CARBON BALANCE OF LAND USE, LAND-USE CHANGE AND FORESTRY (LULUCF) IN THE BRAZILIAN CHACO

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ABSTRACT – In Brazil, the Steppe Savanna and associated vegetation types, typical of the Chaco, are in the Pantanal biome. Land use in this region has caused the suppression of natural vegetation and the emission of greenhouse gases. The knowledge of the phytophysiognomies of the Chaco and its importance for the mitigation and adaptation to climate change can contribute to conservation and protection policies in this region, including specific public policies to support the sustainable use of biodiversity and carbon stock (C). In this work, we present an estimate of the balance between CO_2 emissions and removals associated with land use and land cover changes for the Brazilian Chaco, considering the annual average of C loss or gain in living biomass and dead organic matter in three different periods: 1990 to 2000, 2000 to 2010 and 2010 to 2019. The methodology followed the one recommended by the Fourth National Communication of Brazil to the United Nations Framework Convention on Climate Change, with adaptations. The results show that the natural vegetation of the Brazilian Chaco has been replaced by pasture throughout the studied period (1990-2019). The Savanna Formations had the greatest reduction in area in this period. The balance points to a net emission of 0.12, 0.05, and 0.03 $MgCO_2$ ha^{-1} $year^{-1}$, respectively, in 1990-2000, 2000-2010, and 2010-2019. CO_2 removals predominate especially in the Kadiweu Indigenous Land, and emissions prevail in the Chaco South region.

Keywords: Net GHG emissions; Forest; Pantanal.

BALANÇO DE CARBONO DEVIDO AO USO DA TERRA, MUDANÇA DO USO DA TERRA E FLORESTAS NO CHACO BRASILEIRO

RESUMO – No Brasil, a Savana Estépica e formações associadas, típicas do Chaco, encontram-se inseridas no bioma Pantanal. O uso da terra nessa região tem provocado a supressão da vegetação natural e a emissão de gases de efeito estufa. O conhecimento das fitosionomias do Chaco e de sua importância para a mitigação e adaptação às mudanças climáticas pode contribuir para políticas de conservação e proteção dessa região, incluindo políticas públicas específicas que apoiem o uso sustentável da biodiversidade e do estoque de carbono (C). No presente trabalho é apresentada a estimativa do balanço de CO_2 devido a mudanças no uso da terra para o Chaco brasileiro, considerando a média anual das emissões e remoções relativas às mudanças dos estoques de C na biomassa viva e matéria orgânica morta, em três diferentes períodos: 1990 a 2000; 2000 a 2010 e 2010 a 2019. A metodologia seguiu a preconizada pelo Quarta Comunicação Nacional do Brasil à Convenção-Quadro das Nações Unidas sobre Mudança do Clima, com adaptações. Os resultados mostram que a vegetação natural do Chaco brasileiro vem sendo substituída por pastagem ao longo do período estudado (1990-2019). A Formação Savânica teve a maior redução em área nesse período. O balanço aponta para emissões líquidas de 0,12, 0,05 e 0,03 $MgCO_2$ ha^{-1} ano^{-1}, respectivamente, nos períodos 1990-2000, 2000-2010 e 2010-2019. As remoções de CO_2 predominam especialmente na Terra Indígena Kadiwéu, e as emissões, no sul da região.

Palavras-Chave: Emissões líquidas de gases de efeito estufa; Floresta; Pantanal.

1. INTRODUCTION

In times of climate change and rising global temperatures, governments and the private sector have prioritized controlling greenhouse gas emissions. The impacts of climate change are becoming increasingly complex and difficult to manage, and multiple climatic factors interact with each other and non-climatic factors, creating cascading effects (Lawrence et al., 2020).

Land use dynamics is an important vector of regional and global climate regulation. Vegetation and soil function as a sink for greenhouse gases (GHG), removing and storing carbon (C) in the biomass, and they also function as a source of GHG due to land use changes (IPCC, 2006). The role of land use, land use change and forestry (LULUCF) related activities in mitigating climate change has long been recognized (IPCC, 2019).

