Brazilian Journal of Environment

Comparative assessment of Carbon dioxide levels in the dry and rainy seasons in forested and deforested areas of Miombo forest, Huambo (Angola)

Vicente Miúdo Kimbamba[1]*, Godson R.E.E Ana[2], Luís Manuel Miapia[3]

[1]*Mestre em Gestão Ambiental.pela Pan African University for Life and Earth Sciences Institute (including Health and Agriculture) PAULESI, Nigéria (*Autor correspondente: vicentekimbamba@hotmail.com)*
[2]*Professor in the Department of Environmental Health Sciences, Faculty of Public Health, University of Ibadan, Ibadan, Nigeria*
[3]*Professor do Departamento de Engenharia Florestal, Faculdade de Ciências Agrárias, Universidade José Eduardo dos Santos, Catumbela 13301, Huambo, Angola*

ABSTRACT

This study compared atmospheric CO_2 concentrations during the dry and rainy seasons in two areas of the Miombo forest in Huambo province: Chipipa (degraded) and Chianga (conserved). In each area, three plots (10 m radius) with twenty measurement points were selected. CO_2 was monitored twice daily (morning and afternoon) for 8 days using the SR-510A detector, between August 14 and September 8 (dry season), and December 2 to 21, 2024 (rainy season). Statistical analysis showed significant differences between morning and afternoon CO_2 levels in both areas. In the dry season, Chianga's Plots 1 and 2 had 403.32 ppm and 399.02 ppm, respectively, and Chipipa's Plot 1 had 430.6 ppm. In the rainy season, Chianga's Plots 1 and 2 showed 413.73 ppm and 413.24 ppm, and Chipipa's Plot 1 had 415.6 ppm. Other plots had no significant differences. At the area level, CO_2 was significantly higher in Chipipa (median = 426 ppm) than in Chianga (median = 397 ppm) during the dry season. No significant differences were observed in the rainy season. However, in the rainy season, no significant difference was found between the areas. Additionally, CO_2 concentrations were consistently higher in the dry season compared to the rainy season. These findings show that the degraded area consistently exhibited high levels of CO2, particularly during the dry season. however, during rainy season, no significant differences in CO_2 levels were observed between the two areas, suggesting that rainfall may mitigate the effects of degradation on atmospheric CO_2 dynamics.

Keywords: Climate change, CO_2 emission, Land use, Miombo forest effect.

Avaliação comparativa dos níveis de Dioxido de Carbono nas estações seca e chuvosa em área florestada e desmatada na floresta de Miombo da Província do Huambo (Angola)

RESUMO

Este estudo comparou as concentrações atmosféricas de CO_2 durante as estações seca e chuvosa em duas áreas da floresta de Miombo na província do Huambo: Chipipa (degradada) e Chianga (conservada). Em cada área, foram selecionadas três parcelas (com raio de 10 metros) contendo vinte pontos de medição. O CO_2 foi monitorado duas vezes ao dia (manhã e tarde) durante 8 dias, utilizando o detector SR-510A, entre 14 de agosto e 8 de setembro (estação seca) e de 2 a 21 de dezembro de 2024 (estação chuvosa). A análise estatística mostrou diferenças significativas entre os níveis de CO_2 pela manhã e à tarde em ambas as áreas. Na estação seca, as Parcelas 1 e 2 de Chianga apresentaram 403,32 ppm e 399,02 ppm, respetivamente, enquanto a Parcela 1 de Chipipa registrou 430,6 ppm. Na estação chuvosa, as Parcelas 1 e 2 de Chianga apresentaram 413,73 ppm e 413,24 ppm, e a Parcela 1 de Chipipa teve 415,6 ppm. As demais parcelas não apresentaram diferenças significativas. No nível das áreas, o CO_2 foi significativamente mais elevado em Chipipa (mediana = 426 ppm) do que em Chianga (mediana = 397 ppm) durante a estação seca. Não foram observadas diferenças significativas durante a estação chuvosa.Além disso, as concentrações de CO_2 foram consistentemente mais altas na estação seca em comparação com a estação chuvosa. Esses resultados mostram que a área degradada apresentou níveis elevados de CO_2 de forma consistente, especialmente durante a estação seca. No entanto, na estação chuvosa, não foram observadas diferenças significativas nos níveis de CO_2 entre as duas áreas, o que sugere que a chuva pode mitigar os efeitos da degradação na dinâmica do CO_2 atmosférico.

Evaluación comparativa de los niveles de dióxido de carbono en las estaciones seca y lluviosa en áreas forestadas y deforestadas en el bosque de Miombo de la Provincia de Huambo - Angola

R E S U M E N

Este estudio comparó las concentraciones atmosféricas de CO_2 durante las estaciones seca y lluviosa en dos zonas del bosque de Miombo en la provincia de Huambo: Chipipa (degradada) y Chianga (conservada). En cada zona se seleccionaron tres parcelas (con un radio de 10 metros) con veinte puntos de medición. El CO_2 fue monitoreado dos veces al día (mañana y tarde) durante 8 días utilizando el detector SR-510A, entre el 14 de agosto y el 8 de septiembre (estación seca), y del 2 al 21 de diciembre de 2024 (estación lluviosa). El análisis estadístico mostró diferencias significativas entre los niveles de CO_2 por la mañana y por la tarde en ambas zonas. En la estación seca, las Parcelas 1 y 2 de Chianga presentaron 403,32 ppm y 399,02 ppm, respectivamente, mientras que la Parcela 1 de Chipipa registró 430,6 ppm. En la estación lluviosa, las Parcelas 1 y 2 de Chianga presentaron 413,73 ppm y 413,24 ppm, y la Parcela 1 de Chipipa tuvo 415,6 ppm. Las demás parcelas no presentaron diferencias significativas. A nivel de área, el CO_2 fue significativamente más alto en Chipipa (mediana = 426 ppm) que en Chianga (mediana = 397 ppm) durante la estación seca. No se observaron diferencias significativas durante la estación lluviosa. Además, las concentraciones de CO_2 fueron consistentemente más altas en la estación seca en comparación con la estación lluviosa. Estos resultados muestran que el área degradada presentó niveles elevados de CO_2 de forma constante, especialmente durante la estación seca. Sin embargo, en la estación lluviosa no se observaron diferencias significativas en los niveles de CO_2 entre las dos zonas, lo que sugiere que las lluvias pueden mitigar los efectos de la degradación en la dinámica del CO_2 atmosférico.

Palabras clave: Cambio climático, Emisión de CO_2, Uso de la tierra, Efecto de los bosques de miombo.

1. Introduction

Miombo woodlands represents one of the largest and most ecologically significant biome in southern and central Africa, covering an area of 2.7 million km^2 that spreads across seven countries, which are Tanzania and the Democratic Republic of the Congo (DRC) in the north, Angola and Zambia to the east, and Malawi, Zimbabwe and Mozambique to the south (Andrew et al., 2024). Miombo woodland is of extremely high environmental value as one of the biggest tropical forest ecosystems in Africa and the globe and as a reservoir of biodiversity and climate regulation. More than 150 million people across Africa depend on Miombo and Mopane woodlands for a wide range of products and ecosystem services, underscoring their significant socio-economic importance. These woodlands provide both woody resources, such as timber, charcoal, and firewood, and non-woody products, including medicinal plants, food, fibers, oils, and resins, which are extensively harvested and utilized by rural and urban communities (Kissanga, 2024). By sustaining livelihoods, generating income, and supporting local economies, these ecosystems play a particularly vital role for the most vulnerable households.

