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VEGETATION MORTALITY CAUSED BY FOREST FIRE IN A FRAGMENT IN THE AMAZONIA-CERRADO-PANTANAL ECOTONE: USE OF DRONES IN THE ASSESSMENT

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Resumo

Mortalidade da vegetação causada por incêndio florestal em um fragmento no ecótono Amazônia-Cerrado-Pantanal: uso do drone na avaliação. Incêndios florestais podem acarretar diversos impactos, entre estes ocorre a mortalidade da vegetação. O presente estudo avaliou a dinâmica e mortalidade pós incêndio da vegetação arbórea de um fragmento florestal na região sudoeste de Mato Grosso, fazendo uso de imagens de satélites, dados levantados *in loco* e imagens aéreas de alta resolução, obtidas com Drone. O trabalho também avaliou a eficiência do Drone para estimar parâmetros de mortalidade frente aos dados obtidos *in loco*. Os resultados apontaram que a vegetação foi fortemente impactada pelo incêndio e a incidência do mesmo e consequentemente a maior mortalidade da vegetação ocorreu em regiões mais secas dentro do fragmento. Os dados *in loco* apontaram que 41,91% dos indivíduos arbóreos morreram, enquanto o Drone estimou 37,37% de mortalidade. As estimativas feitas para toda área, baseada nos dados *in loco*, apontaram um total de 328 ind/ha mortos, Área Basal (G) morta de 5,4196 m² e Volume morto de 54,317 m³. Já os dados do Drone apontaram um total de 292 ind/ha mortos, G morta de 7,4260 m² e Volume morto de 94,7573 m³. Comparando os dois métodos a análise estatística apontou diferença entre os valores para o Número de Indivíduos e para Volume, não diferindo as estimativas para G. Conclui-se que o incêndio provocou intenso impacto na área, e que o Drone pode auxiliar nessa avaliação, sendo viável para estimar valores de G em áreas florestais como a avaliada, pois não difere das estimativas feitas com dados obtidos no campo.

Palavras-chave: VANT; Árvores Mortas; Floresta; Dinâmica; Impacto do Fogo.

Abstract

Forest fires can cause several impacts, among which is the mortality of vegetation. The present study evaluated the post-fire dynamics and mortality of the arboreal vegetation of a forest fragment in the southwest region of Mato Grosso, using satellite images, data collected on-site, and high-resolution aerial images, obtained with drone. The work also evaluated the drone efficiency to estimate mortality parameters compared with the data obtained on-site. The results showed that the vegetation was strongly impacted by the fire and its incidence and consequently, the highest vegetation mortality occurred in drier regions within the fragment. On-site data showed that 41.91% of the arboreal individuals died, while the drone estimated 37.37% mortality. The estimates made for the whole area, based on on-site data, indicated a total of 328 dead ind/ha, dead basal area (G) of 5.4196 m², and dead volume of 54.317 m³. Drone data showed a total of 292 dead ind/ha, G of 7.4260 m², and dead volume of 94.7573 m³. Comparing the two methods, the statistical analysis showed a difference between the values for the individuals' number and volume, not differing the estimates for G. It is concluded that the fire caused an intense impact in the area and drone can help in this evaluation, being viable to estimate G values in forest areas as assessed, as it does not differ from the estimates made with data obtained in the field.

Keywords: UAV; Dead Trees; Forest; Dynamics; Fire Impact.

INTRODUCTION

Forest fires can lead to various impacts on vegetation, ranging from effects on nutrient absorption by the plants and photosynthetic activity (SCALON; ROSSATO et al. 2021), to a direct impact on the mortality of specimens existing in the area (BRANDO *et al*., 2014; PEREIRA *et al*., 2016). As for mortality, the occurrence proportion varies depending on the fire intensity, causing a greater effect when the edaphoclimatic conditions are favorable to fire increase (BERENGUER *et al*., 2021), generally occurring during the dry period in Brazil (PINTO *et al*., 2021).

The species composition of the area is also decisive for the mortality rate. In general, areas composed of species typical of the savannah phytophysiognomy are more resistant to fires than species from the forest area, mainly due to their morphological adaptation and because it is a plant community shaped by the fire history (BRANDO *et al*., 2014; SILVA *et al*., 2022). Therefore, multiple factors can influence vegetation mortality in an area subjected to fire impact.

An approach to monitor the fire effect on the plant community is an on-site assessment where there are permanent plots for vegetation evaluation, as it enables us to know the conditions before the fire, facilitating the assessment of its impact on the community (SILVA et *al*., 2020a). However, evaluating exclusively the plots allows only estimates of the effect on the total area. A tool to map large areas of vegetation and possibly evaluate the fire effect throughout the region is the unmanned aerial vehicles, popularly known as drones, as they generate high-resolution aerial images allowing to monitor large areas (TORRESAN *et al*., 2020).

