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LETTER

Improving estimations of GHG emissions and removals from land use change and forests in Brazil

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Abstract

Brazil ranks fifth in greenhouse gas emissions globally due to land use change. As a signatory to the Paris Agreement, Brazil must periodically report its GHG emissions as well as present mitigation targets set in the Nationally Determined Contribution (NDC). The SEEG Brazil Initiative (Greenhouse Gas Emission and Removal Estimating System) generates independent estimates of GHG emissions and removals since 2013, and in 2020, the estimation method for the land use change sector has been improved. This study aimed to (1) present these methodological advancements, including the spatial allocation of annual emissions and removals due to land use change (LUC) in Brazil at a 30 m spatial scale, and (2) explore the emission and removal patterns observed in Brazil from 1990 to 2019. The method presented here is built upon—but improves—the approach used by Brazil's official National Inventories to estimate GHG emissions and removals. The improvements presented here include exploring emissions to the municipality level and using an annual updated time series of land use and land cover maps. Estimated greenhouse gas emissions from the LUC sector ranged from 687 Mt of CO_2e in 2011 to a peak of 2150 Mt of CO_2e in 2003. In 2010, removals nearly offset gross emissions in the sector, with a net emission of 116 Mt of CO_2e. The trend observed in recent years was an increase in emissions, decreasing Brazil's likelihood of meeting its NDC targets. Emission profiles vary across the country, but in every biome, the conversion of primary native vegetation is the predominant transition type. If Brazil managed to curb deforestation, the total GHG emissions from the land use change sector would decrease by 96%, mitigating around 44% of total emissions.

1. Introduction

The land use change (LUC) sector plays a significant role in generating (and potentially curbing) emissions worldwide. In Brazil, greenhouse gas (GHG) emissions are driven mainly by land use change, with 44% of the total national net emissions caused by deforestation (Brazil 2020). According to the International Panel on Climate Change (IPCC) sixth assessment report (2022), nearly 45% of emissions in the LUC sector worldwide are caused by deforestation. This figure is even more dramatic in Brazil, where 95% of the LUC sector's historic gross emissions were driven by deforestation (Brazil 2020). As a signatory to the Paris Agreement, Brazil must document and report its emissions as part of the national effort to mitigate GHG emissions and meet the global warming targets explicitly set in its Nationally Determined Contribution. According to the original 2015 NDC, later revised in 2023, Brazil committed to reduce its 2005 emission levels by 53.1% in 2030.

National emissions are reported by the Science, Technology, and Innovations Ministry (MCTI) in the periodic National Communications of Brazil to the

United Nations Framework Convention on Climate Change (UNFCCC). Brazil has so far submitted four National Communications in 2004, 2010, 2016, and 2020, where the National Inventories of GHG emissions are reported. In the LUC sector, a network of multidisciplinary researchers is consulted to contribute with the most recent available information on the distribution of native vegetation and land use types in Brazil, as well as the known carbon stocks and removal rates per land cover and land use type. The latest Fourth National Inventory (FNI), released in 2020 (Brazil 2020), updated maps and factors used to calculate emissions and removals over the periods considered (1990–1994, 1994–2002, 2002–2010, and 2010–2016, with an additional period of 2002–2005 for the Amazon biome). A critical limitation of the official method is that the transitions are not annual but mapped over 6–8 year periods. These estimates are annualized using the yearly deforestation rates from official sources as proxies whenever available (e.g. PRODES Amazonia and Cerrado, while for the other biomes, an average rate is assumed for each year according to the PMDBBS[4]). Additionally, Brazil submits Biennial Update Reports (BUR), which aim to provide more recent emission estimates also based on deforestation rates as proxies.

A relevant advancement of the FNI method would be to use the available annual land use and land cover maps from the MapBiomas initiative to map transitions. The MapBiomas initiative generates—and continuously updates—land use and land cover time series maps based on the supervised classification of Landsat imagery at a 30 m spatial resolution (https://mapbiomas.org). The adoption of the MapBiomas time series, or else the implementation of its methodology, which is open to the public, by the National Inventories would allow the monitoring of spatially explicit emission and removal patterns on a yearly basis, which in turn would allow better trend detection, at the scales which policy decision-making is made (e.g. municipalities).

The SEEG Brazil (Greenhouse Gas Emission and Removal Estimating System) is an independent initiative by the Climate Observatory[5], which generates extra-official estimates of GHG emissions and removals annually since 2013 for all sectors of the economy (Energy, Industry, Agriculture, Waste, and Land Use). Information on emissions from all sectors and the full picture of emissions in Brazil can be found in the SEEG platform (seeg.eco.br).

[4] The PMDBBS (Projeto de Monitoramento do Desmatamento dos Biomas Brasileiros por Satélite) was an initiative by the Environment Ministry to map deforestation in all Brazilian biomes beyond the Amazon.

[5] The Climate Observatory (Observatório do Clima, OC) is a coalition of civil society organizations working as an articulation network on issues related to climate change in Brazil.

In earlier collections, the land use sector translated deforestation and secondary vegetation maps into emissions and removal estimates based on emission and removal factors from the National Inventories. However, in 2020, the SEEG Initiative took up the challenge to update its LUC sector method by applying annual emissions and removal calculations based on the MapBiomas land use and land cover maps.

This study thus aimed to describe the current methodological framework of the LUC sector of SEEG Brazil. The calculations are still based on the National Inventories regarding the processes quantified, the equations, carbon stocks, and annual removal rates. We demonstrated how the National GHG Inventories and public policies could benefit from using an annual time series of geographically explicit maps to report GHG emissions and removals, improving the temporal resolution and extending the period of the reported results. A second objective is to explore the emission and removal patterns observed in the LUC sector in Brazil at the level of biomes, regions, and municipalities, seeking to elucidate where action is most urgently needed and to pinpoint opportunities to mitigate climate change.

2. Methods

2.1. Processes quantified

The processes in the land use change sector that generate GHG emissions (Brazil 2020), and which we quantified, are:

(a) **Land use change**: Emissions occur when the land cover type is altered from one land use class to another with lower carbon stock levels. For instance, the conversion of forest to pasture or agriculture generates GHG emissions due to forest carbon stock loss, which is not offset by the carbon stock in these new land use types.

(b) **Emissions from the burning of vegetation residues:** Emissions caused by the burning of residual biomass after deforestation include other types of GHG other than CO_2, such as N_2O and CH_4, which have a greater warming potential.

Besides the processes mentioned above, GHG removals by the natural vegetation were also quantified. They include:

(a) **Removals by primary native vegetation within protected areas**: According to the IPCC—Intergovernmental Panel on Climate Change (2006), all emissions and removals taking place in 'Managed Land' can be taken into account since they constitute areas where human intervention has been applied to perform either production, ecological or social functions.

