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A comparative analysis of GHG inventories and ecosystems carbon absorption in Brazil

Luis Miguel da Costa [a,*], Aaron Davitt [b], Gabriela Volpato [b,1], Gislaine Costa de Mendonça [c,2], Alan Rodrigo Panosso [a], Newton La Scala Jr [a]

[a] Department of Exact Sciences, São Paulo State University (UNESP), School of Agricultural and Veterinary Sciences, Jaboticabal, Via de Acesso Prof. Paulo Donato Castellane s/n, 14884-900 Jaboticabal, São Paulo, Brazil

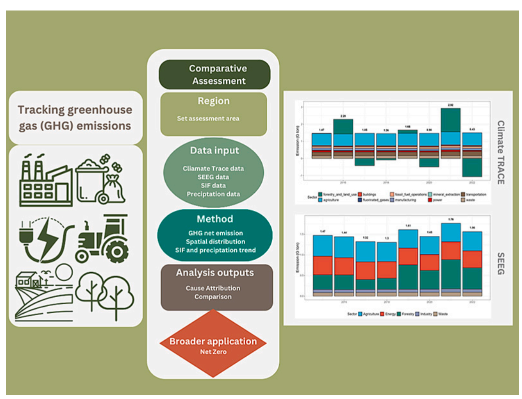
[b] WattTime, Climate Trace, global coalition, Oakland, CA 94609, USA

[c] Nature for Water Facility, The Nature Conservancy, Arlington, VA 22203, USA

HIGHLIGHTS

- A difference of around 1 G ton CO_2eq was observed between the two GHG inventories in some years.
- The main difference in the two GHG inventories relies on the Forestry and Land Use sector.
- Caatinga could be responsible for almost 50 % of GHG removal in Brazil
- An increase in annual precipitation and photosynthesis are associated with higher GHG removal
- Brazil can reach the net-zero target, or even net-sink if deforestation stop

GRAPHICAL ABSTRACT



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ABSTRACT

The global temperature is increasing mainly due to greenhouse gases (GHG) emissions in the last century. While the overall global increase in emissions is due to fossil fuel operations, Brazil has as its primary emitter from forestry and land use, and agriculture sectors. Though these sectors can emit, both can play an important role in mitigating global warming, due to the natural ecosystem and agroecosystem capability of carbon absorption. We aimed to understand the impact of carbon removal on Brazil's national inventory. For that, we compared two GHG inventories - Climate TRACE and SEEG - and explored how precipitation and photosynthesis impact their estimates to determine how the inventories capture seasonal variability. First, we compared the GHG emissions and removals estimates for each sector between both inventories, especially the Forestry and Land Use sector. Moreover, we performed correlation analysis and linear regressions between them, at a biome and pixel level between 2015 and 2022. Our results show that differences between the GHG inventories could reach 1 Giga ton

* Corresponding author.
E-mail address: lm.costa@unesp.br (L.M. da Costa).

[1] Contributed to work entirely while at WattTime and ClimateTRACE, now at Google.

[2] POLUS—Land Use Policy Group, Paulista State University (UNESP), Access Way Prof. Paulo Donato Castellane, s/n, Jaboticabal, SP 14884–900, Brazil.

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of CO_2 eq in some years, mainly due to the forestry sector. Furthermore, in some ecosystems, such as Caatinga, precipitation, and photosynthesis were increasing between 2015 and 2022, thus boosting the removal capacity in this biome. In 2022, the Caatinga GHG removal represented almost 50 % of the total removals in Brazil. A higher removal capacity could significantly contribute to achieving net-zero GHG emissions, especially if deforestation and other anthropogenic disturbances to ecosystems are halted. Our findings suggest that the Climate TRACE inventory captures more seasonal variability than SEEG. This outcome highlights the open issue of carbon removal estimates and also that seasonal aspects could be incorporated to improve our understanding.

1. Introduction

The increase in global temperature is mainly attributed to the greenhouse gases (GHG) emissions since the industrial period. The global warming effect has highlighted the importance of countries reaching net zero GHG emissions by midcentury in order to avoid catastrophic and irreversible changes to the environment (Fankhauser et al., 2022; IPCC, 2021; Riahi et al., 2021). To achieve net zero GHG emissions, an effective strategy is to balance the sectors and areas that are emitting (sources) and those that are removing (sinks) those gases.

Brazil is one of the countries where the energy sector does not contribute a significant amount to the country's GHG emissions since electricity generation is predominantly sourced from hydroelectric power plants (Lima et al., 2020). Instead, the agriculture and land use sectors stand out as the primary contributors to Brazil's greenhouse gas emissions (De Azevedo et al., 2018; Garofalo et al., 2022). In this context, Brazil in 2015 presented its emissions reduction targets in its first nationally determined contributions (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC) (Brazil, 2015). For instance, stopping illegal deforestation until 2030 was one of those targets. Although the Brazilian NDCs have been updated since then, the main solutions and targets have not changed significantly.

Deforestation control has been identified as an important mitigation strategy to reduce the country's GHG emissions in order to achieve net zero, especially in the Amazon Forest due to its large carbon stock (Aragão et al., 2018; Soterroni et al., 2023). Furthermore, besides the necessity of stopping deforestation, Amazon also plays an important role in capturing carbon dioxide (CO_2) from the atmosphere through photosynthesis (Litton et al., 2007; Porcar-Castell et al., 2014; Zhu et al., 2024). Although the photosynthesis process is an important component, in a general manner Amazon Forest is under Climax condition, meaning that the respiration and photosynthesis processes are more or less equal (Odum, 1971; Stinecipher et al., 2022). Moreover, Amazon Forest's importance goes beyond; due to its size (6.7 M km^2), this ecosystem stores large amounts of carbon in above and below-ground biomass and has a unique biodiversity. However, anthropogenic action (mainly deforestation) has been changing this balance (Gatti et al., 2021, 2023), and as a consequence, this biome is releasing large amounts of CO_2 that were stocked through the centuries, hence unbalancing the ecosystem and also increasing forest vulnerability to climate change (Flores et al., 2024).

Moreover, Brazil is a country with a continental scale, thus there is high heterogeneity in their natural environment, reflecting on different large ecosystem responses and sensitivity to precipitation, fire, drought, water balance and global warming potential (da Costa et al., 2023; Lyra et al., 2016; Ribeiro et al., 2021; Titon and Gomes, 2017; Viegas et al., 2022). For instance, other less-known Brazilian biomes also have significant importance in capturing CO_2 (Araujo et al., 2023; Bhattacharyya et al., 2021; De Miranda et al., 2014; Gardon et al., 2020; Soares et al., 2022). Recently Bieluczyk et al. (2023) in an experiment conducted in Atlantic Forest reported that a native forest in this biome can stock >100 Mg C ha^{-1} including above and below-ground biomass and that the restoration with tree species increased the carbon storage more than pasture recovering.

Mendes et al. (2020) studying a Caatinga preserved area, reported that this biome acted as a CO_2 sink in 2014 and 2015 and that this GHG removal was primarily controlled by precipitation. Moreover, the vegetation sink potential is affected by anthropic action, e.g., in the Pantanal biome, the indirect effect of aerosol emission in biomass burning in 2017 led to an inhibition of carbon capture in an order of 1.6 kg m^{-2} (Curado et al., 2024). Thus, their conservancy is essential to balance emissions in order to mitigate climate change.

Furthermore, Caatinga plays a pivotal role in balancing ecosystem exchange in the country's emissions (Jardim et al., 2023). Several studies have shown how different ecosystems respond to rainfall (Allen et al., 2017; Turner et al., 2021), and particularly, arid environments (such as Caatinga) have been reported to be more sensitive to this phenomenon (Besnard et al., 2021; Jiao et al., 2019; Uribe et al., 2021). These studies highlight those ecosystems are water-limited hence, photosynthesis is reduced due to the dependency on water and sunlight availability (Berry et al., 2013; Ryu et al., 2019); however, rainfall events recharge the water supply and become available to the vegetation, boosting photosynthesis and carbon capture.

Although carbon balance estimations and their control mechanism can be made with air gas sampling (Gatti et al., 2021), Eddy covariance techniques (Cabral et al., 2020; Vourlitis et al., 2022), or even with chamber-based methods (Barba et al., 2021; Vaidya et al., 2021), the inference of large-scale fluxes with them is not trivial and quite challenging. The main challenge relies on atmospheric transport and terrain homogeneity. To surpass some of these limitations, inventorying methods using emissions factors in guidelines with IPCC protocols (De Azevedo et al., 2018) and more recently remote sensing approaches (Xiao et al., 2019; Xu et al., 2021) have been used to estimate countries' GHG emissions and removals. In this sense, local and global efforts have been made to develop reliable GHG estimation, such as the System for Estimating Greenhouse Gas Emissions and Removals (SEEG, https://seeg.eco.br/) and Climate TRACE (Tracking Real-time Atmospheric Carbon Emissions; www.climatetrace.org).

SEEG is a Brazilian initiative that combines the National Inventory emissions and emissions factor, IPCC methods to inventory with data provided by several sources to estimate the gross and liquid (net emissions) emissions in five Brazilian sectors on a per year basis, starting from 1990 (De Azevedo et al., 2018). Meanwhile, Climate TRACE, a coalition of organizations working towards improved emissions monitoring, has developed an approach that combines remote sensing, machine learning techniques, and reported data to estimate global greenhouse gas emissions on a per-sector basis. Climate TRACE data includes emissions estimates for Agriculture, Buildings, Fossil Fuel Operations, Forestry and Land Use, Fluorinated Gases, Manufacturing, Mineral Extraction, Power and Waste. The Forestry and Land Use data includes model results from emissions and removals (Xu et al., 2021).

Recently, Lamb et al. (2024) pointed out the necessity to better address the carbon removals in the national inventories. Carbon removals are being unreported and even not being properly accounted for by nations. Although IPCC guidelines also consider GHG removal, the activity-based estimative does not consider the internal variability of the carbon cycle and makes several simplifications in order to be more straightforward. As we mentioned, photosynthesis is a complex process that is affected by natural factors, such as light and rainfalls. In view of this, we seek to understand the carbon removal impact on the national inventory. For this study, we gathered data from two distinct GHG inventories: the SEEG and Climate TRACE estimates to understand how each inventory addresses the carbon removal problem and the role of the Brazilian biomes, especially the lesser-known biomes, e.g., Caatinga, in achieving net-zero emissions. Complementary precipitation data and a photosynthesis proxy (Solar induced Chlorophyll Fluorescence) were used as independent datasets to determine how both inventories capture natural variability and underscore the health of the Brazilian biomes in capturing CO_2, and finally also to understand how these variables impact the GHG estimate.

2. Methods

2.1. Overview

The framework (Fig. 1) highlights the goal of determining the difference among GHG inventories. As a first step, this work consists in defining the analyzed region, in our case, Brazil. Then we acquired the primary data from the national GHG platform (SEEG) and the international (Climate TRACE), as well, the auxiliary data (SIF and Precipitation) were also acquired. The GHG inventories were compared in total net emissions and per-sector emissions for the analyzed period (2015–2022). Climate TRACE data will be spatial distributed over Brazil and the auxiliary data will be used to find relations between GHG and environmental aspects. After the assessment made by the comparison between both inventories and the relations that we found.

2.2. Study area

Brazil has an area of around 8.5×10^6 km^2 (Fig. 2) and its extension is situated inside the tropic region (23.5°N – 23.5°S), thus the climate in most of the country is classified as tropical, and subtropical, with some regions classified as semi-arid climate type (Alvares et al., 2013). Furthermore, due to Brazil's extension, edaphoclimate and biogeography conditions, the country has six larger ecosystems, named: Amazon (AMZ); Atlantic Forest (AF); Caatinga (CAAT); Cerrado (CERR); Pampa (PMP) and Pantanal (PNT).

The Amazon (AMZ) biome is the world's largest tropical rainforest and mainly consists of an evergreen canopy type (Myster, 2016). Regarding AF, only 9 to 12 % of this biome remains and still is considered one of the world's 25 biodiversity hotspots, their canopy ranges from evergreen to lowland (Vitória et al., 2019). Caatinga (CAAT) is a semi-arid environment generally described as a tropical dry forest mostly covered with shrubs and herbaceous vegetation (Moro et al., 2016). The Cerrado (CERR), is the second largest Brazilian biome often described as a Neotropical savanna (dos Reis et al., 2022). The Pampa (PMP) is a natural grassland domain and its climate ranges from subtropical to temperate, due to their location (Roesch et al., 2009). Finally, Pantanal (PNT) is one of the largest wetlands in the world that encompass swamps, seasonal floodplains and riparian forests (Schulz et al., 2019).

2.3. Climate TRACE

From Climate TRACE (Tracking Real-time Atmospheric Carbon Emissions, www.climatetrace.org) we acquired on January 2024 emission and removal estimative of GHG of all sectors covering the period of 2015 to 2022. The Climate TRACE is a coalition that aims to monitor greenhouse gas emissions around the world. To accomplish this goal, Climate TRACE uses a hybrid approach of new techniques such as machine learning and artificial intelligence, with the IPCC's guidelines to inventory GHG emissions. Climate TRACE provides data for nine sectors and various subsectors: Manufacturing, Agriculture, Buildings, Fossil fuel operations, Mineral Extraction, Transportation, Waste, Power and Forestry and Land Use, besides an additional estimative of fluorinated gases. Each of these sectors has its method to account for emissions and, specifically in the Forestry and Land use sector to account for removals.

The manufacturing estimates have seven major processes: aluminium, cement, manufacturing, chemicals, pulp, paper and steel manufacturing. The agriculture sector accounts for emissions in cattle enteric fermentation and manure management, rice cultivation and synthetic fertilizer. The buildings sector accounts for residential and commercial usage and other onsite fuel usage, and this sector makes the estimation using the Emissions Database for Global Atmospheric Research (EDGAR) dataset. Fossil fuel operations account for coal mining, oil and gas production, petrochemicals emissions and refining emissions. The extraction of iron, copper, bauxite and other minerals is accounted for inside the Mineral extraction sector. The transportation sector has estimates of urban areas, domestic and international from air and maritime transports. The waste sector has estimates of solid waste disposal and wastewater treatment. Electricity generation is accounted for in the Power sector. Finally, the Forest and Land use sector accounted for emissions from water reservoirs and also to forests, grasslands, mangroves and wetlands. Each of these processes has its own data source and methodology that can combine reported data with satellite data and the estimates are made through emission factors and machine learning models.

