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Measuring Gross Carbon Dioxide Emissions from Forest Fires in the *Abrace o Pantanal* Project Area*

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Abstract. This study aims to evaluate the impact of the *Abrace o Pantanal* (Embrace the Pantanal) project on reducing carbon dioxide emissions caused by forest fires in the Pantanal biome in Brazil. The project consists of early detection and monitoring of wildfires using high-resolution cameras and satellite data, aided by the Pantera platform, which facilitates communication and the mobilization of firefighting brigades. The project covers 2.5 million hectares of the Pantanal biome, with five cameras installed in the Serra do Amolar region, an area severely affected by wildfires in 2020. To measure the project's impact on reducing carbon dioxide emissions, we used the Intergovernmental Panel on Climate Change (IPCC) Guidelines to calculate gross emissions from forest fires. We also analyzed burned area per year and land cover in the project area from 2016 to 2020 using MapBiomas Fire Collection 1 and Land Use and Land Cover Maps (Collection 6) from Mapbiomas. Our results show that the project reduced burned areas

* This manuscript is the early result of the 2022 wildfire season and research concerning emissions from avoided wildland fires in the Brazilian Wetlands (Pantanal). The financing institution, umgraumeio, is responsible for implementing the Pantera system sponsored by the private sector and has financially supported the research.

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and emissions from fires, with highly discrepant results in 2020 due to catastrophic fires. To verify the concrete impacts of the project, we propose measuring the number of fire outbreaks detected, conducting interviews with firefighters, and comparing the results from 2021 to 2025 with the previous period. The average burned area and carbon dioxide emissions from 2016 to 2020 will be a reference value. Nevertheless, other factors may also affect the frequency and intensity of forest fires, such as climate change, demographic changes, and regulatory and political pressure. Therefore, it is impossible to establish a strict causal relationship between the project and the reduction of burned areas and emissions. In conclusion, the *Abrace o Pantanal* project has shown promising results in reducing carbon dioxide emissions from forest fires in the Pantanal biome. Continued monitoring and evaluation of the project's impact is crucial to understanding the effectiveness of early detection and firefighting measures in preserving the Pantanal's biodiversity and reducing greenhouse gas emissions. Community empowerment (through the appropriation of the technology) has played a major role in the development of the project and its overall impact.

Keywords: Brazilian wetlands, CO_2 emissions, Embrace the Pantanal, wildland fires

Medición de las emisiones brutas de dióxido de carbono de los incendios forestales en la zona del proyecto Abrace o Pantanal

Resumen. Este estudio busca evaluar el impacto del proyecto Abrace o Pantanal (Abrace el Pantanal) en la reducción de las emisiones de dióxido de carbono causadas por los incendios forestales en el bioma del Pantanal, en Brasil. El proyecto consiste en la detección temprana y el seguimiento de los incendios forestales mediante cámaras de alta resolución y datos por satélite, con la ayuda de la plataforma Pantera que facilita la comunicación y la movilización de las brigadas de bomberos. El proyecto abarca 2,5 millones de hectáreas del bioma del Pantanal, con cinco cámaras instaladas en la región de Serra do Amolar, una zona gravemente afectada por los incendios forestales de 2020. Para medir el impacto del proyecto en la reducción de las emisiones de dióxido de carbono, utilizamos las Directrices del Grupo Intergubernamental de Expertos sobre el Cambio Climático (IPCC, por sus siglas en inglés) para calcular las emisiones brutas de los incendios forestales. También analizamos la superficie quemada por año y la cubierta de suelo en la zona del proyecto de 2016 a 2020, utilizando la "Colección de incendios 1" y los "Mapas de uso de tierra y cobertura de suelo" (Colección 6) de Mapbiomas. Nuestros resultados muestran que el proyecto redujo las áreas quemadas y las emisiones causadas por los incendios, con datos muy discrepantes en 2020 debido a los incendios catastróficos de ese año. Para verificar los impactos concretos del proyecto, proponemos medir el número de focos de incendio detectados, realizar entrevistas a los bomberos y comparar los resultados observados de 2021 a 2025 con el periodo anterior. La superficie media quemada y las emisiones de dióxido de carbono de 2016 a 2020 serán usadas como valor de referencia. No obstante, hay otros factores que también pueden afectar la frecuencia e intensidad de los incendios forestales, como el cambio climático, los cambios demográficos y la presión normativa y política. Por lo tanto, es imposible establecer una relación causal estricta entre el proyecto y la reducción de las áreas quemadas y las emisiones. En conclusión, el proyecto Abrace o Pantanal ha mostrado resultados prometedores en la reducción de las emisiones de dióxido de carbono procedentes de los incendios forestales en el bioma del Pantanal. El seguimiento y la evaluación continuados del impacto del proyecto son cruciales para comprender la eficacia de las medidas de detección precoz y extinción de incendios en la preservación de la biodiversidad del Pantanal y en la reducción de las emisiones de gases de efecto invernadero. La capacitación de la comunidad (mediante la apropiación de la tecnología) ha desempeñado un papel fundamental en el desarrollo del proyecto y su impacto global.