However, the expansion of agricultural activities, energy production, and urbanization in the area has led to significant deforestation and forest degradation. Shifting cultivation and unsustainable energy practices have particularly been identified as the main causes of Miombo woodland deforestation, resulting in the loss of approximately 1.27 million hectares annually (Aquino, 2016). This situation has placed an immense pressure on African governments to address the environmental, social and economic impacts of deforestation, which could lead to irreversible damage to ecosystems and local communities.

In the Angolan context, the area occupied by this forest is 30,955,700 ha, which represents 25% of the territory of Angola (Kussumua, 2020). As one of the most widely distributed ecosystems in Angola, Miombo has a large carbon sequestration capacity and provides the rural population with a variety of benefits, such as timber and non-timber biomass products for domestic energy production (firewood and charcoal), livestock fodder, medicinal plants and wild fruits (Miapia, 2021). Although it is a little explored topic, deforestation

rates in Angola have been gradually increasing over time (ENPRF, 2011). The results of the study on deforestation and forest degradation conducted by the authors, Palacios et al., (2015), show a significant decrease in the area of Miombo forest in Huambo Province between 2002 and 2015 and severe forest degradation. National statistics, for example, indicate that, between 2000 and 2019, 359,130 hectares of the original cover were deforested in Huambo Province, which is equivalent to 12.96% of the original cover (Miapia, 2021).

The rise in greenhouse gas emissions has been a major concern globally, as it is one of the contributory factors to climate change. According to IPCCC data, almost half of anthropogenic carbon dioxide emissions were between 1750-2010, where land use changed emissions such as deforestation and agriculture increased exponentially from 490 GtCO2 in 1970 to 680 GtCO2 in 2010 (Edenhofer, 2015). If these patterns continue, scientific projections point to an increase in global average temperatures (IPCC, 2014). Therefore, if nations do not take additional mitigation actions, emissions will continue to grow due to population growth and economic activity.

As CO_2 concentrations increase in the atmosphere due to anthropogenic activities such as the burning of fossil fuels and deforestation, carbon sequestration has become an essential strategy for reducing greenhouse gas emissions. Because forests absorb large amounts of CO_2 during the process of photosynthesis, carbon sequestration in forests was consolidated after the Kyoto Protocol in 1992, when mechanisms for reducing greenhouse gas emissions were approved (Brachtvoge, 2018).

Despite the increased carbon sequestration potential of Miombo forests in Huambo, it is necessary to differentiate how CO_2 emission dynamics vary within a year, specifically between the rainy and dry seasons. During the rainy season, there is more photosynthetic activity for vegetation since water is available, which favors photosynthesis and hence carbon sequestration. While during the dry season, limited water availability significantly constrains photosynthetic activity, primarily by inducing stomatal closure and reducing carbon assimilation efficiency (Marenco, 2014)

The aim of this study was to comparatively evaluate carbon dioxide levels in the dry and rain seasons in forested and deforested areas within the Miombo woodland, in Angola´s Huambo Province. The specific objective were to compare CO_2 levels at different times of day (morning vs afternoon) across both seasons, compare CO_2 concentrations between forested and deforested areas for each season, and assess the CO_2 levels between seasons.

2. Material and Methods

2. 1 Description of the Study Area

The present study was conducted in the Miombo Woodland, located in Huambo province, which covers an area of 34,270 km^2 in the Central Plateau (Miapia, 2021). Huambo is the second province in Angola with the largest biomass stock (IDF, 2018), but it is also among the three provinces with the highest forest cover losses in the country (Mendelsohn, 2009).

Figure 1 – Location map of the study area
Figura 1 – Mapa de localização da zona de estudo
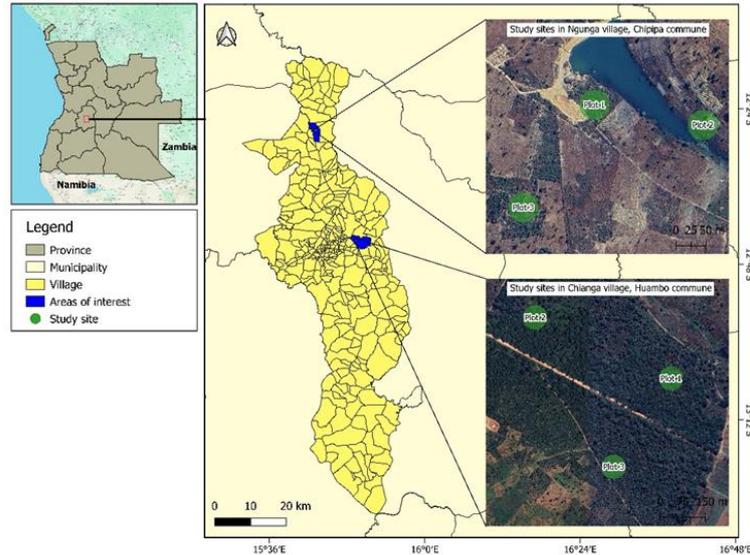
Source: Author (2024)
Fonte: Próprio autor (2024)

The present study was carried out with the primary objective of comparing atmospheric carbon dioxide (CO_2) concentrations in two distinct areas within the Miombo Woodland during the dry and rainy seasons. The Chipipa area, representing the degraded region, and the Chianga area, which corresponds to the conserved area.

The Chipipa area, known as degraded, is a commune in the province of Huambo with latitude: 12° 10' 59" S and longitude: 15° 46' 59" E. The region has faced considerable ecological degradation due to several factors related to deforestation, which results in soil degradation and the complete loss of biodiversity (Sinela et al., 2024). Chianga region, which is under the control of the Huambo Institute of Agricultural Research, is 13 km from the city of Huambo and covers about 2,550 hectares. It is found at an altitude of over 1,500 meters and has tropical savanna deciduous vegetation with rainfall ranging from 800 to 1,396 mm per year. The soil texture is clayey with a pH ranging from 5.2 to 5.5 (Henriques et al., 2009). Chianga is a preserved environment, although it has a moderate level of disturbance due to some neighboring producers and students who carry out experimental activities under the supervision of the Institute. However, the impact of activities in Chianga is smaller when compared to Chipipa, which ensures that the area maintains denser and more balanced vegetation.

2.2 Site Selection and Method of Data collection

The research was carried out during the dry and rainy seasons, with monitoring being conducted in the following periods: for the dry season, from August 14 to September 8, and for the rainy season, from December 2 to 21, 2024. At each site, three plots were chosen at random, with circular layouts of 10 meters diameter, with twenty points randomly positioned in each plot. CO_2 concentration was measured in the morning (8 am) and the afternoon (4 pm) over 8 consecutive days, a total of 8 measurements for each point in the morning and afternoon.

2.3 CO$_2$ Monitoring

The equipment used to monitor CO$_2$ concentrations was the SR-510A detector, that uses the principle of absorption of infrared light sources to measure carbon dioxide concentrations in the atmosphere. The detector has a measurement range of 0 to 9999ppm, with a resolution of 1 ppm and an accuracy of $\pm$ 40 ppm, $\pm$ 10% of the measured value.