Regarding the Forestry and Land Use sector, the estimative is made using several remote sensing datasets. Additionally, the Land Surface Temperature layer in the model can further capture vegetation seasonality, rather than using only land use coverage maps to infer the estimative based on emission factors. A detailed description of this model is

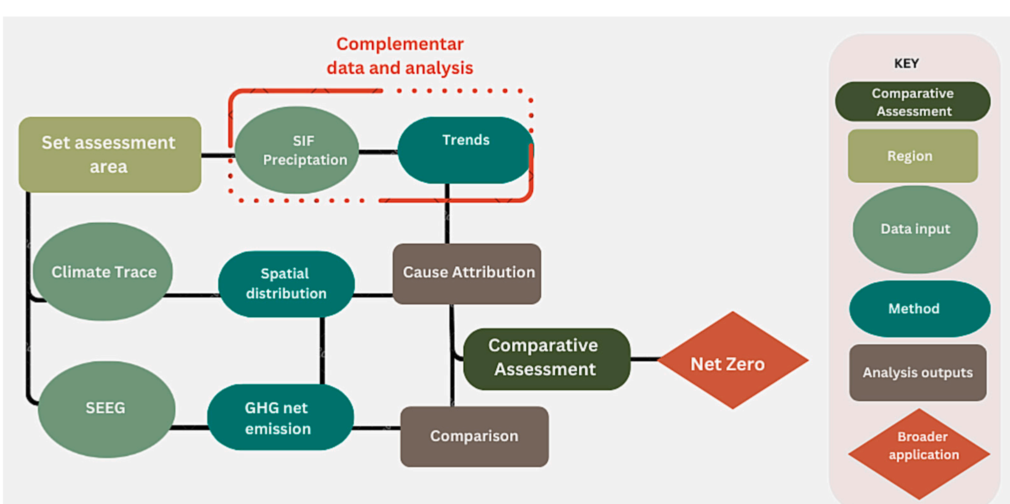

Fig. 1. General Framework for comparing both GHG inventories.

Fig. 2. Brazilian territorial extension and the Biome domain. The division of Brazil's territory into distinct biomes reflects the country's ecological diversity, with each biome representing a unique domain defined by specific climatic, vegetation, and biodiversity characteristics.

provided by Xu et al. (2021). Regarding the other emission sources, the methodology descriptions of each one of those can be found at: https://github.com/climatetracecoalition/methodology-documents

2.4. System of estimative of greenhouse gases emissions and removals (SEEG)

We acquired on January 2024 GHG emission and removal estimative from the System of Estimative of Greenhouse gases Emissions and removals (SEEG, https://seeg.eco.br/), in order to compare with Climate TRACE estimative, concerning the years 2015 up to 2022. The SEEG is a Brazilian initiative that aims to inventory Brazilian emissions on a per-sector basis using IPCC methodology combined with the national emissions factors (De Azevedo et al., 2018). SEEG's GHG estimates started in 1990 and are updated every year, in the version used in this study (v 11) the last year of estimate was 2022. This dataset is categorised into five sectors: agriculture, energy, industry, waste and forestry and land use change.

Regarding the agriculture sector, the SEEG considers direct and indirect emissions of GHG due to animal production, rice cultivation, soil management, liming, nitrogen fertilizer, burning, and other unaccounted emissions. The energy sector accounts for emissions from fossil fuel combustion in road and air transport, emissions in coal mining extraction, and the oil and natural gas industry. Regarding the industry, this sector accounts for emissions from metal production, mineral products, the chemistry industry, HFC emissions, household appliances, and non-energy use of fuels. The waste sector accounts for Solid waste disposal; Treatment of domestic liquid effluents; Industrial Effluent Treatment; Solid waste incineration and open burning; and biological treatment. Finally, the Land Use Change sector first classifies the land use transitions using MapBiomas Land Use and Cover maps with 30 m resolution then they estimate the emission and removal for each vegetation class and subclass. Also, this sector accounts for emissions due to wildfires associated and not associated with deforestation and on the soil organic carbon.

2.5. Precipitations

Daily precipitation was retrieved from the National Aeronautics and Space Administration/World Energy Resources Forecasting Platform (NASA/POWER; https://power.larc.nasa.gov/). The POWER project is a user-friendly platform that provides several meteorological datasets based on reanalysis and remote sensing products. The daily precipitation provided by POWER is derived from NASA's Global Precipitation Measurement (GPM) mission's Integrated Multi-satellitE Retrievals for GPM (IMERG) with 0.1° spatial resolution. Several studies have been using the POWER data for different applications (da Costa et al., 2023; de Souza Rolim et al., 2020) and have a good agreement with ground station data in Brazil (Duarte and Sentelhas, 2020).

In this work, we evaluated this data as an annual cumulated precipitation in 0.5° grid cells covering the Brazilian territory, between 2015 and 2022. We used the precipitation data to understand the influence of the weather on forestry removals since this natural water supply is one the main drives of photosynthesis activity. Furthermore, the annual precipitation data for each grid cell was averaged to each biome in order to perform correlation analysis and make assessments at a biome level.

2.6. Solar induced chlorophyll fluorescence

The Solar Induced chlorophyll fluorescence (SIF) is a signal emitted by chlorophyll *a* molecules and it has been considered a photosynthetic activity proxy (Mohammed et al., 2019). The SIF's remote sensing retrieval has opened new possibilities for studying ecosystem functionalities, such as the response to precipitation, drought, and carbon exchanges (Castro et al., 2020; da Costa et al., 2023; Sun et al., 2018). The SIF signal analyzed here was acquired from the Orbiting Carbon Observatory 2 (OCO-2) v11. The OCO-2 provides SIF measurements at 757 nm and 771 nm, here we only used the 755 nm as this region is closer to one of the peak positions of SIF's spectrum shape (Mohammed et al., 2019), and also only considering the observation in clear sky days (Crisp et al., 2017; Frankenberg et al., 2014).

The OCO-2 SIF data was aggregated in 0.5° grid cells across Brazil and it was analyzed using a linear regression in each grid cell, to determine a photosynthetic enhancement or decline through time. This classification was done based on the slope of the regression analyses, i.e., if the regression slope > 0 this means a photosynthetic enhancement over time, while the decline is when the slope < 0, only considering slopes that are statistically significant using the interquartile rule. Additionality annual SIF averages were submitted to correlation analysis with GHG and precipitation. The SIF data used here are freely available at: https://disc.gsfc.nasa.gov/datasets/OCO2_L2_Lite_SIF_11r/summary/

2.7. Processing

Climate TRACE Brazil emissions data from 2015 to 2022 for sectors stated in section 2.2 was accessed in January 2024 (Climate, 2022). Data in CSV format was processed after decryption using the R programming language (R Core Team, 2024). During the data preprocessing different emissions sources were compiled into a single database, distinguishing among emission sectors and subsectors, as well as identifying emissions from local sources and those originating from non-identified (country). The entire processing was validated by comparing the values of observed sources at local, regional, and national levels with those presented on the Climate TRACE platform. Furthermore, this dataset was used to understand the difference between new methods to inventory GHG emissions and the more classic ones such as from SEEG. Regarding the SEEG data, they provide a sheet of already processed emissions and removals for the country and each sector, using the GWP-AR5, we compared SEEG's data with Climate TRACE. As above mentioned, the OCO-2 SIF data was resampled in 0.5° spatial resolution as monthly averages. About the precipitation, the data was also acquired in 0.5° spatial resolution and was processed as the cumulated year amount. The biome analysis was made through the coordinates that were inside the biome geometry. All the codes used during this work can be accessed at: https://github.com/lm-costa/CT_article

2.8. Statistical analysis

Initially, Climate TRACE emissions were described through descriptive statistical analysis. Subsequently, the normality hypothesis was assessed using the Shapiro-Wilk test ($p > 0.01$). To evaluate the association between emissions and annual precipitations, Pearson's correlation was applied in each biome by considering the entire time series. Finally, the linear regression analysis was conducted, assessing the variables for the assumptions of residuals and homoscedasticity normality ($p > 0.01$). The analyses were performed using the R language as a statistical tool.

Regarding GHG anomaly analysis (Eq. 1), this was carried out by subtracting the emission/removal source from a background only for Climate TRACE data. The background was calculated as the median value for the entire Brazilian country considering all the analyzed period (2015 - 2022). These anomalies were aggregated as a sum of the sources in a 0.5° resolution for each year. We highlight that this analysis was only made for Climate TRACE because they provide georeferenced emission and removal estimates.

$$GHG\ anomaly_{(s,y)} = GHG_{(s,y)} - bkg$$

Where GHG anomaly (M ton CO_2 eq) is the anomaly of the source (*s*) in the year (*y*) and *bkg* is the background GHG concentration.

The SIF was analyzed as a linear regression in a grid cell, where if the regression slope was >0, would mean a possible photosynthetic enhancement and <0 would be a possible photosynthetic decrease through time. First, we aggregated the SIF data as monthly averages in each grid cell, then regression analysis was performed for each pixel, and the slopes were extracted. We only consider the slopes lower or higher than the first and third quartiles.

Finally, using GHG anomalies calculated from Climate TRACE data, annual precipitation and annual SIF averages, we performed Pearson's correlation analyses at a peer pixel level in order to spatially distribute those relations. For this, we only consider correlations with significance levels below 10 % ($p < 0.1$). SEEG's data was not used for those analyses because they only provide data at the municipal level without coordinate, so the correlation pixel-wise with other data sources is not feasible.

3. Results

3.1. Brazil's overall GHG emissions

According to Climate TRACE data, Brazil's GHG emissions (Fig. 3a), excluding the Forestry and Land Use sector, ranged between 1.42 (2016) to 1.54 (2021) gigatonne of CO_2 equivalent (G ton of CO_2 eq) during the study period. Higher emissions occurred in the agriculture sector (0.72 ± 0.02 G ton CO_2 eq year^{-1}), followed by transportation (0.22 ± 0.009 G ton CO_2 eq year^{-1}), waste (0.16 ± 0.005 G ton CO_2 eq year^{-1}), and manufacturing (0.12 ± 0.006 G ton CO_2 eq year^{-1}). In 2016 and 2021 the forestry and land use sector was an emitter, contributing to the overall emissions level to relatively higher magnitudes, 2.28 and 2.92 G ton CO_2eq, respectively. However, this sector acted as a sink by removing CO_2 from the atmosphere for the following years: -1.07 G ton CO_2 eq. (2022), -0.49 G ton CO_2 eq. (2020), and -0.42 G ton CO_2 eq. (2017). According to Climate TRACE data for 2022, the global forestry and land use sector removed 2.39 G ton CO_2 eq (based on summed country totals) with Brazil capturing 1.07 G ton CO_2 eq (~45 %) of the total.

Similarly to the Climate TRACE inventory, the Brazilian Greenhouse Gas Emissions and Removals Estimation System (SEEG, Fig. 3b) also indicates that the year 2021 is the one with higher net emissions, being around 1.76 G ton CO_2 eq (GWP AR5), followed by 2019 (1.61 G ton CO_2 eq), similarly to the observed for the Climate TRACE data (Fig. 3a). Excluding the Forestry and Land use sector, according to SEEG, the higher emitter sector was agriculture (0.85 ± 0.019 G ton CO_2 eq year^{-1}), followed by the energy sector (0.41 ± 0.018 G ton CO_2 eq year^{-1}). It is important to notice that SEEG's energy sector accounts for emissions due to transport and fossil fuel usage.

While both datasets exhibit similar patterns over the years, the magnitude of the net emissions can vary significantly depending on the year. For example, in 2016 and 2021, Climate TRACE estimative is almost 1 Gton CO_2 eq higher than SEEG. On the other hand, the Climate TRACE estimative was 0.4 Gton CO_2 eq lower for 2019 and 1 Gton CO_2

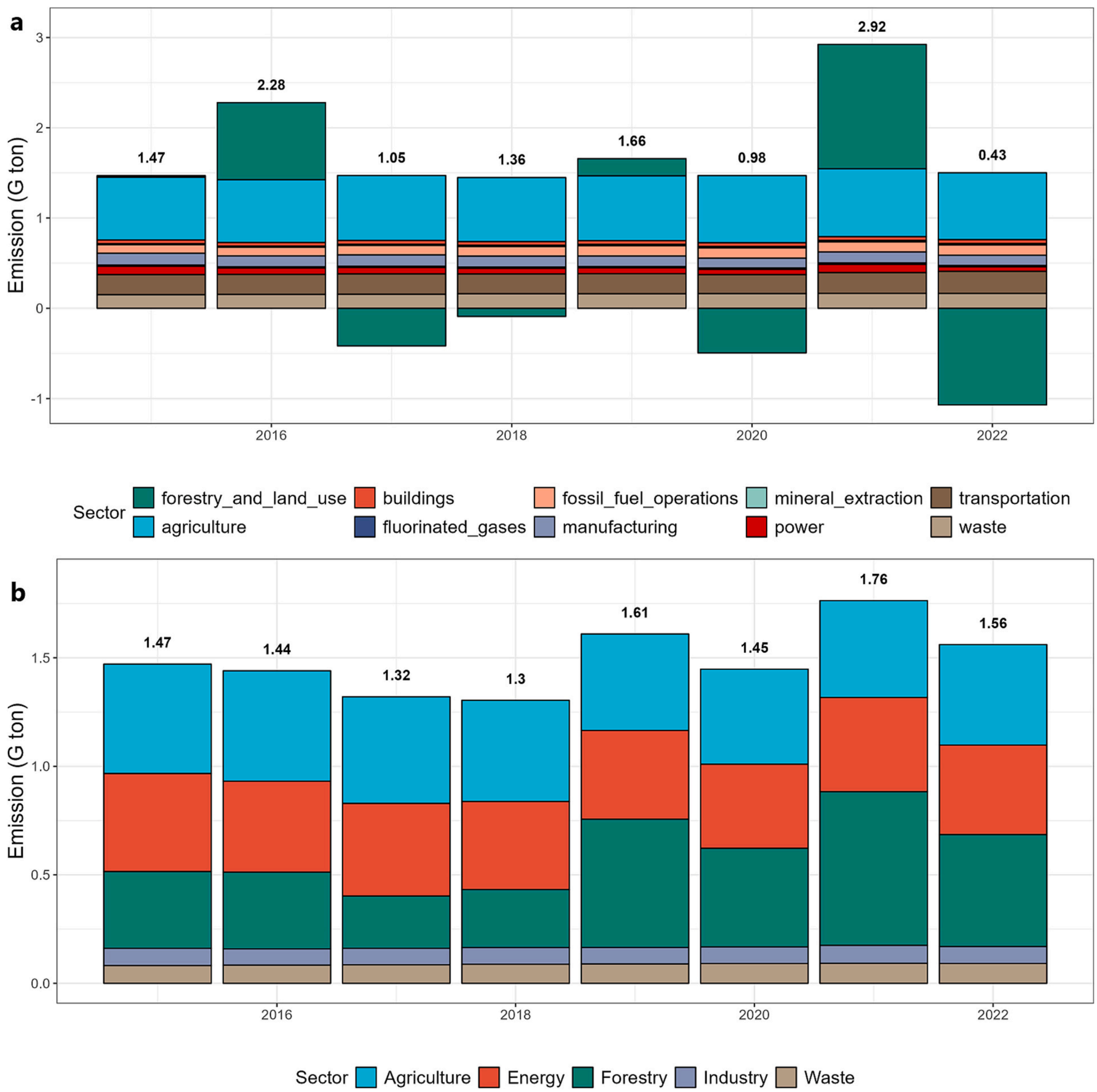

Fig. 3. Brazilian CO_2 eq emissions and net emissions using different emission inventories. a) Climate TRACE's emissions and removals (negative CO_2 eq) data for the following sectors: forestry, agriculture, buildings, fluorinated, fossil, manufacturing, mineral, power, transportation, and waste. b) SEEG's Brazil emissions data for the following sectors: forestry, agriculture, Energy, Industry, and waste. Above the bars, bold numbers represent net emissions (emissions – removals) in the respective year. Please refer to the online version for colors.

eq lower for 2022, compared to SEEG's estimative. However, in 2015, 2017, and 2018 net emissions slightly diverged in quantities around 0.01 G ton CO_2 eq, 0.25 G ton CO_2 eq, and 0.06 G ton CO_2 eq, respectively. Climate TRACE displays annual variability in the Forestry sector, as this sector changes from a net sinker to a net emitter throughout the analyzed period, meanwhile, SEEG's estimative for this sector does not have this pattern, always being a net emitter at the national level. This seasonality in Climate TRACE estimative for this sector could be related to environmental factors, such as precipitation, and this will be further explored in this work.