The world has a total forest area of 31 percent of the total land area. The total carbon stock in forests decreased from 668 gigatonnes in 1990 to 662 gigatonnes in 2020 (FAO, 2020). Forest carbon source-sink dynamics and the total amount of carbon stored vary regionally and are heavily influenced by human land use. These drivers' relative influence and interaction effects vary geographically (Hurteau, 2021). Considering that the pattern of C removal by forests and its release as a result of deforestation and degradation are significant factors in the global C balance (Zhao et al., 2019; Friedlingstein et al., 2020; Kruid et al., 2021), restoring and preserving forest environments are important strategies for climate regulation.

Brazil has the second largest forest area, with 12% of the world's forests (FAO, 2020). Deforestation, fires, the expansion of the agricultural frontier, and the absence of protected areas have heavily threatened some regions of the country. The LULUCF sector was responsible for 24% of net emissions in CO_2 equivalent (GWP-AR5) in 2020, even though it is the only sector responsible for CO_2 removal considered when evaluating national emissions (SEEG, 2022a).

The country has mantained a national structure for fulfilling the commitments related to climate change since it signed the United Nations Framework Convention on Climate Change in 1992. As part of these commitments, Brazil prepared four National Inventories of Anthropogenic Emissions and Removals of Greenhouse Gases not Controlled by the Montreal Protocol, registering and reporting GHG net emissions. The Fourth National Inventory (Brasil, 2021a) presents the annual net emissions from 1990 to 2016, following the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (IPCC, 2006)

The Greenhouse Gas Emissions and Removals Estimation System (SEEG, acronym in Portuguese), an initiative of the Climate Observatory (a coalition of Brazilian civil society organizations to discuss climate change), also performs annual estimates for all sectors of the National Inventory, using a methodology based on the IPCC and the National Inventories. It publishes analytical documents on the evolution of emissions, as well as the data sources and methodologies adopted. In its eighth version, emissions and removals from 1990 to 2019 from the land use change sector and forests were estimated (Albuquerque et al., 2020).

LULUCF is quite diverse among the six Brazilian biomes. The Pantanal biome, recognized as one of the most important wetlands on the planet, covering the states of Mato Grosso and Mato Grosso do Sul, is under high pressure due to land use change. Tomas et al. (2019) report that the most significant change in land use in the Pantanal in recent years has been caused by the intensification of traditional extensive livestock farming to increase productivity. According to Miranda et al. (2018), the intensification of this activity replaced the natural forest with exotic grasses.

Among the phytophisiognomies of the Pantanal, there are those associated with the Steppe Savanna, which are identified as a separate biome, the Chaco, in Argentina, Bolivia, and Paraguay. In Brazil, the Steppe Savanna and associated vegetation types occur only in the South of Pantanal, located in the Southeast of Mato Grosso do Sul state (Silva and Carlini, 2015). Despite the rich biodiversity of the fauna and flora of the Brazilian Chaco, the lack of public policies for planning land use in this region has been causing environmental degradation, deforestation, fires, and the fragmentation of natural vegetation (Silva et al., 2011a).

To reverse this situation, we must understand the land use dynamics in the Brazilian Chaco, and, in this context, it is important to estimate and spatialize the annual balance between anthropogenic GHG emissions and removals due to LULUCF. In this work, we present an estimate of the balance between CO_2 emissions and removals associated with land use and land cover changes for the Brazilian Chaco, considering the annual average of C loss or gain in living biomass and dead organic matter in three different periods: 1990 to 2000, 2000 to 2010 and 2010 to 2019. The methodology followed that the Fourth National Communication of Brazil recommended to the United Nations Framework Convention on Climate Change, with adaptations.

The result of this balance may contribute to the knowledge of the phytophysiognomies of the Chaco and its potential for the mitigation and adaptation to climate change and result in the proposition of conservation and protection policies of this region. It may also contribute to the recognition of Chaco as a biome, including specific public policies that support the conservation and sustainable use of biodiversity and the C stock.