Palabras clave: humedales brasileños, emisiones de CO_2, Abrace el Pantanal, incendios forestales

Avaliação das emissões brutas de dióxido de carbono dos incêndios florestais na região do projeto "Abrace o Pantanal"

Resumo. Neste estudo, pretende-se avaliar o impacto do projeto "Abrace o Pantanal" na redução das emissões de dióxido de carbono causadas pelos incêndios florestais no bioma do Pantanal, no Brasil. O projeto consiste na deteção precoce e seguimento dos incêndios florestais mediante câmeras de alta resolução e de dados por satélite, com a ajuda da plataforma Pantera, que facilita a comunicação e mobilização das brigadas de bombeiros. O projeto abrange 2,5 milhões de hectares do bioma do Pantanal, com cinco câmeras instaladas na região da Serra do Amolar, uma região gravemente afetada pelos incêndios florestais de 2020. Para avaliar o impacto do projeto na redução das emissões de dióxido de carbono, utilizamos as diretrizes do Painel Intergovernamental sobre Mudança do Clima (IPCC, na sigla em inglês) para calcular as emissões brutas dos incêndios florestais. Também analisamos a superfície queimada por ano e a cobertura de solo na região do projeto de 2016 a 2020, utilizando a coleção de incêndios 1 e os mapas de uso da terra e de cobertura de solo (coleção 6) de Mapbiomas. Nossos resultados mostram que o projeto reduziu as áreas queimadas e as emissões causadas pelos incêndios, com resultados muito discrepantes em 2020 devido aos incêndios catastróficos desse ano. Para verificar os impactos concretos do projeto, propomos avaliar o número de focos de incêndio detectados, realizar entrevistas com os bombeiros e comparar os resultados observados de 2021 a 2025 com período anterior. A superfície média queimada e as emissões de dióxido de carbono de 2016 a 2020 são usadas como valor de referência. Contudo, há outros fatores que também podem afetar a frequência e intensidade dos incêndios florestais, como a mudança climática, as mudanças demográficas e a pressão legal e política. Portanto, é impossível estabelecer uma relação causal estrita entre o projeto e a redução das áreas queimadas e das emissões. Em conclusão, o projeto "Abrace o Pantanal" vem mostrando resultados promissores na redução das emissões de dióxido de carbono procedentes dos incêndios florestais no bioma do Pantanal. O seguimento e avaliação continuados do impacto do projeto são cruciais para compreender a eficácia das medidas de deteção precoce e extinção de incêndios na preservação da biodiversidade do Pantanal, bem como da redução das emissões de gases de efeito estufa. O treinamento da comunidade (mediante a apropriação da tecnologia) vem desempenhando um papel fundamental no desenvolvimento do projeto e seu impacto global.

Palavras-chave: zonas úmidas brasileiras, emissões de CO_2, "Abrace o Pantanal", incêndios florestais

1 Introduction

In 2020, a mega-fire of catastrophic proportions affected 26% of the Pantanal in Brazil (Lois, 2021), one of the major world biosphere reserves of the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the largest tropical wetland in the world, with an area of 150,355 km^2 (UNESCO, 2020). During this event, 3.9 million hectares were burned, 17 million vertebrates died (Lois, 2021), and about 115 million tons of CO_2 were emitted into the atmosphere (Pletsch *et al.*, 2021).