2.4 Statistical Analyses

The statistical analysis consisted of two main aspects: within-area and between-area analysis and were carried out with the R software. The within-area analysis was done to test whether differences in CO$_2$ concentration are significant between morning and afternoon periods during dry and rainy seasons, as per the Wilcoxon signed rank test. Additionally, the comparison between regions aimed at comparing CO$_2$ levels in the disturbed and undisturbed Miombo areas with the use of the Mann-Whitney U test and rank-biserial correlation coefficient to establish differences in CO$_2$ levels between areas. Comparisons of CO$_2$ levels between seasons were also analyzed for a better description of differences in CO$_2$ levels between seasons and spaces.

3. Results and Discussion

3.1 CO$_2$ levels in the Dry season (Morning vs. Afternoon CO2 levels Within-Area during the dry season)

A Wilcoxon Signed Rank Test was conducted to find out whether the difference in CO$_2$ concentrations within each plot in the morning and afternoon. The analysis of the CO$_2$ measurements across plots showed plot 1 (W = 7611; p < 0.001) and plot 2 (W = 73365; p = 0.008) of the conserved area had a significant difference in CO2 concentrations between the morning and afternoon measurements.

And in the degraded area, plot 1 (w = 9205.5; 4.87e-08) also showed a significant difference in concentrations between the two periods. However, for plot 3 of the conserved area, no significant difference in carbon dioxide concentrations was observed between the morning and afternoon periods. Similarly, in the degraded area, plots 2 and 3 showed no significant difference in CO$_2$ concentrations, as shown in Table 1.

Table 1 - Analysis of CO$_2$ Concentrations: Morning vs. Afternoon During the Dry Season'
Tabela 1 – Análise das Concentrações de CO$_2$: Manhã vs. Tarde Durante a Estação Seca'

Area	Plot	Statistic	p_value	Significant
Degraded	1	9205.5	4.87e-08	Yes
Degraded	2	6057	0.698546	No
Degraded	3	5954.5	0.982003	No
Conserved	1	7611	0.001718	Yes
Conserved	2	7336.5	0.008399	Yes
Conserved	3	5001.5	0.327658	No

*Values of p < 0.05 indicate that the differences are statistically significant.

Figure 2 illustrates the CO$_2$ concentrations recorded in each plot, segmented according to the different study areas at different times. This visual representation allows a clear comparison between the concentration variations within the plots at different times.

Figure 2 - Carbon dioxide concentrations at plot level (within-area).
Figura 2 – Concentrações de dióxido de carbono ao nível da parcela (dentro da área).
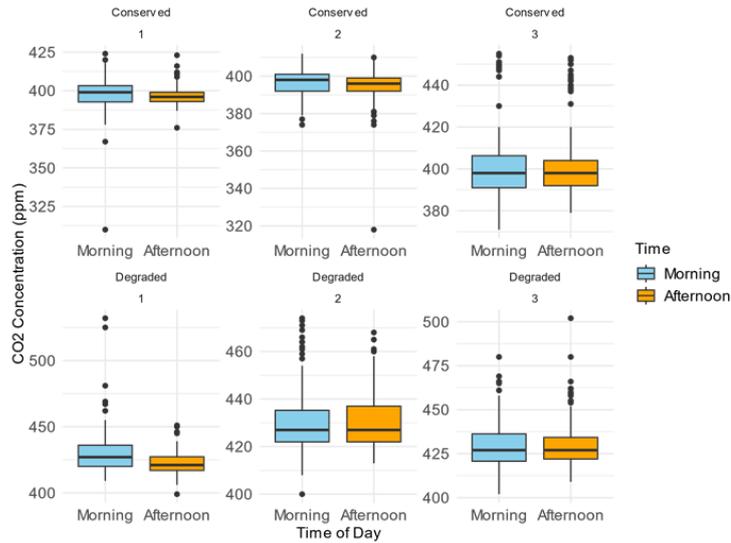
The figure 3 illustrates carbon concentration in degraded and conserved land during the dry season reveal a difference in carbon concentrations between both types of environments. It is clear that carbon concentrations are slightly higher in degraded environments compared to conserved environments.

Figure 3 - Carbon concentration in degraded and conserved area during dry season.
Figura 3 - Concentração de carbono em áreas degradadas e conservadas durante a estação seca.
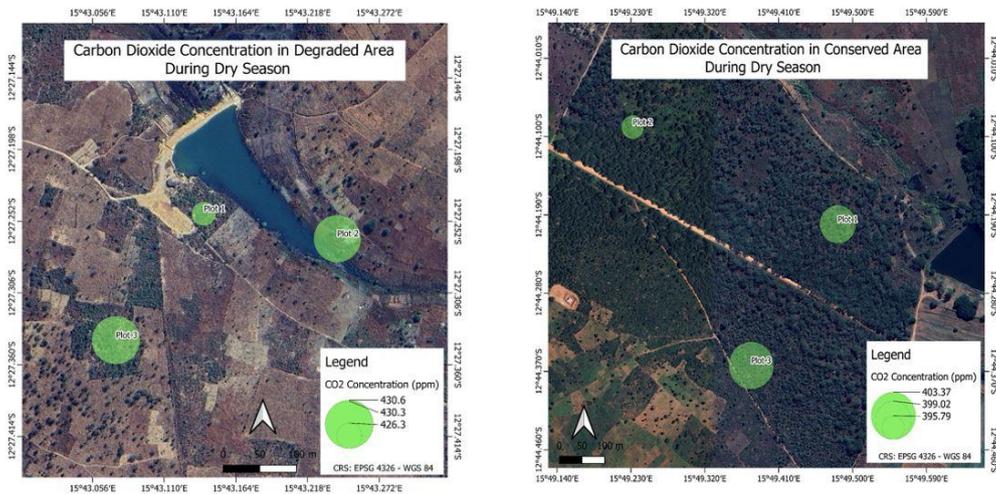
This is because the carbon retention capacity of the soil in the degraded areas reduces, releasing carbon in the form of carbon dioxide (CO_2) into the atmosphere when their land use is altered, e.g., through deforestation or improper exploitation. When land use is modified, whether through deforestation, conversion to croplands, or other forms of unsustainable exploitation, the soil's capacity to retain carbon is substantially reduced, leading to the release of carbon dioxide (CO_2) into the atmosphere. Huang et al. (2024) demonstrated

that global conversions of forests and grasslands to cropland cause average losses of soil organic carbon (SOC) of approximately 24.5% ± 1.53% (−11.03 ± 1.06 Mg ha⁻¹) and 22.7% ± 1.22% (−8.09 ± 0.67 Mg ha⁻¹), respectively. These findings indicate that such transformations shift soils from functioning as carbon sinks to becoming net sources of emissions. This transition contributes to elevated atmospheric CO_2 concentrations and disrupts the stability of the global carbon cycle.

The underlying mechanism is primarily associated with the reduction in organic matter inputs such as litter, root exudates, and dead roots, following vegetation removal, coupled with the physical disturbance of the soil caused by tillage, erosion, and oxidation. These processes accelerate the mineralization of organic carbon, thereby enhancing its release into the atmosphere. Under these conditions, particularly during dry periods, decreased soil moisture and elevated surface temperatures intensify the decomposition of organic matter and amplify carbon losses. Consequently, the conversion of vegetated and productive landscapes into degraded or exposed areas severely compromises the soil's long-term carbon storage capacity and reinforces its role as a contributor to anthropogenic greenhouse gas emissions.