2. MATERIAL E METHODS

2.1. Study area

The extent of the Brazilian Chaco area is controversial and open to discussion. However, its delimitation is important for planning, development, conservation purposes, and even for recognizing the biome nationally. To this end, a first approximation was proposed, whose limit will be used in this work (Figure 1), based on regional mapping of vegetation (Mato Grosso do Sul, 1989; Brasil, 1997; Silva et al., 2011b, c) and on field surveys carried out in 2020 and 2021, to verify the limit and floristic species in the region. The Chaco area was calculated at 24,963 km^2, and it covers partial areas of the municipalities of Corumbá, Miranda, Porto Murtinho, and Caracol. The only urban area within this limit is the city of Porto Murtinho. The original vegetation cover is quite diversified, with Riparian Vegetation (along the rivers), Seasonal Forests, Savanna (Cerrado), Pioneer Formations, Floristic Contacts (floristic transition areas), and Steppe Savanna, the latter being the phytophysiognomy that characterizes the Chaco itself. It is a woody, low and thorny phytophysiognomy, associated with grassland (Silva et al., 2021). The production system in the region is based on cattle grazing on native pastures in areas most susceptible to flooding (from the center to the north of the region), and on cultivated pastures in areas with minor flooding (from the center to the south of the region) (IBGE, 2022).

2.2. Methodological guidelines

The analysis follows the IPCC methodological guidelines (IPCC, 2006) and the indications and data gathered for Brazil present in the Land Use, Land Use Change and Forestry Sector Reference Report of the Fourth National Inventory of Anthropogenic Emissions and Removals of Greenhouse Gases (Brasil, 2020), herein called the Reference Report.

Emissions and removals due to land use and land cover change were estimated by associating information on land use dynamics in an area, between two points in time, with data available in the Reference Report (Brasil, 2020) on C stocks. The stocks reffered to above and below-ground living biomass and dead organic matter (litter and standing or fallen dead wood), considering the initial land use or cover and the final one.

Changes in C stock of biomass were estimated for lands that remained in the same land use classes and those that were converted to a new class in “managed lands”. According to IPCC (2006), the managed lands are those where human interventions and practices have been applied to carry out productive, ecological, or social functions. Emissions and removals do not need to be reported for unmanaged land. The Reference Report (Brasil, 2020) included conservation units (CU) and indigenous lands (IL) as managed areas, obtaining estimates of C removals from natural vegetation within these protected areas.

2.3. Selection of historical land use and land cover data for the Brazilian Chaco region and definition of the periods to be studied

Land use and land cover data came from Collection 5.0 of the MapBiomas Project's Annual Series of Land Use and Land Cover Maps in Brazil (Projeto MapBiomas, 2021). The information obtained from the MapBiomas Project was also used in the methodology carried out by SEEG to estimate emissions (Zimbres et al., 2021). The data source was chosen because it presents annual mappings, since 1985, applying the same method, and also because it presents an adequate resolution for the study area (pixel with a resolution of 30 meters).

Land use and land cover maps from 1990, 2000, 2010 and 2019 were selected to obtain the average annual balance for 10-year periods, except for 2010-2019, which is nine years. We did not include 2020 because the MapBiomas Project survey was unavailable when the present study was performed.

2.4. Compatibility of the key of land use and land cover maps

The key of the land use and land cover maps (Projeto MapBiomas, 2021) does not include classes for identifying secondary vegetation. Thus, it is necessary to identify and delimit it to estimate the balance of emissions and removals according to the Reference Report (Brasil, 2020). The Secondary Vegetation of Forest and Savanna Formations, and Grassland classes were created in the present work. In the Forest and Savanna Formations case, the natural vegetation of a period (Forest Formation or Savanna Formation) that was not classified as such in the previously analyzed periods was considered as Secondary Vegetation. Concerning 1990, the first year of analysis of this study, natural vegetation classified as such in this year was identified as Secondary Vegetation of Forest and as Secondary Vegetation of Savanna if it was not classified as such in 1985, the first annual land use and land cover map of the MapBiomas Project. The same procedure was carried out for the grassland formations, combining the original classes of the MapBiomas Project: "Campo Alagado e Área Pantanosa" (Flooded Grassland and Wetland), and "Formação Campestre" (Grassland Formation), and identifying the Secondary Vegetation of the class called Grassland in the present work.

