°C and estimates their statistical relationship with native vegetation loss in the Amazon and Cerrado. It then examines how these trends spatially overlap with mapped soybean and pasture areas within municipalities exporting soy and beef to China. This approach identifies where production areas important to bilateral trade are exposed to changing climatic conditions; it does not attribute native vegetation loss or climate change to Chinese demand or importing behavior.

The study also evaluates Brazil's regulatory framework for deforestation control and land restoration, considering its role in supporting more resilient production landscapes and addressing climate-related pressures. Finally, it discusses how complementary Brazil–China cooperation through data sharing, sustainable procurement, and financial mechanisms could support policy implementation, restoration efforts, and agricultural supply chain resilience.

Methodology

The methodology of this study adopts an integrated approach that combines the assessment of climate trends and their relationship with land-use change, the analysis of their spatial overlap with agricultural supply zones exporting to China, and an examination of the policy and governance context relevant to agricultural production and trade. This integrated approach aims to inform decision-makers in both countries about the implications of observed climatic changes for export-oriented supply chains.

The analysis begins with an assessment of climate trends over a 30-year period (1993–2023) and an examination of their relationship with native vegetation loss in the Amazon and Cerrado. These trends are then spatially overlaid with mapped soy and pasture areas within municipalities exporting soy and beef to China, allowing the study to assess the exposure of production areas relevant to bilateral trade to changing climatic conditions. These analytical steps are described in more detail below.

To connect this diagnosis to policy-relevant insights, the study also evaluates Brazil's regulatory framework, seeking to identify governance gaps and implementation challenges relevant to deforestation control, land restoration, and supply chain resilience. In this way, the integration of trend analysis and policy evaluation provides a basis for discussing how data sharing, financial mechanisms, and complementary bilateral cooperation can contribute to strengthening supply chain resilience and the long-term stability of agricultural trade between Brazil and China.

Climate Trend Analysis and Its Relationship with Vegetation Loss

Climate trend analysis is conducted in two stages. In the first stage, we examine long-term changes in three climate variables that are highly relevant for agricultural production: annual precipitation volume, rainy season onset, and the number of days with maximum temperatures exceeding 35°C — a threshold widely used in the agronomic literature

as an indicator of acute thermal stress events that can cause irreversible damage to soybean flowers and pods during critical reproductive stages (Silva et al., 2023; Monteiro et al., 2009). Focusing on the Amazon and Cerrado biomes, this step aims to identify areas where climate conditions have been changing consistently over time. The main output of this stage is a set of maps showing areas that exhibit statistically significant trends for each climate variable.

We analyze observed climate patterns over a 30-year period (1993–2023), consistent with standard climatological periods used to assess long-term trends. The analysis is based on historical observations and does not model future climate scenarios or policy interventions. The analysis uses gridded rainfall and daily maximum temperature data from the Brazilian Daily Weather Gridded Database (BRDWGD; Xavier et al., 2022), which provides climate information at approximately 1 × 1 km resolution across Brazil. To determine whether changes over time are statistically consistent rather than random, we apply the non-parametric Mann–Kendall trend test. Areas are classified as having significant trends when results are statistically significant at $p < 0.05$.

The second stage estimates the relationship between native vegetation loss and observed changes in annual precipitation volume, rainy season onset, and the number of days with temperatures above 35°C. While the first stage produces spatial trend maps, this stage generates statistical equations that estimate the association between vegetation loss and changes in temperature, precipitation, and onset. The goal is to assess the statistical relationship between native vegetation loss and localized climate conditions after accounting for geographic factors and broader climate variability.

To evaluate the relationship between climate change and native vegetation loss over a 30-year period, we followed the methodological framework proposed by Leite-Filho et al. (2021, 2024). This analysis combined climate data from the BRDWGD (Xavier et al., 2022) with land-use data from MapBiomas Collection 9, covering the period 1993–2023, in the Amazon and Cerrado biomes. The approach consisted of three steps: (i) mapping cumulative native vegetation loss and the spatial distribution of soybean and pasture areas within 10 × 10 km grid cells. Pasture areas were used as the primary spatial proxy for beef production systems, given the predominance of pasture-based cattle production among Brazil's approximately 2.5 million cattle farmers, of which 87% to 90% finish cattle on pasture, particularly in the Amazon and Cerrado biomes (ABIEC, 2016, 2018; IBGE, Censo Agropecuário 2017; Ermgassen et al., 2020). Feed crops and confined production systems were not explicitly included in the spatial analysis; (ii) detrending climate variables (precipitation, maximum temperature, and onset of the rainy season) using machine learning techniques to remove geographic controls and large-scale climatic effects. The residuals generated through this detrending procedure represent localized climate anomalies that are not explained by static geographic factors, such as latitude, longitude, and elevation, or by broader biome-wide climate variability. These residual anomalies are then used as the basis for assessing the local climate signal potentially associated with native vegetation loss; and (iii) correlating the resulting climate anomalies with vegetation loss patterns to estimate the localized association between native vegetation losses and climate dynamics. The complete methodology for this stage is provided in Appendix A.

Export Data and Delineation of Export-Associated Supply Areas

To identify Brazilian municipalities recording soy and beef exports to China, we used municipal-level soy and beef export data from ComexStat, Brazil's official trade database, covering the period from 1997 to 2025. The database reports export value (Free on Board, FOB, in US dollars) and export volume (net weight, in kilograms) based on four-digit Harmonized System (HS4) codes. Beef exports were quantified using HS4 codes 0201, 0202, 0206, 0210, and 1602, covering fresh or chilled beef, frozen beef, edible offal, salted or dried meat, and prepared meat products. Soy exports were quantified using HS4 codes 1201, 1507, and 2304, representing soybeans, soybean oil, and soybean meal or cake.

ComexStat municipal data identify the municipality associated with the fiscal domicile of the exporting company. This location does not necessarily correspond to where the commodities were produced, aggregated, or physically shipped from Brazil. To delineate potential sourcing areas associated with the recorded export activity, we used a three-step spatial modeling approach. First, we grouped nearby exporting municipalities into broader export regions using spatial cluster analysis. Rather than treating each municipality as an isolated point, this approach identifies geographically proximate groups potentially associated with the same regional export network.

To do this, we applied the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm to municipal centroids. Clusters were defined based on spatial proximity, with parameters calibrated to reflect the distinct geographic structure of soybean and beef export networks in Brazil. Soybean-exporting municipalities tend to be more numerous and concentrated, particularly in the Cerrado. A smaller search radius (130 km) combined with a higher minimum number of municipalities was adopted to avoid over-aggregation and preserve meaningful regional distinctions among export clusters. Beef-exporting municipalities, by contrast, are more sparsely distributed across the Amazon and Cerrado , which justified a larger search

radius (200 km) and a lower minimum cluster size to ensure geographically dispersed but functionally connected export hubs were captured within the same cluster. This calibration approach is consistent with standard practice in density-based spatial clustering, where parameters are adjusted to reflect the spatial characteristics of the dataset rather than derived from a universal rule (Ester et al., 1996), and is broadly aligned with the spatial logic applied in Santos and Costa (2018) to characterize functionally connected agricultural supply zones in the Amazon and Cerrado.

For the second step, we calculated a weighted center of mass for each export cluster, using each municipality's cumulative export volume to China from 1997–2025 as weights. This identifies the geographic center of long-term export activity, giving greater influence to municipalities with larger export volumes. Using cumulative exports reduces the effect of annual fluctuations and better captures territories structurally linked to exports to China.

Finally, we delineated potential sourcing catchments around each weighted cluster centroid to account for production originating beyond the municipalities identified in ComexStat. Using Brazil's DNIT road network, we estimated areas of influence based on transportation accessibility, assuming average speeds of 60 km/h on federal highways and 40 km/h on secondary or unpaved roads (Santos and Costa, 2018). From each centroid, interpreted as a potential aggregation or logistical convergence point, we delineated an eight-hour maximum travel-time isochrone (Santos and Costa, 2018). These isochrones serve as spatial proxies for potential sourcing areas associated with export activity recorded in ComexStat, rather than tracing the verified origin of individual shipments. By using road-network accessibility instead of administrative boundaries, the approach captures production potentially dispersed across surrounding areas and channeled through regional export networks. The climate exposure assessment was subsequently applied within these modeled export-associated areas.

The integration of export data and spatial layers followed a sequential approach. The ComexStat municipal export data—statistical and non-spatial in origin—were first converted into a spatial representation through the clustering and travel-time isochrone procedure described above, yielding modeled supply-area polygons used as the spatial unit of analysis in the subsequent steps. To assess climate exposure within these areas, we overlaid the polygons with two spatial datasets: first, the climate trend maps, to identify where modeled supply areas overlap with regions experiencing statistically significant long-term climate trends; and second, MapBiomas Collection 10, to quantify the area of soybean cropland and pasture within those zones. In this way, the export data informed the geographic delineation of potential sourcing areas, while the exposure assessments were conducted in the spatial domain.

The climatological dataset (1993–2023) and the export dataset (1997–2025) cover different periods by design, as each serves a distinct analytical purpose. The climate data characterize long-term trends in temperature and precipitation and their relationship with native vegetation loss, following the 30-year standard climatological period defined by the World Meteorological Organization. The export data begin in 1997, when Brazil's municipal-level trade records became available, and were used to delineate the modeled supply areas. The integration of these datasets is therefore spatial rather than temporal, and no direct causal relationship between the two time series is assumed or implied.

Assessment of the Current Policy and Regulatory Framework

To assess the policy and governance context relevant to more sustainable and climate-resilient soy and beef supply chains, we assessed Brazil's main legal, policy, and institutional instruments related to deforestation control, land restoration, agricultural productivity, and climate resilience. This analysis provides the policy and governance context needed to interpret the results of the climate trend assessment across agricultural production regions and to identify policy gaps and implementation opportunities related to deforestation and climate-related pressures.

The assessment focused on three complementary dimensions. First, we reviewed the main governance and enforcement instruments aimed at reducing illegal deforestation[1] and improving environmental compliance in agricultural supply chains, including the Brazilian Forest Code[3] and its implementation mechanisms, with particular attention to the Rural Environmental Registry (CAR)[4], embargo systems, and traceability-related governance challenges in soy and cattle supply chains. Second, we examined policy instruments and public programs aimed at restoring productivity on already-cleared land and reducing pressure on native vegetation, including initiatives related to pasture recovery, low-emission agriculture, and native vegetation restoration. Third, we considered how existing institutional arrangements could support implementation through improved data integration, sustainable procurement, and financial incentives, as well as the role Brazil–China cooperation could play in these areas.

This assessment was guided by the central analytical question of whether Brazil's current regulatory and policy framework is aligned with the transition toward more climate-resilient, low-deforestation, and restoration-oriented agricultural supply chains. To address this question, each instrument was examined according to its relevance for: (i) reducing deforestation and improving environmental compliance; (ii) restoring degraded lands and supporting productivity gains on already-cleared land; (iii) strengthening traceability,

monitoring, and land-use governance; and (iv) reducing climate-related risks in major soy- and beef-producing regions, including areas relevant to exports to China.