3.2. Exploring Climate TRACE estimations across biomes

The Climate TRACE spatial distribution of annual sources and removals across Brazil (based on anomaly analysis, Fig. 4) varies from year to year. The focal emissions sources, concentrated within grid cells, are mainly around 0 and 0.5 Megatonnes of CO_2 equivalent (M ton CO_2 eq) but occasionally can reach values higher than 5 M ton CO_2 eq. It is worth noticing that on the coast side, there is an offshore platform, hence explaining the constant higher emissions. Likewise, the majority of focal removals range from -0.5 to 0 M ton CO_2 eq; however, the removals rarely reach values below -1 M ton CO_2 eq and never surpass -5 M ton CO_2 eq in none of the years. Meanwhile SEEG's net emission at the biome level is always higher than 0, but similarly to Climate TRACE one of the biomes with lowest emission levels is Caatinga (0.01 ± 0.01 G ton CO_2 $year^{-1}$, Supplementary Fig. 1).

Furthermore, the distribution of sources/removals (Fig. 4) along biomes shows that in most years Central-South Brazil, where agricultural activity is prominent, is associated with GHG emission sources. On the other hand, in the northeast region, there is the majority of GHG sinks, however, there are some years with lower sink observations spread around the country, such as in 2015; meanwhile, some years have a high frequency of observed sink such as 2020. Complementary, on the biome level, the Caatinga biome emerged as the largest CO_2 capturer (Fig. 5). For instance, out of a total of 1.07 Gton CO_2 eq in 2022, Caatinga captured 0.41 G ton CO_2 eq, followed by Atlantic Forest and Cerrado's ecosystems with 0.32 CO_2 eq and 0.24 CO_2 eq, respectively (Fig. 5). These biomes designate 90 % of the total GHG removal in 2022, with Caatinga responsible for 38 %. According to SEEG's data, Caatinga also has the highest levels of CO_2 removal, however, SEEG's estimates are smaller than Climate TRACE one and have fewer seasonal changes (Supplementary Fig. 2 a).

Similarly to GHG net emission, the distribution of annual precipitation across Brazilian biomes also reveals significant changes throughout the years and biomes (Fig. 5). Amazonia, Atlantic Forest, and Pampa biomes are the ones with the highest precipitation amounts, while Cerrado, Pantanal and Caatinga were the lowest. But in a biome like Caatinga, the annual amount starts as low as 500 mm (2015) and ends as high as 900 mm (2022) presenting a significant increase in its mean precipitation along the period ($r = 0.87$, p-value <0.001). Additionally, in the Caatinga biome, there is a noticeable fluctuation in precipitation amount year after year, alternating more severe droughts to lesser ones from 2015 (drought) to 2016 (lesser drought) and so on. Its net emission (also Fig. 5) shows the same pattern with alternations between positive and negative emissions, due to the forestry sector, coming from 2017 to 2022.

Besides the precipitation, SIF trend analysis using OCO-2 data (see methods, Fig. 6) also reveals that the Caatinga domain is facing a photosynthetic enhancement for the same analyzed period (2015 - 2022). This biome has an average increase of 0.0009 ± 0.005 W m^{-2} sr^{-1} µm^{-1}, ranging as low as -0.001 to as high as 0.003 W m^{-2} sr^{-1} µm^{-1}, meanwhile, a biome such as Pampa is facing an average decrease of

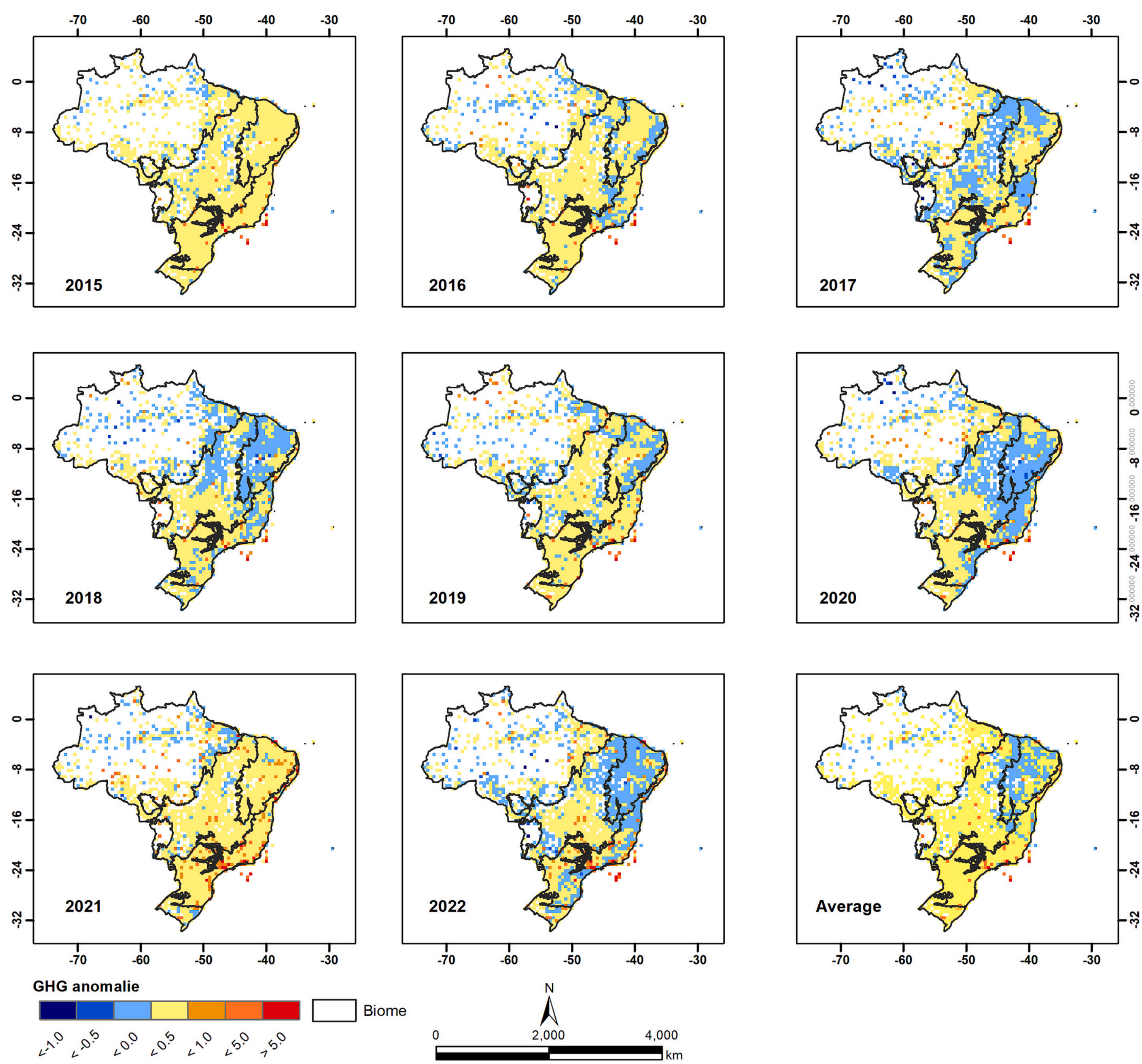

Fig. 4. Climate TRACE GHG anomalies across Brazil between 2015 and 2022, with the average of the period. The spatial distribution of GHG anomalies based on Climate TRACE data is expressed in Megatonne of CO_2 equivalent (M ton CO_2 eq) for all sectors in 0.5 grid cells over the different years using Climate TRACE data. Cooler colors (blue, purple) indicate removals whereas warmer colors (orange, red) indicate emission sources. Please refer to the online version for colors.

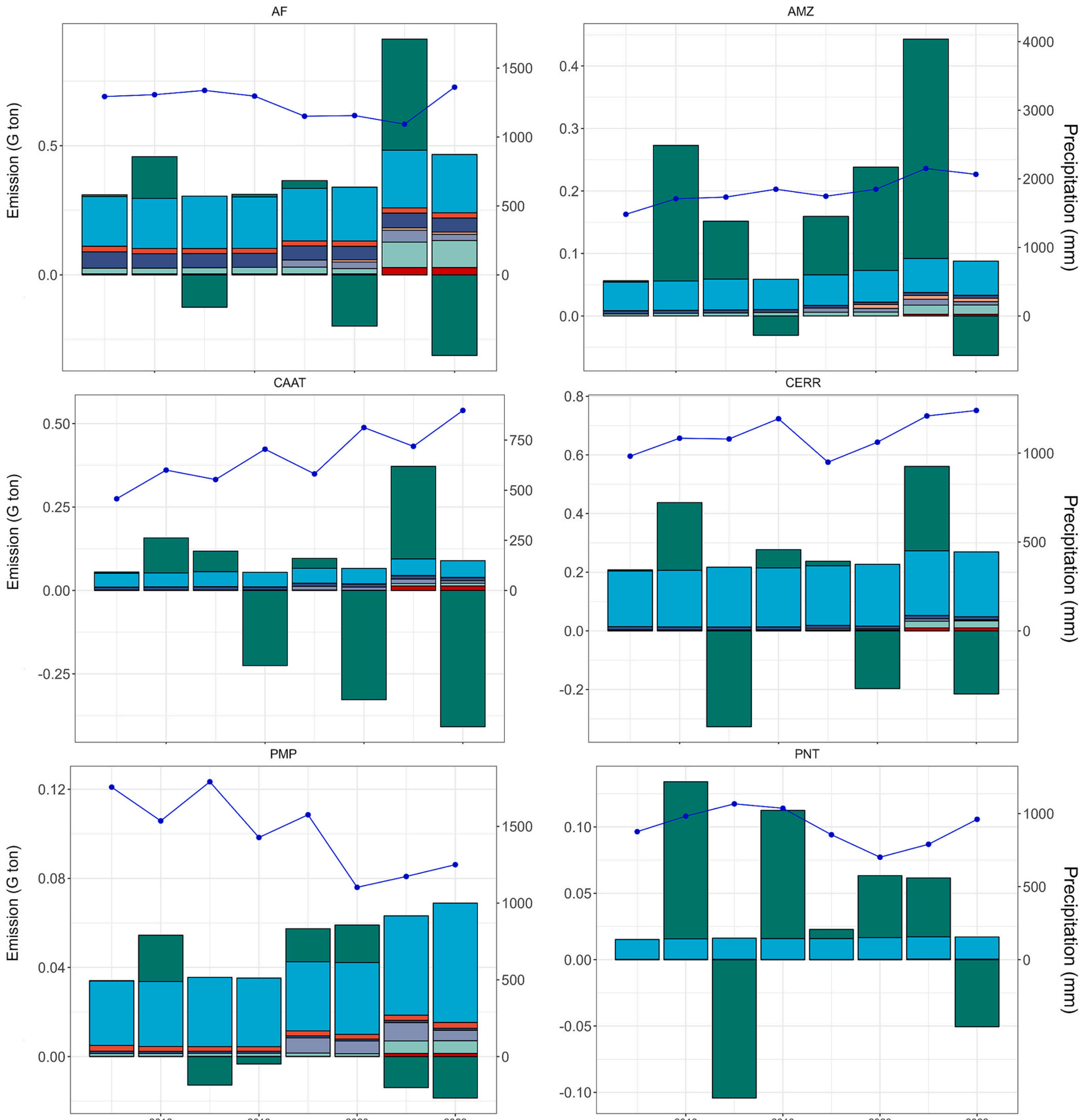

Fig. 5. Brazilian Biomes GHG emissions and net emissions based on Climate TRACE and precipitation data. Where AF is Atlantic Forest; AMZ is Amazon; CAAT is Caatinga; CERR is Cerrado; PMP is Pampa and PNT is the Pantanal biome. Note, that the y-axis for each biome has different ranges. Please refer to the online version for colors.

-0.00069 ± 0.0008 W m^{-2} sr^{-1} μm^{-1}. Moreover, according to Tukey's test, the Caatinga domain had the higher average trend among all the biomes and the Pampa had the lowest (p-value <0.05). This possible photosynthetic activity increasing in the Caatinga domain implies in more CO_2 removals through time, further confirming the GHG anomaly pattern observed in Fig. 3. Complementary, since photosynthesis is a water-dependent process and as the precipitation increases on the Caatinga domain (Fig. 5) this relies upon the observed photosynthesis enhancement over time.