The factors causing this environmental tragedy are associated with a historical drought that struck the region after 30 years of reduced flows of streams and rivers, exposing large areas of peat, a biomass of high combustion, and high temperatures. Still, as an aggravating factor, there is the direct action of humans, with the intent to burn, using fire for management, trash burning, and other criminal objectives harmful to the ecosystem. According to Marengo *et al.* (2016), 98% of forest fires are caused by human activities, whether accidental or criminal. Based on the recent history of occurrences, in addition to predictions, a loss of up to 74% of the Pantanal's native vegetation cover is projected by 2030 (Miranda *et al.*, 2018), with the possibility of new fire events of catastrophic proportions (Berlinck *et al.*, 2022).

Soon after the mega-fire, a group composed of representatives of the Public Ministry, scientists, researchers, non-governmental organizations, and the private sector met to design a resilience plan and monitoring strategy for the Pantanal, aiming to support local institutions that have historically fought fires in the biome.

This collaborative effort resulted in the *Abrace o Pantanal* (Embrace the Pantanal) project, with the holistic vision of monitoring and managing firefighting in real-time and protecting biodiversity. The project translated into the integrated platform called Pantera, which helps coordinate the fight against forest fires, developed by climatech umgrauemeio.

Understanding the growing planetary impacts of wildfires on climate change starts with the emissions caused by them, consisting of 20% of global carbon emissions. Higher emissions trap more heat into the atmosphere, scaling the Earth's temperature. This rise in the Earth's temperature alters wind patterns, which increases oxygen and causes fires to burn at higher temperatures. It also influences plant humidity and flammability by establishing higher atmospheric instability and lowering relative humidity, which makes plants drier by increasing evaporation and consequent dryness.

Wildfires also change the distribution of vegetation by shifting biomes and creating more fuel by altering the dynamics and plant structures, making wildfire progression easier and providing room for fast-growing species that will dry the land and increase biomass fuel.

Emissions from wildfires are just the beginning of a long-term continuous downward spiral of degradation that will affect not only plant species but also vertebrates, soil, water, and, consequently, human health. All those negative impacts are inseparable from extensive social and economic factors, such as increasing poverty, food insecurity, and climate displacement, which impact children and women the most.

As much as 90% of forest wildfires in the United States are caused by people, and it is not different in Brazil. Social, economic, and political reasons related to territory occupancy and radical extractive economy are the triggering reasons behind the rising crisis and aggressiveness of wildfires. To tackle this, it is necessary to go beyond a "one-shot" solution, be it technology, fire operations efficiency, prevention efforts, or an active state that pursues and punishes environmental crimes.

From this perspective, the approach must be holistic, fulfill the principles of firefighting, and bring social well-being into account. Communities must be empowered, and territorial analysis and support must come from governments, private sectors, and academic researchers; every step of the way must be measured, tested, and retrofitted. A step-by-step modeling strategy showed us in the Pantanal ways to implement a 360° approach, bringing all stakeholders together.

The ways to implement it in other UNESCO biosphere reserves impacted by wildfires could follow a similar approach as in the Pantanal, of course, respecting cultural and social organizations to improve the already existing communities' efforts to tackle wildfires.

Expanding this model to areas in the early stages of fire operations that need training, equipment, resources, and government support is one of the building blocks of a long-term strategy. Helicopters and fast-response infrastructure are also key factors in acting fast to prevent fire from spreading and reaching catastrophic conditions. Every fire outbreak starts small; every second counts in fire operations and can be the difference between life and death. Nevertheless, in Brazil, there are no airplanes or helicopters fully dedicated to fire operations.

This paper proposes to showcase how the system aims to reduce the Pantanal's burned area and consequent fugitive carbon dioxide emissions through early detection and rapid response to fires, made possible by implementing the *Abrace o Pantanal* project and the Pantera platform. Subsequently, the authors present the basis for a future evaluation to determine whether the *Abrace o Pantanal* project has managed to decrease its burned area and carbon dioxide emissions.