Within each dimension, policy gaps and implementation opportunities were identified by cross-referencing the formal design of each instrument with available evidence on its implementation performance, drawing on official monitoring and administrative data, such as CAR registration and validation rates, deforestation trends, and evidence on enforcement and traceability coverage, as well as academic and institutional literature assessing policy outcomes, compliance levels, and governance challenges in soy and cattle supply chains. This approach allowed the review to move beyond a normative assessment of legal and policy texts and identify where existing instruments face implementation bottlenecks, coordination gaps, or opportunities for strengthening enforcement, data integration, land restoration, traceability, and risk-aligned finance.

Results and discussion

Climate Trends and vegetation loss in the Amazon and Cerrado

Our results show that over the past three decades, the Amazon and Cerrado biomes have experienced statistically significant (p-value < 0.05) shifts in rainfall patterns, rainy-season duration, and extreme heat exposure (Figure 1). These concurrent climatic changes signal a structural transformation of the environmental conditions underpinning Brazil's soy and beef production systems.

Figure 1 summarizes the results of the climate trend analysis across the Amazon and Cerrado biomes. For rainy-season duration (Figure 1a), the analysis shows a consistent decline across all observed areas of both biomes, although the magnitude varies spatially. On average, the rainy season shortened by approximately 2.5 days per year in the Amazon and 1.5 days per year in the Cerrado. Over 30-years , this corresponds to a cumulative reduction of up to 75 rainy days in parts of the Amazon and 45 rainy days in parts of the Cerrado. In practical terms, this means that the period of the year with regular rainfall has become progressively shorter in many regions.

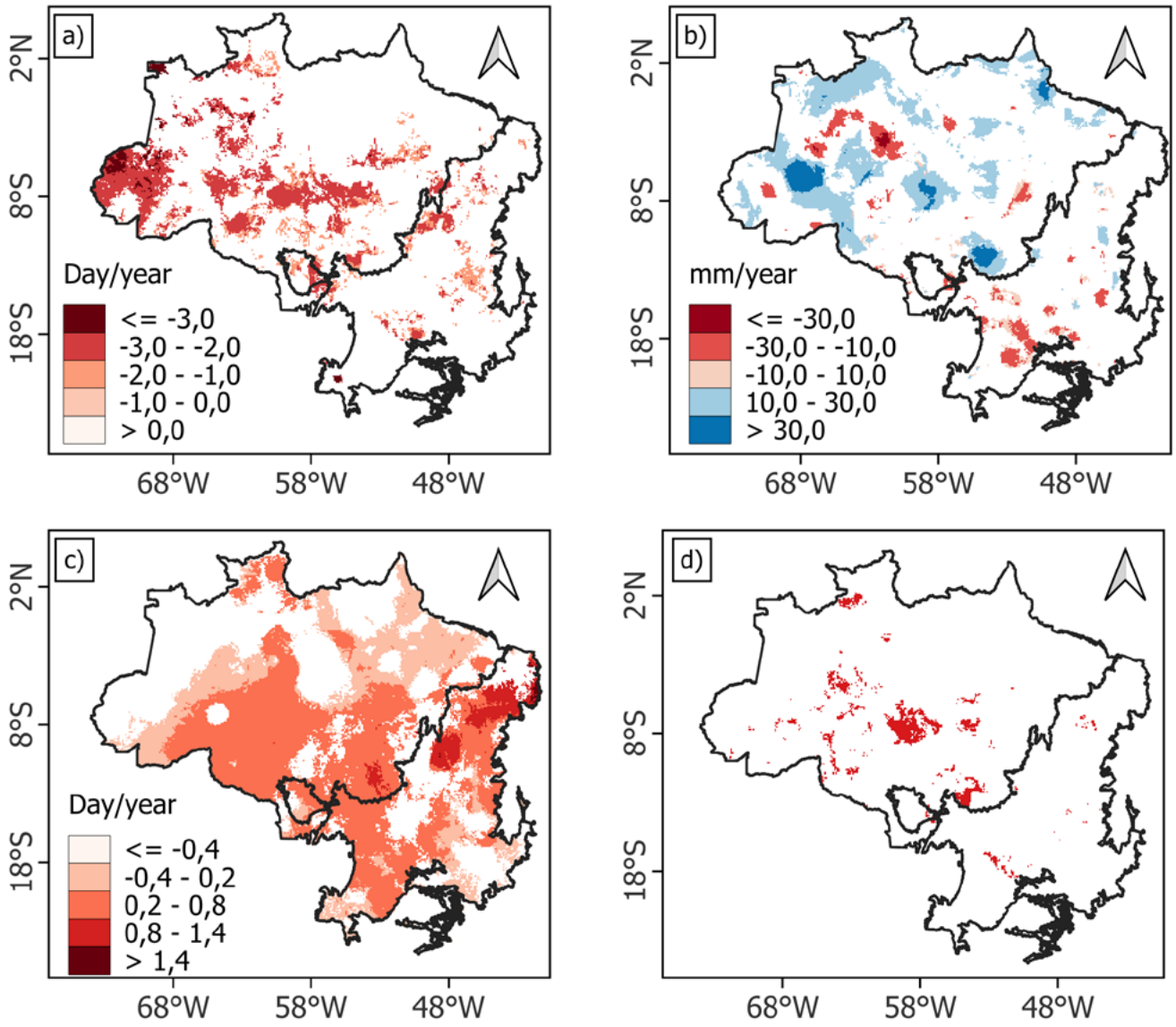
Regarding trends in annual rainfall totals over 1993–2023, Figure 1b shows a spatially heterogeneous pattern across the Amazon and Cerrado, with both increasing and decreasing trends observed across the study area. In the Amazon, some regions, particularly in the western and northern portions, show increasing annual rainfall, while other areas exhibit declining trends. This rainfall increase may be linked to heterogeneous small-scale deforestation patterns, which tend to intensify mesoscale moisture circulation, temporarily enhancing precipitation in deforested areas adjacent to remnant forest. This effect reverses once vegetation loss surpasses critical thresholds, at which point rainfall begins to decline (Leite Filho et al., 2021). In the Cerrado, the pattern is also mixed, although localized decreases in annual precipitation are visible in some central and eastern areas. In some locations, these negative trends reach up to 50 mm per year, which may intensify water stress where rainfall is already becoming more variable.

The number of days with maximum temperatures above 35°C also increased across both biomes (Figure 1c). Positive trends are observed in both the Amazon and the Cerrado, although the increase is generally more pronounced in the Cerrado. On average, the Amazon shows an increase of approximately 0.3 additional hot days per year, while the Cerrado records an increase of about 0.4 days per year. Over a 30-year period, this corresponds to an increase of roughly 9 additional days above 35°C in the Amazon and 12 additional days in the Cerrado.

The relationship between deforestation and regional climate trend is non-linear in the Amazon and predominantly linear in the Cerrado. The regression equations for each relationship are provided in Appendix A. Figure 2 shows that Amazon exhibits critical deforestation thresholds, beyond which small additional losses of vegetation begin to generate much more intense climate impacts. This is visible in the curved shape of the fitted lines in the Amazon panels: at low levels of vegetation loss, the line remains relatively flat, indicating modest climate responses. As deforestation crosses critical thresholds, however, the slope steepens sharply — meaning that each additional percentage point of vegetation loss begins to drive disproportionately larger changes in rainfall onset, rainfall volume, and maximum temperature. In contrast, the straight fitted lines in the Cerrado panels reflect a consistently proportional response throughout the full range of vegetation loss, with no such acceleration. For the onset of the rainy season (Figure 2a), a non-linear response emerges at approximately 47.5% cumulative native vegetation loss. Below this threshold, each additional 10% of deforestation delays the onset of the rainy season by roughly one day. Once this threshold is crossed, the effect intensifies sharply, with each additional 10% of vegetation loss delaying the onset by approximately three days, directly compressing the planting window for rainfed crops.

A similar non-linear pattern is observed for maximum air temperature in the Amazon, with a critical threshold at around 52.5% cumulative vegetation loss (Figure 2e). Below this level, maximum temperature increases at a relatively modest rate of about 0.02°C per percentage point of vegetation loss. Beyond this threshold, warming accelerates dramatically, reaching approximately 0.2°C per percentage point, indicating a tenfold increase in sensitivity and signaling a regime shift in land–atmosphere interactions.

Figure 1 | **Results of the climate trend analysis for the period 1993–2023.**

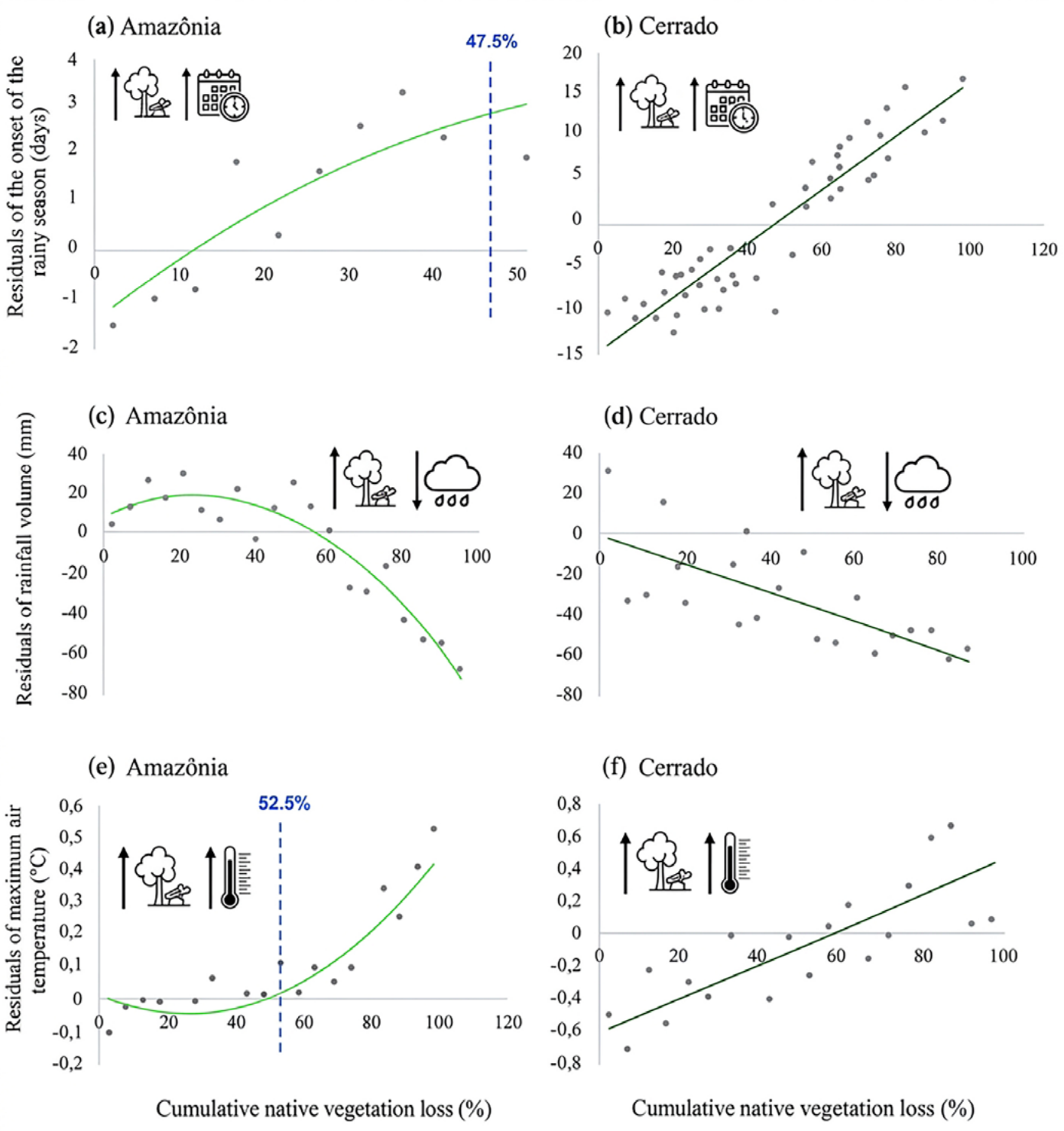


Notes: Panel (a) shows trends in the duration of the rainy season; (b) presents trends in annual precipitation totals; and (c) illustrates trends in the number of days with maximum temperatures above 35 °C. Panel (d) highlights areas where significant trends overlap across the three variables, identifying regions experiencing concurrent climatic changes.