The Reference Report (Brasil, 2020) considers that natural vegetation within a CU or IL is managed. C removals of the natural vegetation in CUs or ILs are counted since the date the areas were established. Maps provided by the Interactive Environmental Licensing Support System (http://sisla.imasul.ms.gov.br) with information about the date of establishment and limits of the CUs (federal, state and municipal) and ILs, were used to identify the natural vegetation in these areas.

2.5. Carbon stock estimate for natural vegetation classes

The key used by the MapBiomas (Projeto MapBiomas, 2021) combines several phytophysiognomies under the Forest Formation and Savanna Formation classes. On the other hand, the Reference Report (Brasil, 2020) presents C stock data disaggregated by phytophysiognomy. In this case, it was necessary to establish an estimate of C stock for the classes adopted in the MapBiomas. We chose to estimate the C stock of each MapBiomas class using the average C stock of the phytophysiognomies that compose them, proposed by the Reference Report (Brasil, 2020). The average of C stock was weighted by the area of occurrence of each phytophysiognomy in the Chaco region, following the methodology proposed by SEEG (Zimbres et al., 2021). The area of each phytophysiognomy in the Chaco region was obtained from the Vegetation Map (IBGE, 2017). Because the Chaco is entirely within the limits of the Pantanal biome, C stock data related to the Pantanal phytophysiognomies provided by Reference Report (Brasil, 2020) were used. The same procedure was carried out for the grassland formations, estimating C stock for the class called Grassland in the present work.

2.6. Generation of transition matrices and estimate of carbon emissions and removals

All types of land use and land cover change were identified in the study periods, and transition matrices were prepared for each period. The matrices were filled in with the emission or removal factors relative to each land use and land cover change identified in the period, based on data provided by Reference Report (Brasil, 2020). According to the authors, the stock data include the C in living biomass (aboveground and belowground) and dead organic matter (litter, standing, and fallen dead wood). The estimates of C loss (emission) and C gain (removal) are made by associating the information on land use dynamics in an area, considering the initial and final land use and land cover (Brasil, 2020) at two different times. All data were converted to tonnes of C emitted or removed per hectare in each period.

2.7. Spatialization of the annual balance of anthropogenic carbon emissions and removals

The methodology of the Reference Report (Brasil, 2020) was followed for the spatial identification of land use change. We identified the dynamics of land use and land cover in the evaluated periods using the georeferenced polygons and generated data in raster format, in which each cell represents a single transition between the years considered. The association of this information to C stock data of the different compartments and emission and removal factors present in the transition matrices allowed us to estimate C loss or gain in tonnes per hectare and year for each raster cell.

Maps of C balance in the Brazilian Chaco region were obtained using the ArcGIS program (ESRI, 2017) for spatial analyses. The data are presented in megagrams of carbon dioxide per year and ha ($MgCO_2$ yr^{-1} ha^{-1}), considering that one tonne equals one megagram and the transformation of C to CO_2 was made by multiplying by the fraction 44/12. The overall Chaco C balance estimate was performed by multiplying the area of each land use and land cover transition type by the corresponding C balance. Final data are averages for the period, presented in tonnes or megagrams of C or CO_2 per year (t $year^{-1}$ or Mg $year^{-1}$). Negative values correspond to removals and positive values to emissions.

3. RESULTS

3.1. Land use and land cover dynamic

The Savanna Formation class presented the largest reduction in area, totaling 47% from 1990 to 2019. The Forest Formation class area reduced 14% from 1990 to 2019. On the other hand, the growth of areas occupied with pasture in this period was 53%, totaling about 5 thousand km^2 in 2019. The suppression of Forest and Savannas was accompanied by the establishment of pastures in 99% to 100% of cases in all periods.

Other land uses, less significant in terms of area, expanded from 1990 to 2019: Annual Crop went from 0.31 to 5.91 km^2; Urban Infrastructure, from 3.05 to 4.85 km^2; Other Uses (without vegetation), from 0.38 to 1.30 km^2; and Planted Forest, from 0 to 0.02 km^2. 61% of the Annual Crop areas occupied areas of Forest or Savanna in 1990.