Those relations are supported by a pixel-wise correlation analysis ($p < 0.1$) between the variables (Fig. 7). Negative correlations between GHG anomaly with annual precipitation amount and with annual SIF averages are mainly observed in the Caatinga domain. Other Biomes, such as Atlantic Forest, can also be observed these negative relations. Meanwhile, in Cerrado and Amazon, there is a more mixed correlation result. In a biome level (Supplementary Fig. 3) the GHG estimates from Climate TRACE also negatively correlate with precipitation in Caatinga ($r = -0.6$, $p < 0.15$), Atlantic Forest ($r = -0.58$, $p < 0.15$) and Pampa ($r = -0.63$, $p < 0.1$), meanwhile, for SEEG's net emissions (Supplementary Fig. 2 b) the only biome that has a negative correlation is

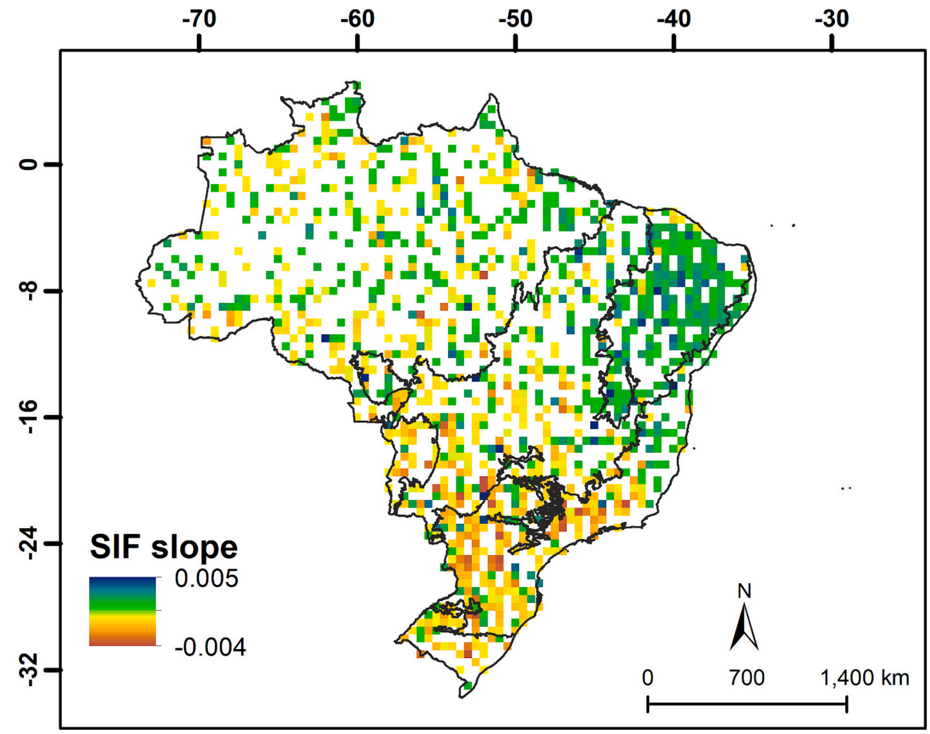

Fig. 6. Photosynthesis long-term trend across Brazilian Biomes. Spatially distribution in 0.5° grid cells of Solar Induced chlorophyll Fluorescence slope over time (2015 to 2022). Please refer to the online version for colors.

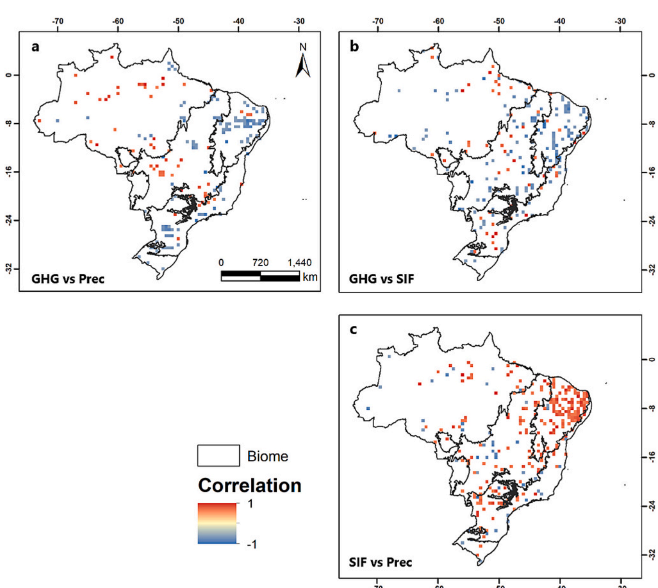

Fig. 7. Correlation analysis at a pixel level (0.5° grid cell) across biomes. GHG anomalies with precipitation (a); GHG anomalies with SIF (b) and SIF with precipitation (c). Only significant correlations ($p < 0.1$) are shown. Please refer to the online version for colors. GHG anomalies were calculated based on Climate TRACE data.

Pantanal ($r = -0.59$, $p < 0.15$). Furthermore, at a pixel level, a positive correlation between SIF and precipitation is observed more frequently, especially over Caatinga.

3.3. *The forestry and land use sector's potential*

Regarding the Forestry and Land Use sector, the emissions are mostly related to the forest land clearing subsector, i.e., deforestation, but also forest land fires and degradation contribute to GHG emissions in some years (Supplementary Fig. 4). While removals, which could vary from as low as 1 to as high as 2 Gton CO_2 per year, are mostly related to CO_2 capture in biomass. If emissions due to forest clearing (deforestation) were stopped and set to zero, the forestry removal capacity would alone be capable of making Brazil a net-zero country, except in 2021 when the net forest land emitted >1 G ton CO_2 eq (Fig. 8).

This outcome evidences the importance of stopping deforestation in Brazil since the removal potential can not only balance emissions closer to zero but could change the country to a GHG sink, with negative net emissions in almost all years, except 2021, the year that net forest land emitted significant amounts of GHG (Fig. 6b); however, the accumulated budget for the period (2015-2022) is negative (-2.02 G ton CO_2 eq).

4. Discussion

4.1. *Brazil's overall GHG emissions*

Brazilian emissions are extremely related to the Forestry and Land use sector and agriculture, however, in other countries the emissions can be more related to economic policies (Adedoyin et al., 2020; Shaari et al., 2024). Recently, Filonchyk et al. (2024), reported that the GHG emissions in Brazil in 2020 and 2022 were 1.28 Gton CO_2 eq and 1.31 Gton CO_2 eq, respectively. They used EDGAR's data set, hence the emissions related to deforestation are not included, underestimating the Brazilian CO_2 emissions. The Forest and Land use sector in Brazil is crucial, their net emission was around 1.8 Gton CO_2 eq. in the 90 decade, however, due to law enforcement the emission due to deforestation decreased to values close to 0.2 Gton CO_2 eq in 2012, after this year the emissions once again starts to rise similar to the current levels reported here (Zimbres et al., 2024). Although the emissions reported by Filonchyk et al. (2024) are underestimated, among the 10 world's largest emitters, Brazil was the last one.

The agricultural sector in Brazil has as a primary source the enteric fermentation. This process is responsible for 27.3 Mg CO_2 eq. ha^{-1} having a footprint on average of 28 kg CO_2 eq. per kg of live weight (Cerri et al.,

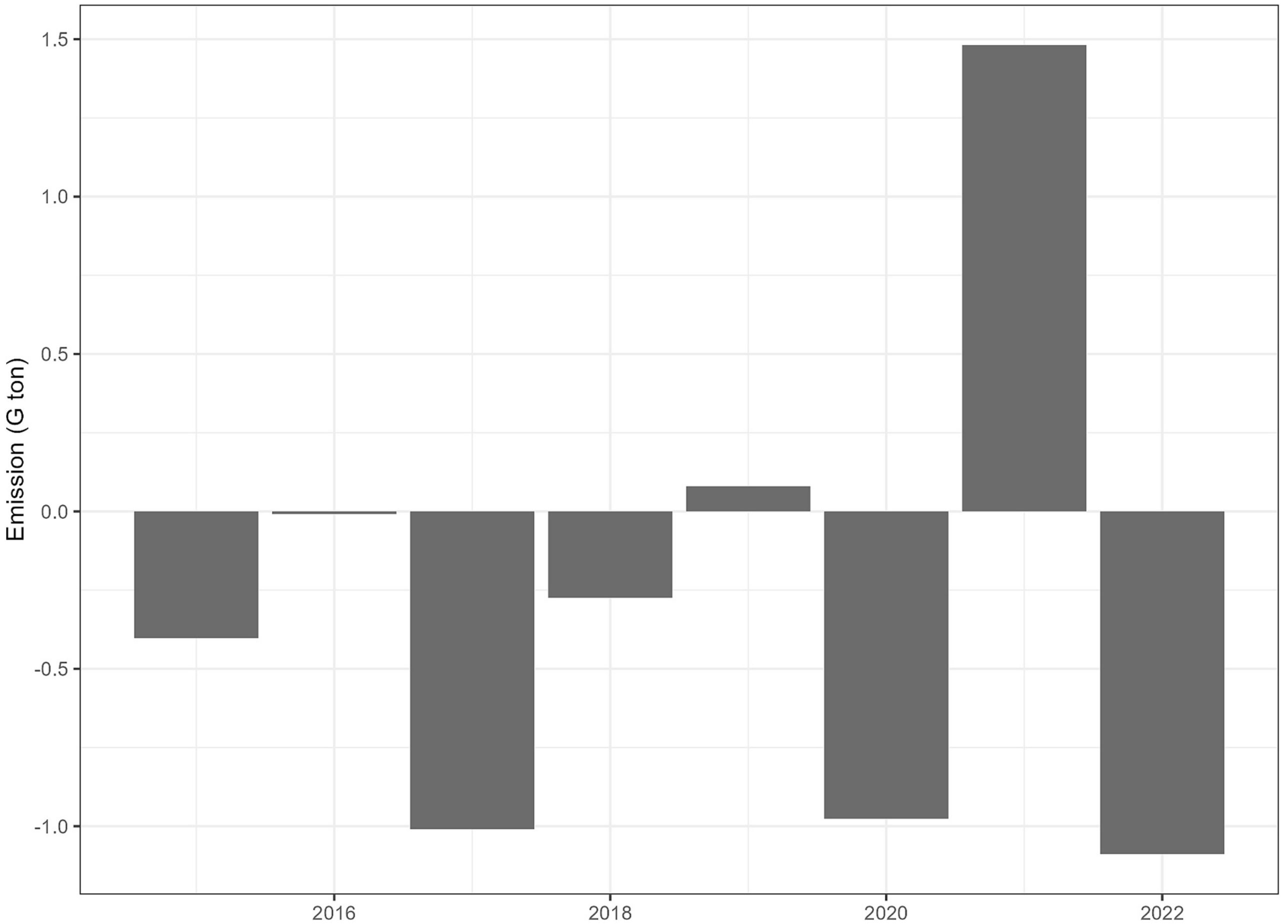

Fig. 8. Land use and Forestry sector and its potential according to Climate TRACE. Brazilian net emissions for all sectors, excluding the emissions related to deforestation over the years. Please refer to the online version for colors.

2016; Leão et al., 2021). Meanwhile, there are pathways to reduce the GHG footprint of this sector, such as the agroforestry system (Bieluczyk et al., 2024; Oliveira et al., 2024; Santos et al., 2024). Besides enteric fermentation, agriculture has a large use of fertilizer and other products that raise the GHG emission from this sector (de Figueiredo et al., 2017; Maciel et al., 2016; Raucci et al., 2015). However, Afforestation, restoration and the adoption of sustainable agriculture practices can reduce GHG emissions (De Figueiredo and La Scala, 2011; Soterroni et al., 2023; Svensson et al., 2024; Zimbres et al., 2024).

4.2. Climate TRACE and SEEG

The disparities noted between SEEG and Climate TRACE (Fig. 3) primarily emerge within the forestry and land use sector and also agriculture, due to contrasting methodologies employed by each (De Azevedo et al., 2018; Xu et al., 2021). Climate TRACE reports forestry emissions using a method developed by CTrees (Xu et al., 2021; https://ctrees.org/). CTrees' approach for estimating forestry emission and removal not only incorporates land use and cover changes but also leverages additional remote sensing datasets, including radar information from the Geoscience Laser Altimeter System (GLAS) and ALOS PALSAR (Advance Land Observation Satellite Phased Array L-band Synthetic Aperture Radar sensor), to infer forest canopy structure and above ground biomass. In addition, CTrees also integrates Land Surface Temperature and burned area information from Moderate-Resolution Imaging Spectroradiometer (MODIS) and a machine learning approach (i.e., random forest) to improve their estimates.

CTrees' combined approach enables the capture of seasonal space-temporal variabilities, as CTrees's estimations reveal a larger carbon imbalance compared to other global GHG inventories. This sensitivity is attributed to the model's blend of several carbon pools (e.g., soil, dead, litter, and freshwater). Thus, the CTrees approach represents a major improvement in GHG inventory reporting, as it potentially captures changes in photosynthetic capacity over time, especially in tropical regions, where water availability serves as an important limiting factor to photosynthesis (Yue et al., 2020).

On the other hand, emission inventories such as SEEG generally adhere to the Intergovernmental Panel on Climate Change (IPCC) guidelines for national greenhouse gas inventories. In these methodologies, the land-use sector footprint typically relies on emission factors and area size, without incorporating additional remote sensing products. Hence, although the IPCC's methodology is widely utilized and recognized, one of its limitations is that it disregards the seasonal variability in photosynthesis intensity. Carbon removal is a complex process since it relies not only on vegetated cover area, but also on climate and local conditions. Lamb et al. (2024) recently pointed out the necessity of better estimates of carbon removals as this is an important feature for countries to achieve their NDC by 2030 and 2050. Complementary, IPCC methods also diverge according to the version used in the inventory, as the more recent ones have lower removals estimates (Kayo et al., 2021).

Furthermore, there are differences in land use and land cover classification, as SEEG uses the MapBiomas classification (Souza et al., 2020), meanwhile, CTrees utilizes the MODIS land cover product. The MapBiomas, a Brazilian collaborative mapping initiative, aims to reveal transformations in the Brazilian territory through land use and land cover monitoring primarily processing and modeling LandSat images at 30 m resolution. This regionalized classification offers certain advantages over global products, which can be more generalized. For instance, one of the major weaknesses of MODIS land cover maps is the coarse resolution, having an overall accuracy of 73 % (Sulla-Menashe et al., 2019); meanwhile, MapBiomas has an overall accuracy higher than 85 % (C. M. Souza et al., 2020). Pedruzzi et al. (2022) showed that MODIS had a misclassification problem, especially in the coastal area. The coarse resolution of global products may not capture a small deforestation increase (Kalamandeen et al., 2018), contributing to an underestimation of these emissions. Moreover, Zimbres et al. (2024) reported that the usage of MapBiomas classification into SEEG estimates for the forestry and land use sector better estimates the carbon removals in Brazil in comparison with the official Brazilian inventory (also based on the traditional IPCC guidelines), released by the government.