Source: Authors

In contrast, the Cerrado displays a more linear and consistent climate response to vegetation loss. The onset of the rainy season is delayed by an average of three days for every 10% increase in cumulative native vegetation loss, with no evidence of threshold effects or changes in slope as deforestation progresses. Likewise, maximum air temperature increases steadily at a rate of approximately 0.1°C per percentage point of vegetation loss, reflecting a persistent but cumulative warming effect in this biome.

Figure 2 | **Relationships between cumulative native vegetation loss and climate anomalies in the Amazon and Cerrado.**



Notes: Figures a) and b) show the residuals of the onset of the rainy season (days) as a function of cumulative native vegetation loss (%); Figures c) and d) show the residuals of rainfall volume (mm); and Figures e) and f) show the residuals of maximum air temperature (°C). Dots represent annual observations, while solid lines indicate the fitted relationships, highlighting non-linear responses in the Amazon and predominantly linear trends in the Cerrado. All regressions are statistically significant ($p < 10\text{-}5$).

Source: Authors

The climate trends identified in this study are consistent with a growing body of literature documenting increasing climate instability across the Amazon and Cerrado. In the Amazon, recent analyses show a marked intensification of heat extremes over the past decades. Luiz-Silva et al. (2025), for example, report that prolonged heat events, hot days, and annual temperature records have become increasingly frequent across the Brazilian Legal Amazon[5]. They found the number of anomalously hot days and nights, those exceeding the 90th percentile of the local historical temperature baseline, grew by approximately 11 days per decade, while heatwave episodes lengthened from 10–20 consecutive days in the 1960s to 30–40 days in recent years. Similar patterns of hydroclimatic stress have been identified in key agricultural regions of the Cerrado. In Western Bahia state (BA), one of Brazil's most important grain-producing regions, Pousa et al. (2019) analyzed long-term time series of precipitation (1980–2015) and river discharge (1978–2015), finding a significant reduction of up to 12% in rainfall since the 1980s, along with declining river discharge across all monitored stations in both the rainy and dry seasons.

In another study conducted by National Institute for Space research (INPE) (Silveira et al., 2025), researchers compared areas with different levels of forest cover in the Amazon and found that more heavily deforested regions exhibit significantly higher land surface temperatures—up to 3°C warmer during the dry season—along with reduced rainfall and fewer rainy days. For the Cerrado, Leite-Filho et al. (2025) combined historical climate observations with modeling of deforestation-induced climate change to assess impacts on soy–maize double cropping systems. Their results show that, since the 1980s, the biome has experienced an average delay of 36 days in the onset of the agricultural rainy season, a 36.7% reduction in total rainfall, and a 1.5°C increase in temperature, with important implications for cropping calendars and agricultural productivity.

Together, these findings point to a situation of climate imbalance that may lead to significant impacts on agricultural production across both biomes. Lapola et al. (2011) show that, without any adaptation measures, climate change could reduce soybean yields by up to 44% under the most severe climate scenario projected for the Brazilian Legal Amazon by 2050, with potentially even greater impacts in the Cerrado. Brazilian soybean production, for example, although adapted to tropical climates, depends on well-distributed cumulative rainfall of approximately 450 to 800 mm to reach its maximum yield potential (Ferreira et al., 2024). The compression of the planting window mentioned earlier directly threatens the soybean–maize succession system (double cropping, Brumatti et al 2020), which constitutes the backbone of land-use efficiency in Brazilian agriculture. This production model relies on a precise climatic sequence that allows farmers to harvest soybeans early enough to plant maize within the same agricultural year. Disruptions of this kind are consistent with broader projections of climate-driven soybean yield losses across the world's leading producing countries by the 2050s, with effects that propagate through international trade to global supply and prices; net exporters such as Brazil are projected to absorb part of this shock by reducing exports, which in turn threatens supply stability for import-dependent buyers such as China (Qiao et al., 2023).

Thermal stress further amplifies these production risks. The increasing frequency of days with temperatures exceeding 35 °C is associated with higher risks of crop losses, particularly during sensitive phenological stages. Statistical analyses show that each 1 °C increase in average temperature is associated with a reduction of approximately 1% to 6% in soybean productivity in the Cerrado since 1980 (Silva et al., 2023). These productivity losses, in turn, may generate additional pressure for agricultural expansion: Lapola et al. (2011) project that under a severe climate scenario, soybean cultivation would require a 49% larger area simply to meet projected 2050 demand — illustrating how climate-driven yield declines can directly translate into new deforestation pressure. Annual temperatures above the threshold of 21 °C are considered detrimental to the full yield potential of the crop, placing expansion areas in the MATOPIBA[6] region within a zone of uncertainty regarding long-term financial returns (Silva et al., 2023). As a result, increasing climate variability may place additional pressure on the economic stability of agricultural frontiers that have driven Brazil's recent growth in soybean production.

The cumulative economic losses associated with climate-related crop failures are substantial, reflecting the combined effects of climatic variability and other structural factors affecting agricultural production. Over the past five decades, Brazil is estimated to have lost approximately 280 million tons of soybean production due to drought events, corresponding to an economic loss of about USD 152 billion (in 2022 prices) (Ferreira et al., 2024). In the Cerrado, evidence further suggests that if no land had been cleared for soy cultivation since 2008, the region would have produced an additional USD 9.4 billion worth of soy—equivalent to nearly 8% of total regional output between 2013 and 2023 (Bentley-McKune, 2025)2023). These findings highlight the complex interaction between land-use change and climatic instability in shaping agricultural productivity across Brazil's main soybean-producing regions.

Climate Trend Effects on Soy and Beef Export Areas Supplying China

Between 1997 and 2025, ComexStat recorded soy exports to China by companies fiscally domiciled in 208 municipalities in the Amazon and Cerrado, and beef exports by companies domiciled in 60 municipalities. Together, these records

accounted for approximately 34% of Brazil's soy exports to China and 45% of its beef exports to China over the period. Export activity was highly concentrated: the leading municipalities—defined as those with the highest cumulative export volumes to China—were Sorriso (Mato Grosso), Luís Eduardo Magalhães (Bahia), and Balsas (Maranhão) for soy, and Barra do Garças (Mato Grosso), Araguari (Minas Gerais), and Ituiutaba (Minas Gerais) for beef. The complete list of the top 20 municipalities by cumulative export volume, as well as the geographic location of the top 10 municipalities for each supply chain, is provided in Appendix B.

Both biomes experienced a steady increase in the number of municipalities recording exports to China over time. As shown in Figure 3, beef exports to China were highly concentrated in the late 1990s. In 1998, only one municipality — *Várzea Grande* (*Mato Grosso* state), located in the Cerrado biome — reported exports to the Chinese market. By 2025, this number had expanded to 37 municipalities, reflecting a rapid spatial diffusion of beef export activity. Over the same period, the volume of beef exports to China from municipalities in the Amazon and Cerrado also increased markedly, reaching approximately 0.89 million tonnes in 2025. Soy exports, by contrast, were already more geographically distributed in the late 1990s. In 1997, eight municipalities exported soy to China, spanning both the Cerrado and Amazon biomes, with a combined export volume of approximately 0.07 million tonnes. By 2025, the number of municipalities exporting soy had increased substantially, reaching 126 municipalities, while export volumes rose to approximately 41.63 million tonnes.

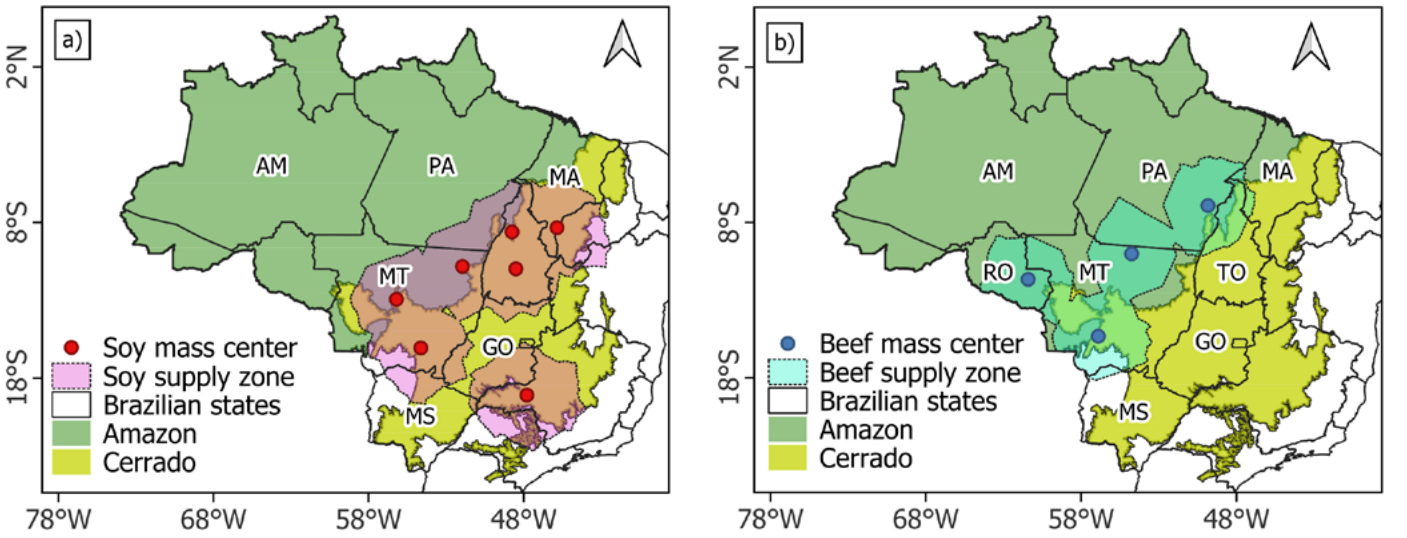
Figure 3 | **Number of municipalities exporting to China located in the Amazon and Cerrado.**



Notes: Panel (a) shows municipalities exporting soybeans, while panel (b) shows municipalities exporting beef.
Source: Authors

The center-of-mass analysis resulted in four weighted aggregation points for beef and seven for soy (Figure 4). Modeled supply areas were then delineated around these points using the travel-time analysis described in the methodology. Detailed cluster maps and travel-time modeling outputs are provided in Appendix C, while Figure 4 presents the consolidated spatial configuration used in the exposure analysis. The modeled areas associated with beef exports extend further north, with aggregation points concentrated in the Amazon, while those associated with soybean exports are more concentrated in the Cerrado biome, particularly in the states of *Tocantins* (TO) and *Mato Grosso* (MT) (Figure 4).