The Annual Crop areas occupied, for the most part, areas of Forest or Savanna Formation suppressed in the corresponding period. This was observed for 61%, 60% and 21% of the total Annual Crop area in 1990-2000, 2000-2010 and 2010-2019, respectively.

The areas under protection in the Chaco in 2000 were the Kadiwéu Indigenous Land and the Estrada Parque Pantanal Area of Special Tourist Interest, which totaled 11.72% of the Chaco area. In 2010 this proportion increased to 11.90% with the creation of the Cachoeira do Apa Municipal Natural Park and the Apa River Sub-Basin Municipal Environmental Protection Area. Notably, the Kadiwéu IL is the largest protected area and represents 10.62% of the Chaco area.

Protection areas such as ILs and CUs strongly contribute to mantaining natural vegetation. Silva et al. (2021) comment that the Steppe Savanna, which is widespread in the Chaco, is more fragmented in the Southern part and is more concentrated along the Paraguai River, while in the northern part, starting from the Aquidabã River, this physiognomy is practically intact, most likely due to the flooding of this area and the existence of the Kadiweu IL, where deforestation is restricted.

3.2. Carbon stock estimate for natural vegetation classes

The estimated C stock for Forest Formation, Savanna Formation, and Grassland areas was, respectively, 124.51, 31.72, 22.51 tC ha^{-1}. These values were also used to estimate the C stock of the Secondary Vegetation of these phytophysiognomies and applied to the estimates of emissions and removals due to anthropogenic use. It is important to note that the unit tonne per hectare and year was used to develop estimates, maintaining the unit presented in the methodology described in Reference Report (Brasil, 2020).

The estimated stocks for the Pantanal biome by Zimbres et al. (2021), which used the same method and database, were: Forest Formation equal to 101.51 tC ha^{-1}, Savanna Formation, 54.58 tC ha^{-1}, and Grassland, 16.67 tC ha^{-1}. When comparing the results, it is noted that the average C stock for the classes Forest Formation and Grassland in the Chaco are slightly higher than those of the Pantanal and lower in the case of the Savana Formation class. In the case of the Savanna Formation, the lower values in the Chaco are due to the predominance of the Forested Steppe Savanna phytophysiognomy, which has a lower stock of C compared to the other Savanna Formations in the region.

3.3. Transition matrices and estimate of carbon emissions and removals

The transition matrices prepared for each period considered the transition between the land use and

Table 1 – Carbon (C) stock and removal values used and sources of data.
Tabela 1 – *Valores de estoque de carbono (C) e remoções empregados e fontes dos dados.*

Land Use and Land Cover	C stock (t ha^{-1})	Complementary Information and Data Source
Forest Formation (FF)	124.51	Estimated for Chaco
Secondary Vegetation (SV) of FF	54.78	0.44 of the original vegetation stock. Table 29(*)
Savanna Formation (SF)	31.72	Estimated for Chaco
SV of SF	13.96	0.44 of the original vegetation stock. Table 29(*)
Planted Forest (PF)	42.89	Average value of C stocks in the years in which the survey was carried out for reforestation in MS. Table 36(*)
Grassland	22.51	Estimated for Chaco
Pasture (P)	7.57	Table 29(*), Pantanal factor
Annual Crop (AC)	5.05	Average value of C stocks in the years in which the survey was carried out for agricultural areas in MS. Table 41(*)
Land Use, Land Cover or Change	**C Removal (t ha1year^{-1})**	**Complementary Information and Data Source**
FF or SF in CU or IL	0.20	Table 29(*), Pantanal factor
SV of FF or SF in previous area of FF or SF	2.77	Applied only in the first identified period. Table 29(*, **)
SV of FF or SF in previous area of PF	2.77	The factor described in the line above was used. No data available on (*).
SV of FF or SF in previous area of P	2.85	Table 29(*), Pantanal factor
SV of FF or SF in previous area of AC	4.73	Table 29(*), Pantanal factor
SV of FF or SF in previous area of Other Uses	0.59	Table 29(*), Pantanal factor
Grassland in CU or IL	0.44	Table 29(*), Pantanal factor
SV of Grassland	1.70	Table 29(*), Pantanal factor
AC	0.03	Average value of the factors in the years in which the survey was carried out for agricultural areas in MS. Table 41(*)
PF	11.45	Average value of factors in the years in which the survey for reforestation in MS was carried out. Table 36(*)
P	---	(*) does not establish annual removal factor for pastures