Furthermore, assessing emissions and removals linked to the agriculture sector, SEEG presents additional advantages compared to Climate TRACE. This is attributed not only to the inclusion of emissions from liming and organic fertilizer, which constitute a major CO_2 source associated with soil management and tropical agriculture in the Brazilian context (Maciel et al., 2016; Raucci et al., 2015) but also to considering soil organic carbon (SOC) emission and removals of atmospheric CO_2 (De Azevedo et al., 2018). Liming is essential in Brazilian agriculture due to acid soils that need pH correction in order to produce; however, this practice can be responsible for at least 10 % (Raucci et al., 2015) of GHG emissions reaching up to 50 % (Cerri et al., 2024). Furthermore, changes in SOC are notably challenging to estimate and model; hence several inventories do not account for this quantity. Although this feature presents some significant uncertainty, SEEG uses regional emission factors based on literature to estimate how different agricultural management practices and internal sector conversion (e.g., from degraded pasture to agriculture) would impact it.

4.3. Climate TRACE emission and its relation with the environment

The region where most GHG sources were observed was in central Brazil (Fig. 4), recently not only the deforestation in this region has been increasing (Ferreira Barbosa et al., 2022) but also the fire outbreaks (Alencar et al., 2022). GHG emissions related to those activities are a major concern in Brazil, according to Zimbres et al. (2024), there was a significant decrease in this sector's emissions between 1990 and 2012, however, after 2012 the emissions related to deforestation increased reaching the levels of net emission of 0.4 Gton CO_2 eq. Gatti et al. (2023) sampling GHG gases with airborne on Amazon biomes also reported that there was an increase in CO_2 emissions due to deforestation led by the decline in law enforcement.

Recently, Brazilian official deforestation records, provided by the DETER system, reported a decrease of 33 % in deforestation in 2023 compared to 2022; however, Cerrado's deforestation increased by 21 % for the same period (da Conceição Bispo et al., 2023). Most of the Cerrado deforestation occurs in the arc of deforestation near the Amazon, and also in the region so-called Matopiba (north portion of this biome) (Machado et al., 2024). The Matopiba region is a contrasting region considering Climate TRACE removals (Fig. 4), however, this could be due to ascribed to methodological differences previously explored. Noojipady et al. (2017) using remote sensing estimated that forest carbon emissions due to cropland conversion in this domain were around 0.01 Gton CO_2 eq year^{-1} (4.69 Tg C year^{-1}), which is more or less consistent with the observed in our study on average. Meanwhile, the fire emission contribution was 2.3 Gton CO_2 between 1985 and 2020 (Gomes et al., 2024). All this anthropic pressure in this ecosystem is changing the surface temperature and evapotranspiration (Rodrigues et al., 2022).

Besides the recent threats that Cerrado is facing, there are more sustainable pathways to follow, such as conservationist practices to reduce CO_2 emissions in agriculture (Corbeels et al., 2016). They observed that under No-Till systems, soil carbon sequestration reached annual rates of approximately 1.61 and 1.48 Mg C ha^{-1} year^{-1} after 11 to 14 years, being comparable with natural Cerrado levels. Nonetheless, substantial portions of native vegetation are still being cleared for intensive tillage within Cerrado nowadays (Garrett et al., 2022), where intensive soil preparation for second-crop plating negatively impacts soil organic carbon storage, along with the resurgence of deforestation.

Moreover, several efforts have been made in Atlantic Forest to restore and preserve the remaining native forest (de Mendonça et al., 2022; Parras et al., 2020; Rother et al., 2023; Vancine et al., 2024), hence contributing to land use transitions, climate resilience and GHG control. In addition to being a global biodiversity hotspot, the Atlantic Forest exhibits the highest organic carbon stocks in soils among Brazilian biomes, reaching 96.4 Mg kg^{-1} at depths $<$30 cm (de Souza Medeiros et al., 2022).

Conversely, GHG removals are frequently observed especially in Caatinga (Northeast), and in some parts of Cerrado and Atlantic Forest biomes, across multiple years. Garofalo et al. (2022) have shown that the Caatinga biome among all the biomes has a higher potential of removing CO_2 from the atmosphere even considering different land use changes. Investigating the ecological services footprint, Parras et al. (2024) introduced the LUEF – Ecological Footprint of Land Use revealing the loss of shrub vegetation in Caatinga as a threat to organic carbon stored.

Recently, it has been reported that among Brazilian biomes the solar-induced fluorescence has the highest sensitivity to rain precipitations in Caatinga (da Costa et al., 2023; Uribe et al., 2021) as SIF in this biome increases mostly when precipitation occurs in higher amounts. This is related to the arid environment being a water-limited environment, and when this limitation is surpassed by precipitation events the photosynthesis process is boosted, thus reflecting a higher sensitivity to this event. In addition, studies conducted with the eddy covariance technique point out that this biome reaches maximum CO_2 assimilation in the wet season being a carbon sink (Jardim et al., 2023; Mendes et al., 2020). A small amount of precipitation significantly increases the gross primary production of this ecosystem, thus explaining the removal potential of ~40 % considering all the country's removals.

Furthermore, in biomes such as the Amazon and Atlantic Forest, there are other key factors besides the precipitation, such as radiation. Uribe et al. (2021) reported that the Amazon biome has a light-following response, meaning that the photosynthetic peaks after precipitation start to decline. This kind of ecosystem can have this response due to deep root structure, which can explore water from higher depths. Furthermore, Uribe et al. (2021) also reported that dry-forests (e.g., Cerrado) have a coupled response between precipitation and light. Although we did not investigate this feature, those relationships could explain the lake of a stronger correlation found in our study.

It is important to notice that the Climate TRACE estimative in the forestry sector employs the CTrees model. Although their methods do not use precipitation data directly in the model, this approach indirectly captures the precipitation role in the forest removal capacity, as they incorporate several data sources and also LST data to consider the sector's seasonality. As the precipitation events occur in the country the water supply increases, boosting the removal capacity and explaining the observed correlation between GHG net emission and precipitation.

4.4. Forestry and land use sector potential

Soterroni et al. (2023) simulated several policy scenarios in Brazil, targeting net-zero emissions, and concluded that only with zero deforestation (legal and illegal) that this mark could be reached, going in agreement with the results presented here. Carbon removals by forest represent a key factor for Brazil to reach the NDC target. As one of the ongoing targets, Brazil committed to restore 12 Mha by 2030 (1Mha year^{-1}). Secondary forest regrowth can reach removals of around 11.01 tons CO_2 ha^{-1} year^{-1} on the Amazon biome (Heinrich et al., 2021), depending on the climate condition. Considering the NDC target of 12 Mha, this would represent around 0.165 Gton CO_2 in the national budget.

Although secondary forest regrowth is important in carbon removal and balance, the net-zero target would not be possible without ending deforestation. Besides the illegal deforestation problem, the Brazilian current Forest Code, a total of around 78 Mha of native vegetation could be legally suppressed in Brazil (Dutra et al., 2024). This represents a major threat to the current effort to restore the 12Mha (Brazil NDC). For instance, in Cerrado, the discontinuation of the Action Plan to Prevent and Control Devegetation and Fires in this ecosystem in 2019 may contribute to an increase of deforestation in this biome after this period ally with the decrease in law enforcement in the region (Machado et al., 2024). The decrease in law enforcement was not only observed in Cerrado, but also in Amazon biomes which are 73 % of Brazil's are (Gatti et al., 2023).

In 2021, net emissions from the forest sector corresponded to approximately 0.7 to almost 1.5 Gton CO_2e, much of it from deforestation (SEEG and Climate TRACE, respectively, Fig. 3). This scenario reflects the governance and actions of the government in place during the period, which reduced environmental protections and encouraged harmful practices, such as the actions of illegal land grabbers and miners, resulting in historic rates of illegal deforestation. Thus, Brazil's environmental governance during Bolsonaro's administration revealed a combination of bad governance and improper governance (Bastos Lima and Da Costa, 2022; Souza et al., 2022).

Completely halting deforestation in Brazil is an ambitious goal with the potential to position the country as a leader in climate change mitigation, especially considering the crucial role of tropical forests in carbon sequestration. However, this also presents several complex challenges and a range of potential outcomes. Among the main challenges are the economic and social pressures linked to sectors such as soy and meat production, which often perform criminally, advancing new illegal agricultural frontiers. This requires an improvement in the country's infrastructure and governance, with policies to encourage sustainable practices and effective inspection mechanisms, as well as the strengthening of monitoring systems and strict enforcement of laws (Richards et al., 2012). It is also necessary to make progress on territorial issues, such as land regularization where public lands and irregular occupations favor illegal practices and conflicts related to the demarcation of indigenous territories, especially in the Amazon (Azevedo-Ramos and Moutinho, 2018). Fighting corruption is also essential for environmental protection.

On the other hand, stopping deforestation would bring benefits to reducing Greenhouse Gas (GHG) emissions. Soares-Filho et al. (2010) estimated that stopping deforestation in the Amazon could reduce up to 70 % of emissions related to land use, representing a reduction of 0.5 Gton CO_2eq per year. The potential outcomes of stopping deforestation could also generate long-term co-benefits for a range of ecosystem services that support both the regional economy and Brazil's climate commitments. Studying the relationship between deforestation and innovation in the Amazon, Leite-Filho et al. (2021) provide important evidence for the goal of net-zero emissions and socioeconomic trends for the country in the face of climate change. The study reveals that, after a critical point of forest loss (55–60 % at some scales), the reduction slowed significantly, harming the sustainability of agriculture and worsening GHG emissions due to the reduction in the region's carbon sequestration capacity and increased emissions due to soil and ecosystem manipulation. These findings indicate that large-scale deforestation leads to a hydrological and economic "negative sum game", where losses in agricultural profits and productivity outweigh local gains. Simulations under weak governance scenarios have projected a reduction of up to 56 % of forests in the Southern Brazilian Amazon (SBA) by 2050, which could generate annual agricultural losses of up to US$1 billion.

In addition, the elimination of deforestation in combination with knowledge transfer, innovation and the development of agroecological practices and other low-impact activities translates into direct benefits for local communities, offering opportunities for sources of income and value-added markets without overburdening natural resources, promoting conservation and the well-being of populations (Shanley and Leda, 2003). Notably, the protection of forests contributes to the preservation of biodiversity and the conservation of a wide range of endemic species, many of which are at risk of extinction due to the destruction of their habitats (Laurance and Useche, 2009). By preserving forests, the increased carbon sequestration capacity of natural vegetation can help offset emissions from other sectors, maintaining resilient ecosystems (Pan et al., 2011).

Achieving zero deforestation in Brazil is a complex and multifaceted process that requires effective public policies, financial support, an inclusive approach for local communities and a gradual transition to sustainable agricultural and land use practices (de Mendonça et al., 2022). In addition to the application of the Brazilian Forest Code on land tenure compliance and environmental liabilities, there is also the need to regulate the carbon market to curb deforestation. Internationally, halting deforestation would strengthen Brazil's role in climate negotiations, increasing its credibility and attracting international partnerships and resources (Fearnside, 2012) such as the involuntary carbon market itself, Payments for Environmental Services (PES) initiatives and Reducing Emissions from Deforestation and Forest Degradation (REDD+) projects.

These initiatives are important economic agents in the transition to a sustainable economy and, consequently, key to mitigating greenhouse gas (GHG) emissions. REDD+ encourages the conservation of forests by valuing the ecosystem services they provide, creating a financial mechanism for those who preserve forest areas and reduce deforestation. PES projects reward landowners who adopt sustainable practices, promoting the recovery of degraded areas and the maintenance of ecosystem services and are pivotal in the land tenure-restoration nexus (de Mendonça et al., 2025). The carbon market, in turn, establishes a system in which companies can offset their emissions by buying carbon credits generated by low-carbon activities, such as forest preservation and ecosystem restoration. By encouraging the reduction and offsetting of emissions, these initiatives contribute to Brazil's net-zero emissions target, promoting sustainable land use and a transition to a low-carbon economy.

5. Conclusion

In this study, we compared two distinguished GHG inventories (Climate TRACE and SEEG) estimates and explored the link between GHG emission/removal with precipitation and photosynthesis proxy (SIF). We observed that both datasets agree in the temporal pattern of GHG emission, with being 2021 the year with the highest emission (1.76 and 2.92 G ton CO_2 for SEEG and Climate TRACE, respectively). Moreover, precipitation and SIF show an increased trend in the Caatinga Biome, explaining the major sink that we observe in this Biome based on Climate TRACE data. Precipitation also partially explains the sinks in Atlantic Forest and Pampa, however for the other ecosystems we did not observe significant correlations. Other environmental conditions such as incoming light or temperature could be associated with their response. Meanwhile, SEEG's data also point out the Caatinga domain as one of the lowest emitters, however, their estimates did not correlate with precipitation data. This outcome is ascribed to SEEG's methods that only consider area information.

Furthermore, Brazil's agriculture is one of the highest emitter sectors in both inventories, however, Climate TRACE does not account for other agricultural emissions such as liming, organic fertilizers and SOC, bringing a potential underestimation of this sector in countries like Brazil, where liming is an important management practice. Moreover, land use and forestry sector have significant differences comparing SEEG and Climate TRACE datasets. In the forestry and land-use sector Climate TRACE uses a combined approach of several remote sensing products, incorporating IPCC guidelines. Although the reliability of SEEG data, their methodology disregards the seasonal variability induced by precipitation on this sector estimates. This significant difference in their carbon removals estimates highlights that this is still an open issue and has to be addressed in the national inventories.

Major natural carbon removals, especially in some biomes like Caatinga, could play an important role in the net GHG balance and budget of Brazil in some years, showing the need to incorporate these seasonal changes into the inventory estimates. The CO_2 capture data is supported by precipitation and SIF-positive trends in the Caatinga biome along the sampling period, as well as the correlation at the biome and pixel level. As the water supply of this ecosystem grows, the photosynthetic capability is boosted by this, thus reflecting higher GHG removals in this domain, strongly favoring the GHG balance of the country in some years. Finally, our results show that avoiding deforestation in Amazon and other biomes along the country would favor the GHG balance, helping Brazil to achieve net zero in the future.