Figure 4 | **Location of Beef and Soy Supply Zones to China.**

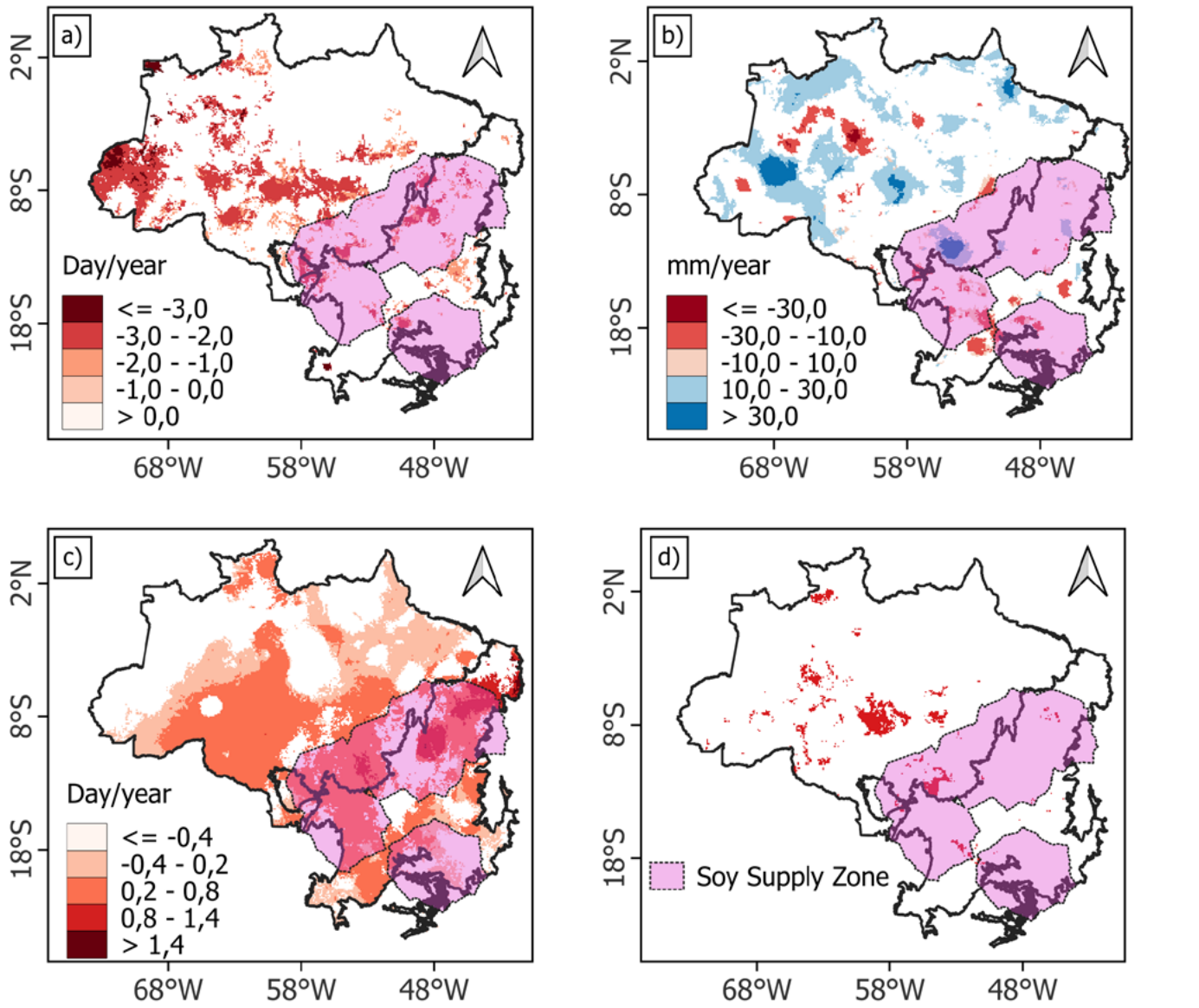


Notes: (a) shows the location of the identified soy supply zone and their respective weighted centers of mass (in red), while (b) presents the beef supply zone and corresponding centers of mass (in blue). The figure also indicates the boundaries of the states of Amazonas (AM), Mato Grosso (MT), Maranhão (MA), Tocantins (TO), Goiás (GO), Mato Grosso do Sul (MS), Rondônia (RO), and Pará (PA).

Source: Authors

Within the soy supply zones, a total of 19 million hectares are under soy cultivation, spanning both the Amazon and Cerrado biomes (approximately 5 million hectares and 14 million hectares, respectively). Of the total soy-cultivated area within the identified supply zones, 3.0 million hectares (15%, Figure 5a) in areas with shifts in the number of rainy days, 3.9 million hectares (20%, Figure 5b) are located in areas experiencing changes in total annual rainfall, and 15.5 million hectares (82%, Figure 5c) in areas with an increasing frequency of days above 35°C. When the three climate variables are considered together, 770 thousand hectares (4% of the total soy-cultivated area, Figure 5d) are located where statistically significant trends in all three climate variables overlap, concentrated primarily in transition zones between the southern Amazon and the Cerrado, as well as in parts of the Cerrado itself.

Figure 5 | **Results of the climate trend analysis for soy supply zone in the period 1993–2023.**



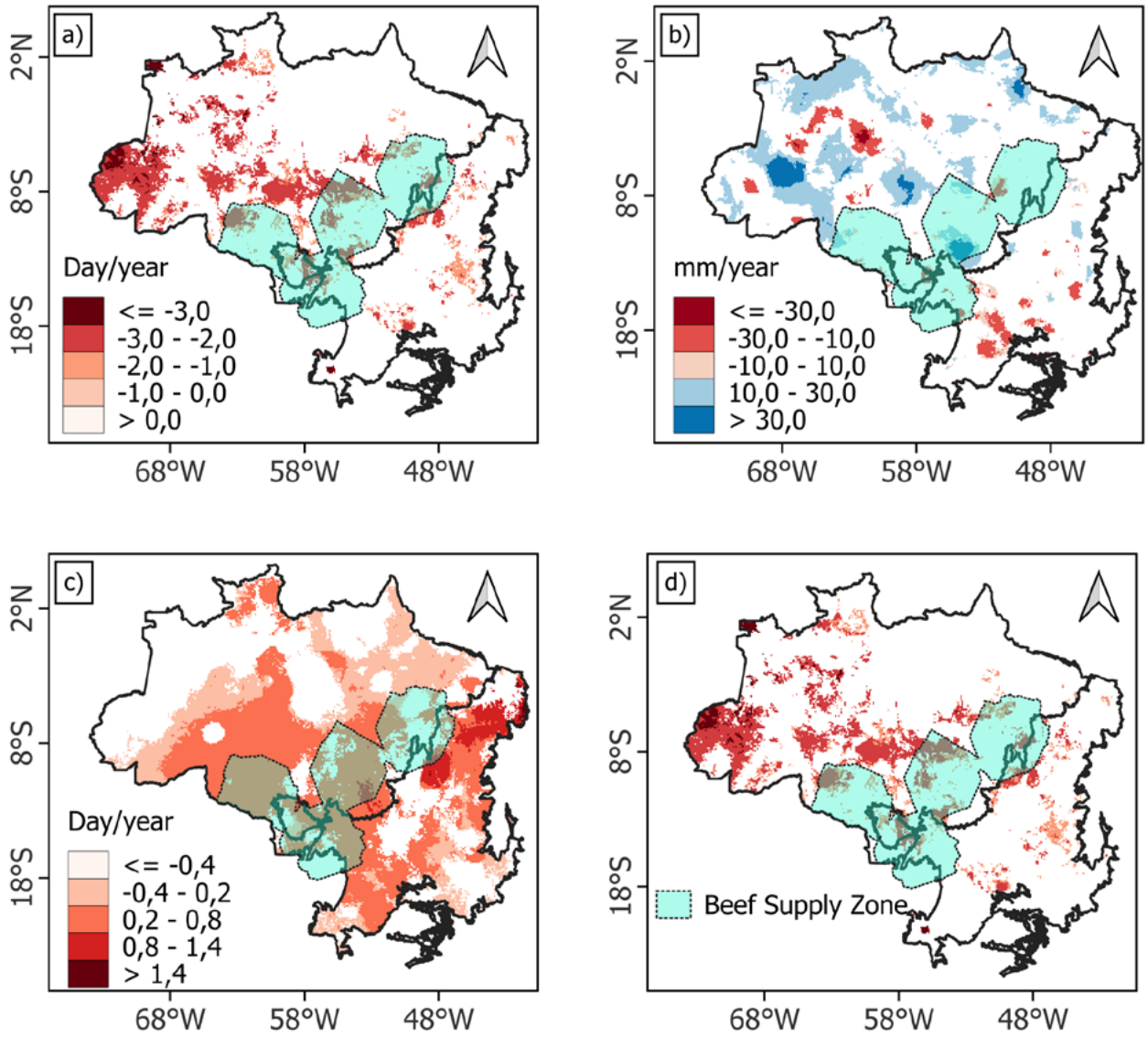
Notes: (a) shows trends in the duration of the rainy season; (b) presents trends in annual precipitation totals; and (c) illustrates trends in the number of days with maximum temperatures above 35 °C. (d) highlights areas where significant trends overlap across the three variables, identifying regions experiencing concurrent climatic changes.

Source: Authors

Beef supply zones were assessed using the same methodological approach. By intersecting pasture areas within the identified beef supply zones with the climate trend maps, we estimated the extent of cattle-producing areas exposed to long-term climatic shifts (light blue shaded areas in Figure 6). Within the identified beef supply zone, a total of 35 million hectares is under pasture, spanning both the Amazon and Cerrado biomes (approximately 28 million hectares and 7 million hectares, respectively).

Among the total pasture area within the identified supply zone, 7.7 million hectares (22%, Figure 6a) with areas showing shifts in the number of rainy days, 2.6 million hectares (7.4%, Figure 6b) overlap with areas experiencing changes in total annual rainfall, and 22 million hectares (62.9%, Figure 6c) with areas where the frequency of days above 35°C is increasing. When the three climate variables are analyzed jointly, 640 thousand hectares (1.8% of the mapped pasture area within the modeled supply zones; Figure 6d) are located where statistically significant trends in all three climate variables overlap, with the largest concentration in northern Mato Grosso.

Figure 6 | **Results of the climate trend analysis for beef supply zone in the period 1993–2023.**



Notes: (a) shows trends in the duration of the rainy season; (b) presents trends in annual precipitation totals; and (c) illustrates trends in the number of days with maximum temperatures above 35 °C. (d) highlights areas where significant trends overlap across the three variables, identifying regions experiencing concurrent climatic changes.

