



RAINFOREST PAYBACK 2

*How forest destruction affects the regional climate,
agricultural productivity, insurance payouts,
and public subsidies in the Amazon*

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Highlights

- From 2000 to 2020, about 20% of the remaining Brazilian Amazon Forest underwent consistent degradation accentuated by climate change and anthropogenic disturbance.
- Local climate over degraded forest has higher max and mean temperatures and lower evapotranspiration, especially at the end of the dry season, resulting in less rainfall, when compared to non-degraded forest.
- Total annual reductions in evapotranspiration from non-degraded forest amount to 22% for degraded forest and 41% for deforested areas. Much less evapotranspiration resulted in an annual rainfall decrease of 4% over degraded forest and 15% over deforested areas. Furthermore, over the dry season (June–September) these decreases reach 14% and 34% for degraded forest and deforested areas, respectively.
- Climate indices, such as consecutive days without rain and number of days with temperatures above 35°C or above 90% percentile are greater over degraded forest, compared with those of non-degraded forest. Conversely, consecutive rainy days are fewer over degraded forest. Those differences are even more accentuated for deforested areas.
- Climate extremes are exacerbating and becoming more frequent, thus affecting the productivity of single maize cropping, soy-maize double cropping, and cattle ranching. In highly deforested areas of southern Amazon, annual number of days with temperature above 35°C and above 90% percentile and consecutive days without rain have risen 5 and 8 times, and 24% over the last two decades, respectively.
- Crop shortfalls are becoming more frequent, entailing higher insurance premiums and a larger number of payouts, and as a result, demanding more public insurance subsidies.
- From 2010–2023, the Rural Insurance Program (PSR) subsidized 23.5 thousand contracts in Legal Amazon (LA), covering an area of 6.7 million hectares of farming and 133 thousand cattle heads, with premiums totaling USD 244 million, of which USD 83 million consist of federal subsidies.
- We estimate that between 2010 and 2023, the increase in climate extremes due climate change in synergy with deforestation was responsible for 95% of the USD 115 million payouts to farmers and ranchers in LA under the PSR. In large deforested areas, the share of deforestation alone accounts for 83%. Yet our dataset represents only 6% of Brazil's PSR premiums, meaning that our findings might be extended many-fold to the country.
- Of 217,000 rural properties receiving credit between 2017 and 2022, 21% showed evidence of post-2008 deforestation in the LA—98% of which was potentially illegal, lacking proper deforestation authorizations and sufficient native vegetation for composing Legal Reserves. Additionally, 8% of financed properties had active federal or state embargoes, yet continued accessing public credit.
- Brazil's Central Bank is now tightening rules by requiring satellite monitoring of post-2019 deforestation and proof of legality to access rural credit¹. Still, lenient transition rules allow financing embargoed properties until 2027. Banks that fail to conduct proper due diligence should be liable for deforestation and climate harm.
- Native vegetation restoration, as mandated by the Forest Code, is essential to mitigate the effects of climate change on farming. Large-scale restoration may reduce by 33% the monetary sum of insurance payouts in LA.
- As climate change intensifies, conserving and restoring native vegetation become ever more essential to maintain the productivity of farming and ranching in the Amazon. Therefore, agribusiness sectors that foment the expansion of pastures and croplands at the expense of native vegetation are committing “agrosuicide”. 

1) CMN n° 5.193 de 19/12/2024 <<https://www.bcb.gov.br/estabilidadefinanceira/exibenormativo?tipo=Resolu%C3%A7%C3%A3o%20CMN&numero=5193>>.

Introduction

In our previous report, we analyzed how deforestation-induced local and regional climate changes affect agricultural production in the Brazilian Amazon, underscoring the interlinkage between forest loss, climate regulation, and agricultural productivity¹. We estimated that between 2006 and 2019 the economic losses due to deforestation amounted to approximately USD 761.3 million for soybean production and USD 273.3 million for maize production, reducing by up to 20% the net revenues from soy-maize double cropping in the region. Additionally, we emphasized the importance of restoring forest cover in degraded areas and low-productivity ranching lands. Achieving the full complian-

ce of Brazil's Forest Code in the state of Pará would result in a forest recovery of 5.5 million ha, triggering earlier onset of the rainy season and substantial increases in rainfall volumes that favor 70% of soy-maize double cropping areas in the state. Forest restoration is thus essential for reestablishing the biome's capacity to regulate local and regional climates, thereby safeguarding both ecosystem integrity and agricultural sustainability.

In this study, we expand our research to assess the impacts of forest degradation on the regional climate. Projections indicate that if sea surface temperature anomalies (such as El Niño episodes) and

associated droughts continue, in addition to high deforestation rates, roughly 55% of the forests of the Amazon will be converted to agricultural lands, logged, damaged by drought, or burned by 2040, emitting 15–26Pg of carbon to the atmosphere and resulting in an irreversible damage to one of the planet's most biodiverse regions². These interconnected drivers not only threaten the structural and functional integrity of the Amazon Forest but also create a positive feedback loop that amplifies local and regional climate changes, posing higher risks of crop shortfalls^{3,4}.

Here, we examine how forest degradation and deforestation in



the Brazilian Amazon have impacted the regional climate over the past two decades and how increase in climate extremes driven by a combination of deforestation and climate change influences crop shortfalls and lower productivity of cattle ranching, hence raising insurance premiums and the number of payouts. We complete our study by assessing as to what extent forest restoration could mitigate these costs.

Potential structural flaws in Brazil's agricultural policy framework—specifically, the absence of environmental safeguards in rural credit programs and the lack of scientific understanding connecting land use, climate extremes, and agricultural losses contribute to the persistence and potential amplification of both environmental degradation and agricultural losses across the region (Fig. 1).

In this context, our results offer insights into how misalignments in policy design—particularly the Rural Credit Program and the Rural Insurance Premium Subsidy Program (PSR)—have enabled the allocation of public resources to agricultural activities without environmental and climate-risk safeguards, undermining as a result Brazil's environmental and climate targets, as well as its agricultural production.

By exploring these interactions, we contribute to a broader understanding of the interconnection between forest destruction, climate resilience, and agricultural productivity for informing climate litigation and advocacy efforts aimed at driving changes within the Brazilian agricultural sector and national policies to combat deforestation and promote sustainable land-use practices in the Amazon region.

Mapping forest degradation and climate differences between non-degraded forest, degraded forest, and deforested areas

Forest degradation—defined as the loss of structure, function, and ecosystem services without complete land-use conversion—has emerged as a driver of biodiversity loss and regional climate change in the Amazon that equates the impacts of deforestation in magnitude^{5,6}. Anthropogenic disturbances, such as selective logging, understory fires, fragmentation, and drought intensification are the main causes of forest degradation^{5,7}, creating feedback loops that increase vegetation flammability, tree mortality, and long-term shifts in species composition⁸⁻¹⁰. Recent evidence shows that degradation has already surpassed deforestation in extent⁶, affecting more than one-third of the Amazon, with reductions of up to 34% in dry-season evapotranspiration and significant carbon emissions¹¹. Large tracts of the eastern Amazon now act as a net carbon source due to combined effects of deforestation, degradation, and fire^{12,13}. To make matters worse, studies indicate that even modest temperature increases might trigger positive feedbacks, pushing the system toward critical resilience thresholds^{5,14}, and climate models project more frequent and severe droughts and precipitation extremes by 2100¹⁵. Recurrent droughts further increase the risk of abrupt cascading transitions to open-canopy states, particularly in southern Amazonia.

Current mapping methods of forest degradation rely heavily on ancillary data of deforestation and fire scars or government statistics on timber production^{6,10}, limiting independence and accuracy of estimates. Here, we used a

FIGURE 1 Feedback loop connecting public funding, environmentally harmful practices, climate impacts and associated agricultural losses, and hence insurance payouts supported by public subsidies.