Future research must focus on the climate change impact on those ecosystems as threatens our current environmental cycle and response, not only in the lesser-known Brazilian biomes but also in other regions of the world, as the framework employed here can be implemented for other regions with national GHG inventories data. Complementary, SEEG and Climate TRACE data are constantly updated, hence future research has to account for the new data release. Nevertheless, here we highlight the gap left behind regarding light and temperature response in Brazilian ecosystems, especially in the Amazon. Besides, although nature provides a pathway to becoming a net-zero country, this only will be possible if Brazil stops deforestation, both legal and illegal, as this is one of the main GHG sources.

Escalating deforestation jeopardizes Brazil's net-zero GHG emissions goals, as the loss of these forests would decrease the country's chances of becoming a net-zero GHG emitter. This reinforces that halting deforestation is essential to maintaining the ecosystem services that support both the regional economy and Brazil's climate commitments. Our outcomes provide valuable insights not only for Brazil but also for the potential of the Agriculture, Forestry and Other Land Use (AFOLU) sector to make other emerging countries a net zero GHG emitter.

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CRediT authorship contribution statement

Luis Miguel da Costa: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Aaron Davitt:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Gabriela Volpato:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation, Conceptualization. **Gislaine Costa de Mendonça:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **Alan Rodrigo Panosso:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Newton La Scala:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

All data are freely available and their respective sources are provided in the text, as well all the codes used to download, process and analyse the data are available at: https://github.com/lm-costa/CT_article.

References

Adedoyin, F.F., Gumede, M.I., Bekun, F.V., Etokakpan, M.U., Balsalobre-lorente, D., 2020. Modelling coal rent, economic growth and CO<inf>2</inf> emissions: does regulatory quality matter in BRICS economies? Sci. Total Environ. 710. https://doi.org/10.1016/j.scitotenv.2019.136284.

Alencar, A.A.C., Arruda, V.L.S., da Silva, W.V., Conciani, D.E., Costa, D.P., Crusco, N., Duverger, S.G., Ferreira, N.C., Franca-Rocha, W., Hasenack, H., Martenexen, L.F.M., Piontekowski, V.J., Ribeiro, N.V., Rosa, E.R., Rosa, M.R., Dos Santos, S.M.B., Shimbo, J.Z., Vélez-Martin, E., 2022. Long-term Landsat-based monthly burned area dataset for the Brazilian biomes using deep learning. Remote Sens. 14 (11), 2510. https://doi.org/10.3390/RS14112510/S1.

Allen, K., Dupuy, J.M., Gei, M.G., Hulshof, C., Medvigy, D., Pizano, C., Salgado-Negret, B., Smith, C.M., Trierweiler, A., Van Bloem, S.J., Waring, B.G., Xu, X., Powers, J.S., 2017. Will seasonally dry tropical forests be sensitive or resistant to future changes in rainfall regimes? Environ. Res. Lett. 12 (2), 023001. https://doi.org/10.1088/1748-9326/AA5968.

Alvares, C.A., Stape, J.L., Sentelhas, P.C., De Moraes Gonçalves, J.L., Sparovek, G., 2013. Köppen's climate classification map for Brazil. Meteorol. Z. 22 (6), 711–728. https://doi.org/10.1127/0941-2948/2013/0507.

Aragão, L.E.O.C., Anderson, L.O., Fonseca, M.G., Rosan, T.M., Vedovato, L.B., Wagner, F. H., Silva, C.V.J., Silva Junior, C.H.L., Arai, E., Aguiar, A.P., Barlow, J., Berenguer, E., Deeter, M.N., Domingues, L.G., Gatti, L., Gloor, M., Malhi, Y., Marengo, J.A., Miller, J.B., Saatchi, S., 2018. 21st century drought-related fires counteract the decline of Amazon deforestation carbon emissions. Nature Communications 2018 9: 1 9 (1), 1–12. https://doi.org/10.1038/s41467-017-02771-y.

Araujo, E.C.G., Sanquetta, C.R., Dalla Corte, A.P., Pelissari, A.L., Orso, G.A., Silva, T.C., 2023. Global review and state-of-the-art of biomass and carbon stock in the Amazon. J. Environ. Manag. 331, 117251. https://doi.org/10.1016/J.JENVMAN.2023.117251.

Azevedo-Ramos, C., Moutinho, P., 2018. No man's land in the Brazilian Amazon: could undesignated public forests slow Amazon deforestation? Land Use Policy 73, 125–127. https://doi.org/10.1016/J.LANDUSEPOL.2018.01.005.

Barba, J., Poyatos, R., Capooci, M., Vargas, R., 2021. Spatiotemporal variability and origin of CO2 and CH4 tree stem fluxes in an upland forest. Glob. Chang. Biol. 27 (19), 4879–4893. https://doi.org/10.1111/GCB.15783.

Bastos Lima, M.G., Da Costa, K., 2022. Quo vadis, Brazil? Environmental Malgovernance under Bolsonaro and the ambiguous role of the sustainable development goals. Bull. Lat. Am. Res. 41 (4), 508–524. https://doi.org/10.1111/BLAR.13336.

Berry, J., Wolf, A., Campbell, J.E., Baker, I., Blake, N., Blake, D., Denning, A.S., Kawa, S. R., Montzka, S.A., Seibt, U., Stimler, K., Yakir, D., Zhu, Z., 2013. A coupled model of the global cycles of carbonyl sulfide and CO2: A possible new window on the carbon cycle. J. Geophys. Res. Biogeosci. 118 (2), 842–852. https://doi.org/10.1002/JGRG.20068.

Besnard, S., Santoro, M., Cartus, O., Fan, N., Linscheid, N., Nair, R., Weber, U., Koirala, S., Carvalhais, N., 2021. Global sensitivities of forest carbon changes to environmental conditions. Glob. Chang. Biol. 27 (24), 6467–6483. https://doi.org/10.1111/GCB.15877.

Bhattacharyya, S.S., Leite, F.F.G.D., Adeyemi, M.A., Sarker, A.J., Cambareri, G.S., Faverin, C., Tieri, M.P., Castillo-Zacarías, C., Melchor-Martínez, E.M., Iqbal, H.M.N., Parra-Saldívar, R., 2021. A paradigm shift to CO2 sequestration to manage global warming – with the emphasis on developing countries. Sci. Total Environ. 790, 148169. https://doi.org/10.1016/J.SCITOTENV.2021.148169.

Bieluczyk, W., Asselta, F.O., Navroski, D., Gontijo, J.B., Venturini, A.M., Mendes, L.W., Simon, C.P., Camargo, P.B., de Tadini, A.M., Martin-Neto, L., Bendassolli, J.A., Rodrigues, R.R., van der Putten, W.H., Tsai, S.M., 2023. Linking above and belowground carbon sequestration, soil organic matter properties, and soil health in Brazilian Atlantic Forest restoration. J. Environ. Manag. 344, 118573. https://doi.org/10.1016/J.JENVMAN.2023.118573.

Bieluczyk, W., Cherubin, M.R., Cerri, C.E.P., Siqueira-Neto, M., Abdalla-Filho, A.L., Castro, J.I.A., Locatelli, J.L., Tsai, S.M., Camargo, P.B. de, 2024. Greenhouse gas fluxes in brazilian climate-smart agricultural and livestock systems: A systematic and critical overview. J. Clean. Prod. 464, 142782. https://doi.org/10.1016/J.JCLEPRO.2024.142782.

Brazil, 2015. Estratégia Nacional de Implementação da NDC do Brasil. https://antigo.mma.gov.br/component/k2/item/15137-discuss%C3%B5es-para-implementa%C3%A7%C3%A3o-da-ndc-do-brasil.html.

Cabral, O.M.R., Freitas, H.C., Cuadra, S.V., de Andrade, C.A., Ramos, N.P., Grutzmacher, P., Galdos, M., Packer, A.P.C., da Rocha, H.R., Rossi, P., 2020. The sustainability of a sugarcane plantation in Brazil assessed by the eddy covariance fluxes of greenhouse gases. Agric. For. Meteorol. 282–283, 107864. https://doi.org/10.1016/J.AGRFORMET.2019.107864.

Castro, A.O., Chen, J., Zang, C.S., Shekhar, A., Jimenez, J.C., Bhattacharjee, S., Kindu, M., Morales, V.H., Rammig, A., 2020. OCO-2 solar-induced chlorophyll fluorescence variability across ecoregions of the Amazon Basin and the extreme drought effects of El Niño (2015–2016). Remote Sensing *12* (7), 1202. https://doi.org/10.3390/RS12071202.

Cerri, C.C., Moreira, C.S., Alves, P.A., Raucci, G.S., Castigioni, B.D.A., Mello, F.F.C., Cerri, D.G.P., Cerri, C.E.P., 2016. Assessing the carbon footprint of beef cattle in Brazil: a case study with 22 farms in the state of Mato Grosso. J. Clean. Prod. 112, 2593–2600. https://doi.org/10.1016/J.JCLEPRO.2015.10.072.

Cerri, C.E.P., Damian, J.M., Alves, P.A., Cerri, D.G.P., Cherubin, M.R., 2024. On-farm greenhouse gas emissions and soil carbon stocks of a soybean–maize system. Nutr. Cycl. Agroecosyst. 128 (3), 309–324. https://doi.org/10.1007/S10705-024-10356-7.

Climate TRACE, T. R. A. C. E, 2022. Climate TRACE Inventory. https://climatetrace.org/inventory.

Corbeels, M., Marchão, R.L., Neto, M.S., Ferreira, E.G., Madari, B.E., Scopel, E., Brito, O. R., 2016. Evidence of limited carbon sequestration in soils under no-tillage systems in the Cerrado of Brazil. Scientific Reports 2016 6:1 6 (1), 1–8. https://doi.org/10.1038/srep21450.

Crisp, D., Pollock, H., Rosenberg, R., Chapsky, L., Lee, R., Oyafuso, F., Frankenberg, C., Dell, C., Bruegge, C., Doran, G., Eldering, A., Fisher, B., Fu, D., Gunson, M., Mandrake, L., Osterman, G., Schwandner, F., Sun, K., Taylor, T., Wunch, D., 2017. The on-orbit performance of the orbiting carbon Observatory-2 (OCO-2) instrument and its radiometrically calibrated products. Atmos. Meas. Tech. 10 (1), 59–81. https://doi.org/10.5194/AMT-10-59-2017.

Curado, L.F.A., de Paulo, S.R., da Silva, H.J.A., Palácios, R.S., Marques, J.B., de Paulo, I. J.C., Dalmagro, H.J., Rodrigues, T.R., 2024. Effect of biomass burning emission on carbon assimilation over Brazilian Pantanal. Theor. Appl. Climatol. 155 (2), 999–1006. https://doi.org/10.1007/S00704-023-04673-0/FIGURES/7.

da Conceição Bispo, P., Picoli, M.C.A., Marimon, B.S., Marimon Junior, B.H., Peres, C.A., Menor, I.O., Silva, D.E., de Figueiredo Machado, F., Alencar, A.A.C., de Almeida, C. A., Anderson, L.O., Aragão, L.E.O.C., Breunig, F.M., Bustamante, M., Dalagnol, R., Diniz-Filho, J.A.F., Ferreira, L.G., Ferreira, M.E., Fisch, G., Silva-Junior, C.H.L., 2023. Overlooking vegetation loss outside forests imperils the Brazilian Cerrado and other non-forest biomes. Nature Ecology & Evolution 2023 8:1 8 (1), 12–13. https://doi.org/10.1038/s41559-023-02256-w.

da Costa, L.M., de Mendonça, G.C., Araújo Santos, G.A. de, Moraes, J.R. da S.C. de, Colombo, R., Panosso, A.R., La Scala, N., 2023. High spatial resolution solar-induced chlorophyll fluorescence and its relation to rainfall precipitation across Brazilian ecosystems. Environ. Res. 218, 114991. https://doi.org/10.1016/J.ENVRES.2022.114991.

De Azevedo, T.R., Costa, C., Brandão, A., Dos Santos Cremer, M., Piatto, M., Tsai, D.S., Barreto, P., Martins, H., Sales, M., Galuchi, T., Rodrigues, A., Morgado, R., Ferreira, A.L., Barcellos, E., Silva, F., De Freitas Viscondi, G., Dos Santos, K.C., Da Cunha, K.B., Manetti, A., Coluna, I.M.E., Kishinami, R., 2018. SEEG initiative estimates of Brazilian greenhouse gas emissions from 1970 to 2015. Scientific Data 2018 5:1 5 (1), 1–43. https://doi.org/10.1038/sdata.2018.45.

de Figueiredo, E.B., Jayasundara, S., de Oliveira Bordonal, R., Berchielli, T.T., Reis, R.A., Wagner-Riddle, C., La Scala, N., 2017. Greenhouse gas balance and carbon footprint of beef cattle in three contrasting pasture-management systems in Brazil. J. Clean. Prod. 142, 420–431. https://doi.org/10.1016/J.JCLEPRO.2016.03.132.

De Figueiredo, E.B., La Scala, N., 2011. Greenhouse gas balance due to the conversion of sugarcane areas from burned to green harvest in Brazil. Agric. Ecosyst. Environ. 141 (1–2), 77–85. https://doi.org/10.1016/J.AGEE.2011.02.014.

de Mendonça, G.C., Costa, R.C.A., Parras, R., de Oliveira, L.C.M., Abdo, M.T.V.N., Pacheco, F.A.L., Pissarra, T.C.T., 2022. Spatial indicator of priority areas for the implementation of agroforestry systems: an optimization strategy for agricultural landscapes restoration. Sci. Total Environ. 839. https://doi.org/10.1016/J.SCITOTENV.2022.156185.

de Mendonça, G.C., Abdo, M.T.V.N., da Costa, L.M., Costa, R.C.A., Pacheco, F.A.L., Ribeiro, M.C., Zakia, M.J.B., Borma, L.D.S., Pissarra, T.C.T., 2025. Watershed's spatial targeting: Enhancing payments for ecosystem services to scale up agroecosystem restoration through nature-based solutions. Ecosyst. Serv. 71, 101679. https://doi.org/10.1016/j.ecoser.2024.101679.