Source: Authors

This pattern of exposure has direct implications for the stability of Brazil's export-oriented agricultural systems, given the central role of the Chinese market and the concentration of production in regions facing increasing climatic pressures. China currently imports approximately 64% of its soybeans from Brazil, while the Chinese market absorbs around 73% of Brazil's total soybean exports (ComexStat, 2025). According to Ali et al. (2022), economic model projections under high-emissions scenarios (RCP 8.5) indicate that, by 2030 total soybean production in Brazil could decline by up to 13.1% due to extreme climate shocks relative to 2011, while Brazilian gross soybean exports could decrease by 15.2%. These projections suggest that climate-related shocks affecting Brazilian agricultural production may have important implications for trade dynamics, particularly given the scale and concentration of Brazil–China agricultural flows.

Beyond direct impacts on yields, climate change may also affect the nutritional quality of soybean production and the stability of export supply chains. While most studies focus primarily on production volumes, emerging evidence suggests that rising atmospheric CO_2 concentrations can alter the chemical composition of soybeans, reducing protein concentration in seeds and affecting mineral content (Peng et al., 2026). This may have implications for import requirements in major consuming markets such as China, where roughly 80% of imported soybeans are processed into soybean meal for animal feed (FAO, 2024).

Climate-related pressures also extend beyond the farm gate to the infrastructure supporting agricultural exports. In a country where more than 60% of soybean transport relies on road freight, export flows are particularly exposed to disruptions associated with extreme weather events, such as heavy rainfall that blocks roads or droughts that lower river levels and disrupt waterway transport (Fliehr et al., 2019). In addition, structural dependencies—such as Brazil's reliance on imported fertilizers—can interact with climatic variability and geopolitical shocks, affecting production costs and supply stability (Cardoso et al., 2025).

Together, these factors indicate that climate variability and broader structural conditions may affect the stability and resilience of soybean supply chains, particularly in regions that are highly integrated into export markets. In the beef sector, climate impacts are also significant, though often mediated by pasture degradation. Reduced rainfall in the southern Amazon, affecting both pasturelands and soybean production, may generate economic losses of up to USD 1 billion annually for the regional agribusiness sector (Leite-Filho et al., 2021). As the geographic distribution of recorded beef exports to China has expanded, climate resilience has become relevant to a broader set of Brazilian production regions participating in export-oriented supply chains. Maintaining Brazil's position as a leading agricultural exporter will increasingly depend on the ability to manage these pressures through adaptation, land-use governance, and productivity gains in already-cleared areas. These measures are critical not only for environmental sustainability, but also for preserving the economic stability of export-oriented regions.

Governance of Deforestation in Brazil: Regulation and Restoration Instruments

The overlay between climate trends and beef and soy supply zones shows that a substantial share of the areas linked to exports to China are already experiencing significant changeswith up to 82% of soy-cultivated areas and 62.9% of pasture areas within the identified supply zones exposed to an increasing frequency of days above 35°C. In addition, changes in rainfall patterns affect approximately 15% of the identified soy supply areas and 22% of the pasture supply areas, although these areas may partially overlap with those exposed to increasing temperatures. In this context, the results of this study suggest that deforestation control and restoration play an important role not only in reducing greenhouse gas emissions and ensuring regulatory compliance, but also in supporting agricultural productivity, addressing climate-related pressures, and contributing to socioeconomic stability in export-oriented regions.

Curbing deforestation and restoring already-cleared land are mutually reinforcing strategies, rather than separate objectives: increasing productivity on degraded pastures relieves the economic pressure to clear additional native vegetation, while restoring native vegetation cover helps moderate local temperature and sustain the rainfall patterns on which agricultural productivity depends (Spracklen & Garcia-Carreras, 2015; Lawrence & Vandecar, 2015; Flach et al., 2021; Leite-Filho et al., 2021). However, productivity gains on cleared land reduce pressure on remaining forest only when paired with strong enforcement and monitoring; absent this, they may instead raise land values and incentivize further conversion (Gibbs et al., 2015; Müller-Hansen et al., 2019; Skidmore et al., 2020). This is especially relevant in the Amazon and Cerrado, where our results suggest that native vegetation loss is associated with observed changes in climate conditions over the past 30 years. Because this loss —not only pasture degradation—is itself implicated in the climate shifts observed in this study, restoring key landscape functions requires combining pasture recovery with native vegetation restoration, not pasture recovery alone. In this context, increasing production in already cleared areas, recovering degraded pastures, and restoring native vegetation can jointly sustain agricultural productivity and consequently support the long-term stability of trade relations between Brazil and China.

In response to this challenge, Brazil already has in place a regulatory framework composed of complementary instruments, including the Forest Code, the ABC+ Plan (2020–2030)[7], the Caminho Verde Program[8], PLANAVEG[9], and PPCDAm. Among these, the Forest Code (Law No. 12,651/2012) remains the main legal pillar, requiring the conservation of native vegetation in Permanent Preservation Areas (APPs) and Legal Reserves, with implementation centered on the Rural Environmental Registry (CAR). According to the federal CAR dashboard (SFB, 2026), only 589,328 registrations—approximately 7.2% of the 8.2 million registered rural properties—had completed environmental compliance analysis by March 2026, which limits the reliability of the system for environmental screening in commercial and financial transactions.

On the production side, the ABC+ Plan establishes the national framework for promoting low-carbon and climate-adapted agriculture, encouraging pasture restoration, the adoption of Integrated Crop–Livestock–Forestry (ICLF) systems, and improved soil management to increase productivity on already cleared lands. Evidence from the first phase of the ABC Plan (2010–2020) shows significant progress: the area under pasture restoration reached 26.8 million hectares—exceeding the initial target of 15 million hectares—while Integrated Crop–Livestock–Forestry systems expanded to 10.76 million hectares, more than doubling the original target of 4 million hectares (MAPA,

2021). The Caminho Verde Program focuses on the recovery and productive intensification of degraded areas, aiming to restore or convert up to 40 million hectares (Brazil, 2023a). This approach is consistent with evidence showing that maintaining and restoring vegetation cover helps moderate warming and preserve rainfall patterns essential for agricultural productivity (Spracklen & Garcia-Carreras, 2015; Flach et al., 2021). Together, these instruments support the expansion of more resilient agricultural production, function as risk management tools, and contribute to strengthening the resilience of agricultural production in export-oriented regions.

In terms of restoration and enforcement, PLANAVEG reinforces the role of native vegetation in climate and hydrological regulation (Lawrence & Vandecar, 2015; Leite-Filho et al., 2021), while PPCDAm acts as the primary enforcement mechanism, integrating monitoring, sanctions, and credit restrictions. Evidence shows that these measures have reduced deforestation and induced productive intensification (Schmitt and Scardua, 2015; Hänggli et al., 2023; Massoca & Brondízio, 2022), suggesting that productivity gains in already cleared areas scale more effectively when economic incentives are combined with strong enforcement. A review of PPCDAm's four phases (2004–2019) shows that its initial implementation period (2004–2012) was particularly effective, contributing to an 84% reduction in deforestation in the Amazon by 2012 compared to 2004 (Reis and Corazza, 2025). However, the effectiveness of these instruments is not immune to political change (Dutra and Fearnside, 2023). Brazil's experience between 2019 and 2022 demonstrated that environmental enforcement can deteriorate rapidly under administrations less committed to deforestation control (Cavalcante and Costa, 2023), with direct consequences for monitoring capacity, fine collection, and the protection of Indigenous and traditional territories. Instruments anchored in legislation — such as the Forest Code and CAR — offer greater institutional stability, as reversing them requires legislative action. Nevertheless, their effective implementation remains heavily dependent on executive commitment, budget allocation, and inter-agency coordination (Dutra and Fearnside, 2023). This political vulnerability underscores the complementary value of stable private supply-chain commitments and international cooperation in supporting the continuity of domestic deforestation-control efforts across political cycles.

Despite this robust institutional architecture, enforcement gaps remain a central constraint. Significant restoration liabilities—estimated at over 40 million hectares—combined with perceived economic costs, monitoring weaknesses, and low sanction effectiveness continue to undermine compliance (Spavorek et al., 2017; Rajao et al., 2020). As a result, illegal deforestation persists even within formal markets through "laundering" mechanisms(Rajão et al., 2020; Loomis et al., 2026), while low fine collection rates reduce the deterrent effect of penalties (Schmitt e Scardua, 2015; Carvalho et al., 2019). These challenges are further exacerbated by structural limitations in state capacity, institutional coordination, and local political dynamics, particularly in agricultural frontier regions and the Cerrado (Massoca and Brondízio (2022; Hänggli et al., 2023; Dutra e Fearnside, 2023).

In this context, deforestation governance increasingly depends on the ability to integrate existing instruments. Accelerating CAR validation and modernizing SICAR[10] into a Monitoring, Reporting, and Verification (MRV) system are essential for enabling scalable verification of environmental compliance. Evidence from platforms such as SeloVerde[11] shows that automated data cross-checking and near real-time monitoring can increase transparency and reduce costs, while enabling conditional access to credit, insurance, and markets (Rajão et al., 2020; Inter-American Dialogue, 2025). Beyond the public regulatory framework, private and hybrid governance mechanisms have also played a meaningful role in shaping land-use outcomes. The Soy Moratorium, established in 2006 as a voluntary agreement between major trading companies, sectoral entities, and civil society organizations, restricted the purchase of soy produced on land deforested after July 2008 in the Amazon biome. Despite its voluntary nature, the agreement contributed to a significant reduction in deforestation linked to soy: before its adoption, approximately 30% of soy expansion occurred on recently deforested areas; after, that share fell to around 1% (Gibbs et al., 2015). However, the Moratorium's future is currently uncertain following a suspension ordered by Brazil's antitrust authority (CADE) in August 2025, which opened an investigation into potential anticompetitive effects. Its geographic scope has also been limited exclusively to the Amazon biome, leaving the Cerrado without an equivalent instrument. In this transitional context, the continued engagement of major Chinese trading companies — including COFCO International — in deforestation- and conversion-free sourcing commitments (COFCO International, 2025) illustrates how private supply-chain governance can complement public regulatory frameworks, even as voluntary instruments face institutional uncertainty.

In parallel, deforestation-free supply chains require the integration of land-use systems and livestock traceability. The disconnect between CAR and the Animal Transit Guide (GTA) limits the identification of deforestation risks in cattle supply chains, particularly due to the role of indirect suppliers, through which animals originating from deforested areas can be "laundered"(Loomis et al., 2026). First-tier indirect suppliers alone account for approximately 37% of deforestation in key states, and integrating their records into formal traceability systems could expand monitoring coverage from 55% to 89% of remaining forest (Loomis et al., 2026). This disconnect, however, is not merely a technical or

administrative gap to be closed with better data infrastructure: the GTA was originally designed for sanitary control, and its repurposing as an environmental traceability proxy since 2018 has been actively contested by industry and political actors with incentives to preserve data opacity (Choquet, 2025). Without systematic integration between GTA records and validated CAR data, environmental non-compliance remains difficult to detect in complex production networks.

Strengthening governance therefore depends on improving enforcement without imposing excessive bureaucratic burdens that could compromise production or access to credit. Monitoring effectiveness depends not only on technical systems, but also on institutional capacity and political incentives (Loomis et al., 2026). This is particularly relevant given that major soy- and beef-producing regions, including the modeled areas associated with exports to China—overlap with areas experiencing high levels of climate stress.