(*) Data source: (Brasil, 2020).
**"Due to the impossibility of identifying the dynamics and time of growth of these areas between the years mapped, for the Fourth National Inventory, we decided to consider CO_2 removals by secondary vegetation only in the first period identified in the mapping. Therefore, for secondary vegetation that remains as secondary vegetation in the year mapped later, removals were not considered." (free translation from Brasil, 2020).
(*) Fonte do dado: (Brasil, 2020).
***"Devido à impossibilidade de identificação da dinâmica e tempo de crescimento dessas áreas entre os anos mapeados, para o Quarto Inventário Nacional, optou-se por considerar as remoções de CO_2 por vegetação secundária apenas no primeiro período identificado no mapeamento. Sendo assim, para uma vegetação secundária que permanece como vegetação secundária no ano mapeado posteriormente, não foram consideradas remoções." (Brasil, 2020).*

land cover classes adopted in the study area (Table 1). The final factors to estimate emissions and removals are described (Table 1), including the data sources.

The annual balance of anthropogenic C emissions and removals was estimated for each land use and land cover transition by applying the values of the final factors (Table 1) to the equations established in the Appendix A1 of the Reference Report (Brasil, 2020). Following the method proposed in the Reference Report, we considered that the land use conversions occurred in the middle of the analyzed period. The final result of the annual balance was made by dividing the final value by the number of years in the period considered.

3.4. Spatialization of the annual balance of carbon anthropogenic emissions and removals

The annual balance of anthropogenic C emissions and removals for the periods studied was spatialized (Figure 1). The final balance for the Chaco region resulted in net emissions of 817,091 MgC year^{-1} or 2,996,005 MgCO_2 year^{-1} from 1990 to 2000; 352,229