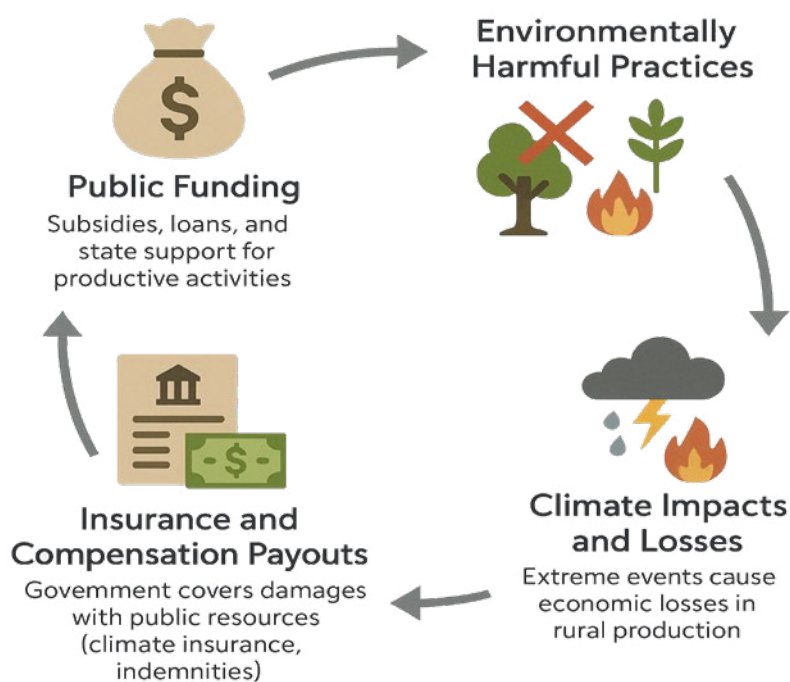
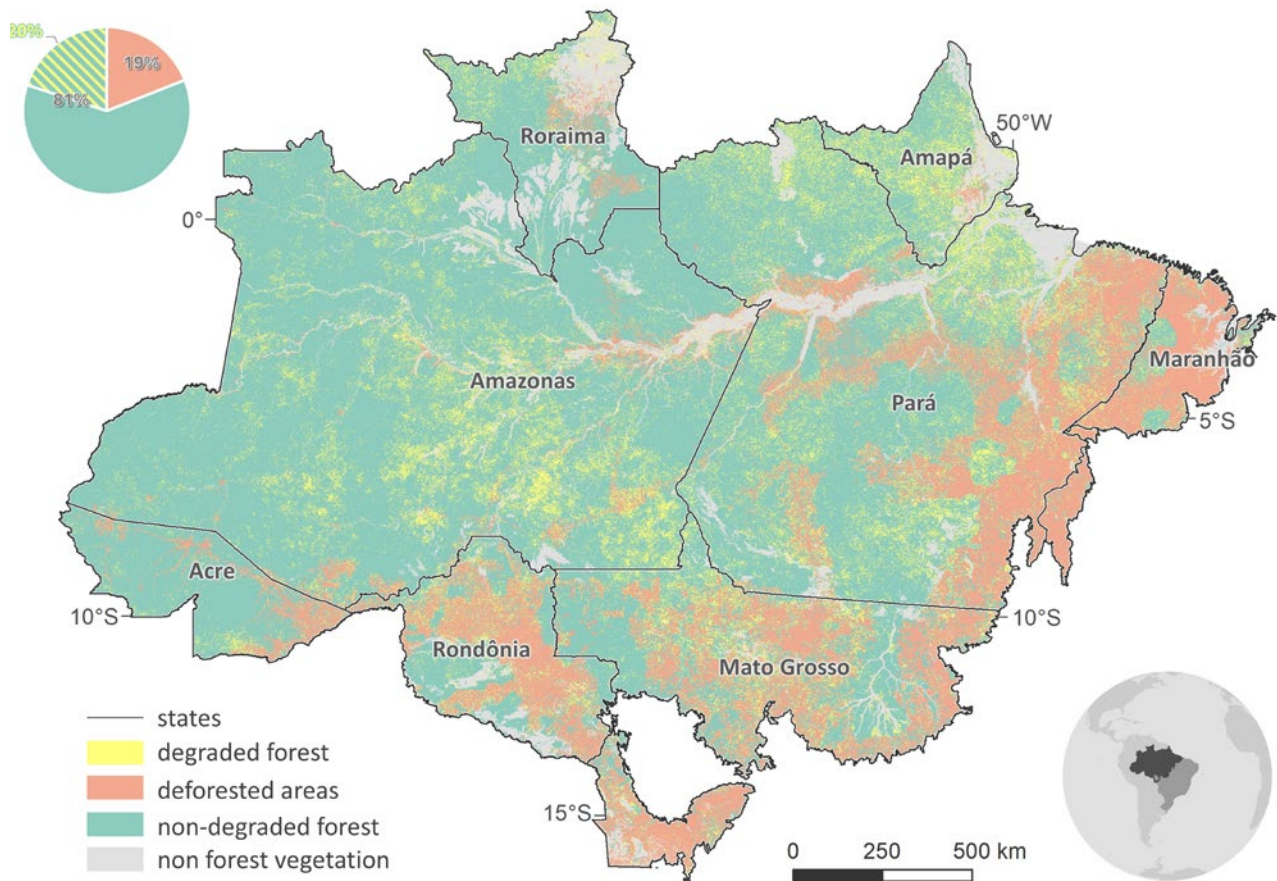


FIGURE 2 Geographic distribution of non-degraded forest, degraded forest, and deforested areas in the Brazilian Amazon.



time-series of vegetation indices derived from remote sensing, independent of deforestation mapping or other ancillary data, to directly detect structural and functional changes in the forest, thereby reducing uncertainties and improving estimates of degradation impacts on the regional climate.

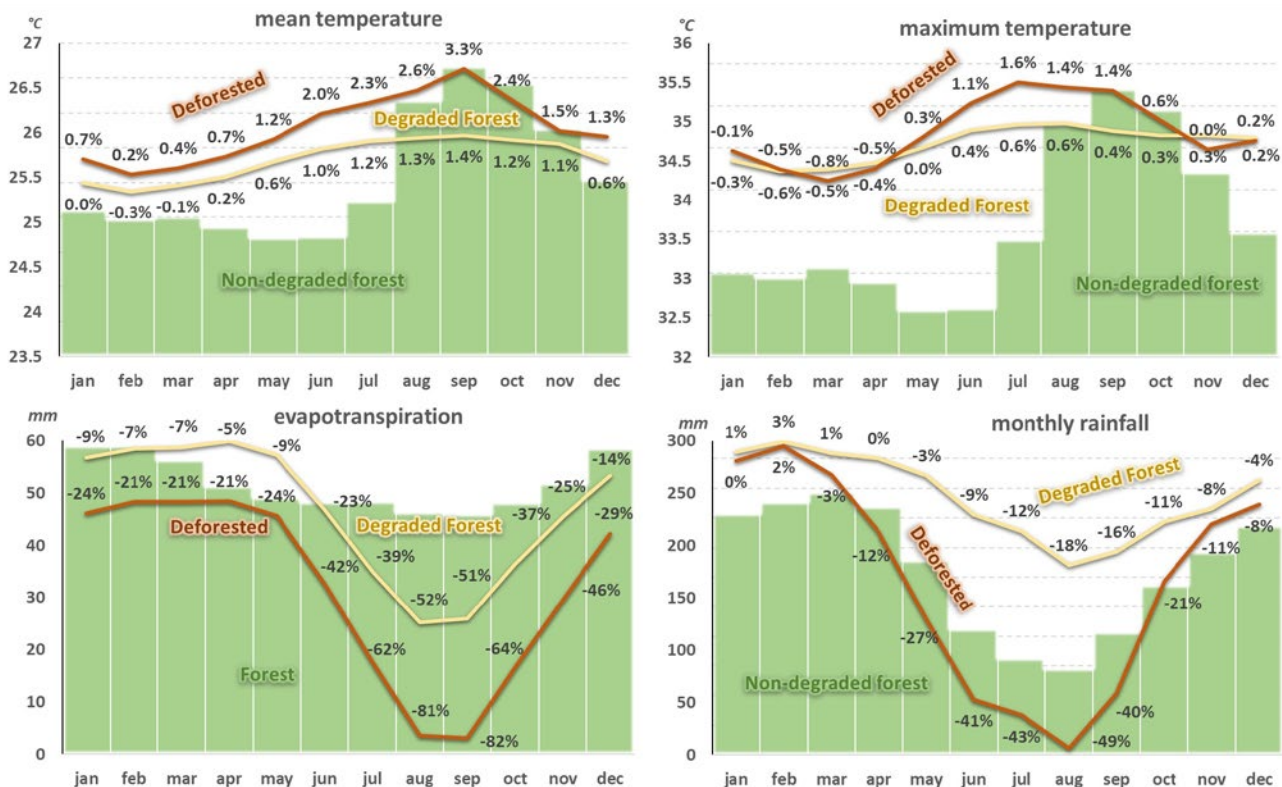
We applied MOD13A1.061 product¹⁶ (Terra Vegetation Indices, 16-day composite, 500 m resolution) from 2000 to 2024 to estimate vegetation

degradation. The identification of degradation was based on the temporal trajectory of the Normalized Difference Vegetation Index (NDVI) on a pixel-by-pixel basis. We considered “degraded” any forest pixel that, from a given point in the historical series onward, showed a drop in NDVI with a minimum of three consecutive years, and thereafter maintained a decreasing trend without returning to values higher or equal than those observed before the initial drop. This criterion

prioritizes persistent changes, reducing the influence of seasonal fluctuations or noise on remote-sensed imagery. As of 2024, our method indicates that 20% of the remaining forest in the Brazilian Amazon exhibits consistent degradation, while 19% has been deforested (Fig. 2).