Taken together, the instruments analyzed suggest that a political and institutional context is emerging to support a transition from a model based on territorial expansion to one centered on productivity intensification supported by restoration. Yet the durability of this transition depends on more than the existence of the right policies — it requires consistent enforcement, stable funding, and governance structures resilient enough to withstand political cycles. . When combined with climate adaptation strategies, these policies can help stabilize or sustain soy and beef production under changing climate conditions, reduce pressure on native vegetation, and protect export capacity.

For Brazil–China relations, these dynamics are strategically significant. This significance is reinforced by the structural weight of China in Brazil's beef trade relative to other markets: while the EU absorbs only around 5% of Brazil's beef exports, China accounts for more than 50%, a trade orientation that limits the leverage of EU due-diligence regulations such as the EUDR (Loomis et al., 2026) and is unlikely to be matched by formal regulatory convergence between the EU and China in the short to medium term (Vasconcelos et al., 2024). The concentration of export production in areas simultaneously exposed to climatic pressures and environmental liabilities suggests that maintaining stable and predictable supply will increasingly depend on Brazil's capacity to restore, adapt, and strengthen land-use governance. In this sense, bilateral cooperation that supports traceability, data integration, and climate-aligned finance is not only an environmental agenda, it is a supply-chain risk management strategy with direct implications for long-term trade stability. Failure to advance this agenda may increase production volatility, heighten regulatory and reputational risks, and affect the long-term stability of export-oriented sectors.

Policy Implications: Operationalizing Brazil–China Cooperation Through Data, Procurement, and Finance

Building on the spatial exposure analysis and the assessment of Brazil's policy framework, this section discusses potential areas for complementary Brazil–China cooperation. Investments in climate-resilient agriculture are increasingly important, but their effectiveness depends on the extent to which financial and institutional arrangements incorporate the interlinkages between deforestation, climate change, and agricultural productivity. More specifically, most agricultural finance instruments still treat climate risk as exogenous, even though empiricalevidence suggests that deforestation is associated with changes in productivity and revenues (Leite-Filho et al., 2021; Flach et al., 2021), constituting a material risk for credit, insurance, and supply chains. When this relationship is not recognized, capital may continue to flow toward activities that undermine long-term stability (Carreira et al., 2024; Hänggli et al., 2023). Aligning finance with climate-resilient and deforestation-free production can be understood as a way to address misaligned incentives that may undermine long-term stability.

From a production perspective, technical solutions for climate-resilient intensification are already well established. Practices such as pasture recovery and Integrated Crop–Livestock–Forest (ILPF) systems increase productivity, improve soil moisture retention, and stabilize production under climate stress (Pereira et al., 2024; Embrapa, 2019). These practices are particularly relevant in production regions where significant climate trends overlap with mapped soy and pasture areas within the modeled export-associated supply zones. However, the existence of these solutions does not guarantee their large-scale adoption. Their implementation requires upfront investment, technical assistance, and learning processes, which constrain uptake in the absence of appropriate financial instruments (Pereira et al., 2024; Massoca & Brondízio, 2022). Moreover, a second structural limitation emerges: productivity gains alone do not ensure reductions in deforestation. Under weak enforcement, they may increase land values and incentivize forest conversion (Müller-Hansen et al., 2019). Evidence from the Amazon shows that intensification reduces deforestation only when combined with strong regulation and monitoring (Gibbs et al., 2015; Skidmore et al., 2020), reinforcing the need to condition financial support on compliance with socio-environmental regulations.

This implies that the challenge is not only financial or technological, but also institutional. Land-use decisions are shaped not only by public policy but also by commercial dynamics within supply chains. Buyer–supplier relationships influence production incentives and market access (Carreira et al., 2024; Barreto & Gibbs, 2015). In this sense, incorporating

climate and deforestation risk criteria into supply-chain finance—through traceability, CAR validation, and territorial risk screening—can be as influential as public credit in shaping land-use outcomes (Gibbs et al., 2015).

It is at this point that the spatial contribution of this study becomes relevant. The analysis identifies modeled soy and beef supply areas associated with exports to China where significant climate trends overlap with mapped production. This evidence can help inform—but does not by itself determine—the territorial targeting of credit, guarantees, and technical assistance for climate-resilient production. Additional project-level information on environmental compliance, productive conditions, implementation capacity, costs, and expected benefits would be required to guide individual investment decisions (Hänggli et al., 2023; Carreira et al., 2024).

In the specific context of Brazil–China relations, this territorial evidence provides a concrete basis for moving beyond project-level "green finance" toward risk-aligned financial arrangements. China's green development guidelines and Brazil's domestic programs, such as ABC+ and the National Program for the Conversion of Degraded Pastures (PNCPD), offer complementary foundations for scaling climate-resilient production. Thus, aligning these agendas through conditional finance, risk-screened procurement, and targeted investment can contribute to strengthening supply security while reducing deforestation-related risks. Importantly, this process builds on an already established institutional landscape—including COSBAN, BRICS, BASIC, and the CBERS satellite program (CEBRI, 2019; Thives et al., 2022a; Søndergaard et al., 2023; State Council of China, 2021; MOFCOM & MEE, 2021)—as well as emerging private-sector commitments to traceability and deforestation-free supply chains (COFCO International, 2025; Søndergaard et al., 2023).

To operationalize this cooperation, however, clear entry points are required. Data integration and traceability provide one of the most practical pathways. Brazil already possesses extensive public datasets, such as CAR and GTA, while Chinese regulatory frameworks emphasize transparency and environmental risk management in overseas sourcing. In practice, this creates an area of convergence between policy frameworks in which traceability functions as enabling infrastructure rather than a market-access condition. Greater interoperability and appropriate data-sharing arrangements could allow validated Brazilian monitoring data to inform risk screening by Chinese policymakers, importers, and financial institutions, subject to applicable data-governance and access requirements.

Once these risks become visible, the challenge increasingly shifts from information to incentives. Extreme climate events are already generating measurable macroeconomic impacts, while financial markets are increasingly pricing deforestation exposure (International Monetary Fund, 2024; Addoum et al., 2024). Extreme climate events are already generating measurable macroeconomic impacts, while financial markets are increasingly pricing exposure to deforestation and climate risk (International Monetary Fund, 2024; Addoum et al., 2024). At the same time, financing decisions can influence land-use outcomes by directing capital toward—or away from—activities associated with native vegetation loss. Together, these two directions reflect the logic of double materiality: environmental change can create financial risks, while financial decisions can generate environmental impacts.

This implies that the transition depends on reallocating capital toward production systems that increase output on already-cleared land, reduce climate sensitivity, ensure verified environmental compliance, and minimize regulatory risks (Souza et al., 2020; Gil et al., 2023; Ribeiro et al., 2021; Addoum et al., 2024).

At this stage, financial instruments become an important mechanism for translating this logic into practice. Risk-based instruments—such as sustainability-linked loans, preferential credit for verified producers, and traceability-linked supply-chain finance—can support the adoption of climate-resilient systems in export-oriented regions (Souza et al., 2020; Addoum et al., 2024; Flach et al., 2021; Flammer & Mariz, 2025). However, realizing the potential of these financial instruments requires addressing an important governance challenge: environmental risk verification cannot be delegated to financial institutions without adequate support structures. Credit analysts and risk managers need to be trained to assess deforestation and climate compliance, and to interpret the monitoring data required for meaningful due diligence; without this capacity, risk-based finance may default to superficial or inconsistent screening, undermining its ability to channel capital toward genuinely climate-resilient and deforestation-free production. The empirical record illustrates the scale of this gap: by 2017, only 47% of soy exports from the Cerrado were covered by zero-deforestation commitments — well below the nearly 90% achieved in the Amazon — and corporate monitoring frameworks typically cover only direct suppliers, leaving the roughly 34% of Mato Grosso soybean exports routed through indirect channels outside corporate oversight (Peng et al., 2026; Gibbs et al., 2015; Rajão et al., 2020). Closing these gaps requires standardized, publicly available risk indicators. The spatial exposure indicators developed in this study can help inform this broader effort, alongside validated property- and supply-chain-level data and state-led verification infrastructure, such as a modernized SICAR functioning as an MRV system, that allows banks, investors, and buyers to rely on validated public data rather than conducting independent and often incomplete assessments.

Strengthening this verification foundation is, in this sense, an important enabling condition for making financial instruments effective and it is also where Brazil's existing assets become most relevant. By leveraging its monitoring systems, restoration policies, and accumulated experience in low-carbon agriculture, Brazil is well positioned to contribute to emerging international approaches that link forest protection, climate resilience, and agricultural production. More than an environmental agenda, this represents a strategy to reduce production and trade vulnerabilities in systems increasingly exposed to climate and regulatory risks, and an opportunity to strength the competitiveness, predictability, and long-term resilience of its export sectors within the Brazil–China nexus.

Conclusion

This study documents statistically significant changes in rainfall patterns, rainy-season conditions, and extreme heat exposure across the Amazon and Cerrado, as well as a statistical relationship between these climate variables and native vegetation loss. The spatial analysis further shows that these trends overlap with mapped soy and pasture areas within modeled supply zones associated with exports to China. Together, the findings indicate that climate and land-use dynamics are increasingly relevant to the resilience of Brazilian production landscapes and, consequently, to long-term stability of one of the world's most important South–South agri-food trade relationships.

The results reinforce that controlling deforestation and restoring degraded lands should not be understood solely as climate or compliance objectives. In the Amazon and Cerrado, these measures can help maintain rainfall regulation, reduce thermal stress, protect agricultural productivity, and strengthen the resilience of export-oriented production systems. Key producing states identified in the analysis—including Mato Grosso, Pará, Tocantins, Maranhão, and Bahia—represent important contexts for coordinated climate and land-use action. Yet because native vegetation loss can affect climate at both local and regional scales, effective responses cannot be confined to the areas where multiple climate trends overlap: region-wide action across the Amazon and Cerrado is required to protect the hydrological and thermal stability on which agricultural productivity depends.

Brazil already has a relevant institutional architecture to support this transition, including the Forest Code, CAR, ABC+, PLANAVEG, and PPCDAm. However, the effectiveness of this framework depends on improving implementation. Improving monitoring systems, strengthening traceability and compliance protocols, accelerating CAR validation, reinforcing enforcement, and expanding incentives for restoration and sustainable intensification are important steps to reduce the exposure of agricultural supply chains to both climate and deforestation-related risks. More broadly, advancing public and private debates on these themes—and translating them into practical governance arrangements—can contribute to more consistent and scalable responses in regions facing greater climate exposure.

Given the scale of bilateral soy and beef trade, the resilience of Brazilian production landscapes is a shared strategic interest for Brazil and China. For Brazil, improving governance and resilience in the Amazon and Cerrado can help sustain productivity on already-cleared lands, support producer income, strengthen regulatory compliance, advance climate commitments, and maintain the long-term competitiveness of its agricultural exports. For Chinese policymakers, importers, financial institutions, and other market actors, engagement with more resilient and traceable supply chains can contribute to more stable and predictable sourcing conditions while supporting broader sustainability objectives. These complementary interests create opportunities for cooperation without changing the distinct responsibilities of each country or substituting for the implementation of Brazil's domestic land-use policies.