To this end, the first section after this introduction will describe the monitored area and the operation of monitoring and early detection through the Pantera platform. Next, the methodological approach for determining burned areas and consequent estimates of fugitive carbon dioxide emissions from forest fires will be discussed. The third section will expose the results of burned areas and estimated emissions in the monitored region for 2016-2020. Finally, the monitoring of burned areas (also called fire scars) and their respective emissions will be proposed for the following five years to verify whether the implemented system allowed the reduction of both.

2 Project area, early detection, and monitoring operation

2.1 Monitoring and early detection

The *Abrace o Pantanal* project to protect the Pantanal was embraced by the JBS company, which sponsored the implementation of its first phase. The project started its operational stage in the pre-fire season in Brazil. The main stakeholders of the project are JBS, its sponsor; umgrauemeio, in charge of developing and implementing the system that monitors and detects wildfires, besides aiding in resource management for firefighting; local brigades, responsible for using the Pantera system and effectively fighting the detected outbreaks, comprised of Brigada Aliança in the South region, Instituto Homem Pantaneiro (IHP) in the Center region, and Serviço Social do Comércio (Sesc) Pantanal in the North region. The centers of each brigade received computers, monitors, and a video panel to facilitate the detection and confirmation of outbreaks and their rapid combat.

The project's first phase monitors 2.5 million hectares of the Pantanal biome. The monitoring happens through high-resolution cameras installed on top of communication towers at up to 60 meters height and various satellite data. The Pantera software carries out early detection through an artificial intelligence algorithm that identifies fire outbreaks using the images of the cameras and notifies system operators. Camera monitoring alone can identify fire outbreaks within a 15 km radius in approximately three minutes. The triangulation of camera views makes it possible to determine the exact position of a fire outbreak to facilitate the fight. However, the complementary use of satellite data enables the cameras to be pointed at a potential outbreak up to 30 km to verify that it is indeed a fire outbreak.

In the first phase of the *Abrace o Pantanal* project, five cameras were distributed throughout the Serra do Amolar territory, a central region of the Pantanal under the governance of the IHP, which had more than 90% of its protection network affected by the 2020 mega-fires. Figure 1 shows the position of the cameras in the region.

Rapid response is the result of the communication, mobilization, and combat planning capacity of the brigades facilitated by the Pantera platform. The integration of information on the brigades' location, resources, and available equipment, activation time,