The monthly climate series from 2000–2023/2024 revealed statistically significant differences ($p < 0.05$) between non-degraded

FIGURE 3 Monthly mean and maximum temperatures, monthly rainfall between 2000 and 2024, and monthly evapotranspiration between 2000 and 2023 for areas of non-degraded forest and the differences from those values for degraded forest and deforested areas.



forest, degraded forest, and deforested areas for mean maximum temperature, mean temperature, total precipitation, and total evapotranspiration throughout the year, with the differences accentuated over the dry season (Fig. 3).

Local climate over degraded forest has higher max and average temperatures. Total annual reductions in evapotranspiration from non-degraded forest amount to 22% for degraded forest and 41% for deforested areas. Much less evapotranspiration resulted in an annual rainfall decrease of 4% over degraded forest and 15% over deforested areas. Furthermore, over the dry season (June-September) these decreases reach 14% and 34% for degraded forest and deforested areas, respectively.

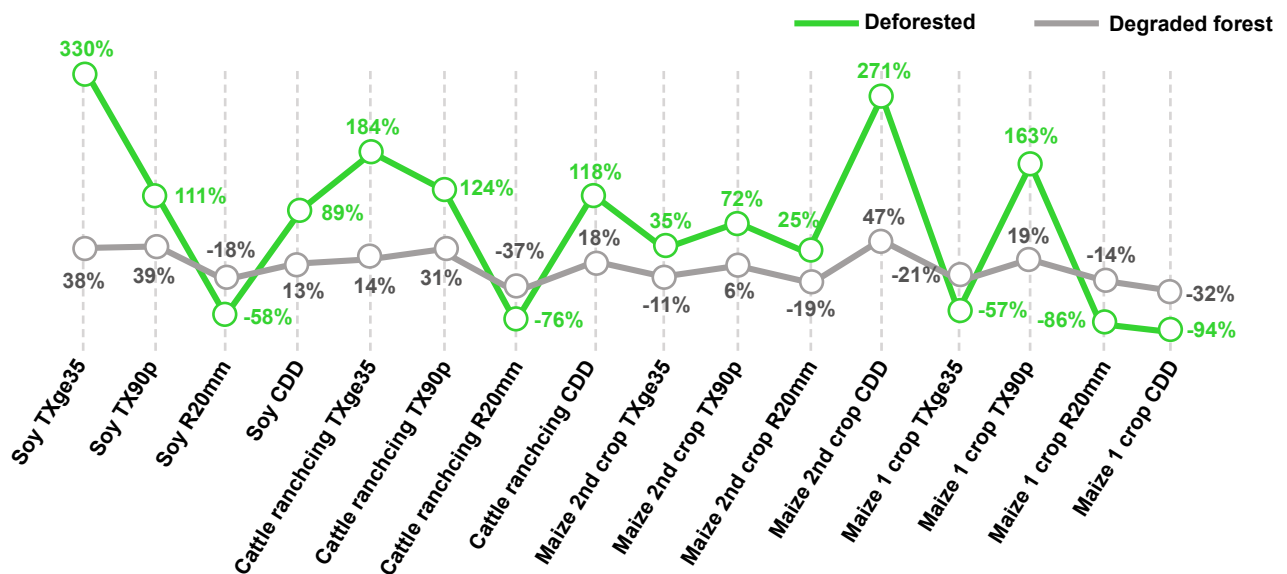
Yet our figures are conservative because the effect of deforestation on rainfall reduction augments when analyzed at a broader scale³.

"Local climate over degraded forest has higher max and average temperatures."

Non-degraded forest areas differ significantly from degraded forest and deforested areas in climate indices (CDD, Tx90p, Txge35, R20mm) across the agricultural calendar of soybean, cattle ranching (annual), and single- and second-crop maize ($p < 0.05$) (except for R20mm in second-crop maize and Txge35 for soybean and cattle ranching). Compared with non-degraded forest areas, deforested areas generally show stronger extreme warming and greater aridity: heat indices TXge35 (days with $T_{max} \geq 35^\circ\text{C}$) and TX90p (days above the 90th percentile of T_{max}) rise sharply for soybean cultivation season (+330% and +111%) and over the year for cattle ranching (+184% and +123%), and for the second-crop maize (TX90p +72%; TXge35



FIGURE 4 Percentage difference between climate indices for soy, cattle ranching, maize single and second crops in deforested and degraded forest from non-degraded forest.



+34.5%). The CDD index (maximum number of consecutive dry days) also increases in deforested areas—soybean (+89%) and second-crop maize (+271%)—indicating longer dry periods through the respective cultivation periods; it also grows over the year, affecting cattle ranching (+118%). In contrast, R20mm (days with

rainfall ≥ 20 mm) decreases in deforested areas (soybean -57.6%; cattle ranching -76%; single-crop maize -85.8%), suggesting fewer rainy days.

Degraded forests follow the same pattern but with smaller magnitudes (e.g., soybean: TXge35 +38.2% and TX90p +38.7%; yearly:

TXge35 +14% and TX90p +30.7%). CDD rises moderately (soybean +12.8%; cattle ranching +17.5%; second-crop maize +46.5%), and R20mm tends to decline (soybean -17.5%; livestock -37.4%; second-crop maize -19.1%; single-crop maize -14%) (Fig. 4).



Relationship between Rural Insurance Program (PSR) payouts, deforestation, and trend of change of climate indices

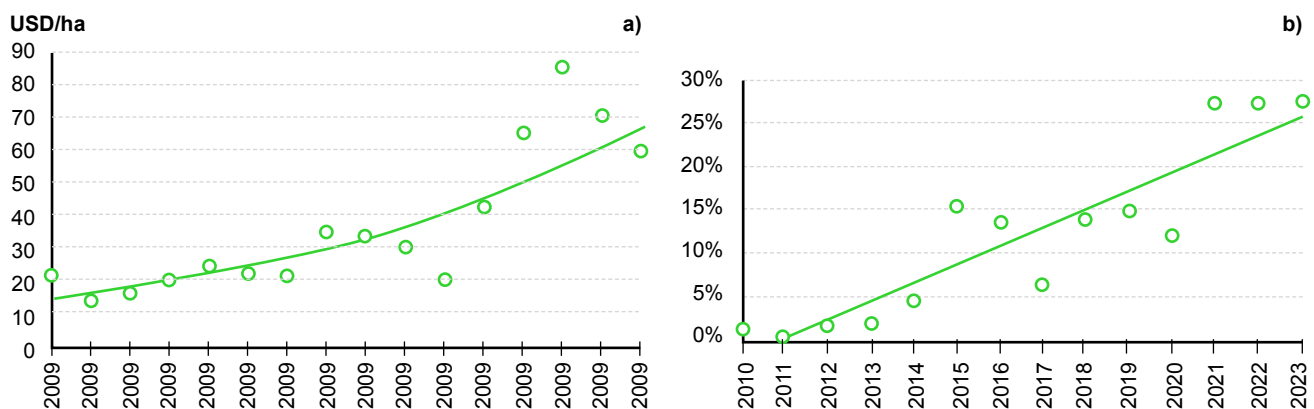
Established in 2005 as part of Brazil's agricultural risk management strategy, the Rural Insurance Program (PSR) has expanded from 21.7 thousand subsidized operations in 2006 to 193.4 thousand in 2020. The program partially covers the rural producer's insurance premiums through government subsidies. By

2023, it increased premium subsidies to 40% for most agricultural activities while maintaining a rate of 20% for soybeans. Additional regional incentives raised subsidies to up to 30% of the total soy insurance premiums in the Northeast and North regions^{II}—the latter marked by high deforestation pressure. Between 2020 and 2023, the North—which largely overlaps with the Amazon biome—received limited federal support under the PSR. While national coverage remained significant, with insured areas

reaching over 13 million hectares in 2020 and over BRL 1 billion allocated annually, the North accounted for only 0.5–2.3% of the insured area and less than 1.1% of producers served. These figures sharply contrast with southern Brazil, which had received over 60% of contracts and the equivalent of nearly half of the insured area.