During the dry season, the dynamics of carbon within ecosystems undergo significant alterations, especially in areas where vegetation cover is reduced. The limited availability of green biomass results in a substantial decrease in the system's photosynthetic capacity, leading to an insufficient carbon sequestration to offset the emissions produced by organic matter decomposition. Under these conditions, the reduction in soil moisture and the increase in surface temperature intensify the mineralization of organic matter, which in turn enhances the release of carbon dioxide (CO_2) and other gases into the atmosphere. This imbalance causes a temporary accumulation of carbon in the upper soil layers, which, without the protection of dense vegetation, tends to be rapidly lost through oxidation or erosion once the rains return. In contrast, preserved areas exhibit a more stable and resilient behavior in the face of seasonal variations. The presence of dense, diverse, and structurally complex vegetation ensures a continuous carbon flux among the atmosphere, biomass, and soil, even under water stress conditions.

Levels of CO₂ Between-(conserved vs degraded Area)

The Mann-Whitney U test was conducted to compare CO_2 concentrations in Miombo forest between degraded area. The test yielded a U-statistic of 882,388.5 and a p-value of 4.27e-264 which is significantly less than the conventional alpha level of 0.001. This indicates a significant difference between the two groups, in other words, the CO_2 concentrations differ significantly between the degraded and conserved areas. The result of the rank-biserial correlation (rb = −0.9149) indicates a large negative effect size. It implies that CO_2 concentrations are consistently higher in the degraded area compared to the conserved area (Figure 4).

Figure 4 - Carbon dioxide concentrations at area level (between-area)
Figura 4 - Concentrações de dióxido de carbono a nível da zona (entre áreas)
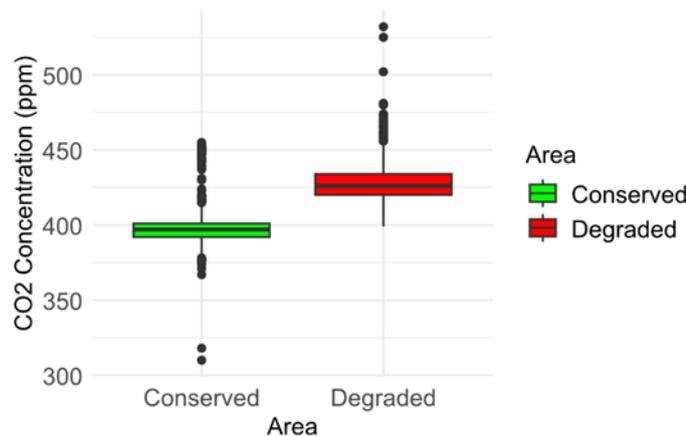
The analysis of CO_2 concentrations in different plots in the degraded and preserved areas showed remarkable patterns of variability in carbon dioxide concentrations, indicating significant differences in carbon dynamics between the two forest conditions. These results reinforce the consequences of environmental changes on the carbon cycle but also provide valuable data on how forest degradation affects the processes of respiration and photosynthesis, which are fundamental for understanding the biogeochemical cycles.

Within the conserved area, the significant differences between plots 2 and 3 suggest that, although the environment has been conserved, the micro environmental conditions of the plots might have imposed some influence on CO_2. The difference among the plots in CO_2 is due to the variability of plant species, decomposition rate of organic matter, and due to differences in soil structure and soil respiration (Texeira et al., 2014).

CO_2 release into the atmosphere is a component of the carbon cycle and one of the predominant processes accountable for global climate change (Ferreira et al., 2005). Carbon losses take place particularly as CO_2 is released during respiration, when microbiota decomposes residues and soil organic matter or when organic compounds are lost via leaching and erosion (Primieri et al., 2017). Temperature, humidity, nutrient concentration, and photosynthesis rates can alter CO_2 exchange between soils and the atmosphere (Ma & Lu, 2011; Neto et al., 2011). Soil respiration activities can exhibit enormous variation in CO_2 concentration in relation to temperature, humidity, and diurnal biological activity (Villela et al., 2012). Soil respiration is also more pronounced during the day, and high temperature and availability of sunlight promote microbial metabolism and organic matter decomposition (Ramos, 2010; Silva et al., 2015).

Experiments carried out by Zhangui et al. (2023), in which he researched the soil respiration and temperature and precipitation sensitivity, revealed that the rate of soil respiration with the moderate increase in temperature and precipitation rises. However, the maximum values of this gas are registered at the hours of maximum biological activity. Whereas, during milder hours or declining temperature and reduced biological activity, the respiration rate in the soil decreases, also causing a drop in CO_2 content. These daily variations in CO_2 emissions reveal the complexity of interactions between the soil, atmosphere, and the soil microbiota, with instant effects on climatic dynamics since the soil is capable of playing either a role as a source or sink for carbon.

Within the conserved area, by being conducive to denser and/or less disturbed plant cover, it encourages greater photosynthetic rates and control over CO_2 emissions, thus explaining the lower variability recorded in plot 3. The absence of significant differences in plot 3 in the area conserved reflects greater homogeneity in environmental conditions within this plot. Conserved forests have a high capacity to better regulate greenhouse gas emissions and have been documented in the literature, with studies such as (Harris & Gibbs, 2021), which point to the role of forests as carbon sinks, absorbing more CO_2 than they release, especially in areas with intact vegetation and high biodiversity.

In the degraded area, a significant difference was observed in plot 1, indicating that degraded environmental conditions have a more pronounced impact on CO_2 concentrations. Environmental degradation in forests is commonly linked to the loss of vegetation, biodiversity and modification of soil structure (Lima, 2022). These factors directly interfere with carbon flow.

In a study conducted by Oliveira & Nero (2023), who investigated the simulation of deforestation based on the variation of protected areas and its relationship with the estimate of CO_2 emissions, a correlation was observed between the extent of deforested areas and CO_2 levels. Soares et al. (2019), in their study on the environmental impacts caused by deforestation, highlight that, in addition to putting biodiversity at risk, deforestation significantly increases the concentrations of greenhouse gases in the atmosphere.

In plots 2 and 3 of the degraded area, the absence of significant differences suggests a certain uniformity in the carbon dynamics between these locations. Forest degradation can considerably affect CO_2 fluxes through the main mechanisms, such as changes in photosynthesis due to the reduction of plant biomass and increased soil respiration, which is caused by the exposure of organic matter to aerobic decomposition (Ma & Lu, 2011; Neto et al., 2011). All these changes, both in land use and in soil cover, can cause changes in the dynamics existing in these fragments, causing an imbalance in this process. The rate of CO_2 release decreases over time, due to the selective action of microorganisms that decompose (Pulrolnik, 2009). Based on this fact, the CO_2 concentrations may vary within the same zone. The reason is that microbial metabolism is not uniform at all locations; it may be affected by substrate availability, humidity, temperature, and other environmental factors.

This may explain the significant difference observed in plot 1.