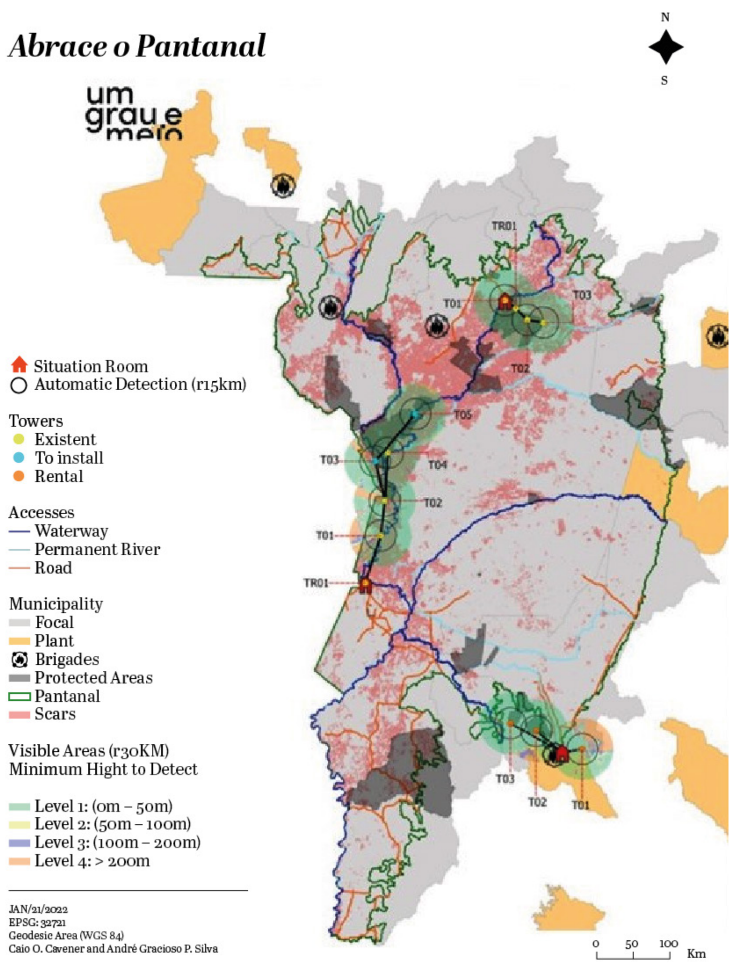

Figure 1. Positioning of the communication towers in the *Abrace o Pantanal* project. *Source*: Own elaboration.

travel time to the outbreak location, time to fight and extinguish the outbreak, and contact of landowners in the territory allows a rapid response to fire, drastically reducing negative impacts such as loss of biodiversity and greenhouse gas emissions.

2.2 Project area and emissions verification

As described above, the project area is subdivided into three clusters—North, Central, and South. Figure 2 shows the geographical boundaries of the monitored areas and the 30 km monitoring radius in relation to the towers' positions.

To estimate burned area reduction and their respective emissions, the area resulting from the intersection between the 30 km radius of monitoring towers and the project area was considered. In case the project area is outside the monitoring radius, the system will not be able to identify any fire outbreak, making the burned area reduction in the region independent of the Pantera system. Simultaneously, if the area is within the monitoring radius but outside the project area, the detected outbreak will not necessarily be responded to by the project brigades. Thus, these areas were disregarded for analysis purposes. Figure 3 shows the area considered for analysis. The determined area is 436,667 hectares.

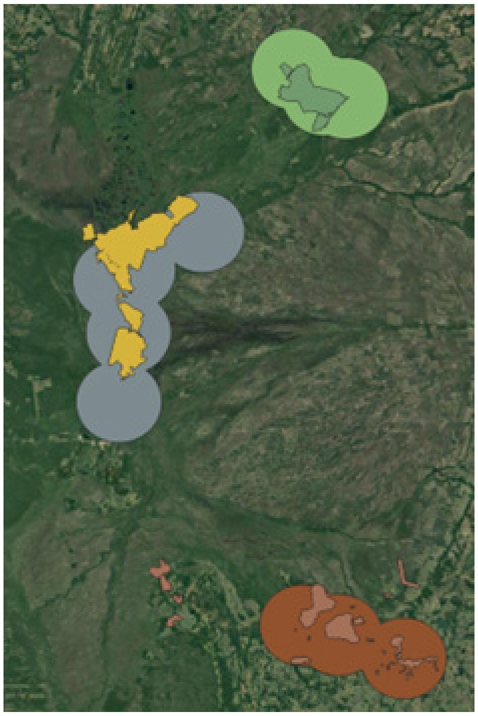

Figure 2. Project area and monitored area. The circles represent the 30 km radius regarding the position of the towers. *Source*: Own elaboration.

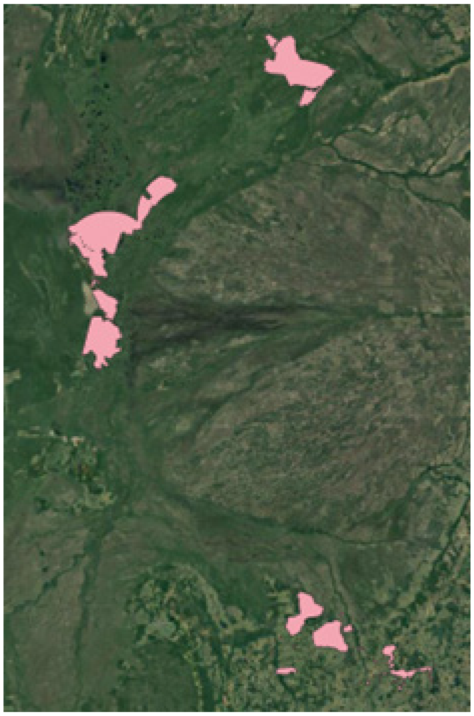

Figure 3. Intersection between project area and the monitoring radius of the towers. *Source*: Own elaboration.