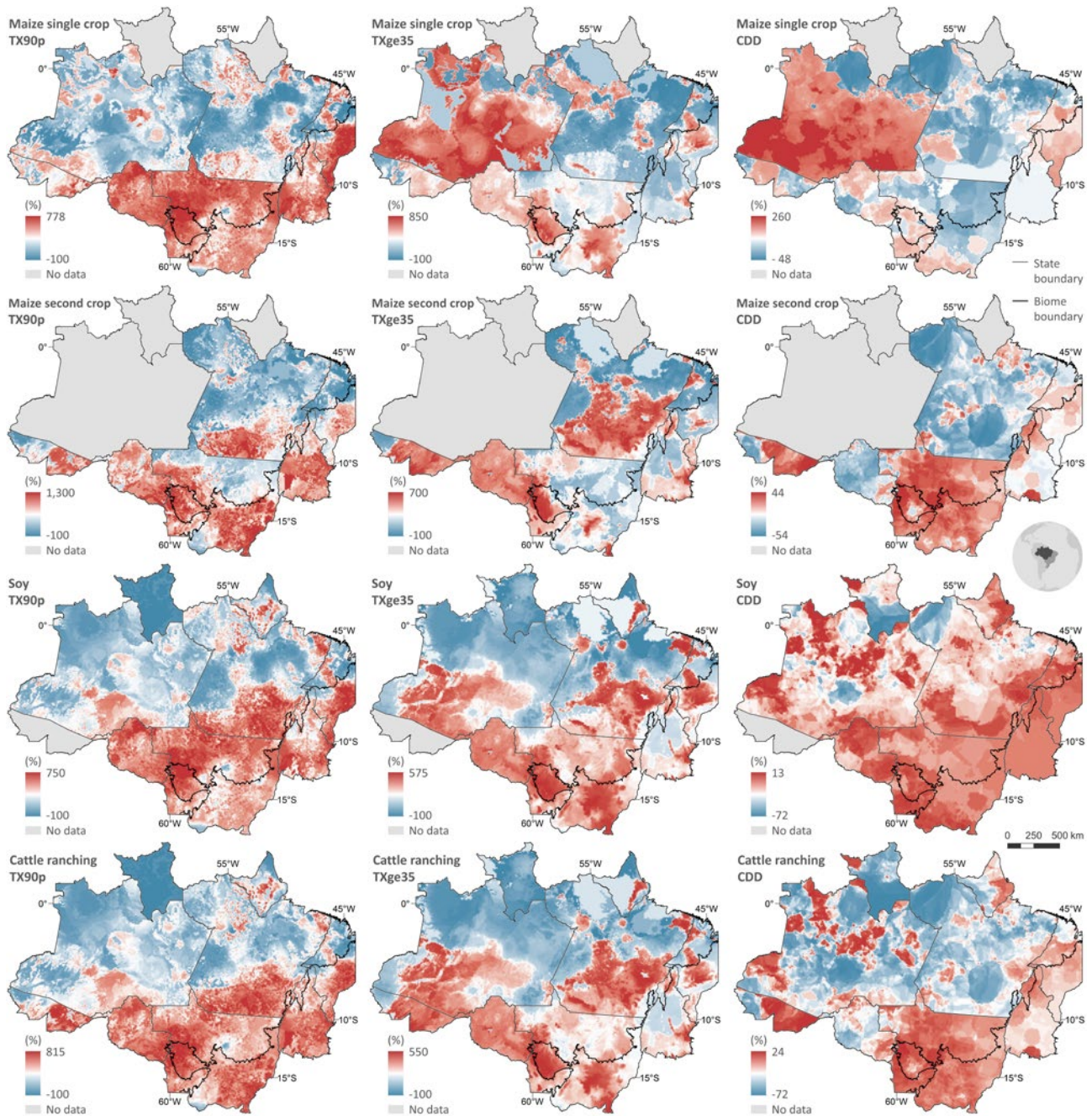
In LA, the number of payouts in relation to the number of contracts has increased over time, entailing higher insurance premiums (Fig. 5),

FIGURE 5 Growth trend of insurance premium values and the ratio of payouts/number of insurance contracts. Values of premium in BRL are inflated to August 2025 and converted to USD.



II) <https://www.gov.br/agricultura/pt-br/assuntos/riscos-seguro/seguro-rural/limites-percentuais-de-subvencao>.

FIGURE 6 2000-2020 trend of change for climate indices for maize single and second crop, soy, and cattle ranching. Note that variations across states depend also on different intervals of the states' cultivation calendars.



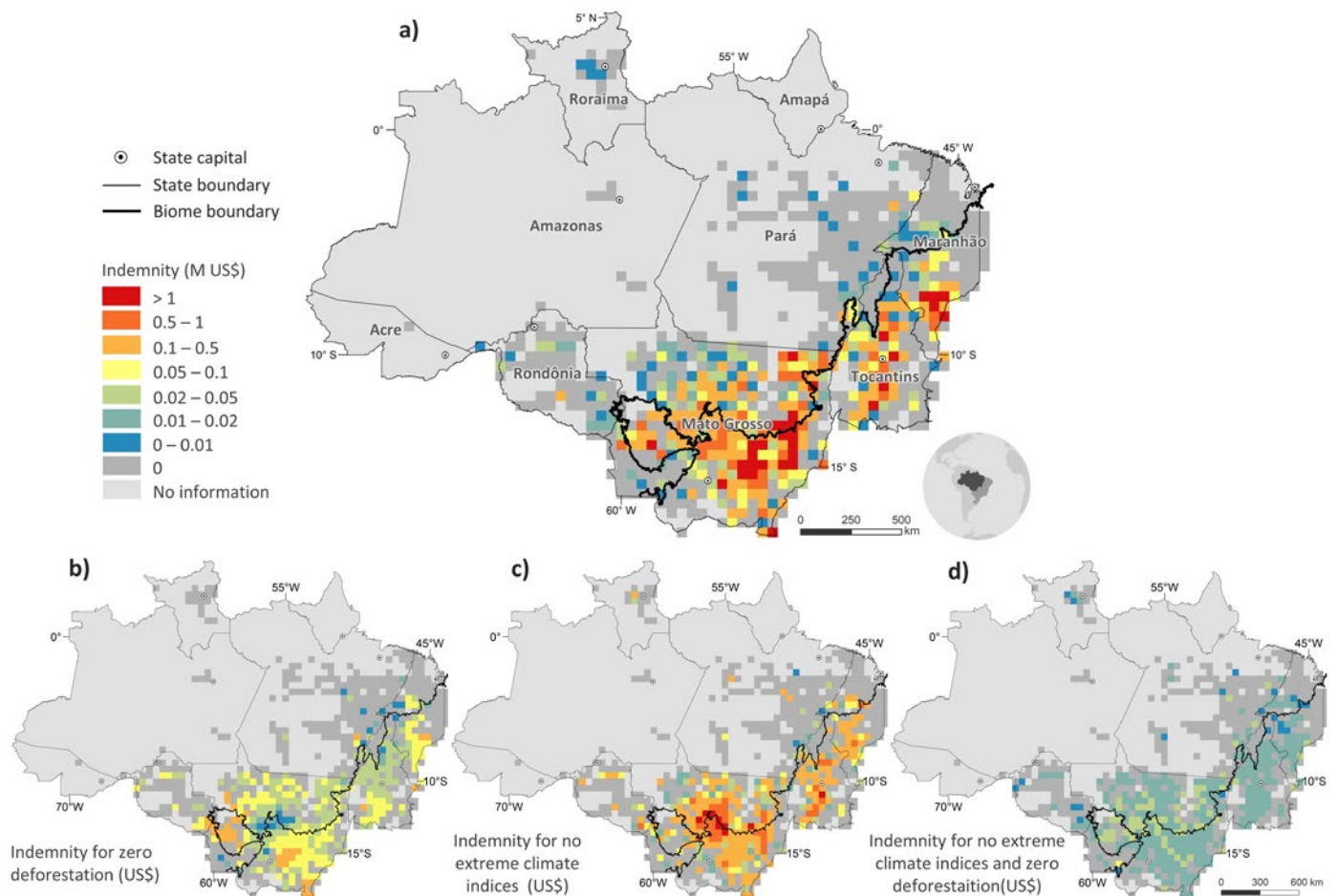
which might be related to elevated risk of crop shortfalls as a result of exacerbated climate extremes (Fig. 6). Droughts represent 83% and excessive rains 17% of climate-related payouts.

We applied a Generalized Linear Model (GLM) to examine the

determinants of the monetary sums of payouts. The slope of the GLM linear fit per cell (50 × 50 km) for the period 2010–2023 showed higher sums of payouts along the deforestation arc (Fig. 7a). The proportion of deforested area ($p = 0.001$) showed a significant effect. The temporal trends of

climate extremes (Fig. 6) were significant: TX90p ($p = 0.047$), CDD ($p = 0.469$), TXge35 ($p = 0.0085$), and R20mm ($p = 0.001$). Taken together, the results indicate that increasing heat extremes, namely TX90p, supported by more consecutive dry days (CDD) are positively associated with the trend

FIGURE 7. a) Payouts values from 2010 to 2023 and scenarios of payouts **b)** without deforestation, **c)** climate change and **d)** without climate change and deforestation.



of increase of the insurance payouts, as are less rainfall days (R20mm).