De Miranda, S. do C., Bustamante, M., Palace, M., Hagen, S., Keller, M., Ferreira, L.G., 2014. Regional variations in biomass distribution in Brazilian savanna woodland. Biotropica 46 (2), 125–138. https://doi.org/10.1111/BTP.12095.

de Souza Medeiros, A., dos Santos, T.C., Maia, S.M.F., 2022. Effect of long-term and soil depth on soil organic carbon stocks after conversion from native vegetation to conventional tillage systems in Brazil. Soil Tillage Res. 219, 105336. https://doi.org/10.1016/J.STILL.2022.105336.

de Souza Rolim, G., de Oliveira Aparecido, L.E., de Souza, P.S., Lamparelli, R.A.C., dos Santos, É.R., 2020. Climate and natural quality of Coffea arabica L. drink. Theor. Appl. Climatol. 141 (1–2), 87–98. https://doi.org/10.1007/S00704-020-03117-3/TABLES/1.

dos Reis, J.B.A., do Vale, H.M.M., Lorenzi, A.S., 2022. Insights into taxonomic diversity and bioprospecting potential of Cerrado endophytic fungi: a review exploring an unique Brazilian biome and methodological limitations. World Journal of Microbiology and Biotechnology 2022 38:11 38 (11), 1–23. https://doi.org/10.1007/S11274-022-03386-2.

Duarte, Y.C.N., Sentelhas, P.C., 2020. NASA/POWER and DailyGridded weather datasets—how good they are for estimating maize yields in Brazil? Int. J. Biometeorol. 64 (3), 319–329. https://doi.org/10.1007/S00484-019-01810-1/FIGURES/4.

Dutra, D.J., Silveira, M.V.F., Mataveli, G., Ferro, P.D., Magalhães, D. da S., de Medeiros, T.P., Anderson, L.O., Aragão, L.E.O.E.C. de, 2024. Challenges for reducing carbon emissions from land-use and land cover change in Brazil. Perspectives in Ecology and Conservation 22 (3), 213–218. https://doi.org/10.1016/J.PECON.2024.04.004.

Fankhauser, S., Smith, S.M., Allen, M., Axelsson, K., Hale, T., Hepburn, C., Kendall, J.M., Khosla, R., Lezaun, J., Mitchell-Larson, E., Obersteiner, M., Rajamani, L., Rickaby, R., Seddon, N., Wetzer, T., 2022. The meaning of net zero and how to get it right. Nat. Clim. Chang. 12 (1), 15–21. https://doi.org/10.1038/S41558-021-01245-W.

Fearnside, P.M., 2012. Brazil's Amazon forest in mitigating global warming: unresolved controversies. Clim. Pol. 12 (1), 70–81. https://doi.org/10.1080/14693062.2011.581571.

Ferreira Barbosa, M.L., Haddad, I., da Silva Nascimento, A.L., Máximo da Silva, G., Moura da Veiga, R., Hoffmann, T.B., Rosane de Souza, A., Dalagnol, R., Susin Streher, A., Souza Pereira, F.R., Oliveira e Cruz de Aragão, L.E., Oighenstein Anderson, L., 2022. Compound impact of land use and extreme climate on the 2020 fire record of the Brazilian Pantanal. Glob. Ecol. Biogeogr. 31 (10), 1960–1975. https://doi.org/10.1111/GEB.13563.

Filonchyk, M., Peterson, M.P., Yan, H., Gusev, A., Zhang, L., He, Y., Yang, S., 2024. Greenhouse gas emissions and reduction strategies for the world's largest greenhouse gas emitters. Sci. Total Environ. 944, 173895. https://doi.org/10.1016/J.SCITOTENV.2024.173895.

Flores, B.M., Montoya, E., Sakschewski, B., Nascimento, N., Staal, A., Betts, R.A., Levis, C., Lapola, D.M., Esquível-Muelbert, A., Jakovac, C., Nobre, C.A., Oliveira, R. S., Borma, L.S., Nian, D., Boers, N., Hecht, S.B., ter Steege, H., Arieira, J., Lucas, I.L., Hirota, M., 2024. Critical transitions in the Amazon forest system. Nature 2024 626: 7999 626 (7999), 555–564. https://doi.org/10.1038/s41586-023-06970-0.

Frankenberg, C., O'Dell, C., Berry, J., Guanter, L., Joiner, J., Köhler, P., Pollock, R., Taylor, T.E., 2014. Prospects for chlorophyll fluorescence remote sensing from the orbiting carbon Observatory-2. Remote Sens. Environ. 147, 1–12. https://doi.org/10.1016/J.RSE.2014.02.007.

Gardon, F.R., Santos, R.F. dos, Rodrigues, R.R., 2020. Brazil's forest restoration, biomass and carbon stocks: A critical review of the knowledge gaps. For. Ecol. Manag. 462, 117972. https://doi.org/10.1016/J.FORECO.2020.117972.

Garofalo, D.F.T., Novaes, R.M.L., Pazianotto, R.A.A., Maciel, V.G., Brandão, M., Shimbo, J.Z., Folegatti-Matsuura, M.I.S., 2022. Land-use change CO2 emissions associated with agricultural products at municipal level in Brazil. J. Clean. Prod. 364, 132549. https://doi.org/10.1016/J.JCLEPRO.2022.132549.

Garrett, R.D., Grabs, J., Cammelli, F., Gollnow, F., Levy, S.A., 2022. Should payments for environmental services be used to implement zero-deforestation supply chain policies? The case of soy in the Brazilian Cerrado. World Dev. 152, 105814. https://doi.org/10.1016/J.WORLDDEV.2022.105814.

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., Crispim, S.P., Neves, R.A.L., 2021. Amazonia as a carbon source linked to deforestation and climate change. Nature 2021 595:7867 595 (7867), 388–393. https://doi.org/10.1038/s41586-021-03629-6.

Gatti, L.V., Cunha, C.L., Marani, L., Cassol, H.L.G., Messias, C.G., Arai, E., Denning, A.S., Soler, L.S., Almeida, C., Setzer, A., Domingues, L.G., Basso, L.S., Miller, J.B., Gloor, M., Correia, C.S.C., Tejada, G., Neves, R.A.L., Rajao, R., Nunes, F., Machado, G.B.M., 2023. Increased Amazon carbon emissions mainly from decline in law enforcement. Nature 2023 621:7978 621 (7978), 318–323. https://doi.org/10.1038/s41586-023-06390-0.

Gomes, L., Schüler, J., Silva, C., Alencar, A., Zimbres, B., Arruda, V., Silva, W.V. da, Souza, E., Shimbo, J., Marimon, B.S., Lenza, E., Fagg, C.W., Miranda, S., Morandi, P. S., Marimon-Junior, B.H., Bustamante, M., 2024. Impacts of fire frequency on net CO2 emissions in the Cerrado savanna vegetation. Fire 7 (8), 280. https://doi.org/10.3390/FIRE7080280/S1.

Heinrich, V.H.A., Dalagnol, R., Cassol, H.L.G., Rosan, T.M., de Almeida, C.T., Silva Junior, C.H.L., Campanharo, W.A., House, J.I., Sitch, S., Hales, T.C., Adami, M., Anderson, L.O., Aragão, L.E.O.C., 2021. Large carbon sink potential of secondary forests in the Brazilian Amazon to mitigate climate change. Nature Communications 2021 12:1 12 (1), 1–11. https://doi.org/10.1038/s41467-021-22050-1.

IPCC, I.P.on C.C., 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), v.1. Cambridge University Press, Cambridge, United Kingdom and New York, NY, US, p. 2214. https://doi.org/10.1017/9781009157896.

Jardim, A.M. da R.F., Morais, J.E.F., de Souza, L.S.B., de Marin, F.R., Moura, M.S.B., de Morellato, L.P.C., Montenegro, A.A. de A., Ometto, J.P.H.B., de Lima, J.L.M.P., Dubeux Júnior, J.C.B., Silva, T.G.F. da, 2023. Sink or carbon source? How the Opuntia cactus agroecosystem interacts in the use of carbon, nutrients and radiation in the Brazilian semi-arid region. J. Hydrol. 625, 130121. https://doi.org/10.1016/J.JHYDROL.2023.130121.

Jiao, W., Chang, Q., Wang, L., 2019. The sensitivity of satellite solar-induced chlorophyll fluorescence to meteorological drought. Earth's Future 7 (5), 558–573. https://doi.org/10.1029/2018EF001087.

Kalamandeen, M., Gloor, E., Mitchard, E., Quincey, D., Ziv, G., Spracklen, D., Spracklen, B., Adami, M., Aragaõ, L.E.O.C., Galbraith, D., 2018. Pervasive rise of small-scale deforestation in Amazonia. Scientific Reports 2018 8:1 8 (1), 1–10. https://doi.org/10.1038/s41598-018-19358-2.

Kayo, C., Kalt, G., Tsunetsugu, Y., Hashimoto, S., Komata, H., Noda, R., Oka, H., 2021. The default methods in the 2019 refinement drastically reduce estimates of global carbon sinks of harvested wood products. Carbon Balance Manag. 16 (1), 1–13. https://doi.org/10.1186/S13021-021-00200-8/TABLES/1.

Lamb, W.F., Gasser, T., Roman-Cuesta, R.M., Grassi, G., Gidden, M.J., Powis, C.M., Geden, O., Nemet, G., Pratama, Y., Riahi, K., Smith, S.M., Steinhauser, J., Vaughan, N.E., Smith, H.B., Minx, J.C., 2024. The carbon dioxide removal gap. Nat. Clim. Chang. 2024, 1–8. https://doi.org/10.1038/s41558-024-01984-6.

Laurance, W.F., Useche, D.C., 2009. Environmental synergisms and extinctions of tropical SpeciesSinergismos Ambientales y Extinciones de Especies Tropicales. Conserv. Biol. 23 (6), 1427–1437. https://doi.org/10.1111/J.1523-1739.2009.01336.X.

Leão, B., Schettini, S., Antônio, L., Jacovine, G., Nolasco, S., Neto, O., Moreira, C., Torres, M.E., José, S., Soares Da Rocha, S., Villanova, P.H., De Magalhães, A., Obolari, M., Paula, M., Rufino, M.X., Le~, B., Ercio Antˆ Onio Gonçalves Jacovine, L., Jos, S., De Magalh~, A., Rufino, X., 2021. Silvopastoral systems: how to use them for carbon neutral milk production? Carbon Management 12 (4), 377–384. https://doi.org/10.1080/17583004.2021.1951843.

Leite-Filho, A.T., Soares-Filho, B.S., Davis, J.L., Abrahão, G.M., Börner, J., 2021. Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. Nature Communications 2021 12:1 12 (1), 1–7. https://doi.org/10.1038/s41467-021-22840-7.

Lima, M.A., Mendes, L.F.R., Mothé, G.A., Linhares, F.G., de Castro, M.P.P., da Silva, M.G., Sthel, M.S., 2020. Renewable energy in reducing greenhouse gas emissions: reaching the goals of the Paris agreement in Brazil. Environmental Development 33, 100504. https://doi.org/10.1016/J.ENVDEV.2020.100504.

Litton, C.M., Raich, J.W., Ryan, M.G., 2007. Carbon allocation in forest ecosystems. Glob. Chang. Biol. 13 (10), 2089–2109. https://doi.org/10.1111/J.1365-2486.2007.01420.X.

Lyra, A. de A., Chou, S.C., Sampaio, G. De O., 2016. Sensitivity of the Amazon biome to high resolution climate change projections. Acta Amazon. 46 (2), 175–188. https://doi.org/10.1590/1809-4392201502225.

Machado, R.B., Aguiar, L.M., Bustamante, M.M., 2024. Why is it so easy to undergo devegetation in the Brazilian Cerrado? Perspectives in Ecology and Conservation 22 (3), 209–212. https://doi.org/10.1016/J.PECON.2024.08.003.

Maciel, V.G., Zortea, R.B., Grillo, I.B., Lie Ugaya, C.M., Einloft, S., Seferin, M., 2016. Greenhouse gases assessment of soybean cultivation steps in southern Brazil. J. Clean. Prod. 131, 747–753. https://doi.org/10.1016/J.JCLEPRO.2016.04.100.

Mendes, K.R., Campos, S., da Silva, L.L., Mutti, P.R., Ferreira, R.R., Medeiros, S.S., Perez-Marin, A.M., Marques, T.V., Ramos, T.M., de Lima Vieira, M.M., Oliveira, C.P., Gonçalves, W.A., Costa, G.B., Antonino, A.C.D., Menezes, R.S.C., Bezerra, B.G., Santos e Silva, C.M., 2020. Seasonal variation in net ecosystem CO2 exchange of a Brazilian seasonally dry tropical forest. Scientific Reports 2020 10:1 10 (1), 1–16. https://doi.org/10.1038/s41598-020-66415-w.

Mohammed, G.H., Colombo, R., Middleton, E.M., Rascher, U., van der Tol, C., Nedbal, L., Goulas, Y., Pérez-Priego, O., Damm, A., Meroni, M., Joiner, J., Cogliati, S., Verhoef, W., Malenovský, Z., Gastellu-Etchegorry, J.P., Miller, J.R., Guanter, L., Moreno, J., Moya, I., Zarco-Tejada, P.J., 2019. Remote sensing of solar-induced chlorophyll fluorescence (SIF) in vegetation: 50 years of progress. Remote Sens. Environ. 231, 111177. https://doi.org/10.1016/J.RSE.2019.04.030.

Moro, M.F., Nic Lughadha, E., de Araújo, F.S., Martins, F.R., 2016. A Phytogeographical Metaanalysis of the semiarid Caatinga domain in Brazil. Bot. Rev. 82 (2), 91–148. https://doi.org/10.1007/S12229-016-9164-Z/TABLES/7.

Myster, R.W., 2016. The physical structure of forests in the Amazon Basin: a review. Bot. Rev. 82 (4), 407–427. https://doi.org/10.1007/S12229-016-9174-X/TABLES/9.

Noojipady, P., Morton, C.D., Macedo, N.M., Victoria, C.D., Huang, C., Gibbs, K.H., Bolfe, L.E., 2017. Forest carbon emissions from cropland expansion in the Brazilian Cerrado biome. Environ. Res. Lett. 12 (2), 025004. https://doi.org/10.1088/1748-9326/AA5986.

Odum, E.P., 1971. Fundamentals of Ecology.

Oliveira, P.P.A., Bernardi, A.C.C., Pezzopane, J.R.M., Bosi, C., Júnior, F.P., Tadini, A.M., Martin-Neto, L., Rodrigues, P.H.M., 2024. Potential of integrated trees-pasture-based systems for GHG emission mitigation and improving soil carbon dynamics in the Atlantic forest biome, southeastern of Brazil. Eur. J. Agron. 158, 127219. https://doi.org/10.1016/J.EJA.2024.127219.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the world's forests. Science 333 (6045), 988–993. https://doi.org/10.1126/SCIENCE.1201609/SUPPL_FILE/PAPV2.PDF.