Regarding CO_2 concentrations at the plot level (within the area), the results indicate a significant difference between the two groups, that is, CO_2 concentrations differ significantly between degraded and preserved areas. This outcome is caused by the minimal vegetation cover and land use modification in the Chipipa region, because, where there is degradation, vegetation that has a substantial contribution to sequestering CO_2 via photosynthesis is degrading or non-existent, this can result in increased CO_2 emissions as a result of lower vegetation cover and loss of vegetation and soil carbon sequestration capacity (Abreu, 2024). Changes in land use, due to agricultural activity, and extractivism, reduce soil carbon stocks, as well as contribute to CO_2 emissions into the atmosphere (Petrere, 2010).

In a study conducted by Reis (2019) which examined CO_2 fluxes in the soil-atmosphere interface in a Northeast Portugal agroforestry with varying management, it was noted that the soil with vegetation cover was a carbon sink with fluxes of -0.97 µmol m^{-2} s^{-1}, but it was a source for the period of June to July. The bare mobilized soil was 1.88 µmol m^{-2} s^{-1}, serving as a source of CO_2 emissions during the experiment. On the other hand, the conserved section has thicker cover with greater carbon sequestration potential. In Chipipa's situation, the use of conservation systems or methods such as direct planting, crops and animal integration, etc., favour carbon content in the soil and hence increases CO_2 sequestration from the atmosphere.

CO_2 levels in the Rainy season *(Morning vs. Afternoon* CO_2 levels *Within-Area during the rainy season)*

A Wilcoxon Signed-Rank Test was conducted to determine if there was a significant difference in CO_2 concentration between the morning and afternoon measurements within each plot. To compare CO_2 concentrations recorded in the morning and afternoon during the rainy season, a Wilcoxon Signed-Rank Test was applied. The results are summarized in Table 2, which presents the statistical analysis of CO_2 concentration differences across all sampled plots.

Table 2 - Analysis of CO_2 Concentrations: Morning vs. Afternoon During the Rainy Season
Tabela 2 - Análise das Concentrações de CO_2: Manhã vs. Tarde Durante a Estação das Chuvas

Area	Plot	Statistic	p-value	Significant
Conserved	1	7611	0.001718	Yes
Conserved	2	7336.5	0.008399	Yes
Conserved	3	5001.5	0.327658	No
Degraded	1	9205.5	4.87e-08	Yes
Degraded	2	6057	0.698546	No
Degraded	3	5954.5	0.982003	No

*Values of $p < 0.05$ indicate that the differences are statistically significant.

Results indicated a highly significant difference in CO_2 concentrations between morning and afternoon measurements for Plot 1 (W = 7611, $p < 0.01$) and Plot 2 (W = 7336.5, $p < 0.01$) of the conserved area. In degraded area, an extremely high significant difference was found for Plot 1 (W = 9205.5, $p < 0.001$). The remaining plots (in both areas) did not show any significant difference.

To assess the within-area variation of CO_2 concentrations in the degraded area, measurements were analyzed at the plot level. The results are presented in Figure 5, showing the distribution of CO_2 concentrations across the different plots within the degraded site

Figure 5 - Carbon dioxide concentrations at plot level (within-area analysis) in Degraded area
Figura 5 - Concentrações de dióxido de carbono a nível das parcelas (análise dentro da zona) na zona degradada
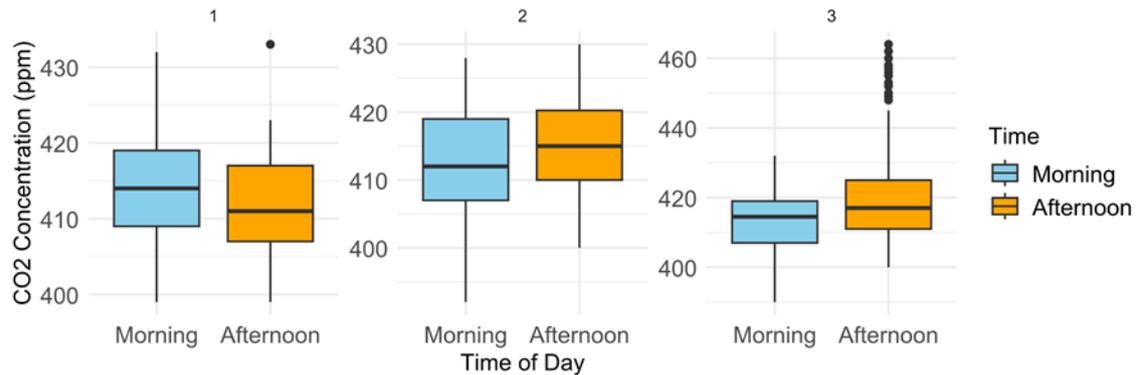
Similarly, to examine the within-area variation of CO_2 concentrations in the conserved area, plot-level measurements were analyzed. Figure 6 illustrates the distribution of CO_2 concentrations across the plots in the conserved site

Figure 6 - Carbon dioxide concentrations at plot level (within-area analysis) in Conserved area
Figura 6 - Concentrações de dióxido de carbono a nível das parcelas (análise dentro da zona) na zona conservada
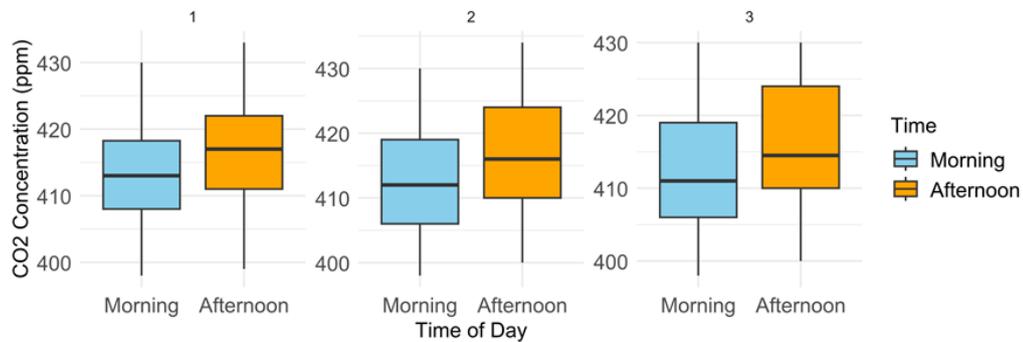
Figures 5 and 6, illustrate the CO2 concentrations recorded in each plot, segmented according to the different study areas at different times. This visual representation allows a clear comparison between the concentration variations within the plots at different times.

The figure 7, illustrate carbon concentration in degraded and conserved land during the rainy season reveal a difference in carbon concentrations between both types of environments.