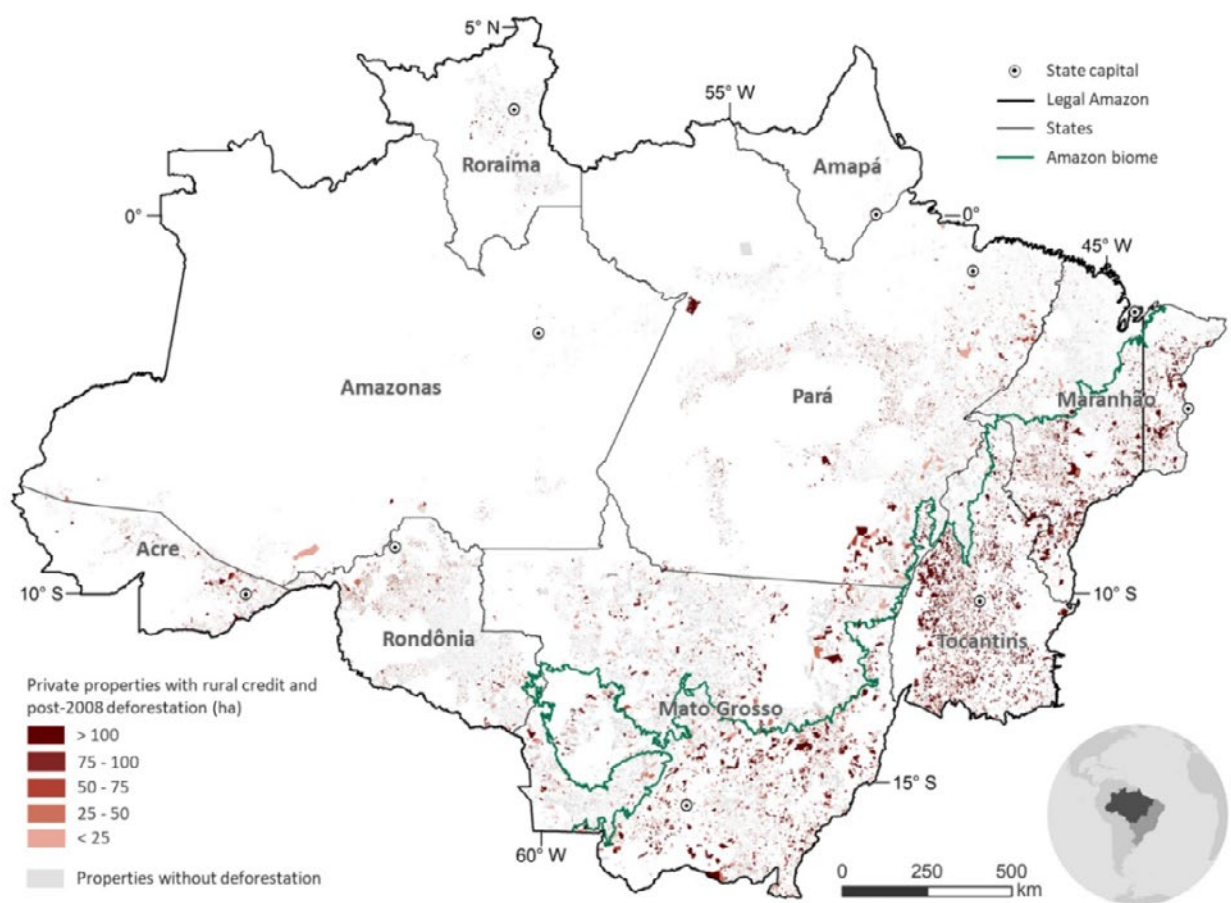
Out of a total of USD 115 million of insurance payouts between 2010 and 2023^{III}, our simulations estimate a reduction of USD 109 million in a scenario without deforestation and climate extremes, USD 95 million in a scenario without deforestation, and USD 35 million without the effect of

climate extremes (Fig. 7b, c, d). The restoration scenario, aimed at restoring up to 50% of native vegetation, points to a reduction of USD 38 million, i.e., a 33% decrease in compensation payouts.

"Rural Insurance Program has expanded from 21.7 thousand subsidized operations in 2006 to 193.4 thousand in 2020."

^{III}) Values in BRL updated to August 2025 and converted to USD.

FIGURE 8 Farms with post-2008 deforestation that received loans from 2017 to 2022 in LA.



Rural credit supporting deforestation

Our deforestation analysis revealed that out of 217,000 rural properties receiving credit between 2017 and 2022, 21% showed evidence of post-2008 deforestation in the LA—98% of which was potentially illegal, lacking proper deforestation authorizations and sufficient native vegetation for composing Legal Reserves (Fig. 8). Additionally, 8% of financed properties had active federal or state embargoes yet continued accessing public credit. Government resources have thus financed environmental violations while imposing resulting costs on the Brazilian society.

The Central Bank's manual for rural credit (MCR) required banks to ban credit for private rural properties overlapping protected areas or with embargoes by IBAMA (The federal environmental agency), but not for other environmental violations, and if a property is embargoed after being funded, the bank must halt disbursement. However, in the same period, only 9% of private properties with deforestation were embargoed or inspected by environmental agencies in Mato Grosso and Pará states, pointing out to the inefficiency of this criterium to exclude deforesters. 

"Government resources have thus financed environmental violations while imposing resulting costs on the Brazilian society."

Conclusions and recommendations

Our analyses demonstrate that climate change causing more frequent and intense droughts and consequent wildfires, in addition to anthropogenic disturbance, have consistently degraded 20% of the remaining Amazon Forest between 2000 and 2020, and this is a conservative figure, given our methodology and time-period of analysis. In turn, degraded forest due to higher temperatures and lower evapotranspiration also affects local precipitation, reinforcing climate change's impacts.

Climate extremes are exacerbating and becoming more frequent, thus

affecting the productivity of single maize cropping, soy-maize double cropping, and cattle ranching. In highly deforested areas of southern Amazon, annual number of days with temperature above 35°C and above 90% percentile and consecutive days without rain have risen 5 and 8 times, and 24% over the last two decades, respectively.

Crop shortfalls are becoming more frequent, entailing higher insurance premiums and a larger number of payouts, and as a result, demanding larger public insurance subsidies. Between 2010 and 2023, the increase in climate extremes due

climate change in synergy with deforestation was responsible for 95% of the USD 115 million payouts to farmers and ranchers in LA under the PSR. In large deforested areas, the share of deforestation alone accounts for 83%. Yet our dataset represents only 6% of Brazil's PSR premiums, meaning that our findings might be extended many-fold to the country. Complementing PSR, PROAGRO, Brazil's nationwide program, provides guarantees/indemnities to agricultural producers in the event of losses due to adverse weather or diseases, including provisions for smallholders. The program





faces a severe fiscal crisis; payouts quadrupled from USD 200 million in 2017 to USD 1.2 billion in 2021, requiring increasing National Treasury funding. In total, we estimate a national insurance market for crops and livestock with premiums situated between USD 2 and USD 3 billion per year and payouts around half of those values^{IV}.

Of 217,000 rural properties receiving rural credit between 2017 and 2022, 21% showed evidence of post-2008 deforestation in LA, ~98% of which was potentially illegal, and 8% had active federal or state embargoes. In 2023, the Central Bank responded with Resolution 5,081/2023 (extending legality checks to entire properties) and Resolution 5,193/2024 (to enter into force in 2026, requiring PRODES monitoring and proof of legality for post-2019 deforestation). While these measures strengthen rural credit governance, risks will persist until they are fully imple-

mented and enforced. In this respect, private banks that fail to conduct proper due diligence should be liable for deforestation and climate harm. For consulting environmental compliance and deforestation records for bank loans, public platforms, like SeloVerde^V, could be expanded nationwide under the auspice of the Ministry of the Environment (MMA), as the official free-access system.

Large-scale restoration, in accordance to Brazil's Forest Code, may reduce by 33% the monetary sum of insurance payouts in LA. Such a result supports better planning of the insurance market and subsidies regarding agro-climatic risk exposure. As growing climate-related risks raises rural insurance premiums, insurance companies would need innovative solutions, such as directing lower premiums to more climate resilient regions that possess larger native vegetation cover.

Our results are also critical for informing climate litigation and advocacy efforts to drive policy changes in the Brazilian agricultural sector at both the regional and federal levels to improve compliance with environmental regulations. Therefore, exploring the interactions between climate variability and forest degradation, along with deforestation, is central to understanding the broader implications for agricultural viability and the health of the forest ecosystems of the Amazon.

In sum, as climate change intensifies, conserving and restoring native vegetation become ever more essential to maintain the productivity of farming and ranching in the Amazon. And this is undeniable; agribusiness sectors that foment the expansion of pastures and croplands at the expense of native vegetation are thus committing "agrosuicide". 