Ultimately, this study suggests that the future stability of Brazil–China agricultural trade will depend not only on production capacity, but also on the resilience and governance of the landscapes that support Brazilian soy and beef production. Strengthened domestic implementation in Brazil, complemented by cooperation on data integration, monitoring, sustainable procurement, financial mechanisms, and territorial restoration, can help align agricultural competitiveness, climate resilience, and the long-term stability of bilateral supply chains.

Appendix A

Relationship between vegetation loss and climate variables (1993–2023)

The methodology used to estimate local climate changes associated with the loss of native vegetation is based on a statistical framework that combines detrending procedures and regression analysis (Leite Filho et al. 2021,2024). The main objective of this method is to isolate the climate signal associated with local deforestation from other drivers of climate variability, including geographic controls and large-scale climate change.

To achieve this, the analysis applies a three-step detrending procedure designed to remove spatial and temporal sources of variability unrelated to vegetation loss (Leite Filho et al. 2021,2024). In the first step, the spatial variability of climate is modeled using machine learning algorithms to replicate spatial patterns of rainfall and temperature as a function of latitude, longitude, and elevation for each 10 km × 10 km grid cell. This step allows the estimation of expected climate conditions based solely on geographic characteristics.

In the second step, external influences are removed from the observed climate variables. First, the predicted values generated by the spatial models are subtracted from the observed climate values, thereby eliminating the effect of static geographic controls such as location and altitude. Second, the biome-wide mean for each climate variable is removed for each year in order to eliminate large-scale climatic signals, including interannual variability driven by phenomena such as El Niño–Southern Oscillation (ENSO) and broader anthropogenic climate change trends. The resulting residuals represent the climate anomalies used in the subsequent analysis.

The third step consists of validating the detrending procedure. Validation is conducted by verifying that the annual mean of the calculated anomalies is approximately zero across the biome, confirming that geographic patterns and interannual variability have been effectively removed and that the remaining signal reflects localized climatic responses.

After isolating the climate anomalies, the analysis evaluates their relationship with the historical loss of native vegetation. The fraction of vegetation loss within each grid cell is categorized into 19 classes, representing increasing levels of deforestation (for example, class 1 corresponds to less than 5% vegetation loss, while class 19 represents areas with 90–95% vegetation loss). Regression models are then applied to quantify the relationship between climate anomalies and the percentage of vegetation loss.

Both linear and second-degree polynomial regression models are used depending on the behavior of each climate variable. Linear models are applied when the response of the climate variable to vegetation loss is approximately proportional, such as the precipitation response observed in the Cerrado biome. Quadratic models are used when nonlinear responses are detected, allowing the identification of potential tipping points in the climate–deforestation relationship.

To parameterize the model, calibrated regression equations were estimated linking climate anomalies (dependent variables) to the cumulative percentage of native vegetation loss ($D_{i,j,t}$) for each grid cell. For anomalies in the onset of the rainy season ($I_{i,j,t}$), the following relationships were identified.

For the Amazon biome:

$$I_{(i,j,t)} = -0.009D^2_{(i,j,t)} + 0.13D_{(i,j,t)} - 1.59 \quad (1)$$

where *i* and *j* represent the spatial coordinates (latitude and longitude), and *t* represents time. This quadratic formulation indicates a nonlinear response of rainfall onset anomalies to cumulative deforestation, with a critical threshold occurring at approximately 47.5% forest loss, after which the magnitude of the delay in the rainy season increases more rapidly.

For the Cerrado biome, the relationship is linear and expressed as:

$$I_{(i,j,t)} = 0.31D_{(i,j,t)} - 13.59 \quad (2)$$

where *i* and *j* represent the spatial coordinates (latitude and longitude), and *t* represents time. For anomalies in annual precipitation volume $V_{(i,j,t)}$ the relationship estimated for the Amazon biome is:

$$V_{(i,j,t)} = -0.018D^2_{(i,j,t)} + 0.91D_{(i,j,t)} + 7.92 \quad (3)$$

where *i* and *j* represent the spatial coordinates (latitude and longitude), and *t* represents time. Similarly to the onset of the rainy season, this equation shows that although the overall trend is also positive, it is not linear, since the presence of the quadratic term indicates that the impact of deforestation on rainfall volume anomalies may change direction at higher levels of native vegetation loss, as demonstrated by Leite-Filho et al. (2021).

For the Cerrado biome, the relationship is linear and expressed as:

$$V_{(i,j,t)} = -0.61D_{(i,j,t)} - 0.85 \quad (4)$$

where *i* and *j* represent the spatial coordinates (latitude and longitude), and *t* represents time. The model suggests an average reduction of 6 mm in rainfall volume for every 10% loss of native vegetation. However, the absence of a quadratic term in this relationship indicates that the effect of native vegetation loss on rainfall volume anomalies remains consistent, without changes in direction as the fraction of native vegetation loss increases.

For maximum temperatures ($T_{(i,j,t)}$), the relationship with the loss of native vegetation in the Amazon can be analyzed through the following estimated regression equation 5. The inclusion of a quadratic term suggests that the impact of native vegetation loss on temperature anomalies may intensify at higher levels of native vegetation loss.

$$T_{(i,j,t)} = 0.00009D^2_{(i,j,t)} - 0.005D_{(i,j,t)} + 0.008 \quad (5)$$

where *i* and *j* represent the spatial coordinates (latitude and longitude), and *t* represents time. In the Cerrado, this relationship can be understood through a linear equation.

$$T_{(i,j,t)} = 0.01D_{(i,j,t)} - 0.56 \quad (6)$$

Appendix B

List of Municipalities that Export to China: Top 20 for Soy and Beef

Table B1 | **Top 20 Brazilian Municipalities Exporting Soy to China (1997–2025)**

MUNICIPALITY	STATE (UF)	BIOME	SOY EXPORTS TO CHINA (KG)
Sorriso	MT	Cerrado	24,105,860,000
Luis Eduardo Magalhães	BA	Cerrado	19,755,730,000
Balsas	MA	Cerrado	16,562,300,000
Querência	MT	Amazônia	13,807,060,000
Rondonópolis	MT	Cerrado	12,217,590,000
Uberlândia	MG	Cerrado	10,093,680,000
Primavera do Leste	MT	Cerrado	9,985,446,000
Nova Mutum	MT	Cerrado	9,157,300,000
Sinop	MT	Amazônia	8,656,638,000
Cuiabá	MT	Cerrado	6,647,014,000
Campo Novo do Parecis	MT	Cerrado	6,319,034,000
Canarana	MT	Cerrado	6,292,750,000
Lucas do Rio Verde	MT	Cerrado	6,285,809,000
Diamantino	MT	Cerrado	6,257,443,000
Barreiras	BA	Cerrado	6,080,466,000
Unaí	MG	Cerrado	5,096,932,000
Palmas	TO	Cerrado	4,728,567,000
Campo Verde	MT	Cerrado	4,662,899,000
Paragominas	PA	Amazônia	4,593,511,000
Água Boa	MT	Cerrado	4,559,933,000

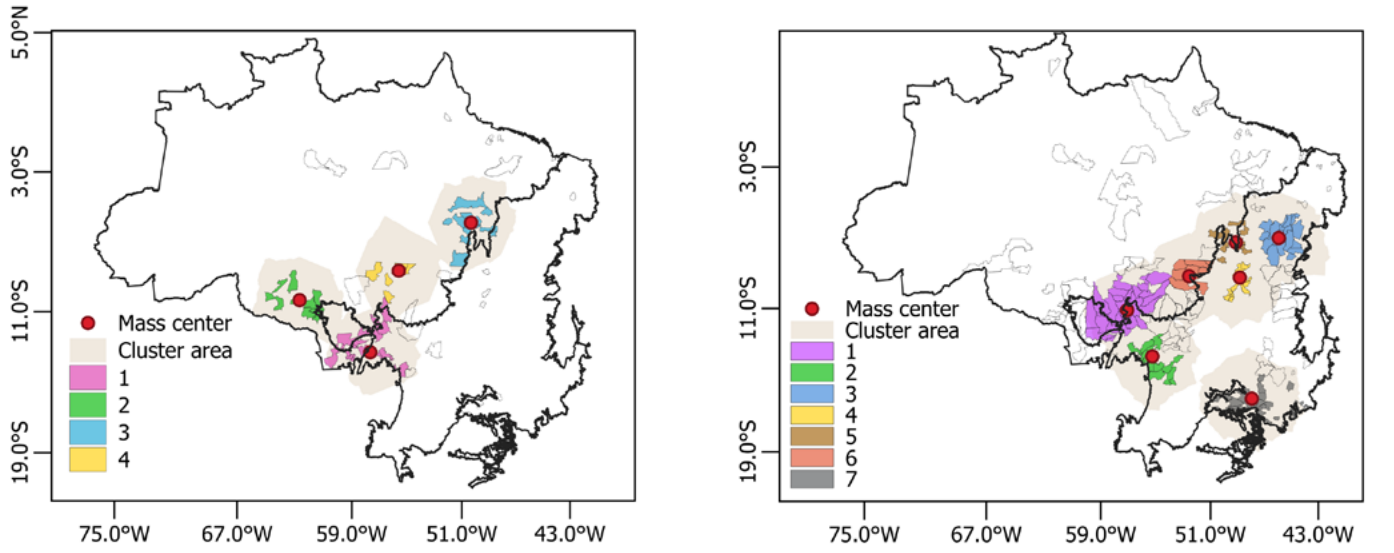
Table B2 | **Top 20 Brazilian Municipalities Exporting Beef to China (1997–2025)**

MUNICIPALITY	STATE (UF)	BIOME	BEEF EXPORTS TO CHINA (KG)
Barra do Garças	MT	Cerrado	407,674,939
Araguari	MG	Cerrado	367,960,034
Ituiutaba	MG	Cerrado	354,793,259
Várzea Grande	MT	Cerrado	344,141,845
Rolim de Moura	RO	Amazônia	229,215,030
Iturama	MG	Cerrado	185,374,947
Gurupi	TO	Cerrado	168,609,212
Paraíso do Tocantins	TO	Cerrado	161,827,205
Tangará da Serra	MT	Cerrado	156,434,696
Água Azul do Norte	PA	Amazônia	154,738,377
Matupá	MT	Amazônia	137,015,762
Barra do Bugres	MT	Amazônia	133,109,615
Rondonópolis	MT	Cerrado	131,971,147
Castanhal	PA	Amazônia	122,960,970
Vilhena	RO	Amazônia	120,626,119
Rio Maria	PA	Amazônia	98,727,390
São Geraldo do Araguaia	PA	Amazônia	90,158,974
Guarantã do Norte	MT	Amazônia	77,542,326
Pontes e Lacerda	MT	Amazônia	75,009,409
Diamantino	MT	Cerrado	71,991,971