Figure 7 - Carbon Dioxide Concentration in Degraded and Conserved Area During Rainy seasons
Figura 7 - Concentração de dióxido de carbono em áreas degradadas e conservadas durante as estações chuvosas
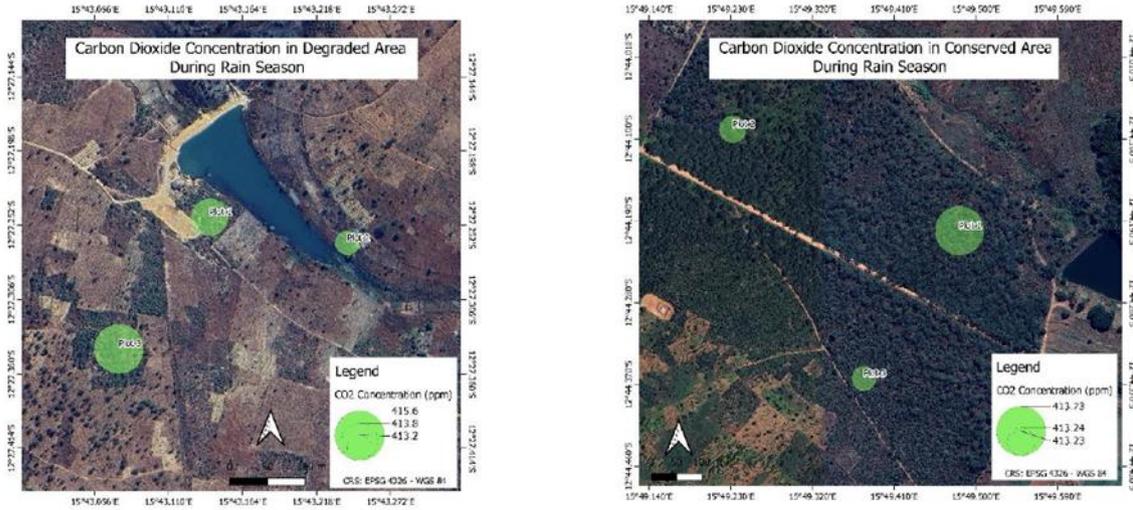

Source: Author (2024)
Fonte: Próprio autor (2024)

Between-Area Analysis (conserved vs degraded)

To compare CO_2 concentrations at the area level between degraded and conserved sections of the Miombo forest, the results of the Mann-Whitney U test are illustrated in Figure 8, which shows the distribution of CO_2 concentrations across the two areas. The test yielded a U-statistic of 448913 and a p-value of 0.327429 which is greater than the conventional alpha level of 0.05. This indicates a non-significant difference between the two groups, in other words, the CO_2 concentrations do not differ between the degraded and conserved areas.

Figure 8 - Carbon dioxide concentrations at area level (between-area)
Figura 8 - Concentrações de dióxido de carbono a nível da zona (entre áreas)
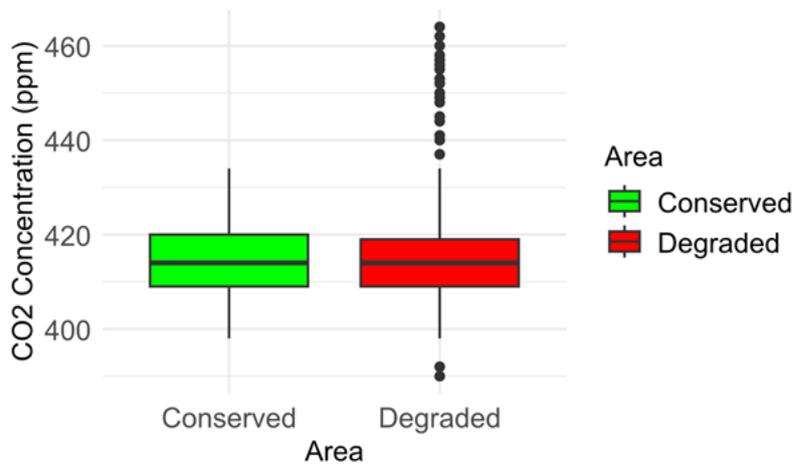
For the rainy season, the analysis of CO_2 concentrations in different plots in the degraded and preserved areas also showed notable patterns of variability in carbon dioxide concentrations, indicating differences in carbon dynamics between the two forest conditions. The results indicated a highly significant difference in CO_2 concentrations between the morning and afternoon measurements for Plot 1 and Plot 2 of the preserved area and from Plot 1 to the degraded area, indicating notable variations in carbon dynamics between these points, suggesting that different environmental factors may be influencing these results. For example, rainfall may have directly influenced CO_2 concentrations by promoting CO_2 dissolution and increasing soil moisture.

In his study Pinotti (2017), highlighted that moisture can contribute or hinder CO_2 production, since the optimal level of moisture intensifies the respiration process, providing better conditions for microbial activity, resulting in increased CO_2 emissions from the soil to the atmosphere.

In a study of CO_2 efflux in an Amazonian Cerrado Transition Forest, conducted by Pinto Junior et al.(2007), the concentration of CO_2 varied significantly throughout the year, and the highest value was recorded in August (2.88 $\mu mol\ m^{-2}\ s^{-1}$), due to the low soil water content characteristic of the dry period. On the other hand, the highest concentrations were recorded in October (8.45 $\mu mol\ m^{-2}\ s^{-1}$), during the rainy period. The rise in moisture content at this phase created optimum conditions for soil microbial activity, and the subsequent rise in CO_2 efflux reflected the direct effect of soil moisture on microbial respiration, with the rainy season as the most effective phase in the rise in environmental activity and hence in CO_2 emissions.

This suggests that, at certain times of the day, rainfall favoured microbial activity, resulting in higher CO_2 concentrations. On the other hand, when the amount of water in the soil increased significantly, CO_2 production was reduced, because excess water negatively affected microbial activity, which ends up corroborating the work of (Chambers et al., 2004), which states that soil saturation caused by high precipitation limits the diffusion of CO_2 during the microbial respiration.

According to the author, the efflux of CO_2 from the soil depends on the gradient of gas transport in the soil and between the soil and the atmosphere, and this is affected by the fraction of soil pores filled with air or water. The other plots (in both areas) did not present significant differences, suggesting a certain uniformity in the carbon dynamics between these locations.

Regarding CO_2 concentrations at the plot level (within the area), the results indicate that CO_2 concentrations do not differ between the degraded and preserved areas, that is, there were no significant differences between the degraded area and the preserved area during the rainy season. Since parameters such as temperature, humidity level, nutrient availability and photosynthetic rates can alter CO_2 exchanges between soils and the atmosphere (Ma & Lu, 2011; Neto et al., 2011).

In the context of the degraded area, moisture from rainfall may have favoured an increase in the carbon sequestration process, by improving vegetation conditions and microbial activity in the soil. This factor may have contributed to the fact that, at certain times, CO_2 concentrations in the degraded area approached those observed in the preserved area, which reflects a certain balance in the carbon capture process as the vegetation recovered and the carbon sequestration capacity increased. Taking into account that younger and smaller trees tend to allocate more carbon (Conterno, 2023).

3.2 CO_2 levels Between seasons (dry and rainy season)

To assess seasonal differences in CO_2 concentrations, the results of the Mann-Whitney test are presented in Figure 9, which illustrates CO_2 levels during the dry and rainy seasons.