^{IV}) <https://www2.susep.gov.br/menuestatistica/SES/premiosesinistros.aspx?id=54>

^V) <https://www.semas.pa.gov.br/seloverde>

Methods

Mapping forest degradation

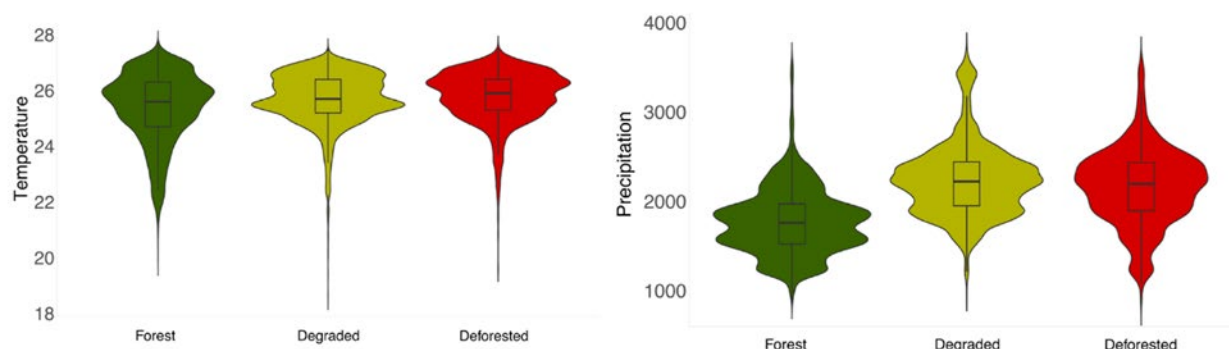
We used the MOD13A1.061 product¹⁶ (Terra Vegetation Indices, 16-day composite, 500 m resolution) from 2000 to 2024 to estimate vegetation degradation. The identification of degradation was based on the temporal trajectory of the Normalized Difference Vegetation Index (NDVI) on a pixel-by-pixel basis. We considered “degraded” any forest pixel that, from a given point in the historical series onward, showed a drop in NDVI, with a minimum of three consecutive years, and thereafter maintained a decreasing trend without returning to values higher or equal than those observed before the initial drop. This criterion prioritizes persistent changes, reducing the influence of seasonal fluctuations or noise on remote-sensed imagery.

Climate differences between non-degraded forest, degraded forest, and deforested areas

We compared climate shifts between deforested areas, degraded forest, and non-degraded forest limited to the Amazon biome by using monthly mean maximum temperature, monthly mean temperature, monthly mean total precipitation from 2000 to 2024 based on the ERA5 Monthly Aggregates product (ECMWF/C3S)¹⁷. Evapotranspiration from 2000 to 2023 comes from PML_V2 0.1.8: Coupled Evapotranspiration and Gross Primary Product (GPP)¹⁸. To avoid the direct influence of deforested areas on estimates in degraded forests, we selected only degraded forest pixels that were at least 5 km away from any deforested or other native vegetation, such as savannas. We

assessed differences between the three groups using generalized linear models (GLM)¹⁸. To control seasonal effects, we used months as control variables. We only processed climate data after deforestation and initial degradation for respective pixels. To verify whether the groups were comparable in a long-term climatic context (i.e., “pairable”), we used historical WorldClim (1950–2000)¹⁹ data on mean temperature and mean precipitation. Results indicated statistically non-significant differences ($p > 0.05$) between the groups, supporting that the comparisons were carried out between climatically pairable sets (Fig. 9).

FIGURE 9 Comparison between non-degraded, degraded forest, and deforested areas, indicating that the compared pixels do not differ ($p > 0.05$) from each other, in relation to the historical climate, 1950-2000.



IV) https://developers.google.com/earth-engine/datasets/catalog/CAS_IGSNRR_PML_V2_v018?hl=pt-br#bands

Rural Insurance Program (PSR)

Between 2006 and 2024, Brazil registered over 1.2 million proposals under the PSR, covering over 93 million hectares and insuring 568 thousand animals (Tables 1,2). The total insured value reached BRL 291.9 billion, with premiums amounting to BRL 20.6 billion and federal subsidies totaling BRL 7.26 billion. In contrast, municipalities within the Amazon Biome accounted for only 19.7 thousand proposals—just 1.6% of the national total—covering 5.4 million hectares of soy crops. These contracts amounted to BRL 14.8 billion in insured value, with BRL 701.5 million in premiums and BRL 222.5 million subsidized by the federal government (Tables 1,2).

Relationship between payouts, deforestation, and trend of change of climate indices

To evaluate the relationship between agricultural insurance payouts for soybean, cattle ranching, and single- and second-crop maize and climate indices, we used administrative data from the Rural Insurance Premium Subsidy Program (PSR). These data provide information on payout values, insurance value, spatial location of the insurance contract, year, and type of insured product between 2010 and 2023. The monetary sum of payout values in a 50×50 km grid was used as the dependent variable.

To investigate the determinants of monetary sum of payouts, we calculated the following extreme climate indices according to the agricultural calendar for soybean and first- and second-season maize according to CONAB (*Companhia Nacional de Abastecimento*) calendars for the LA states^{VII} and for the entire year

for cattle ranching: TX90p (percentage of days with daytime maximum temperature above the 90th percentile), 2) TXge35 (number of days when TX ≥ 35 °C) and 3) CDD (maximum number of consecutive dry days, precipitation < 1.0 mm), and R20mm (number of days with precipitation ≥ 20 mm for the years 2010 to 2023). As predictors, we used the trends (percentage increase or decrease) of these indices, calculated pixel by pixel, over the same period. In addition, we included the proportion of deforested area, the number of insurance contracts, and crop area, and the number of cattle heads. The number of insurance contracts, crop area and the number of cattle heads were used as control variables in the model.

The climate indices were calculated from the Brazilian Daily Weather Gridded Database (BR-DWGD)²⁰. This dataset, originally at a spatial resolution of ≈10×10 km, integrates data from 4,360 points, including 3,625 rain gauges and 735 meteorological stations. The BR-DWGD employs

TABLE 1 Rural Insurance Program (PSR) - summary of proposals and coverage					
Region	Period	No. of Proposals	Insured Area (ha)	Insured Amount (BRL)	Premium (BRL)
Brazil	2006–2024	1.2 million	93.2 million	291.9 billion	20.6 billion
Legal Amazon States	2006–2024	34.1 thousand	9.3 million	25.1 billion	1.3 billion
Amazon Biome Municipalities	2006–2024	19.7 thousand	5.4 million	14.8 billion	701.5 million

TABLE 2 Rural Insurance Program (PSR) - Federal Subsidy Summary		
Region	Period	Federal Subsidy (BRL)
Brazil	2006–2024	7.3 billion
Legal Amazon States	2006–2024	415.3 million
Amazon Biome Municipalities	2006–2024	222.5 million

VII) <https://www.gov.br/conab/pt-br/aceso-a-informacao/institucional/publicacoes/outras-publicacoes/calendario-agricola-plantio-e-colheita>



six distinct interpolation methods to generate gridded data for various climate variables, with a cross-validation approach used to compare observed data at specific points with interpolated estimates, ensuring the selection of the optimal interpolation scheme for each climate variable. The dataset demonstrates high correlation with in situ data ($r^2 \approx 0.8\text{--}0.9$), ensuring its reliability for our analysis. We then calculated the trend of these indices from 2000 to 2020.

Because these data may present a spatial structure, we first tested a model that allows control for spatial autocorrelation of observations, namely a spatial autoregressive SAR model²¹; however, this model indicated no significant spatial effect. Thus, we performed tests with non-spatial models: Generalized Linear Models (GLM) and Generalized Additive Models (GAM). To avoid overfitting, models

were compared using AIC (Akaike Information Criterion) to determine which provided the best balance between fit and number of parameters. We used the selected model to estimate four scenarios: (1) without the effect of deforestation; (2) without the trend of changes in climate indices; (3) combining scenarios 1 and 2, and 4) with restoration and/or maintenance of at least 50% native vegetation to identify potential reductions in payouts costs under these scenarios.

The proportion of deforested area had a positive and significant effect on payouts (Coef. = 228,593.4; $p = 0.0361$). Among the climate indices, significant positive effects were observed for CDD (consecutive dry days; Coef. = 14,648.81; $p = 0.0213$) and TX90p (90th percentile of maximum temperatures; Coef. = 59.2894; $p = 0.0451$), indicating that greater persistence of consecutive

dry days and more exceptionally hot days are associated with larger monetary sum of payouts. R20mm had a negative effect (Coef. = -1,012.61; $p = 0.0392$), suggesting that fewer rainy days (rainfall ≥ 20 mm) are related to higher payouts. TXge35 was also negative (Coef. = -145.688; $p = 0.0416$). This pattern is consistent with an increase in relative heat extremes (captured by TX90p), without necessarily implying more days above 35 °C (TXge35), as well as a context of less frequent rainfall events (R20mm).