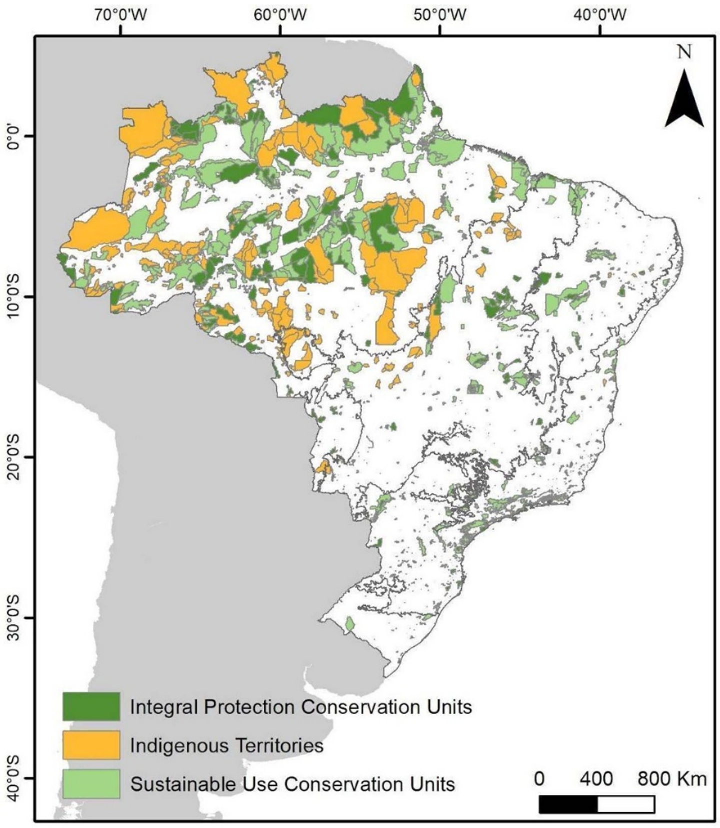

Figure 1. Protected areas (Indigenous Territories and Conservation Units) in Brazil in 2019 used to quantify GHG removals in primary forests/woodlands and grasslands. Gray boundaries within Brazil are the limits of each biome. Spatial information on the location and date of creation for each protected area was compiled based on the Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio) and the Fundação Nacional dos Povos Indígenas (FUNAI) databases.

Removals by the primary native vegetation outside of protected areas, on the other hand, are not quantified. The FNI interpretation includes Conservation Units (UCs, in Portuguese) and Indigenous Territories (TIs, in Portuguese) as Managed Land (figure 1), and carbon removals by primary native vegetation within these protected areas are therefore considered anthropogenic in nature and are quantified (Brazil 2020). To carry out this quantification, we obtained spatial information on the location and date of creation for each protected area from the Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio) and the Fundação Nacional dos Povos Indígenas (FUNAI) official databases. To deal with any existing overlap between and within these layers, we dissolved all polygons with the same creation date (since, for our purpose, it did not matter whether the protected area was an Indigenous Territory or a Conservation Unit), and older polygons had precedence over newer ones.

(b) **Removals by secondary vegetation**: Removals in secondary woodlands and grasslands are quantified over all national territories, according to the FNI (Brazil 2020).

(c) **Removals by other types of land use change**: Removals associated with other types of land use change are also quantified when conversion occurs from one land cover type to another with higher levels of carbon stock (e.g. pasture converted to forest plantation).

2.2. Equations

The IPCC—Intergovernmental Panel on Climate Change (2006), adopted by the Fourth National Inventory (Brazil 2020), proposed emissions or removals by land use change to be calculated using two approaches, depending on the type of transition. In the 'gain-loss' method, net emission/removal from the difference between carbon uptake and loss from the transition by area unit are calculated as follows:

$$\Delta C = \sum_{ijk} Aijk \times (CI - CL)\, ijk$$

where:

ΔC: Annual carbon stock change, in tons per year;

CI, CL: Carbon stock gain (removal) and loss rates from the classes before and after the transition, in tons per hectare per year;

A: Transition area, in hectares;

ijk: Indices corresponding to the type of climate (i), vegetation (j), and management (k).

An example of the gain-loss method would be the yearly carbon removal of secondary vegetation growing in an area (only gain, no loss).

In the 'stock-difference' method, emissions/removals are calculated by the difference in the average stocks at the beginning and the end of the inventoried period:

$$\Delta C = \sum_{ijk} \left(\frac{Ct2 - Ct1}{t2 - t1} \right)$$

where:

ΔC: Carbon stock change, in tons per year;

$Ct1$, $Ct2$: Initial and final carbon stock in the considered period, in tons;

$t1$, $t2$: Year of the beginning and the end of the considered period.

An example would be the conversion of primary native vegetation to pasture, where the carbon stock change would be the carbon stock in that type of primary native vegetation minus the carbon stock in pasture per unit of area. Since SEEG calculates annual changes, time parameters always have a value of 1.

In some cases, these two types of equations are combined when a transition comprises the loss of a known stock at $t1$ and the subsequent 1 year removal rate of the new class after the transition. That is the case when the new class after conversion does not quickly assume a new mean stock value, for instance, as in the loss of native forest for implementing a forest plantation or as in the transition of pasture towards perennial crops.

The equation types applied to all kinds of land use and land cover transitions considered in this study are presented in SM1.

The National Inventories also provide information on the changes in soil carbon stocks based on types of land use conversion. At the time of the present study, we did not have access to the soil carbon stock map upon which these calculations were made, and so far, we do not present estimates concerning changes in the organic carbon stock in the soil. This, however, does not represent a large deficit in our results since the FNI estimates that emissions caused by organic carbon shifts in the soil accounted for approximately 2% of the Brazilian gross emissions (Brazil 2020). Finally, another difference concerning the FNI and SEEG is that the FNI considers emissions related to selective logging in the Amazon, which also comprised about 3% of gross emissions in the most recent period.

2.3. Spatial analyses

The generation of annual transitions forms the basis of the SEEG land use change sector calculations. From SEEG Collection 8 onwards, the method for quantifying these transitions became spatially explicit, taking advantage of the land use and land cover time series available from the MapBiomas Project. In this new approach, the annual land cover maps are stabilized and filtered to consolidate the main transitions each year. Then, the calculations based on stocks and removal rates from the FNI are applied (Brazil 2020). With this new methodological approach, SEEG began producing estimates at the scale of individual municipalities. This paper presents the methods and results of the SEEG Collection 9, launched in 2022, which covered the period from 1990 to 2019, based on MapBiomas Collection 6. Although the MapBiomas time series originally covered a period from 1985 to 2020, we discarded the first 5 years and the last year due to greater uncertainty in the series' first and last years.

The method presented here has five steps, which are fully detailed in SM1: (1) the generation of native vegetation loss (deforestation) and gain (regeneration) masks, according to a moving-window temporal filter (figure 2); (2) the generation of stabilized and parsimonious transition of land use and land cover maps (figure 3); (3) the combination of year-to-year land use and land cover maps to produce transition maps, which store the information from before and after the change; (4) the zonal quantification of the transitions, according to regions of interest (biomes, states, municipalities, and protected areas); and (5) the application of equations with stocks and removal rates per transition type to generate estimates of emissions and removals. The first four steps consist of the spatial treatment of the MapBiomas maps and were conducted in the Google Earth Engine platform. The final step was done using software R. All steps and scripts used to perform the analyses are publicly available on GitHub (2024).

3. Results

The estimated greenhouse gas emissions from the land use change (LUC) sector throughout the analyzed period ranged from 687 Mt of CO_2e in 2011 to a peak of 2150 Mt of CO_2e in 2003 (figure 4). This marked decrease in gross emissions between 2004 and 2011 highlights the successful implementation of a series of policies from the government at the time to halt deforestation in the Amazon, such as greater command and control in the region as well as the soy moratorium. This, together with the creation of protected areas, caused removals to nearly offset emissions in the sector in 2010 (net emissions reached 116 Mt of CO_2e (figures 4 and 5(a)). However, emissions began to rise slightly after that, and the trend observed in the last 3 years of the time series was an increase in emissions (figure 4), mainly due to, once more, increasing deforestation in the Amazon (figure 5(b)).