Figure 9 - Carbon dioxide levels in dry and rainy seasons
Figura 9 - Níveis de dióxido de carbono nas estações seca e chuvosa
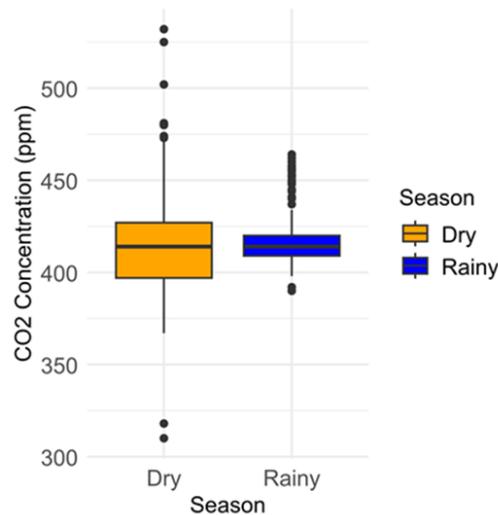
From the comparison of the carbon dioxide concentrations between degraded and preserved areas during the rainy and dry seasons, it was observed that the CO_2 concentration was consistently higher in the degraded area than in the preserved area. This observation is based on the decreased carbon sequestration potential owing to the decrease in photosynthesis and the greater release of stored carbon in the soil. In addition, changes in land use, combined with management practices, contribute to changes between soil carbon inputs and outputs, as they directly affect the soil structure and its microbiota (Primieri, 2017). When there is deforestation for agriculture, livestock, and urbanization, the carbon stored by trees and in the soil is released into the atmosphere (Rodrigues, 2021).

In Brazil, changes in land use are responsible for 44% of greenhouse gas emissions (De Sousa, 2022). According to Primieri (2017), changes in land use represent the human actions that most affect this balance. The magnitude of carbon losses can reach a range of 25 to 75%, depending on previous levels of land use, management and climate (Lal, 2006). The concentration of carbon dioxide in degraded areas is often associated with an imbalance between the rates of carbon absorption and emission, with degraded areas tending to release more CO_2 into the atmosphere than in preserved areas (Santa Brigída, 2023).

In a study conducted by Romua et al. (2024), carried out in northern Mozambique, which aimed to assess the main human activities that most contribute to the degradation of the Miombo forest, it was found that agriculture stands out as the main cause of deforestation. The research ascertained that the expansion of agriculture has led to the massive loss of 174.5 hectares of forest. In the Angolan situation, the author Kussumua (2021) ascertained that deforestation for charcoal production, agriculture, and forest fires are the principal drivers of forest degradation. Among the various components of soil organic matter, microbial biomass is considered a highly sensitive indicator of changes caused by land use and is considered the central compartment of the carbon cycle (Pulrolnik, 2009).

When viewed from the angle of use and management, soil has the ability either to emit carbon dioxide into the atmosphere or to serve as a storage site for carbon in organic matter (IPCC, 2001). Conservation land areas where soil and vegetation remain undisturbed improve the balance of carbon cycling in favor of carbon capture and CO_2 storage (Santa Brigída, 2023). In this light, the observed outcome demonstrates that preserved areas possess a higher capacity for carbon storage, while conversely, the deforested areas do nothing but act

as sources of carbon dioxide, thereby aggravating the climate change effects.

The absence of alternative income sources is quoted to be a force driving the anthropic pressure on the Miombo ecosystem (Sanfilippo, 2014). The activity, driven by the increasing demand for land use in agriculture and charcoal production, undermines the integrity of the forest and its ecosystem services like carbon sequestration, climate regulation and biodiversity. This scarcity of alternative sources of income calls for the urgency of sustainable management interventions in a bid to limit forest degradation.

3. Conclusion and Recommendations

The results of this study indicate that the levels of CO_2 in the Miombo forest are significantly impacted by land degradation as well as changing seasons. The CO_2 levels were consistently higher in the degraded forest than in the conserved forest, particularly during the dry season, with the implication that soil degradation might enhance the emission of greenhouse gases. Besides, the CO_2 was greatly varied between morning and afternoon samples in line with the dynamics of soil respiration due to the impacts of such factors as temperature, humidity, and organic matter. Moreover, CO_2 concentration was greater during the dry season, indicating the impact of seasonality on carbon flux.

These findings support the need for forest protection at priority levels and use of sustainable land use management in a bid to fight CO_2 emissions and address the broader issue of climate change. Drawing from these findings, several recommendations can be advanced.

Plans to restore degraded land by means of reforestation or afforestation programs should be implemented in order to prevent the excessive CO_2 emissions associated with soil degradation. This can be done by introducing indigenous vegetation that enhances soil quality and increases carbon sequestration. Since there are bound to be fluctuations in CO_2 concentration seasonally, a more efficient monitoring system should be adopted to quantify carbon emissions annually. This will allow better comprehension of soil respiration seasonal patterns and its interconnection with climate change.

Policy interventions and public awareness campaigns both at the national and local levels would be necessary to re-establish the importance of keeping forests and land management on the path towards sustainable development. National and local policy interventions would assist in offering incentives to landowners in adopting low-carbon emission approaches and ecological restoration. Further research is needed to investigate some of the interactions between vegetation cover, carbon emissions, and soil degradation in the Miombo forest. The more one understands these issues, the better carbon flux prediction models will be created and the better mitigation practices will be formulated.

These recommendations, as indicated by the findings of this research, are aimed at ensuring an effective measure for reducing CO_2 emissions, enhancing the resilience of the Miombo forest, and fight climate change impacts in the Miombo.

4. Acknowledgments

5. References

Abreu, N. L., Ribeiro, E. S. D. C., Sousa, C. E. S. D., Moraes, L. M., Oliveira, J. V. C. D., Faria, L. D. A., ... & Silva, T. C. D. (2024). Mudanças de uso da terra e emissão de gases de efeito estufa: uma explanação sobre os principais drivers de emissão. **Ciência Animal Brasileira**, 25, 77646E.

ANDREWS, Christopher A. et al. Resilience, remoteness and war shape the land cover dynamics in one of the world's largest miombo woodlands. **Trees, Forests and People**, v. 17, p. 100623, 2024.

Aquino, A. R. (2016, August 9). Combating Deforestation in the Miombo Forests of Southern Africa. Retrieved from https://blogs.worldbank.org/pt/nasikiliza/combate-ao-desmatamento-nas-florestas-de-miombo-da-africa-austral

BRACHTVOGEL, C., FERNANDES, A. C. D. Q., NIEDACK, L., PEREIRA, Z. V., & PADOVAN, M. P. (2018). Sistemas Agroflorestais Biodiversos: Potencial para Sequestro de Carbono. **Cadernos de Agroecologia**, 13(2), 1.

CHAMBERS, J. Q.; TRIBUZY, E. S.; TOLEDO, L. C.; CRISPIM, B. F.; HIGUCHI, N.; DOS SANTOS, J.; DE ARAÚJO, A. C.; KRUIJT, B.; NOBRE, A. D.; TRUMBORE, S. Respiration from a tropical forest ecosystem: partitioning of sources and low carbon use efficiency. **Ecological Applications**, v. 14, p. S72–S88, 2004.

Conterno, L. (2023). Como o efeito do CO_2 nas plantas afeta o aquecimento global? https://jornal.usp.br/ciencias/como-o-efeito-do-co2-nas-plantas-afeta-o-aquecimento-global/

Dewees, P. A., B. M. Campbell, Y. Katerere, A. Sitoe, A. B. Cunningham, A. Angelsen & S. Wunder. (2010). Managing the miombo woodlands of Southern Africa: policies, incentives and options for the rural poor. **Journal of natural resources policy research**, 2(1), 57-73.