Parras, R., de Mendonça, G.C., Costa, R.C.A., Pissarra, T.C.T., Valera, C.A., Fernandes, L.F.S., Pacheco, F.A.L., 2020. The configuration of forest cover in Ribeirão Preto: A diagnosis of Brazil's forest code implementation. Sustainability (Switzerland) 12 (14). https://doi.org/10.3390/SU12145686.

Parras, R., de Mendonça, G.C., da Costa, L.M., Rocha, J.R., Costa, R.C.A., Valera, C.A., Fernandes, L.F.S., Pacheco, F.A.L., Pissarra, T.C.T., 2024. Land use footprints and policies in Brazil. Land Use Policy 140, 107121. https://doi.org/10.1016/J.LANDUSEPOL.2024.107121.

Pedruzzi, R., Andreão, W.L., Baek, B.H., Hudke, A.P., Glotfelty, T.W., Dias de Freitas, E., Martins, J.A., Bowden, J.H., Pinto, J.A., Alonso, M.F., de Almeida, Toledo, Abuquerque, T., 2022. Update of land use/land cover and soil texture for Brazil: impact on WRF modeling results over São Paulo. Atmos. Environ. 268, 118760. https://doi.org/10.1016/J.ATMOSENV.2021.118760.

Porcar-Castell, A., Tyystjärvi, E., Atherton, J., Van Der Tol, C., Flexas, J., Pfündel, E.E., Moreno, J., Frankenberg, C., Berry, J.A., 2014. Linking chlorophyll a fluorescence to photosynthesis for remote sensing applications: mechanisms and challenges. J. Exp. Bot. 65 (15), 4065–4095. https://doi.org/10.1093/JXB/ERU191.

R Core Team, 2024. R: A language and environment for statistical ## computing.

Raucci, G.S., Moreira, C.S., Alves, P.A., Mello, F.F.C., Frazão, L.D.A., Cerri, C.E.P., Cerri, C.C., 2015. Greenhouse gas assessment of Brazilian soybean production: a case study of Mato Grosso state. J. Clean. Prod. 96, 418–425. https://doi.org/10.1016/J.JCLEPRO.2014.02.064.

Riahi, K., Bertram, C., Huppmann, D., Rogelj, J., Bosetti, V., Cabardos, A.M., Deppermann, A., Drouet, L., Frank, S., Fricko, O., Fujimori, S., Harmsen, M., Hasegawa, T., Krey, V., Luderer, G., Paroussos, L., Schaeffer, R., Weitzel, M., van der Zwaan, B., Zakeri, B., 2021. Cost and attainability of meeting stringent climate targets without overshoot. Nat. Clim. Chang. 11 (12), 1063–1069. https://doi.org/10.1038/S41558-021-01215-2.

Ribeiro, F.L., Guevara, M., Vázquez-Lule, A., Paula Cunha, A., Zeri, M., Vargas, R., 2021. The impact of drought on soil moisture trends across Brazilian biomes. Nat. Hazards Earth Syst. Sci. 21 (3), 879–892. https://doi.org/10.5194/NHESS-21-879-2021.

Richards, P.D., Myers, R.J., Swinton, S.M., Walker, R.T., 2012. Exchange rates, soybean supply response, and deforestation in South America. Glob. Environ. Chang. 22 (2), 454–462. https://doi.org/10.1016/J.GLOENVCHA.2012.01.004.

Rodrigues, A.A., Macedo, M.N., Silvério, D.V., Maracahipes, L., Coe, M.T., Brando, P.M., Shimbo, J.Z., Rajão, R., Soares-Filho, B., Bustamante, M.M.C., 2022. Cerrado deforestation threatens regional climate and water availability for agriculture and ecosystems. Glob. Chang. Biol. 28 (22), 6807–6822. https://doi.org/10.1111/GCB.16386.

Roesch, L.F.W., Vieira, F.C.B., Pereira, V.A., Schünemann, A.L., Teixeira, I.F., Senna, A.J. T., Stefenon, V.M., 2009. The Brazilian Pampa: A fragile biome. *Diversity 2009, Vol. 1*. Pages 182-198 1 (2), 182–198. https://doi.org/10.3390/D1020182.

Rother, D.C., Romanelli, J.P., Rodrigues, R.R., 2023. Historical trajectory of restoration practice and science across the Brazilian Atlantic Forest. Restor. Ecol. 31 (8). https://doi.org/10.1111/REC.14041.

Ryu, Y., Berry, J.A., Baldocchi, D.D., 2019. What is global photosynthesis? History, uncertainties and opportunities. Remote Sens. Environ. 223, 95–114. https://doi.org/10.1016/J.RSE.2019.01.016.

Santos, C.O. dos, Pinto, A. da S., Santos, M.P. dos, Alves, B.J.R., Neto, M.B.R., Ferreira, L. G., 2024. Livestock intensification and environmental sustainability: an analysis based on pasture management scenarios in the brazilian savanna. J. Environ. Manag. 355, 120473. https://doi.org/10.1016/J.JENVMAN.2024.120473.

Schulz, C., Whitney, B.S., Rossetto, O.C., Neves, D.M., Crabb, L., de Oliveira, E.C., Terra Lima, P.L., Afzal, M., Laing, A.F., de Souza Fernandes, L.C., da Silva, C.A., Steinke, V. A., Torres Steinke, E., Saito, C.H., 2019. Physical, ecological and human dimensions of environmental change in Brazil's Pantanal wetland: synthesis and research agenda. Sci. Total Environ. 687, 1011–1027. https://doi.org/10.1016/J.SCITOTENV.2019.06.023.

Shaari, M.S., Sulong, A., Ridzuan, A.R., Esquivias, M.A., Lau, E., 2024. The carbon conundrum: exploring CO2 emissions, public debt, and environmental policy. Emerging Science Journal 8 (3), 933–947. https://doi.org/10.28991/ESJ-2024-08-03-08.

Shanley, P., Leda, L., 2003. The impacts of Forest degradation on medicinal plant use and implications for health Care in Eastern Amazonia. BioScience 56 (6), 573–584.

Soares, M.O., Bezerra, L.E.A., Copertino, M., Lopes, B.D., Barros, K.V. de S., Rocha-Barreira, C.A., Maia, R.C., Beloto, N., Cotovicz, L.C., 2022. Blue carbon ecosystems in Brazil: overview and an urgent call for conservation and restoration. Front. Mar. Sci. 9, 797411. https://doi.org/10.3389/FMARS.2022.797411/BIBTEX.

Soares-Filho, B., Moutinho, P., Nepstad, D., Anderson, A., Rodrigues, H., Garcia, R., Dietzsch, L., Merry, F., Bowman, M., Hissa, L., Silvestrini, R., Maretti, C., 2010. Role of Brazilian Amazon protected areas in climate change mitigation. Proc. Natl. Acad. Sci. USA 107 (24), 10821–10826. https://doi.org/10.1073/PNAS.0913048107/SUPPL_FILE/ST03.DOCX.

Soterroni, A.C., Império, M., Scarabello, M.C., Seddon, N., Obersteiner, M., Rochedo, P.R. R., Schaeffer, R., Andrade, P.R., Ramos, F.M., Azevedo, T.R., Ometto, J.P.H.B., Havlík, P., Alencar, A.A.C., 2023. Nature-based solutions are critical for putting Brazil on track towards net-zero emissions by 2050. Glob. Chang. Biol. 29 (24), 7085–7101. https://doi.org/10.1111/GCB.16984.

Souza, C.M., Shimbo, J.Z., Rosa, M.R., Parente, L.L., Alencar, A.A., Rudorff, B.F.T., Hasenack, H., Matsumoto, M., Ferreira, L.G., Souza-Filho, P.W.M., de Oliveira, S.W., Rocha, W.F., Fonseca, A.V., Marques, C.B., Diniz, C.G., Costa, D., Monteiro, D., Rosa, E.R., Vélez-Martin, E., Azevedo, T., 2020. Reconstructing three decades of land use and land cover changes in Brazilian biomes with Landsat archive and earth engine. Remote sensing *12* (17), 2735. https://doi.org/10.3390/RS12172735.

Souza, L.E.V., de Fetz, M., Zagatto, B.P., Pinho, N.S., 2022. Violence and illegal deforestation: the crimes of "environmental militias" in the Amazon Forest. Capital. Nat. Social. 33 (2), 5–25. https://doi.org/10.1080/10455752.2021.1980817.

Stinecipher, J.R., Cameron-Smith, P., Kuai, L., Glatthor, N., Höpfner, M., Baker, I., Beer, C., Bowman, K., Lee, M., Miller, S.M., Parazoo, N., Campbell, J.E., 2022. Remotely sensed carbonyl sulfide constrains model estimates of Amazon primary productivity. Geophys. Res. Lett. 49 (9), e2021GL096802. https://doi.org/10.1029/2021GL096802.

Sulla-Menashe, D., Gray, J.M., Abercrombie, S.P., Friedl, M.A., 2019. Hierarchical mapping of annual global land cover 2001 to present: the MODIS collection 6 land cover product. Remote Sens. Environ. 222, 183–194. https://doi.org/10.1016/J.RSE.2018.12.013.

Sun, Y., Frankenberg, C., Jung, M., Joiner, J., Guanter, L., Köhler, P., Magney, T., 2018. Overview of solar-induced chlorophyll fluorescence (SIF) from the orbiting carbon Observatory-2: retrieval, cross-mission comparison, and global monitoring for GPP. Remote Sens. Environ. 209, 808–823. https://doi.org/10.1016/J.RSE.2018.02.016.

Svensson, J., Avashia, V., Boer, R., Chaturvedi, R.K., Cotta, M., Dubeux, C., Sugih Immanuel, G., La Rovere, E.L., Patange, O., Rossita, A., Vishwanathan, S.S., 2024. The AFOLU sector's Role in National Decarbonization: A Comparative Analysis of Low-GHG Development Pathways in Brazil. Climate Policy, India and Indonesia. https://doi.org/10.1080/14693062.2024.2391048.

Titon, B., Gomes, F.R., 2017. Associations of water balance and thermal sensitivity of toads with macroclimatic characteristics of geographical distribution. Comp. Biochem. Physiol. A Mol. Integr. Physiol. 208, 54–60. https://doi.org/10.1016/J.CBPA.2017.03.012.

Turner, A.J., Köhler, P., Magney, T.S., Frankenberg, C., Fung, I., Cohen, R.C., 2021. Extreme events driving year-to-year differences in gross primary productivity across the US. Biogeosciences 18 (24), 6579–6588. https://doi.org/10.5194/BG-18-6579-2021.

Uribe, M.R., Sierra, C.A., Dukes, J.S., 2021. Seasonality of tropical photosynthesis: A pantropical map of correlations with precipitation and radiation and comparison to model outputs. *Journal of geophysical research*. Biogeosciences 126 (11). https://doi.org/10.1029/2020JG006123.

Vaidya, S., Schmidt, M., Rakowski, P., Bonk, N., Verch, G., Augustin, J., Sommer, M., Hoffmann, M., 2021. A novel robotic chamber system allowing to accurately and precisely determining spatio-temporal CO2 flux dynamics of heterogeneous croplands. Agric. For. Meteorol. 296, 108206. https://doi.org/10.1016/J.AGRFORMET.2020.108206.

Vancine, M.H., Muylaert, R.L., Niebuhr, B.B., Oshima, J.E. de F., Tonetti, V., Bernardo, R., De Angelo, C., Rosa, M.R., Grohmann, C.H., Ribeiro, M.C., 2024. The Atlantic Forest of South America: spatiotemporal dynamics of the vegetation and implications for conservation. Biol. Conserv. 291. https://doi.org/10.1016/J.BIOCON.2024.110499.

Viegas, L.M.D., Sales, L., Hipólito, J., Amorim, C., de Pereira, E.J., Ferreira, P., Folta, C., Ferrante, L., Fearnside, P., Malhado, A.C.M., Rocha, C.F.D., Vale, M.M., 2022. We're building it up to burn it down: fire occurrence and fire-related climatic patterns in Brazilian biomes. PeerJ 10, e14276. https://doi.org/10.7717/PEERJ.14276/SUPP-6.

Vitória, A.P., Alves, L.F., Santiago, L.S., 2019. Atlantic forest and leaf traits: an overview. Trees 2019 33:6 33 (6), 1535–1547. https://doi.org/10.1007/S00468-019-01864-Z.

Vourlitis, G.L., Pinto, O.B., Dalmagro, H.J., Zanella, Enrique, de Arruda, P., de Almeida Lobo, F., de Souza Nogueira, J., 2022. Net primary production and ecosystem carbon flux of Brazilian tropical savanna ecosystems from Eddy covariance and inventory methods. *Journal of geophysical research*. Biogeosciences 127 (8), e2021JG006780. https://doi.org/10.1029/2021JG006780.

Xiao, J., Chevallier, F., Gomez, C., Guanter, L., Hicke, J.A., Huete, A.R., Ichii, K., Ni, W., Pang, Y., Rahman, A.F., Sun, G., Yuan, W., Zhang, L., Zhang, X., 2019. Remote sensing of the terrestrial carbon cycle: A review of advances over 50 years. Remote Sens. Environ. 233, 111383. https://doi.org/10.1016/J.RSE.2019.111383.

Xu, L., Saatchi, S.S., Yang, Y., Yu, Y., Pongratz, J., Anthony Bloom, A., Bowman, K., Worden, J., Liu, J., Yin, Y., Domke, G., McRoberts, R.E., Woodall, C., Nabuurs, G.J., De-Miguel, S., Keller, M., Harris, N., Maxwell, S., Schimel, D., 2021. Changes in global terrestrial live biomass over the 21st century. *Science*. Advances 7 (27). https://doi.org/10.1126/SCIADV.ABE9829/SUPPL_FILE/ABE9829_SM.PDF.

Yue, C., Ciais, P., Houghton, R.A., Nassikas, A.A., 2020. Contribution of land use to the interannual variability of the land carbon cycle. Nature Communications 2020 11:1 11 (1), 1–11. https://doi.org/10.1038/s41467-020-16953-8.

Zhu, W., Xie, Z., Zhao, C., Zheng, Z., Qiao, K., Peng, D., Fu, Y.H., 2024. Remote sensing of terrestrial gross primary productivity: a review of advances in theoretical foundation, key parameters and methods. GIScience and Remote Sensing 61 (1). https://doi.org/10.1080/15481603.2024.2318846.

Zimbres, B., Shimbo, J., Lenti, F., Brandão, A., Souza, E., Alencar, A., 2024. Improving estimations of GHG emissions and removals from land use change and forests in Brazil. Environ. Res. Lett. 19 (9), 094024. https://doi.org/10.1088/1748-9326/AD64EA.