3 Methodology

To measure gross carbon dioxide emissions from forest fires in the project area between 2016 and 2020, first, we used Equation 2.7 of the Intergovernmental Panel on Climate Change (IPCC) Guidelines (Eggelston *et al.*, 2006) as a basis:

$$L_{fire} = A \times M_b \times C_f \times G_{ef} \times 10^{(-3)} \quad \text{(Equation I)}$$

Where:

L_{fire}: amount of carbon dioxide emitted, in tons;

A: burned area, in hectares;

Mb: mass of fuel available for burning, in ton/hectare;

Cf: combustion factor, dimensionless (how much of the fuel mass burns)

Gef: emission factor, in g/kg (how much of the burned mass is converted into carbon dioxide).

Each L_{fire} corresponds to the total carbon dioxide emission of a specific vegetation within the project area. Therefore, to arrive at the final value, it is necessary to sum all the gross emission plots per vegetation.

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The burned area is calculated based on the adaptation of Equation 21 of the VMD0015 Methods (version 2.2) (Verra, 2020)[1]:

$$A = \sum_{q=1}^{Q} A_{burn,q,t} \qquad \text{Equation II}$$

Where:

$A_{burn,q,t}$:	burned area, in hectares, obtained from the scar maps of MapBiomas Fire Collection 1 (MapBiomas, 2022a), in stratum q, in year t;
q:	1, 2, 3... Q post-natural disturbance stratum where there is fire incidence;
t:	1, 2, 3... t year in which the burned area was verified.

To obtain $A_{burn,\,q,t}$, MapBiomas Fire Collection 1 (MapBiomas, 2022a) was used. This toolkit includes the following data: annual occurrence of fire scars; monthly occurrence of fire scars; and fire frequency. The information used was the annual occurrence of fire frequency. There, for each year, the burned area is stored in a different band, called "burned_area," followed by the year of detection. Data are limited to the period between 1985 and 2020 in the current collection. All mapping is performed with mosaics of Landsat satellite images with a pixel resolution of 30 meters. The MapBiomas product was chosen for this survey because it uses good-resolution images from the Landsat 5, 7, and 8 satellites, and artificial intelligence algorithms (deep neural networks) are able to process these data for a more accurate result.

To determine the land cover of burned areas, the present study used the Land Use and Land Cover Maps (Collection 6), also from Mapbiomas (MapBiomas, 2022b). Based on the cross-referencing of burned areas and land cover and land use data, it was possible to estimate other factors to consider and carbon dioxide emissions from fire.

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1 The equation proposed by Verra (2020) is as follows:

Where:

$$A = \sum_{q=1}^{Q} A_{burn,q,t} \qquad \text{Equation II}$$

$A_{burn,q,i,t}$: Area burned in post-natural disturbance stratum q in stratum i, in year t, in hectares;

q: 1, 2, 3... Q post-natural disturbance stratum where there is fire incidence;

i: 1, 2, 3... M strata;

t: 1, 2, 3... t year in which the burned area was verified.

The authors have suppressed the *i* variable for it would not change the analysis and therefore was unnecessary.

IPCC establishes that emissions analysis may be of Tier 1, using generic factors provided by IPCC; Tier 2, which are factors that consider local data in their compositions; and Tier 3, based on specific factors with data collected from the field. All factors used here come from the IPCC Guidelines (Eggelston *et al.*, 2006) and are generic. Thus, it is not to determine emissions very precisely expected in this paper, only to estimate the scale of impact of the monitoring and early detection allowed by the Pantera platform. To this end, the factors used for each land cover type are equivalent to a Tier 1 estimate according to IPCC criteria.

Table 1 below brings together the land cover types identified in the analyzed area and their respective Gef and Mb x Cf factors—the IPCC (2006) tables directly indicate a product between the two.

Phytophysiognomy	Mb x Cf (ton/hectare)	Gef (g/kg)
Forest Formation	83.9	1,580
Savanna Formation	4.6	1,613
Flooded Field and Swampy Area	4.6	1,613
Countryside Formation	23.7	1,613
Pasture	23.7	1,613

Table 1. Factors used in the analyzed area. *Source*: Eggelston *et al.* (2006).