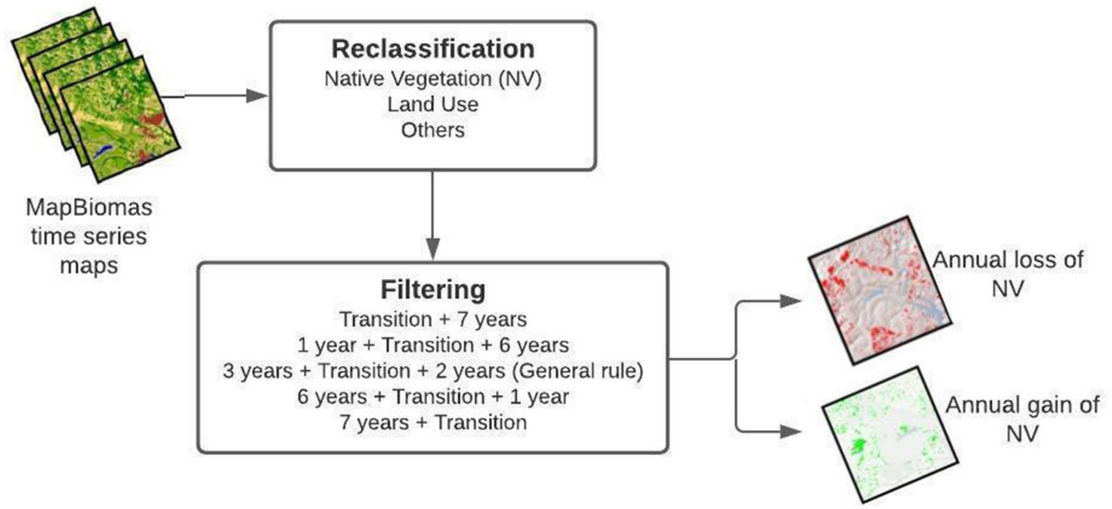

Figure 2. Temporal rules for generating the deforestation mask (native vegetation loss) and the regeneration mask (native vegetation gain) for each year of the MapBiomas time series.

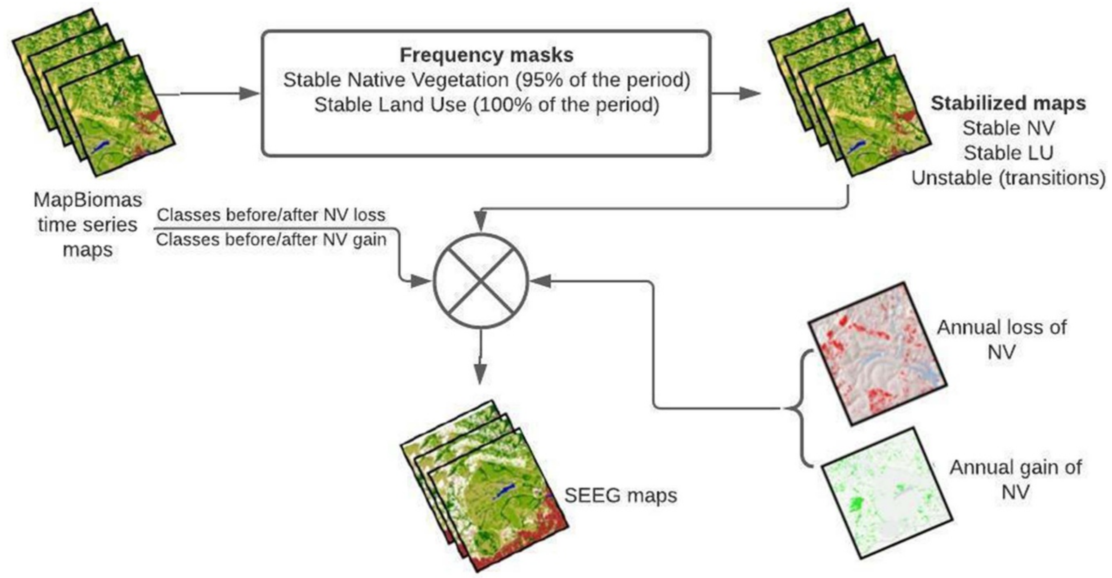

Figure 3. Steps involved in generating stabilized annual land use and land cover maps from the MapBiomas time series, which are subsequently used to quantify the transitions considered in the SEEG land use change sector.

Removals in protected areas showed the most significant increase throughout the time series, not because the vegetation within these areas showed a high removal rate over time, but due to the creation of more conservation units and the demarcation of indigenous reserves between 2003 and 2016. However, this trend practically halted in the last years of the time series, and since then, the observed increase in removals has been due to secondary vegetation growth alone (figure 4, SM2).

Emissions in the Amazon drive the national pattern over time (figure 5). Indeed, in 2019, the amount of emissions caused by land use change in the Amazon exceeds by ten-fold the emissions observed in the Cerrado, the second highest emitter of GHG in Brazil (figure 6), even though the Amazon is only about two times larger than the Cerrado (approximately 4 million hectares in the Amazon versus 2 million hectares in the Cerrado).

The predominant type of transition driving these patterns is still deforestation, namely the conversion of primary forests (which include forests and woodland savannas) into pasture or cropland, except in the Pampa, where the main transition type observed is the conversion of primary non-forest vegetation into pasture/agriculture (SM2, SM3–7). Conversion of primary forests into pasture/agricultural land is widespread in the northern region. The

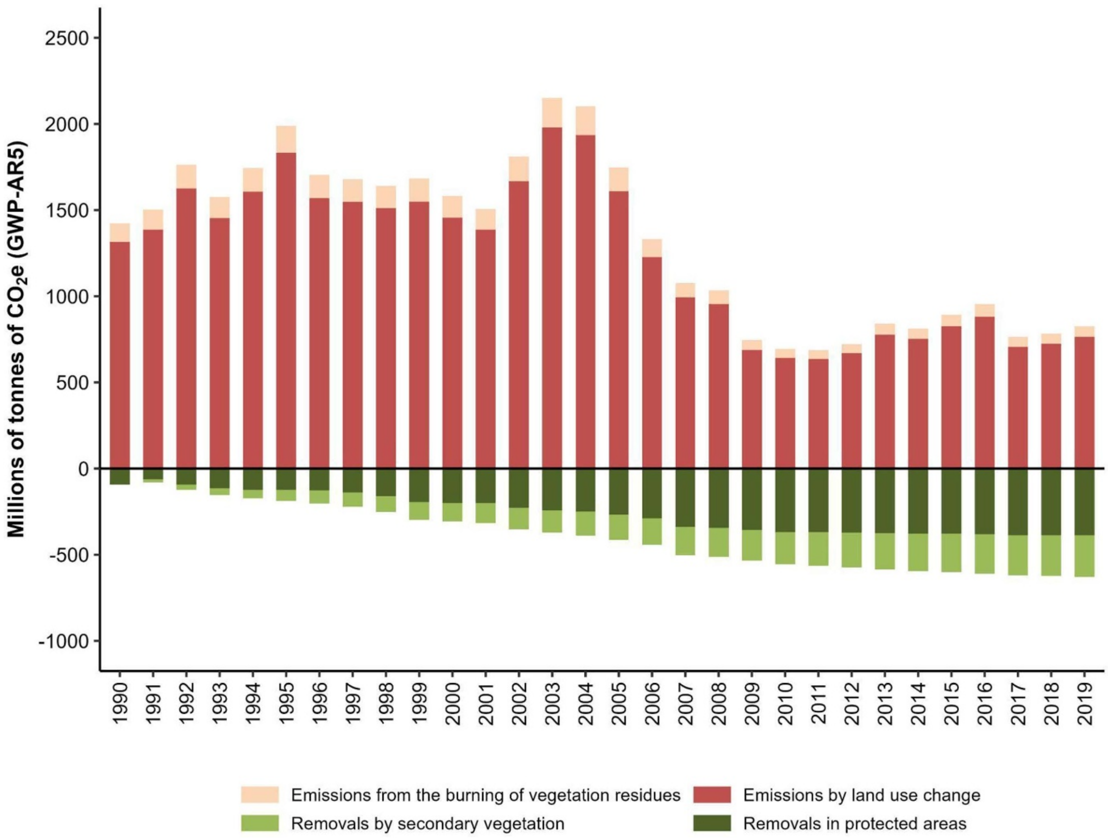

Figure 4. National gross CO_2e emission and removal patterns of land use change in Brazil along the time series and in each of the four categories considered by this study.