DE SOUZA, Gessica Cardoso Pereira et al. **Crescimento econômico, desmatamento e emissões de gases de efeito estufa: análises prospectivas para os biomas brasileiros numa perspectiva de sustentabilidade.** 2022.

Edenhofer, O. (Ed.). (2015). Climate change 2014: mitigation of climate change (Vol. 3). Cambridge University Press.

ENPRF. (2011). Estratégia Nacional de Povoamento e Repovoamento Florestal. Projeto de Avaliação Espacial do estado das Florestas e Ecossistemas Sensíveis de Angola. **Instituto de Desenvolvimento Florestal.**

FERREIRA, E. A. B.; RESCK, D. V. S.; GOMES, A. C. **Medidas do fluxo de CO_2 do solo pelos métodos da absorção alcalina e analisador de gás infravermelho em diferentes sistemas de manejo no Cerrado.** 2005.

Harris, N., & Gibbs, D. (2021, January 22). Forests absorb twice as much CO_2 as they emit per year. Retrieved from https://www.wribrasil.org.br/noticias/florestas-absorvem-duas-vezes-mais-co2-do-que-emitem-por-ano.

HENRIQUES, I. C. M., MONTEIRO, A. Y MOREIRA, I., (2009). Efeito dos tratamentos fitossanitários na produção de cultivares de batateira (Solanum tuberosum L.) no Planalto do Huambo (Angola). **Revista de Ciências Agrárias**, 32, 182-193.

HUANG, Xingzhao et al. Land use change alters soil organic carbon: constrained global patterns and predictors. Earth's Future, v. 12, n. 5, p. e2023EF004254, 2024.

IPCC. (2001). *Climate change 2001:* **The scientific basis**. 881p. Cambridge: Cambridge University.

IPCC. (2014). Summary for policymakers In: *Climate Change 2014:* **Impacts, Adaptation, and Vulnerability.** Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Inventário Florestal Nacional. IDF-Instituto de Desenvolvimento Florestal; Inventário Florestal Nacional: Luanda, Angola, 2018. [Google Scholar]

KISSANGA, Raquel. Valorização, impactos e utilizações dos recursos florestais da província da Huíla (Angola). 2024.

Kussumua, S. F. (2021). Panorama florestal em Angola. **Ojeando la Agenda**, (70), 2.

Kussumua, S. F., & Quissindo, I. A. B. (2020). Análise da área florestal e do uso do solo da floresta de miombo angolano entre 2001-2018. **Revista Eletrónica KULONGESA–TES**, 2(2), 181-192.

Lal, R. (2006). Soil carbon sequestration in Latin America. In: Lal R, Cerri CC, Bernoux M, Etchevers J, Cerri E, editores. *Carbon sequestration in soils of Latin America*. **New York: Haworth Press.**

Lima, S. S. (2022). **Dinâmica do uso do solo e cobertura vegetal da Ibiapaba, uma área prioritária para conservação da caatinga, e seu entorno entre os anos de 2005 à 2020.**

Ma, K., & Lu, Y. (2011). Regulation of microbial methane production and oxidation by intermittent drainage in rice field soil. **FEMS microbiology ecology**, 75(3), 446-456.

Mendelsohn, J.M. (2009). Landscape changes in Angola. In **Biodiversity of Angola. Science & Conservation**: *A Modern Synthesis*; Huntley, B.J., Russo, V., Lages, F., Ferrand, N., Eds.; Springer: Berlin/Heidelberg, Germany.

MIAPIA, Luis M., et al. (2021). Deforestation and Biomass production in Miombo forest in Huambo (Angola): a balance between local and global needs. **Forests,** 12(11), 1557.

Neto, E. S., Carmo, J. B., Keller, M., Martins, S. C., Alves, L. F., Vieira, S. A., Piccolo, M. C., Camargo, P., Superior, E., Luiz, D. A. (2021). Soil-atmosphere exchange of nitrous oxide, methane and carbon dioxide in a gradient of elevation in the coastal Brazilian Atlantic. **Biogeosciences.**

Pinotti, C. R. (2017). **Variabilidade espaço-temporal da emissão de CO_2 do solo em área de eucalipto no Cerrado do Mato Grosso do Sul**.

PINTO-JUNIOR, O. B.; SANCHES, L.; DALMOLIN, A. C.; DE NOGUEIRA, J. S. Efluxo de CO_2 do solo

em floresta de transição Amazônia Cerrado e em área de pastagem. **Acta Amazonica**, 39(4), 813-821, 2009.

PRIMIERI, Silmar; MUNIZ, Aleksander Westphal; LISBOA, Henrique de Melo. (2017). Dinâmica do carbono no solo em ecossistemas nativos e plantações florestais em Santa Catarina. **Floresta e Ambiente**, 24, e00110314.

Reis, L. B. (2019). **Estudo comparativo dos fluxos de CO₂ na interface solo-atmosfera em sistema agroflorestal com manejo contrastante no nordeste de Portugal** (Master's thesis, Instituto Politécnico de Bragança, Portugal).

Ribeiro, N. S., Snook, L. K., de Carvalho Vaz, I. C. N., & Alves, T. (2019). Gathering honey from wild and traditional hives in the Miombo woodlands of the Niassa National Reserve, Mozambique: What are the impacts on tree populations?. **Global Ecology and Conservation**, 17, e00552.

ROMUA, Cássimo Lacerda et al. (2024). Atividades antrópicas que contribuem para a degradação da Floresta de Miombo na envolvente do Monte Unango, em Moçambique. **Ciência Florestal,** 34(4), e88227-e88227.

Ryan, C.; Williams, M.; Grace, J. (2011). Above and Belowground Carbon Stocks in a Miombo Woodland Landscape of Mozambique. **Biotropica**, 43, 423–432.

RODRIGUES, Vinícius Picanço; GUZZO, Daniel; PACHECO, Gabriela Marques Bordallo. (2021). **Análise de custo-benefício do desmatamento na Amazônia para atividade pecuária**.

Sanfilippo, M. (2014). Trinta árvores e arbustos do miombo Angolano. **Guia de Campo para a Identificação.**

SILVA, Mylena Vieira et al. (2015). Análise do perfil vertical de CO₂ em uma área de floresta na Amazônia central. **Ciência e Natura**, 37(1), 22-26.

SINELA, A. et al. (2024). Restaurando pastagens degradadas: pomares transformam pátios escolares para um futuro promissor. Huambo: **FAO**.

Soares, T. O., de Almeida, A. A., de Morais, A. E. F., da Costa Sousa, M. C. B., & Leite, T. S. A. (2019). IMPACTOS AMBIENTAIS CAUSADOS PELO DESMATAMENTO: UMA REVISÃO SISTEMÁTICA DA LITERATURA. **Revista Saúde e Meio Ambiente**, 9(2).

TEIXEIRA, A. P. A. (2014). A influência da variabilidade espacial e sazonal sobre o efluxo de dióxido de carbono do solo em ambientes modificados na FLONA Caxiuanã-PA.

YU, Hao; SONG, Wei. Research progress on the impact of land use change on soil carbon sequestration. Land, v. 12, n. 1, p. 213, 2023.

Zhang, Zheyu et al. (2023). Responses of soil respiration and its sensitivities to temperature and precipitation: A meta-analysis. **Ecological Informatics**, 75, 102057.