Rural credit supporting deforestation

We began our investigation by analyzing the relationship between rural credit and deforestation at the farm level in the Amazon region. To do so, we used data from the Rural Credit system from the Central Bank of Brazil (SICOR) from 2017 to

2022, as well as from the National System of Rural Environmental Registration (SICAR) (Table 3). We integrated the georeferenced rural properties and rural credit data into a PostgreSQL geographic database and its PostGIS extension. We only used data on rural credit received by private properties uniquely identified by the CAR code (SICAR) filled in at the SICOR dataset, filtering only those located in the states of LA. Then, we cross-referenced the private rural property boundaries that received loans with deforestation maps covering 2009 to 2021 from

PRODES Brasil (Table 3). Then, we calculated zonal statistics by property and filtered only those with deforestation greater than 6.25 hectares (PRODES minimum detection threshold). Subsequently, we superimposed embargoed areas, environmental fines (illegal deforestation), and deforestation permits at the federal and state levels for Pará and Mato Grosso due to the public availability of environmental state inspection geodata. Then, we compared the dates of embargoes, fines, deforestation, deforestation permits, and rural loans. Finally, we

identified the properties with post-2008 deforestation targeted by environmental inspection (infraction notices, fines, and embargoes) that received rural credit in the period.

To build a robust credit-related geospatial database, invalid or atypical geometries—such as linear features and polygons outside the Brazilian territory with perimeters exceeding 105 kilometers—were excluded from the analysis to improve spatial accuracy. The spatial integration process involved two main types of

TABLE 3 Datasets used to analyze rural credit and deforestation at the property level.

Theme	Description	Source	Period covered
Rural credit	Rural private properties that received loans.	Central Bank of Brazil	2017-2022
	Rural credit operations		2013-2022
CAR	Brazil's national environmental registry of rural properties (CAR)	SFB (Brazilian Forest Service)	2023
Deforestation	Annual deforestation in Brazil	INPE (National Institute of Space Research)	2000-2021
Embargoed areas	Embargoed areas in the state of Mato Grosso.	SEMA (Secretary of Environment) – Mato Grosso state	2011-2023
	Lifting of embargoed areas in the state of Mato Grosso.		
	Embargoed areas in the state of Pará.	SEMAS (Secretary of Environment)-Pará state	2008-2022
	Federal embargoed areas	IBAMA (Institute of Environment and Natural Resources)	1988-2023
Vegetation Suppression Authorization	Authorization of vegetation suppression in the state of Mato Grosso	SEMA (Secretary of Environment) – Mato Grosso state	2000-2023
	Federal Authorization of vegetation suppression	IBAMA (Brazilian Institute of Environment and Natural Resources)	2017-2023
Environmental Fines	Environmental fines applied in the state of Mato Grosso	SEMA (Secretary of Environment) – Mato Grosso state	2000-2023
	Federal environmental fines applied	IBAMA (Institute of Environment and Natural Resources)	1977-2023
Administrative boundaries	State boundaries	IBGE (Institute of Geography and Statistics)	2019
Legal Amazon	Legal Amazon boundary	MMA (Ministry of Environment and Climate Change)	2020

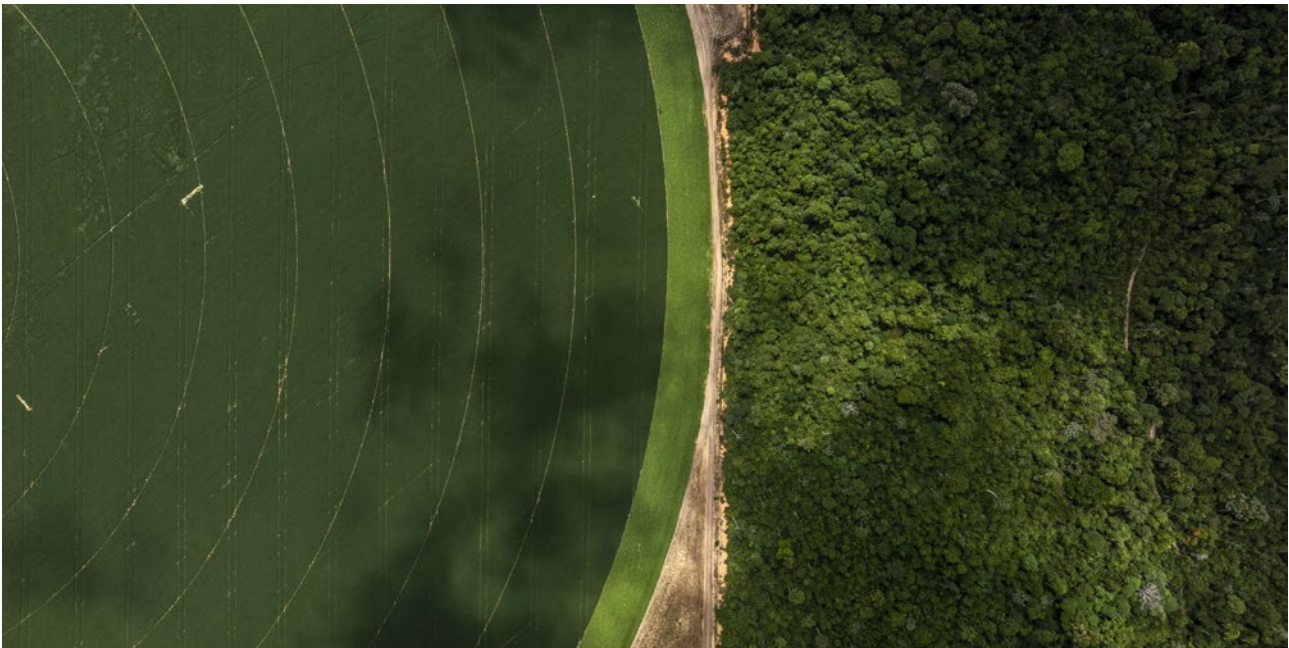
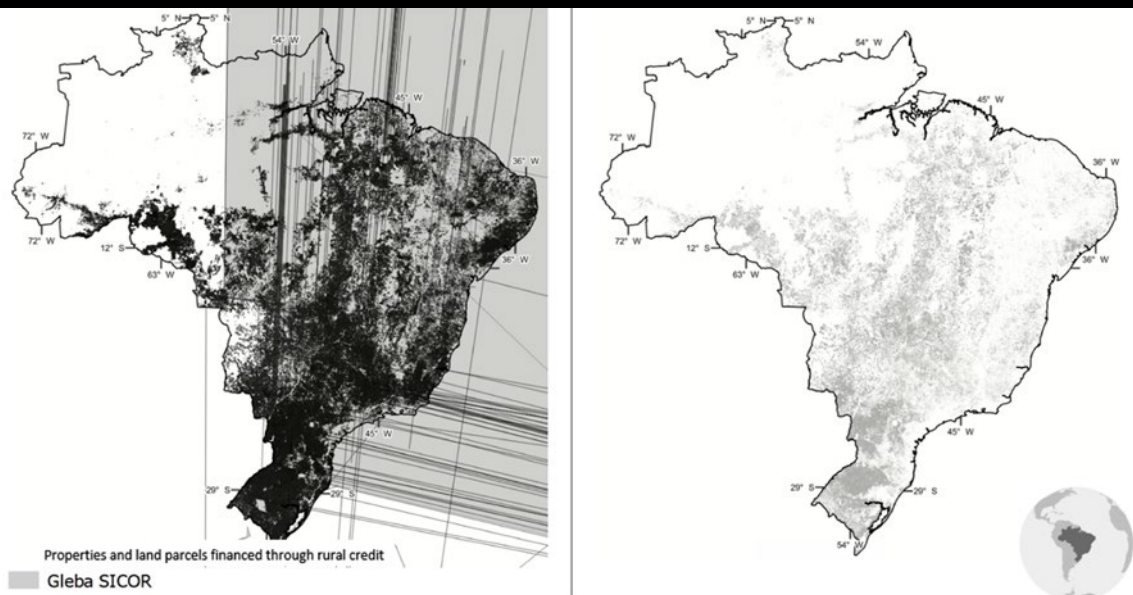


FIGURE 10 Geospatial database of plots of land financed through rural credit identified by property code and credit operation.



geospatial cross-referencing. First, an intersection procedure was used to identify direct spatial overlaps between the financed plot of land and property boundaries. Second, a prioritization was applied to resolve multiple overlaps, selecting a single CAR record per operation within a plot of land. This selection was based on a hierarchy of criteria: whether the financed plot of land was entirely contained within the