highest emitter municipalities are located in the states of Pará, where Altamira and São Félix do Xingu lead the regional (and national) rank, but also include Portel, Novo Progresso, Itaituba, and Pacajá among the ten greatest gross emitters (figure 7, SM3). The states of Rondônia (Porto Velho), Amazonas (Lábrea and Apuí), and Roraima (Caracaraí) also feature in the top ten gross emitter municipalities in the North region (figure 7, SM3).

In the Northeast, all top ten emitter municipalities are in the states of Maranhão or Piauí (SM4), located in the MATOPIBA[6] region, which is the current deforestation frontier of the Cerrado biome. In this region, conversion from primary forest to pasture or agriculture is also the predominant transition type, but elsewhere in the Northeast, conversion categories vary more widely, and the conversion of secondary forests to pasture/agriculture is widespread in the eastern portion of the region, where land use is older and more consolidated (SM4).

In the Midwest region, patterns are driven mainly by Mato Grosso, where conversion of primary forest to pasture or agriculture is also the predominant transition type (SM5). They are followed by transitions between types of pasture and cropland, which take place mainly in Goiás and Mato Grosso do Sul. In central Goiás, the deforestation of secondary forests into pasture or agriculture is also predominant (SM5).

In the Southeast region, the state of Minas Gerais is responsible for the largest gross emissions, which include the conversion of primary forest into pasture/agriculture in the East (SM6). Conversion of secondary forests and between different types of pasture and agricultural areas are also widespread in the region (SM6).

In the South, the states of Rio Grande do Sul and Paraná lead the rank of highest gross emitters due to the conversion of primary non-forest vegetation (natural grasslands) and primary forests into pasture/agriculture, respectively (SM7). The conversion of primary forests into forest plantations is also a large source of emissions in the region (SM7).

The main land use pattern driving removal patterns is the growth of primary forests in protected areas in the Amazon (figure 8 and SM2) and the growth of secondary vegetation in other regions (SM2 and SM8). In Pampa and Pantanal, which are largely composed of natural grasslands, the land

[6] MATOPIBA is a region comprising of the states of Maranhão, Tocantins, Piauí, and Bahia, which concentrates the highest deforestation rates in the Cerrado biome.

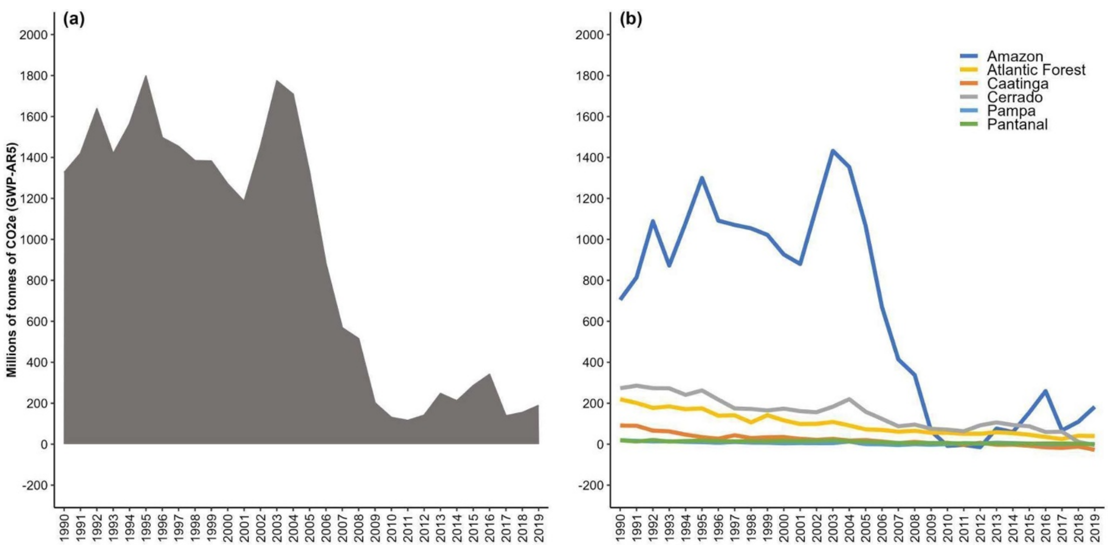

Figure 5. Net CO_2e emissions of the land use change along the time series at the national level (a) and according to the six Brazilian biomes (b).

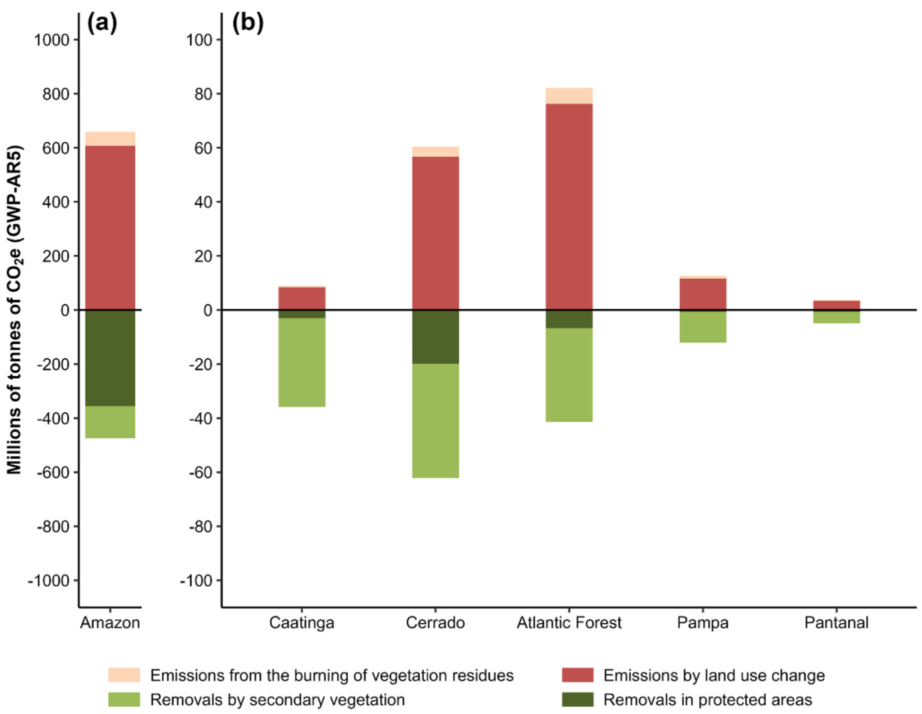

Figure 6. CO_2e emission and removal patterns from land use change in 2019 per Brazilian biome and each of the four categories considered by this study. Patterns for the Amazon (a) are presented separately from the other biomes (b) due to the large difference in scale.

use class (secondary non-forest vegetation) drives removal patterns (SM2).