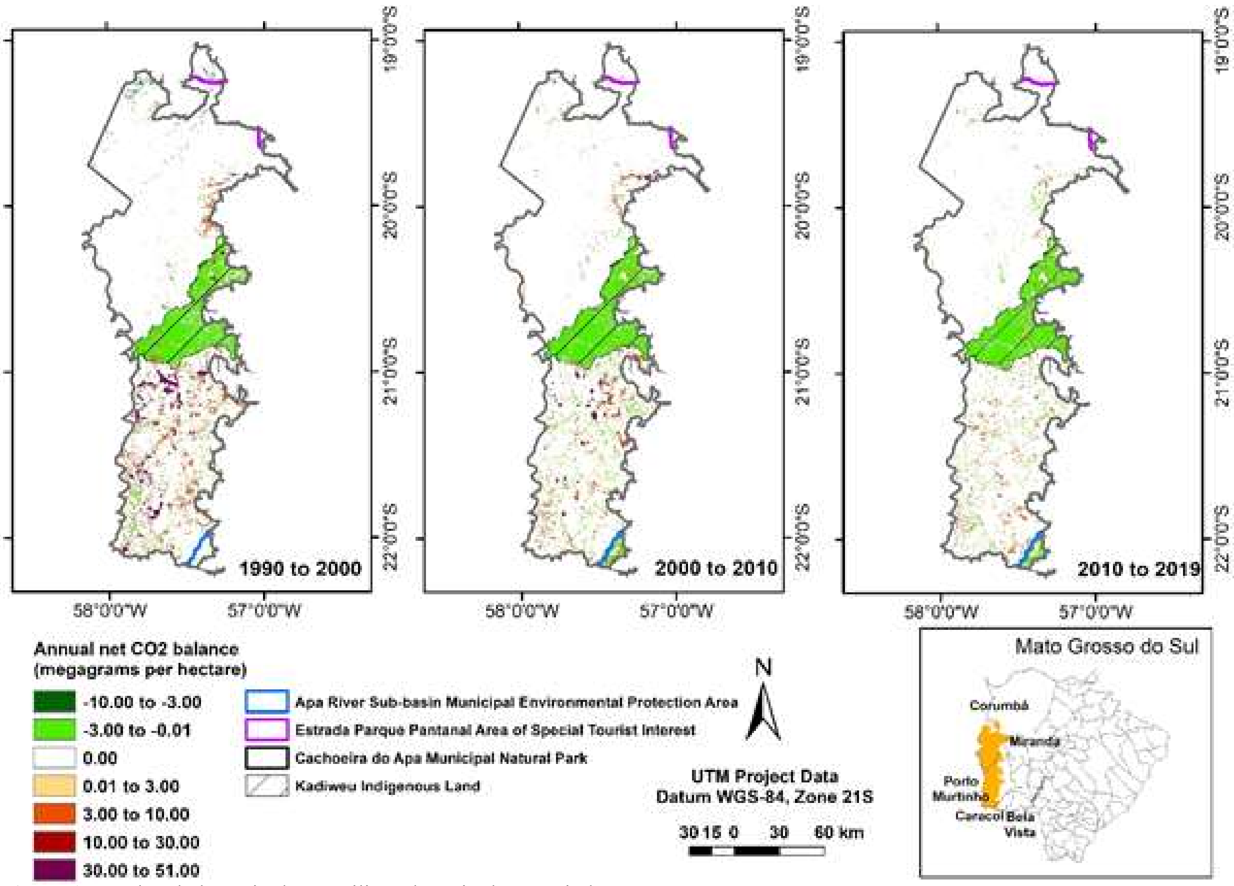

Figure 1 – Carbon balance in the Brazilian Chaco in three periods.
Figura 1 – *Balanço de carbono no Chaco brasileiro em três períodos.*

MgC yr^{-1} or 1,291,506 $MgCO_2$ year^{-1} from 2000 to 2010; and 167,008 MgC year^{-1} or 612,361 $MgCO_2$ year^{-1} from 2010 to 2019.

When analyzing the removals separately, we observed that they represent 87,892 MgC year^{-1} from 1990 to 2000, showing a slight increase in the period 2000-2010 (89,214 MgC year^{-1}) and falling again in 2010-2019 (83,921 MgC year^{-1}). Most of this removal is due to natural vegetation in CU areas and the Kadiwéu IL. Removal under these conditions equals 63%, 73%, and 82% of the estimated total removals in 1990-2000, 2000-2010, and 2010-2019, respectively. The data show the importance of protected areas in this region for removing GHG in the atmosphere.

4. DISCUSSION

Net emissions (in $MgCO_2$ ha^{-1} year^{-1}) in the periods 1990 to 2000, 2000 to 2010, and 2010 to 2019 (respectively, in the Pantanal: 0.79, 0.53, and 0.08 (SEEG, 2022b); and in the Chaco: 0.12, 0.05, and 0.03) show that the Chaco region presented lower mean values than the Pantanal in all periods. A progressive reduction of these values can also be observed in the periods studied in both regions.

Land use change dynamics in the Brazilian Chaco differ from the Chaco's dynamics in other countries. Baumann et al. (2016) applied Landsat satellite image archive to rebuild land use change over the past 30 years across the Chaco biome (in Bolivia, Paraguay, and Argentina). Between 1985 and 2013, more than 142,000 km^2 of the Chaco forests, equaling 20% of all forest, was replaced by croplands (38.9%) or grazing lands (61.1%). Of those grazing lands in 1985, about 40% were subsequently converted to cropland. These land-use changes resulted in substantial carbon emissions, totaling 824 TgC between 1985 and 2013, and 46.2 TgC for 2013 alone. Most of these emissions came from forest-to-grazing land conversions (68%). In the Brazilian case, we found that the suppression of Forest and Savanna Formations, considering the period 1990 to 2010, was 21% of the area of these formations (the base year 1990), replaced almost entirely by pastures (more than 99%). Emissions due to the loss of Forest and Savanna Formations in the period were 1.16 10^6 tC or 1.16 TgC.