4 Results

Table 2 displays the results found for burned area per year and land cover in the analyzed area.

Year	Forest Formation	Savanna Formation	Flooded Field and Swampy Area	Countryside Formation	Pasture	Total
2020	44,547.13	29,793.60	18,725.52	78,219.62	1,600.67	**172,886.54**
2019	1,101.72	2,139.03	2,210.43	12,827.17	2,415.66	**20,694.01**
2018	62.52	387.48	0.00	206.18	5.24	**661.42**
2017	1,668.23	1,602.49	611.83	5,590.77	2,299.83	**11,773.15**
2016	133.63	3,269.20	141.64	2,224.58	57.01	**5,826.06**

Table 2. Burned area per year and phytophysiognomy in the analyzed area (hectares).

Finally, Table 3 displays the estimated CO_2 emissions from the application of Equation I.

Year	Forest Formation	Savanna Formation	Flooded Field and Swampy Area	Countryside Formation	Pasture	Total
2020	5,905,256.65	221,062.55	138,939.61	2,990,187.46	61,190.57	**9,316,636.84**
2019	146,046.21	15,871.17	16,400.95	490,358.34	92,346.09	**761,022.76**
2018	8,287.78	2,875.02	0.00	7,881.87	200.32	**19,244.99**
2017	221,143.91	11,890.16	4,539.66	213,724.51	87,918.13	**539,216.36**
2016	17,714.26	24,256.81	1,050.94	85,041.47	2,179.38	**130,242.86**

Table 3. Estimated CO_2 emissions from fire in the analyzed area, by phytophysiognomy (ton CO_2).

The highly discrepant results of burned area and emissions in 2020 in relation to the other study years draw attention. This is due to the catastrophic fires that occurred that year, as highlighted in the introduction of this article. Predictions such as those of Berlinck *et al.* (2022), which assume that climate change may incur similar new disasters, underscore the importance of early detection and firefighting in the region, preventing future fires of such proportions.

5 Discussion

The behavior of the emissions is not linear. Therefore, the arithmetic average of burned area and consequent carbon dioxide emissions has been considered a reference value to verify the impact of the Pantera system monitoring. If the values observed over the next five years are lower than the averages summarized in Table 4, it will be evidence that the *Abrace o Pantanal* project, together with other firefighting measures, has reduced the burned area and emissions from fires in the region.

It is important to note that there is no strict causal relationship between the efforts of the *Abrace o Pantanal* project and the reduction of burned areas. Other reasons may affect the frequency and intensity of forest fires, such as climate, demographic, regulatory, and urban changes, as well as political pressure, among others.

	Forest Formation	Savanna Formation	Flooded Field and Swampy Area	Countryside Formation	Pasture	Total
Average Burned Area (ha)	9,502.65	7,438.36	4,337.88	19,813.66	1,275.68	**42,368.24**
Average Emissions (ton CO2)	1,259,689.76	55,191.14	32,186.23	757,438.73	48,766.90	**2,153,272.76**

Table 4. Average burned area and CO_2 emissions by land cover between 2016 and 2020 in the analyzed area.

To strengthen this analysis in the future, we will measure the number of fire outbreaks detected in both periods (2016 to 2020 and five years after initiating the *Abrace o Pantanal* project). The relationship between the number of fires detected and burned areas is a solid indicator of firefighting efficiency. If there is the same number of outbreaks in two different periods but a discrepancy in the sum of burned areas, it can be concluded that the *Abrace o Pantanal* project is one of the factors causing this difference.

Based on the premise that rapid detection of fire outbreaks allows for faster fighting and, consequently, smaller fires, it is necessary to verify the perception of firefighters regarding the increase in fighting efficiency. Thus, interviews will be conducted with firefighters from Sesc Pantanal, IHP, and Aliança da Terra to collect their reports on changes in the dynamics of firefighting after the beginning of the *Abrace o Pantanal* project.

By combining the variation of burned areas, the number of fires identified, and the firefighters' reports from 2021 to 2025 in relation to the previous period, an analysis of the real impacts of the *Abrace o Pantanal* project will be carried out in terms of the reduction of areas lost to fire and its consequent CO_2.

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