The national patterns of net CO2e emissions and removals are also dominated by municipalities in the Amazon (figure 9). Those municipalities with the highest amounts of protected areas dominate the removal patterns, presenting negative net emissions. They are located mainly in the state of Amazonas, with a single municipality in the state of Amapá (Laranjal do Jari) and one in Pará (Oriximiná). Net emission patterns are not too different from the patterns of gross emissions, and the municipalities responsible for the largest gross emissions also present the largest net emissions.

Additionally, we compared the main national patterns obtained by our estimations with the official estimates from the Fourth National Inventory (FNI). The Inventory calculates emissions based on three main periods: 1994–2002, 2002–2010, and 2010–2016. An additional period for the Amazon

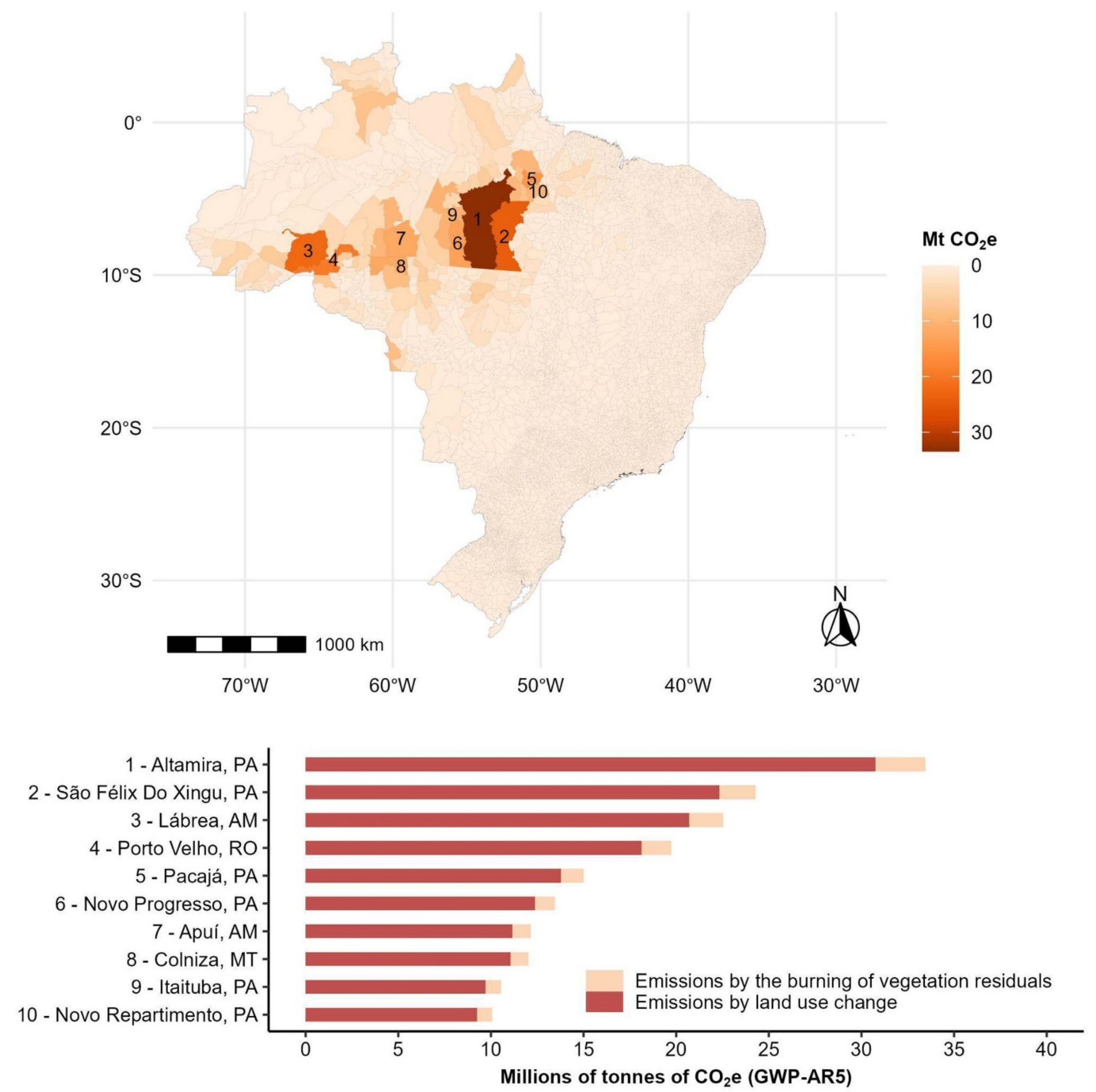

Figure 7. Gross CO_2e emissions by land use change per municipality in Brazil, and the ranking of the ten greatest emitter municipalities in 2019.

biome is reported (2002–2005; SM9). Overall, gross and net emissions are compatible between methods, with the largest difference being observed for the gross emissions of the 2002–2010 period, which are 23% higher according to the FNI (figure 10). The major differences obtained for this period are caused by higher gross emissions observed in the Cerrado, the Caatinga, and Pampa, according to the FNI (SM9). Stark differences could also be observed in the case of Caatinga in the final period (2010–2016).

According to SEEG, the Caatinga has been a net sink of carbon dioxide since 2013 due to decreased deforestation rates, while carbon sequestration in protected areas has grown at a small but continual pace. While gross emissions in the final period for the Caatinga are compatible, the FNI does not capture this continuous increase of removals in protected areas.

While patterns are compatible for the Amazon and Pantanal, in the Atlantic Forest, the FNI estimates are systematically lower than the SEEG estimates (SM9). The FNI is evaluated over large intervals (6–8 years). This may fail to capture transitions occurring within these periods, especially in more highly dynamic regions, such as the Atlantic Forest. On the other hand, the opposite could be observed for the Cerrado, where gross and net emissions were systematically larger in the FNI (SM9).

These differences in gross emissions may be related to land cover and land use mappings between the FNI and the MapBiomas. To help understand them, we compared the areas mapped as deforestation by both initiatives in the compatible periods (1994–2002, 2002–2010, 2010–2016), and we observed relevant spatial differences (SM11). The largest proportions of overlap were observed for the Amazon and the Cerrado biomes, although the FNI