Pötzschner et al. (2022) highlight that global maps underestimate the carbon stored in Chaco vegetation dramatically. They identified that most of the remaining above-ground biomass (AGB) stored in Chaco woodlands is located in Argentina (2.4 Gt AGB), followed by Paraguay (1.13 Gt AGB), and Bolivia (1.11 Gt AGB). Their results also highlight that 71% of the remaining AGB is located outside protected areas, and around half of the remaining AGB occurs on land used by traditional communities. Considerable co-benefits appear to exist between protecting traditional livelihoods and carbon stocks. The analyzes reveal a substantial risk of continued high carbon emissions should agricultural expansion progress.

The use of fire in land management is another factor that contributes to the degradation of the Chaco vegetation, as well as in the Pantanal (Brasil, 2020). In 2020, fire was observed in four million hectares of forest, savanna, and shrubland, almost one-third of the Pantanal area. The total loss of these events will take months to calculate, but the impacts are long-lasting (Libonati et al., 2020). When an area is burned, there is a direct loss of animals and plants present there, with risks to the maintenance of biodiversity and the release of gases that contribute to the intensification of the greenhouse effect. The soil becomes poor in nutrients, which hinders the development of native vegetation (Chaves et al., 2020).

Considering the significant contribution of protected areas in CUs and ILs to the C balance in the Chaco, including Brazil, public policies aimed at protecting and conserving vegetation are of fundamental importance. The dynamics of land use in the biome also indicate that, in addition to measures to reduce the conversion of natural vegetation, the adoption of low-carbon agriculture practices can be promising to reduce greenhouse gas emissions.

The National Policy on Climate Change (Brasil, 2009) provides for financial mechanisms related to climate change mitigation. In this context, the Low Carbon Agriculture Plan (ABC Plan) was launched from 2010 to 2020 and updated from 2020 to 2030 (Brasil, 2021b). The ABC Plan is considered an instrument for integrating the actions of governments (federal, state, and municipal), the productive sector, and civil society, to reduce GHG emissions from agricultural activities. Among low-carbon agriculture practices, integrated systems, which integrate crop, livestock and (or) forestry activities in intercropping, crop rotation, or crop succession, stand out. These systems have a high potential for reducing GHG emissions, contributing to climate regulation and the provision of other ecosystem services (Nair et al., 2010; Nair et al., 2011; Tonucci et al., 2011; Nogueira et al., 2016; Waldron et al., 2017). The Fourth National Inventory (Brasil, 2021a) presents a detailed discussion about Brazilian public policies, programs, projects, and other initiatives for climate change mitigation and adaptation.

The results presented in this work are conditioned to the available data used, which do not allow for greater detail on spatial scale and do not present information on land management.

5. CONCLUSIONS

The natural vegetation of the Brazilian Chaco has been predominantly replaced by pasture over the period studied, from 1990 to 2019.

The formation of natural vegetation that had the greatest reduction in area in this period was the Savanna Formation.

The Chaco region presented lower average values of annual net emission per hectare and year than the Pantanal in the periods: 1990 to 2000, 2000 to 2010 and 2010 to 2019.

The annual CO_2 balance shows that removals predominate in conservation units (CU) and indigenous lands (IL), especially the Kadiwéu IL, and emissions predominate in the southern Brazilian Chaco.

The balance resulted in higher net emissions from 1990 to 2000, reduced from 2000 to 2010 and reduced again from 2010 to 2019. Further studies are needed to show whether this trend has changed in recent years.

AUTHOR CONTRIBUTIONS

Elaine C. C. Fidalgo (Corresponding Author): conceptualization, data aquisition, data analysis, results discussion, writing – original draft and review; Joyce Maria Guimarães Monteiro, conceptualization, results discussion, writing – original draft and review; Rachel Bardy Prado, results discussion, writing – original draft and review; João dos Santos Vila da Silva, results discussion, writing – original draft and review.

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