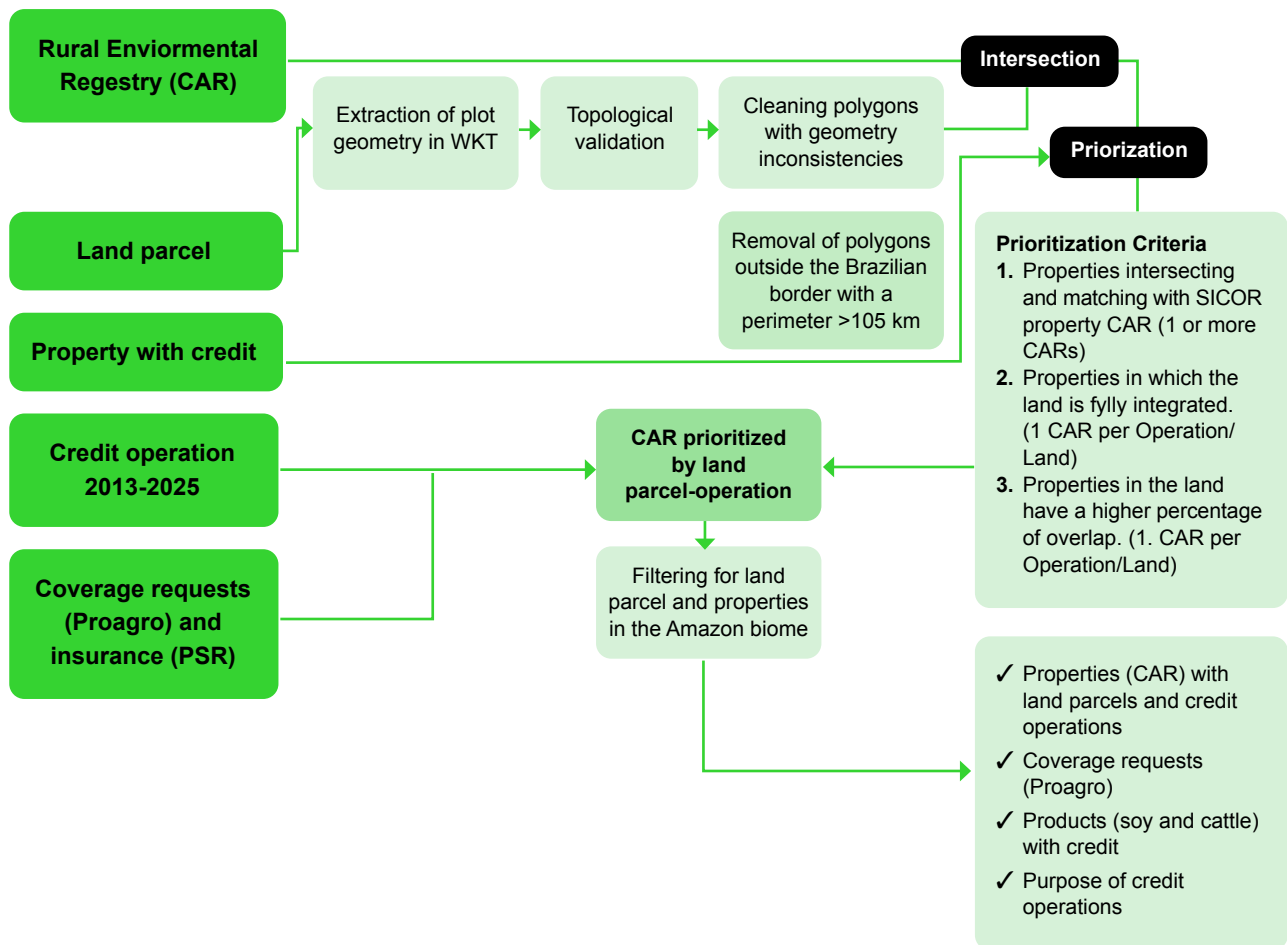
property, whether it had the highest percentage of spatial overlap, and whether there was a direct match with the SICOR property code. All geometries were converted to Well-Known Text (WKT) format and underwent topological validation and cleaning before being analyzed. Additional filtering was applied to retain only the plots of land and rural properties located within the Amazon biome (Fig.10).

"Greater persistence of consecutive dry days and more exceptionally hot days are associated with larger monetary sum of payouts."

As a result of an extensive geospatial data processing and integration of credit operations, plots of land, and rural property data, we successfully created a nationwide geospatial database for Brazilian rural programs and operations (Fig. 11). We also

integrated other geospatial and tabular datasets to analyze government climate-related agricultural subsidies and insurance coverage, namely PSR. This dataset unlocked numerous analytical and modeling opportunities. 

FIGURE 11 Main methodological steps for integrating databases related to rural credit and insurance by identifying financed properties and plots of land.



References

- 1) Leite-Filho, A. et al. (2024). How deforestation-induced local and regional climate changes affect agricultural production in the Brazilian Amazon. https://csr.ufmg.br/ara_project/wp-content/uploads/2024/10/deforestation-induced_local_and_regional_climate_changes.pdf.
- 2) Nepstad, D. C. et al. (2008). Interactions among Amazon land use, forests and climate: Prospects for a near-term forest tipping point. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1498), 1737–1746. <https://doi.org/10.1098/rstb.2007.0036>.
- 3) Leite-Filho, A. et al. (2021). Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. *Nature Communications*, 12(2591). <https://doi.org/10.1038/s41467-021-22840-7>.
- 4) Leite-Filho, A. et al. (2024). Climate risks to soy-maize double-cropping due to Amazon deforestation. *International Journal of Climatology*, 44(4), 1245–1261. <https://doi.org/10.1002/joc.8381>.
- 5) Brando, P. M. et al. (2025). Tipping points of Amazonian forests: Beyond myths and toward solutions. *Annual Review of Environment and Resources*, 50. <https://doi.org/10.1146/annurev-environ-111522-112804>.
- 6) Matricardi, E. A. T. et al. (2020). Long-term forest degradation surpasses deforestation in the Brazilian Amazon. *Science*, 369(6509), 1378–1382. <https://doi.org/10.1126/science.abb3021>.
- 7) Flores, B. M. et al. (2024). Critical transitions in the Amazon forest system. *Nature*, 626(7999), 555–564. <https://doi.org/10.1038/s41586-023-06970-0>.
- 8) Balch, J. K. et al. (2015). The susceptibility of southeastern Amazon forests to fire: Insights from a large-scale burn experiment. *BioScience*, 65(9), 893–905. <https://doi.org/10.1093/biosci/biv106>.
- 9) Rocha, L. G. da et al. (2025). Fire-induced floristic and structural degradation across a vegetation gradient in the southern Amazon. *Forests*, 16(8), 1218. <https://doi.org/10.3390/f16081218>.
- 10) Lapola, D. M. et al. (2023). The drivers and impacts of Amazon forest degradation. *Science*, 379(6630). <https://doi.org/10.1126/science.abp8622>.
- 11) Gatti, L. V., Basso, L. S., Miller, J. B., Gloor, M., Gatti Domingues, L., Cassol, H. L. G., Tejada, G., Aragão, L. E. O. C., Nobre, C., Peters, W., Marani, L., Arai, E., Sanches, A. H., Corrêa, S. M., Anderson, L., Von Randow, C., Correia, C. S. C., Cris, “Amazonia as a carbon source linked to deforestation and climate change,” *Nature*, 2021.
- 12) Gatti, L. V. et al. (2021). Amazonia as a carbon source linked to deforestation and climate change. *Nature*, 595, 388–393. <https://doi.org/10.1038/s41586-021-03629-6>.
- 13) Cowling, S. A. et al. (2004). Contrasting simulated past and future responses of the Amazonian forest to atmospheric change. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 359(1443), 539–547. <https://doi.org/10.1098/rstb.2003.1427>.
- 14) Brando, P. M. et al. (2014). Abrupt increases in Amazonian tree mortality due to drought–fire interactions. *Proceedings of the National Academy of Sciences*, 111(17), 6347–6352. <https://doi.org/10.1073/pnas.1305499111>.
- 15) Duffy, P. B. et al. (2015). Projections of future meteorological drought and wet periods in the Amazon. *Proceedings of the National Academy of Sciences of the United States of America*, 112(43), 13172–13177. <https://doi.org/10.1073/pnas.1421010112>.
- 16) National Aeronautics and Space Administration - NASA. (2022). MODIS: Moderate Resolution Imaging Spectroradiometer. <https://modis.gsfc.nasa.gov/data/dataproduct/>.
- 17) Copernicus Climate Change Service - C3S. (2017). ERA5: ECMWF’s fifth generation of atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS). <https://cds.climate.copernicus.eu/cdsapp#!/home>
- 18) Nelder, J. A. & Wedderburn, R. W. M. (1972). Generalized linear models. *Journal of the Royal Statistical Society: Series A (General)*, 135(3), 370. <https://doi.org/10.2307/2344614>.
- 19) Fick, S. E. & Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, 37(2), 4302–4315. <https://doi.org/10.1002/joc.5086>.
- 20) Xavier, A. C. et al. (2022). New improved Brazilian daily weather gridded data (1961–2020). *International Journal of Climatology*, 42(16), 8390–8404. <https://doi.org/10.1002/joc.7731>.
- 21) Montero, J. (2012). SAR models with nonparametric spatial trends: A P-spline approach. 54(177), 89–111.

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