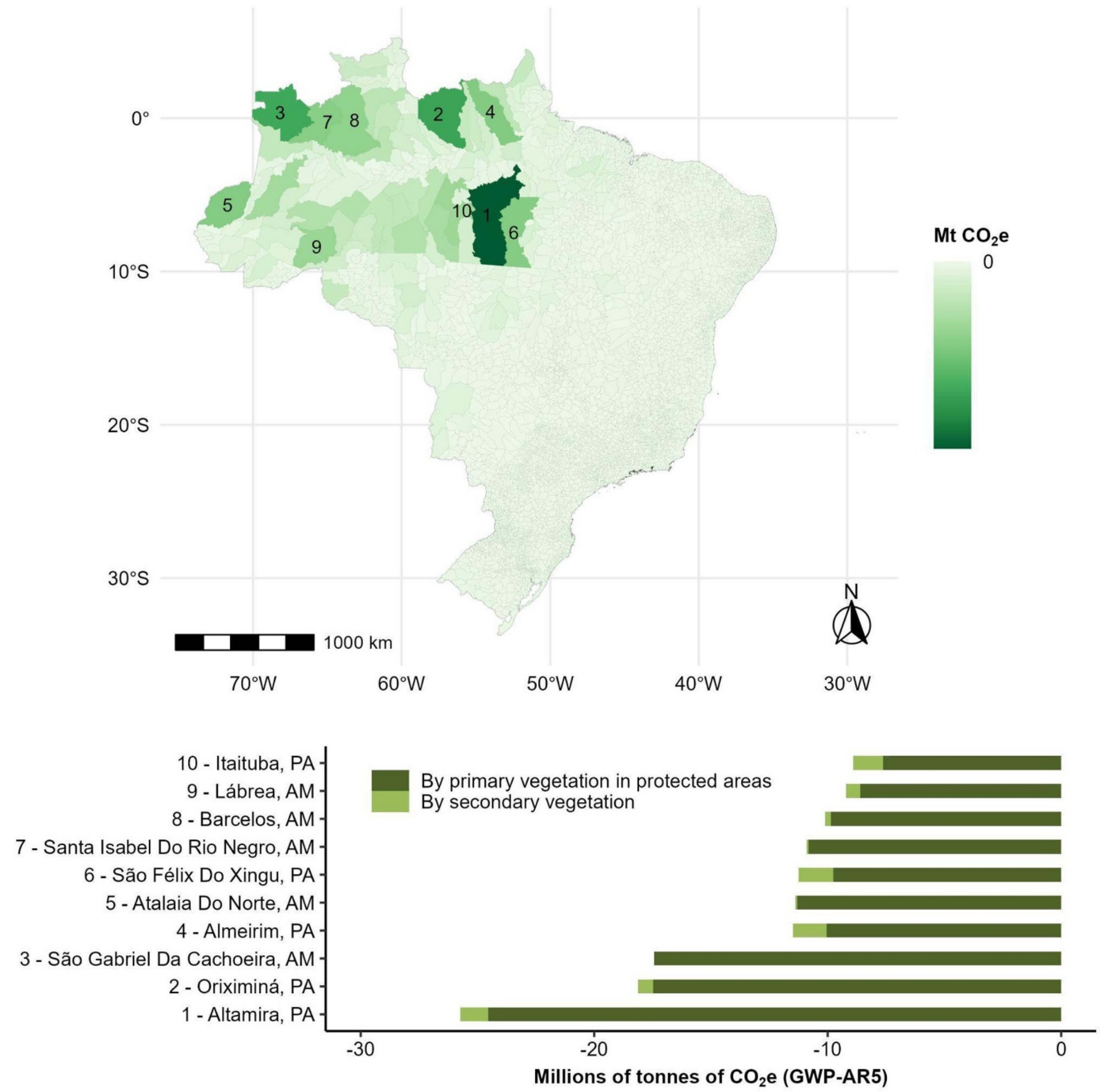

Figure 8. CO_2e removals by land use change per municipality in Brazil, and the ranking of the ten greatest remover municipalities in 2019.

mapped a relevant amount of areas as deforestation in the intermediate period (2002–2010) for the Cerrado, which the SEEG system did not (SM12). Also, stark differences could be observed in the Atlantic Forest, Caatinga, and Pampa, with a larger amount of deforestation being mapped by MapBiomas over the entire period, possibly due to the fact that deforestation polygons in these biomes are generally smaller. Since the FNI mapping is done by visual inspection, many of these small areas can be overlooked by the observer. Caatinga showed the highest inconsistencies between products, and net emissions was only a little below gross emissions according to the FNI, indicating that the FNI may be missing the recovery of the native vegetation in Caatinga mapped by MapBiomas.

In contrast, in Pantanal, more deforestation areas have been classified by the FNI, especially in the intermediate period as well (SM11). This may be due to the fact that much of the areas classified as pasture in Pantanal is actually native pastureland (classified by MapBiomas as natural grasslands), and the FNI might have interpreted these areas as conversion to exotic pastures (pers. comm.). Finally, when considering the entire period analyzed by the FNI (1994–2016), the proportion of overlap was greater, indicating that some of the differences must be temporal (SM12), possibly due to adjustments made by the FNI over past maps to correct some of the errors found in a later mapping effort (pers. comm.).

Finally, we conducted an accuracy analysis based on the validation dataset used by the MapBiomas initiative to generate their statistics of accuracy. This dataset consists of 85 000 independent validation points collected and visually classified by experts over Landsat satellite images for each year of the time series. The accuracy results of the FNI land cover and land use maps showed overall lower global accuracies

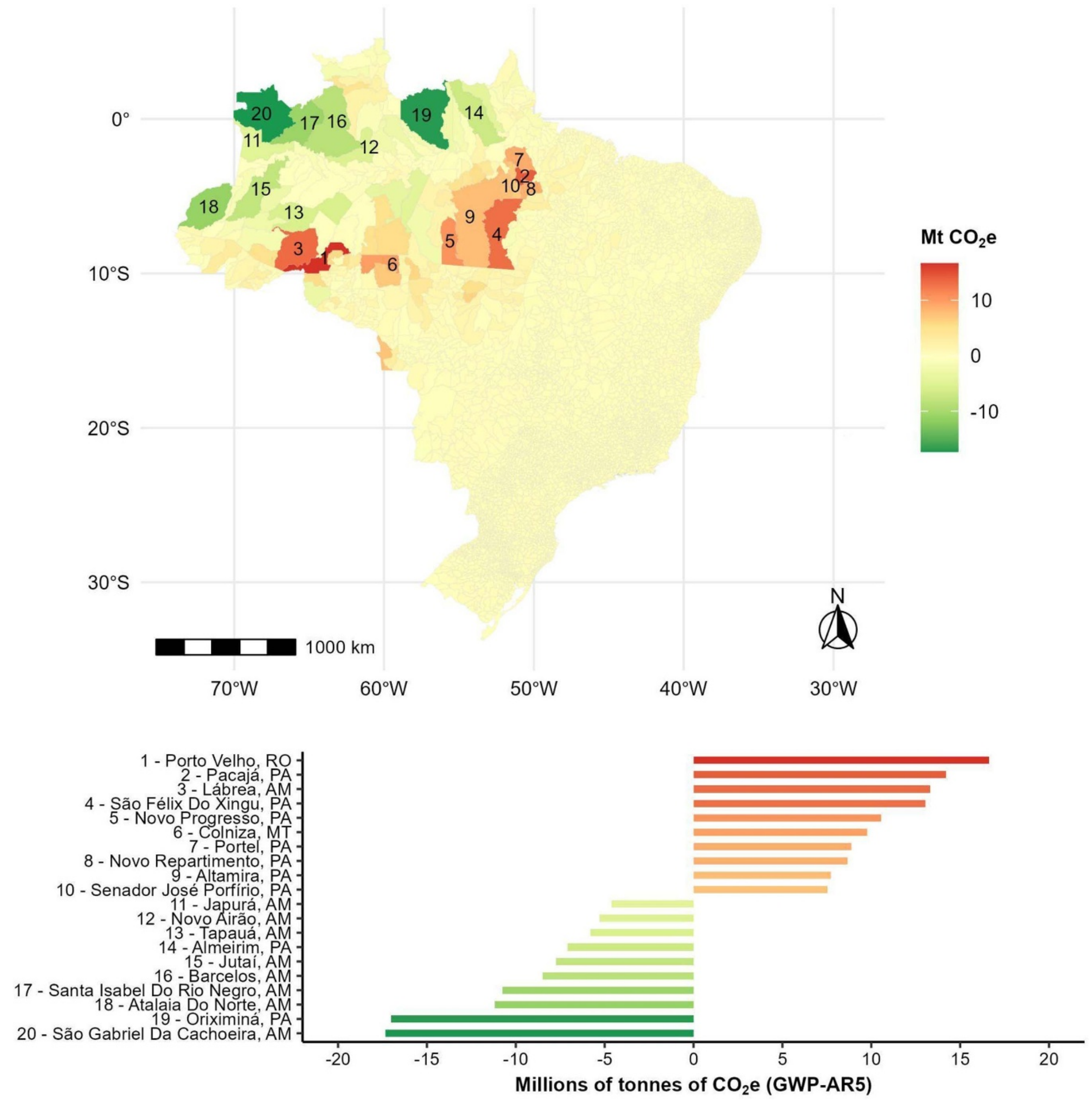

Figure 9. Net CO_2e emissions/removals of land use change per municipality in Brazil, and the ranking of the ten greatest net emitter and net remover municipalities in 2019.

in the FNI than in the MapBiomas Collection 6, especially for the Pantanal and Pampa biomes (table 1).