Appendix C

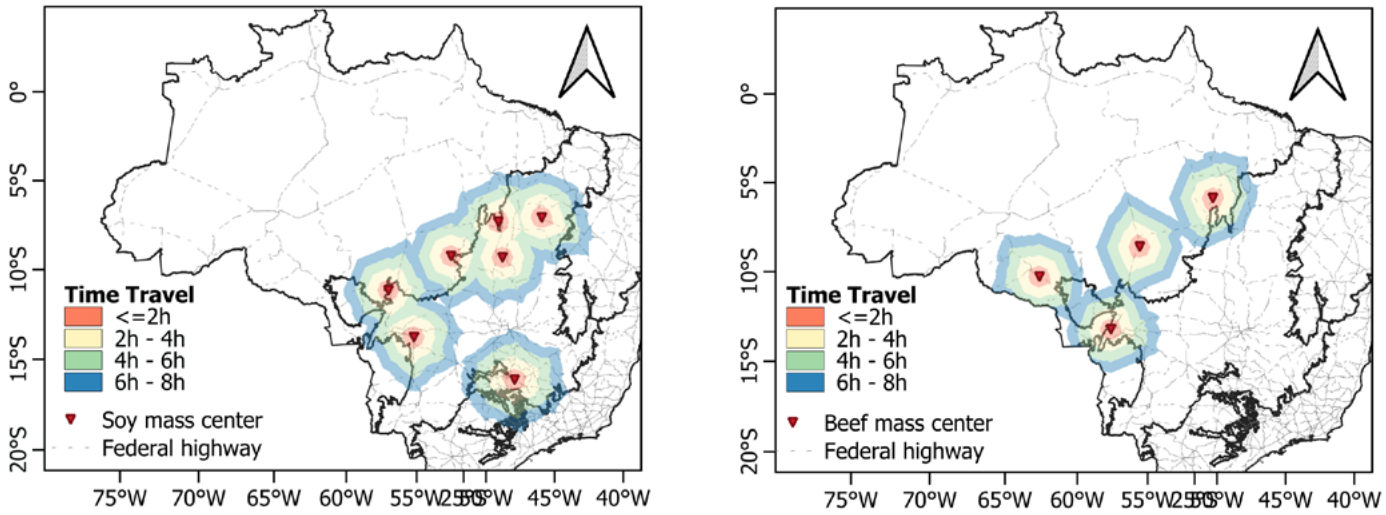
Clusters and Centers of Mass of Municipalities Exporting to China

Figure C1 | **Location of the municipalities comprising the identified cluster and the corresponding weighted center of mass of municipalities that exported soy to China between 1997 and 2025.**



Source: Authors

Figure C2 | **Results of the influence zone calculated using cumulative travel time. The red area represents the distance that can be reached within two hours of travel, the yellow band represents distances of up to four hours, the green band up to six hours, and the blue band up to eight hours.**



Source: Authors

Endnotes

1. In Brazil, deforestation is defined as the suppression of native vegetation cover, regardless of whether it occurs within legally protected areas or not. Under the Brazilian Forest Code (Law No. 12,651/2012), the legality of vegetation removal depends on the location and extent of clearing on a given rural property. Vegetation removal is considered legal when it occurs outside Permanent Preservation Areas (APPs) — such as riparian buffers, hilltops, and steep slopes — and outside the Legal Reserve, a portion of each rural property that must be maintained under native vegetation (ranging from 20% in the Cerrado to 80% in the Amazon biome), and when the landowner holds prior authorization from the competent environmental authority. Conversely, deforestation is considered illegal when it takes place within APPs or Legal Reserves without authorization, when it exceeds the area permitted for clearing, or when it occurs without the required environmental licensing. It is important to note that the distinction between legal and illegal deforestation does not capture all environmentally harmful land-use change: clearing that complies with the minimum Forest Code requirements may still contribute to habitat loss, biodiversity decline, and local climate alterations, particularly in the Cerrado, where legal reserve requirements are significantly lower than in the Amazon

2. PPCDAm is the Action Plan for the Prevention and Control of Deforestation in the Legal Amazonia. It was created in 2004, with the objectives of continuously and consistently reducing deforestation and creating the conditions for a sustainable development model in the Legal Amazon. It is structured around three thematic axes: land and territorial management, monitoring and control, and the promotion of sustainable productive activities. Implemented during Lula's first two terms, the plan was associated with a 67% reduction in deforestation, but was discontinued in 2019 under Jair Bolsonaro's administration, a period followed by a 73% increase in deforestation according to 2022 data. It was reestablished in Lula's third term through Decree No. 11,367, of January 1, 2023. The current fifth phase emphasizes integrating intelligence and accountability actions against illegal deforestation, improving the Rural Environmental Registry (CAR), coordinating with states on enforcement, and developing traceability systems for agricultural products and timber in the Amazon

3. Forest Code: Federal law (Law No. 12,651/2012) that establishes the rules for native vegetation protection on rural properties in Brazil, including Permanent Preservation Areas (APPs) and Legal Reserve requirements, which vary by biome.

4. CAR (Cadastro Ambiental Rural) is the Rural Environmental Registry. It is a mandatory national eletronic public registry for all rural properties, designed to integrate environmental information for control, monitoring, environmental and economic planning, and combating deforestation. It was established under Article 29 of the Forest Code (Law No. 12,651/2012) with the purpose of identifying and monitoring vegetation cover, Permanent Preservation Areas (APPs), Legal Reserves, restricted-use areas, and consolidated areas on each property.

5. The "Legal Amazon" (Amazônia Legal) is an administrative designation established by Brazilian law (Law No. 1,806/1953) encompassing nine states located wholly or partially within the Amazon basin: Acre, Amapá, Amazonas, Mato Grosso, Pará, Rondônia, Roraima, Tocantins, and part of Maranhão (west of the 44th meridian). Covering approximately 5 million km^2 — roughly 59% of Brazil's territory — it is larger than the Amazon biome as defined by ecological boundaries, as it includes areas of Cerrado and transition vegetation. The Legal Amazon serves as the primary territorial unit used by INPE (Brazil's National Institute for Space Research) for official deforestation monitoring through the PRODES system, and is the standard reference unit for deforestation data reported in Brazilian policy and academic literature.

6. MATOPIBA refers to an agricultural frontier region in Brazil encompassing parts of the states of Maranhão, Tocantins, Piauí, and Bahia. The region has undergone rapid agricultural expansion in recent decades—particularly soybean production—and is predominantly located within the Cerrado biome, including areas of ecological transition with the Amazon.

7. ABC+ Plan (2020–2030): Brazil's national plan for Low Carbon Agriculture, which promotes the adoption of sustainable agricultural practices — such as no-till farming, integrated crop-livestock-forest systems, and degraded pasture recovery — to reduce greenhouse gas emissions from the agricultural sector.

8. Caminho Verde Program is a federal government initiative that seeks to drive environmental recovery and productivity gains in agriculture through the restoration of degraded areas and the promotion of sustainable practices, launched in 2025 by the Ministry of Agriculture, Livestock and Supply (MAPA) in partnership with other ministries, financial institutions, and the private sector. Of Brazil's roughly 280 million hectares used for agriculture and livestock, about 165 million are pastureland, with approximately 82 million hectares in some degree of degradation; the program's goal is to recover up to 40 million hectares of low-productivity pastures over the next ten years, converting them into high-yield agricultural land without the need for further deforestation. It launched with an initial allocation of R$30 billion in financing for sustainable agricultural and forestry production systems, channeled through accredited financial institutions, and is complemented by the Eco Invest auction mechanism, which blends public and private capital to fund the recovery of degraded land

9. PLANAVEG: The National Plan for Native Vegetation Recovery (Planaveg) is the main implementation instrument of Brazil's National Policy for Native Vegetation Recovery (Proveg), established by Federal Decree No. 8,972/2017. It was first launched through Interministerial Ordinance No. 230/2017, with the objective of expanding and strengthening public policies, financial incentives, markets, and agricultural best practices needed to recover at least 12 million hectares of native vegetation by December 31, 2030, in line with the commitment Brazil made in 2015 at COP21 under the Paris Agreement. A revised version (Planaveg 2025–2028) divides the recovery target into three fronts: 9 million hectares in Permanent Preservation Areas, Legal Reserves, and Restricted Use Areas; 2 million hectares in public areas such as Conservation Units and Indigenous Lands; and 1 million hectares in low-productivity rural areas, through practices such as agroforestry systems and crop-livestock-forest integration.

10. SICAR is the Sistema Nacional de Cadastro Ambiental Rural (National Rural Environmental Registry System), the federal digital platform that consolidates and standardizes data submitted to the Rural Environmental Registry (CAR) across Brazil's states. While the CAR is the self-declaratory registration instrument through which rural landholders report property boundaries and vegetation status, SICAR is the IT infrastructure that integrates these state-level registrations into a single national database, intended to support validation, cross-checking, and public access to property-level environmental data.

11. SeloVerde is a state-level Brazilian digital platform that integrates rural property data from the Rural Environmental Registry (CAR), satellite-based deforestation monitoring, and supply chain traceability systems to automate environmental compliance verification. By cross-referencing land-use data with deforestation alerts and trade records, the platform enables financial institutions, traders, and buyers to screen suppliers for environmental risk in near real-time, reducing the cost and time associated with manual auditing processes.

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About the authors

Ana Beatriz dos Santos is a Research Analyst of the Forests and Land Use Program at WRI Brasil, based in São Paulo, Brazil.

Contact: ana.santos@wri.org

John James Loomis is a former intern at WRI Brasil and currently serves as a Research Associate at the Global Development Institute at the University of Manchester and an Associate Researcher at FGV Earth. He is based in the United Kingdom.

Contact: john.loomis@manchester.ac.uk

Karoline Silva is a Research Analyst of the Forests and Land Use Program at WRI Brasil, based in São Paulo, Brazil.

Contact: karoline.silva@wri.org

Emily Ane Dionizio is a GHG Protocol Specialist II of the Forests and Land Use Program at WRI Brasil, based in São Paulo, Brazil.

Contact: emily.dionizio@wri.org

Rodrigo Bellezoni is an Independent Consultant based in São Paulo, Brazil.

Contact: rodrigo.bellezoni@gmail.com

Virginia Antonioli is Agri-Food Manager of the Forests and Land Use Program at WRI Brasil, based in São Paulo, Brazil.

Contact: virginia.antonioli@wri.org

Argemiro Teixeira Leite-Filho is a Researcher in Integrated Spatial Modelling of Terrestrial Systems at Brazil's National Institute for Space Research (INPE), based in São José dos Campos, Brazil.

Contact: argemiro.filho@inpe.br

Julia Faro is Land Use & Supply Chains Manager of the Forests and Land Use Program at WRI Brasil, based in São Paulo, Brazil.

Contact: julia.faro@wri.org

Mariana Oliveira is the Director of the Forests and Land Use Program at WRI Brasil, based in São Paulo, Brazil.

Contact: mariana.oliveira@wri.org

Author Contributions

Ana Beatriz, John and Karoline were responsible for drafting the initial manuscript and conducting the literature review, and all contributed to the subsequent revision and editing of the manuscript. Ana Beatriz, Emily, Rodrigo and Argemiro were responsible for methodology development, data collection, and preliminary data analysis. Ana Beatriz, Karoline and Rodrigo conceived the original research idea and contributed to the critical revision and editing of the manuscript. Julia and Rodrigo were responsible for overall project coordination and grant management and participated in the revision of the manuscript. Emily, Virginia, Julia and Mariana also contributed to the revision and editing of the manuscript. All authors have read and approved the final version of the manuscript.

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WRI BRASIL

São Paulo
R. Cláudio Soares, 72 cj. 1510
CEP: 05422-030

Porto Alegre
Av. Independência, 1299
CEP: 90035-077

WRIBRASIL.org.br

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