4. Discussion

4.1. Advancements of the SEEG method for the land use change sector

The method used by the present study to estimate emissions and removals of GHG associated with land use change (LUC) is still based on the method of the Brazilian National Communications by the MCTI but improves upon it by taking the opportunity provided by the MapBiomas initiative to quantify transitions occurring annually from 1990 to 2019 and spatially, allocating the estimates to the level of municipalities. Higher accuracy maps, such as those provided by the MapBiomas initiative, are in itself an improvement since the supervised land cover mapping by each National Communication is not consistent over time in terms of methodology and is subject to the effect of the observer. Differences in the interpretation of deforestation events and, moreover, corrections conducted over earlier maps between one mapping effort and another may cause temporal inconsistencies between periods.

The stabilization step is crucial for obtaining relevant and non-spurious transitions and reducing uncertainty since the MapBiomas annual maps are temporally independent. Global accuracy of the land use and land cover maps of MapBiomas Collection 6 is the highest between available products (table 1). Moreover, our method can be improved to produce spatially explicit emission and removal estimates based on the transitions at the greatest resolution possible from the land use and land cover maps (30 m). With this data available, a user-oriented platform can be built where estimates of emissions and removals

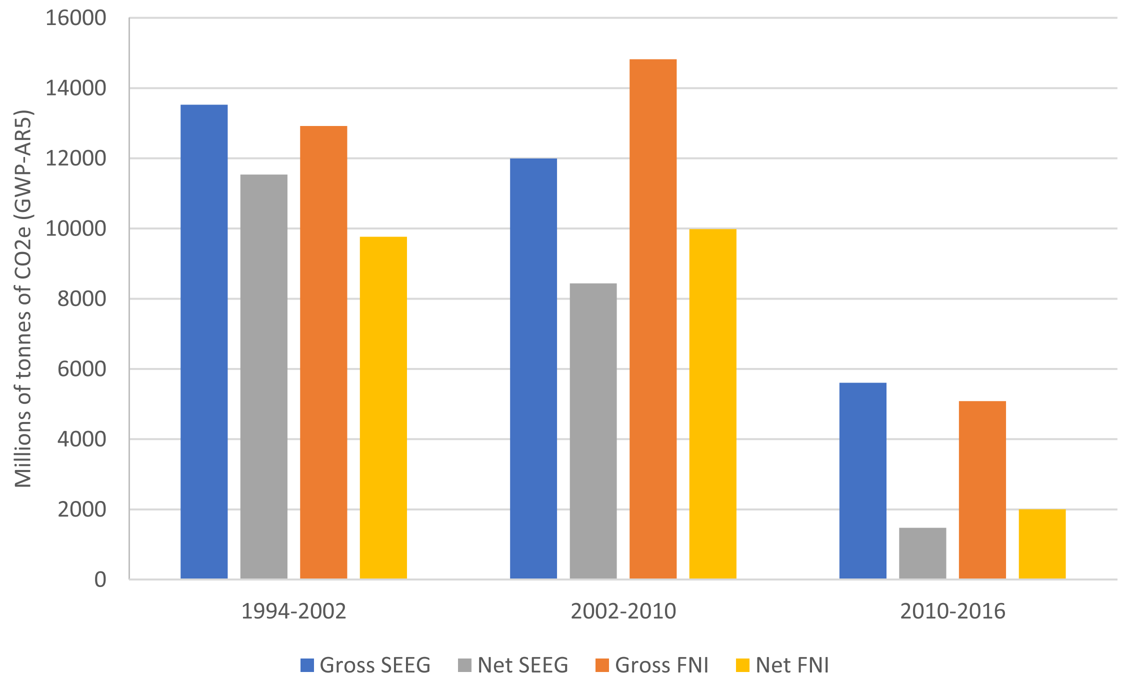

Figure 10. Comparison of the gross and net CO_2e emissions of Brazil's land use change sector estimated by the SEEG and the Fourth National Inventory in the periods analyzed by the Inventory.

Table 1. Average accuracy (%) of the FNI and MapBiomas land cover and land use mapping (global and per biome), based on 85 000 independent validation points visually inspected by experts.

	FNI	MapBiomas Collection 6
Amazon	87.0	96.6
Caatinga	69.0	75.0
Cerrado	63.0	74.9
Atlantic Forest	65.0	85.5
Pampa	23.0	84.8
Pantanal	48.0	73.5
Global	**72.0**	**87.4**

at any spatial region of interest can be provided. This will require the generation of an algorithm to apply the calculations directly over the transition maps. Also, with these advancements, an error propagation approach would be possible, considering the error of the land use and land cover maps and the error from carbon stock maps used. As it stands, the carbon stock map from the FNI does not provide error estimates.

In any case, as it currently stands, the spatial level of detail provided by the SEEG collection is suitable for management decision-making, providing detailed estimation of transition types for all of the 5570 Brazilian municipalities. This way, as well as informing potential improvements for the National Inventories to come, we provide data and methods that can potentially form the basis of local inventory efforts. Specific municipalities interested in generating a local profile of emissions can use the SEEG system to explore patterns and methods, save time and resources, further improve their local reporting, and develop strategies for their emission mitigation actions.

However, a source of uncertainty to both the SEEG and the FNI methods is related to carbon stocks. Total biomass stocks are based on native vegetation types, either single values obtained from the literature or mean values from a continuous biomass map, as in the case of the Amazon biome. Also, biomass stocks are based on single potential (past) biomass maps. A possible, very interesting development would be to generate dynamic bookkeeping biomass maps for each year, which would also take into consideration the loss of biomass stock due to less conspicuous degradation events (e.g. fire, selective logging, edge effects) as well as stock gains in both primary and secondary forests. The existence of such a monitoring system would render average emission and removal factors unnecessary. It would be a major advancement in terms of the level of detail and accuracy of the country's GHG emissions and removals.

4.2. Emission and removal patterns

Emission profiles vary widely across the country, but in every biome, the conversion of primary native vegetation (forest or non-forest vegetation) is the predominant transition type driving emissions. Especially in the Amazon, where deforestation rates had been increasing up to 2021 (10 851 km^2 in 2020 and 13 235 km^2 in 2021, according to PRODES), emissions shape the national patterns. In other regions, other types of transitions are predominant, but the conversion of native vegetation to farming is always the leading transition. It is necessary to highlight the conversion of primary vegetation in the MATOPIBA region in the northern Cerrado biome (Northeast region). This is one of Brazil's most important deforestation frontiers, showing high conversion rates of the biologically richest savanna in the world. The Cerrado is a global hotspot due to its great biodiversity as well as to the current anthropogenic pressure it faces (Mittermeier *et al* 2011, Strassburg *et al* 2017).

In more consolidated regions of Brazil, such as the coastal regions, covered mainly by the Atlantic Forest, conversion patterns driving emissions are mainly caused by the loss of secondary vegetation, an already well-discussed issue in the biome (Rosa *et al* 2021). The growth of secondary vegetation also drives removal patterns. In these regions, the preservation of secondary vegetation areas is an asset for reaching the forest restoration goal of 16 million hectares of restored native vegetation, as mentioned in the Brazilian NDC. In the South, it is remarkable that the conversion of primary forests is the predominant type of transition in areas covered by the Atlantic Forest since the region is also more consolidated regarding historical land use. Similarly, in the Pampa biome, in the state of Rio Grande do Sul, the loss of primary non-forest vegetation (natural grasslands) is also noteworthy. We defend that the conservation of these areas of primary vegetation must be a priority, both in the Atlantic Forest and the Pampa.

The current method counts removals by primary forest within protected areas as a human-driven GHG removal (IPCC 2006). In this sense, removals in protected areas in the Amazon also drive the national patterns since large conservation units and indigenous territories contain large tracts of primary forest.

4.3. Caveats and considerations

Some caveats of the FNI and the method proposed here involve including removals of primary vegetation in protected areas as anthropogenic removals. When a tract of primary forest is reclassified as a new protected area, the carbon accounting system starts to register both its emissions and removals, while earlier (as non-managed land) removals were not counted. Since in these areas, removals are more prominent than emissions, this gives the impression that large amount of GHGs have been abated, when, in reality and in absolute terms, very little has changed.

Added to that, removal rates by the primary vegetation may be overestimated. On one hand, studies that indicate a dynamic equilibrium of the carbon stock in primary vegetation in pristine conditions (Fearnside 1996, Vieira *et al* 2004, Pyle *et al* 2008, Malhi *et al* 2015, Brando *et al* 2019) so that removal rates in these forests would be null. On the other hand, and more concerning, high rates of forest degradation and deforestation are being detected within protected areas in the Amazon, either by fire, selective logging, mining activities, or climate change, and forests that were previously major carbon sinks are now becoming sources of GHG (Brando *et al* 2019, Gatti *et al* 2021, Heinrich *et al* 2023, Lapola *et al* 2023). In that case, the method adopted by the FNI (and here) is most likely overestimating carbon uptake and the role of creating protected areas to mitigate the loss of carbon stocks due to land use change. That is the main reason why we choose to communicate results in terms of gross emissions and gross removals rather than net emissions. Should only net emissions be discussed, the responsibility of Brazil and individual states and municipalities in mitigating emissions in the land use change sector would be minimal, without any incentive to curb deforestation.

Another important challenge that we strongly suggest should be taken up by the National Inventories, is the need to directly consider emissions from degradation, especially by wildfire. Fire is a major driver of degradation in Brazil, especially in the Amazon (Lapola *et al* 2023), which is not adapted to the natural occurrence of fire, differently from other biomes such as Cerrado and Caatinga (Miranda *et al* 2010). The FNI does not estimate these emissions, mainly due to a lack of information on the behavior of burned native vegetation in terms of post-fire recovery and mortality. The SEEG system just recently began a modeling exercise, yet to be published, to fill this gap (which can be found in the SEEG system platform, under the category of emissions 'Not Considered in the Inventory [NCI]') and provided some concerning preliminary results, indicating that fire in Brazil could increase net emissions by 20% in average over the time series. The incorporation of these components by the FNI—and then by SEEG—would thus give a bigger picture of emissions taking place in the country.

4.4. The current policy situation

Deforestation in Brazil has been shown to be a mainly illegal activity. Over 98% of deforestation polygons detected do not have an environmental license or overlap with existing protected areas, as shown by the MapBiomas Alerta annual deforestation report (MapBiomas 2021). Today, land grabbing is the main driver of deforestation in the Amazon, where around 33% of deforestation in 2021 was located on public land (Alencar *et al* 2021). Also, high deforestation rates are being observed even within protected areas and indigenous territories (Conceição *et al* 2021, Mataveli *et al* 2022). In terms of mitigation, the most straightforward recommendation is that the Brazilian environmental legislation be reinforced, and illegal deforestation should be stopped altogether (Coelho *et al* 2022). If all deforestation in Brazil were successfully curbed, Brazil would emit 96% less GHG in the LUC sector, representing 44% less GHG overall.

Banning all illegal deforestation is proposed in the first Brazilian NDC, as well as restoring 16 million hectares by 2030. The current patterns of emissions and removals observed in this study show that this is possible. Brazil saw its deforestation rates drop starkly between 2005 and 2010, and gross emissions were almost offset by removals in protected areas in 2010. Carbon neutrality in the LUC sector is thus not a far-fetched target but requires political will. Deforestation rates in the Amazon in 2020 exceeded 10 000 km^2 (PRODES Amazônia), far above the 3925 km^2 yr^{-1} predicted in the National Policy on Climate Change (Climate Observatory 2020). The IPCC's sixth annual report (2022) admonished that weak institutions and insecure land rights are major hindrances to curbing deforestation trends in developing countries. Brazil possesses strong institutions and environmental agencies (e.g. IBAMA), but their work must be backed by political will.

There has been, however, little incentive for environmental policies to be complied with in Brazil since the last administration, which governed between 2018 and 2022, has made minor efforts in that sense and even signals support and engagement in legislation propositions that relax the environmental regulations in place (Coelho-Junior *et al* 2022). Moreover, the new NDC presented by Brazil in 2023 has decreased the level of ambition in relation to the previous NDC, which is in clear violation of the terms of the Paris Agreement, which states that subsequent NDCs should only increase their levels of ambition. Considering the current NDC, Brazil could easily meet its targets without significantly changing its current deforestation rates, which are sky-high. Indeed, the Climate Action Tracker has classified Brazilian ambitions as 'insufficient,' which means that if every country adopted the same level of ambition as Brazil, the world would see an increase in temperature between 2 °C to 3 °C by the end of the century.

In this context, ranking municipalities according to their emission patterns can point out where the problem mainly lies and exert pressure on each of these municipalities to act despite the federal government in the face of such information made available to the public. But more than exposing individual municipalities, the SEEG system's goal is propositional, seeking to help discuss possible solutions. Solutions include actions that can be taken on by the municipal public sector, but also by the private sector, and that can enhance carbon removal (e.g. local plans for ecological restoration of degraded areas and implementation of payments for ecological services) or reduce emissions (strengthen mechanisms of environmental enforcement and the local implementation of green fiscal incentives). A guide of potential public policy solutions for emission mitigation is available on the SEEG website (https://plataforma.seeg.eco.br/solutions/), and the document is an ongoing collaborative effort.

5. Conclusion

This study demonstrated the importance and great potential of Brazil to generate and report annual emission and removal estimates for the LUC sector, using available time series land use and land cover maps. With the approach presented here, three main limitations of the National Inventories can be overcome with: (i) the annualization of estimates without resorting to proxies; (ii) a more extended and up-to-date period reported, without the current 4 year gap between the last map produced and the present; and (iii) avoiding missing emissions and removal patterns within the analyzed periods, which are masked when comparing land use and land cover maps over a long time-interval. The presentation and discussion of results at a spatially disaggregated scale, at the level of municipalities, is also an advancement of the current method.

After highlighting the main challenges and caveats of the current method, which mainly relate to the implications of considering removals in protected areas as one of the mitigation strategies of net emissions and the lack of emission estimates from degradation, we discussed how Brazil has been missing a major opportunity to mitigate nearly half of its emissions by not controlling deforestation. Curbing deforestation, mainly of primary vegetation, has been successfully done in the Amazon in past decades, and the current administration has signaled a commitment to more proactive environmental policies and climate change mitigation actions. Expectations are high, and the Brazilian society should remain engaged and vigilant.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/SEEG-Brazil/SEEG_MUT.

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