The drone has been an important tool in environmental impact evaluation, with uses in the forestry area (FIGUEIREDO *et al*., 2020). In native areas, some studies indicate that this tool allows estimating the biomass data, monitoring and accurately identifying dominant and codominant trees in the community's canopy (KAMEYAMA; SUGIURA 2020; TORRESAN *et al*., 2020). Despite these studies, there is a deficiency in research assessing the drones' efficiency in evaluating the fire's effect on the tree community, especially research comparing the high-resolution aerial image data with data obtained in the field to test the method's viability.

The present study aims to evaluate, with a drone, the dynamics and mortality of post-forest fire vegetation in a fragment located in the transition between the Amazon-Cerrado-Pantanal biomes, in the southwest region of Mato Grosso.

MATERIAL AND METHODS

Study area

The studied area is a forest fragment of approximately 245.6 hectares, located in the Florestan Fernandes rural settlement, on the border between the municipalities of São José dos Quatro Marcos and Araputanga, in the southwest region of the State of Mato Grosso (Figure 1). The studied fragment is located in the Amazon-Cerrado-Pantanal ecotone region, within the Amazon biome. The phytophysiognomy of the site is Forest, classified as Semideciduous Seasonal Forest (BRASIL, 1982).

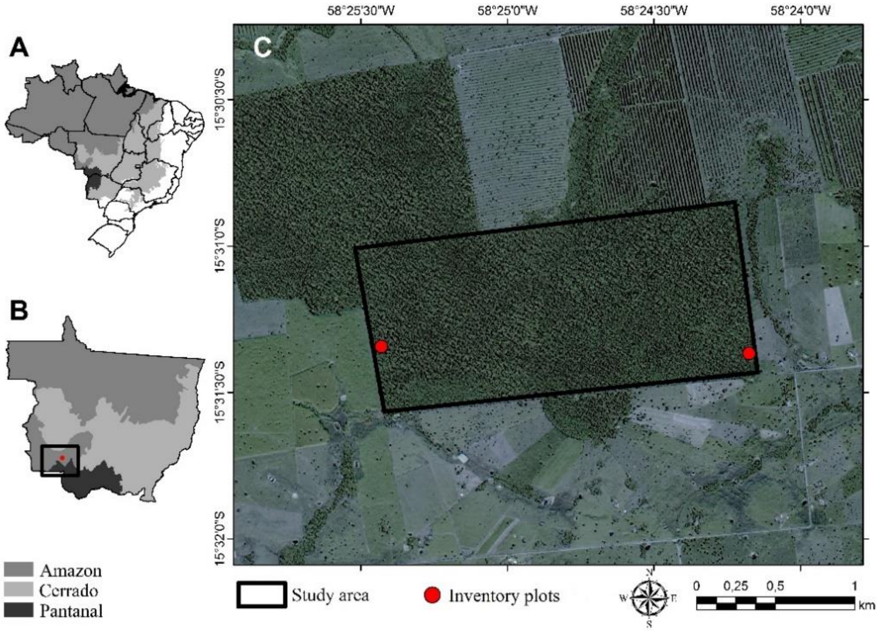

Figure 1. Study area. A – Map of Brazil; B – Map of Mato Grosso with emphasis on the region studied; C – Area of the evaluated fragment in the Florestan Fernandes Rural Settlement.

Figura 1. Área do estudo. A – Mapa do Brasil; B – Mapa de Mato Grosso com destaque para a região estudada; C – Área do fragmento avaliado no Assentamento Florestan Fernandes.

The area's tree vegetation is monitored by permanent forest inventory plots, installed, and evaluated by the research group associated with HPAN - Herbário do Pantanal "*Vali Joana Pott*", UNEMAT, Cáceres, Mato Grosso, in partnership with the Long-Term Ecological Project: Site 15 - Cerrado-Amazon Forest Transition. The studied area is located in an agricultural landscape matrix and its limits are surrounded by small and medium-sized properties, of which the vast majority use the land for agriculture and livestock. It also connects with a forest reserve area and a silviculture area.

Vegetation dynamics

The assessment of vegetation dynamics was carried out through visual temporal analysis of satellite images for the period before the fire and immediately after the fire and through ortho-photomosaic (high-resolution aerial image), generated from mapping carried out with a drone, to evaluate the area one year after the fire in the studied fragment.

The satellite images were obtained from the CBERS-4A from the Image Catalog of the National Institute for Space Research - INPE (INPE, 2022), and the Wide Scanning Multispectral and Panchromatic Camera (WPM) was selected. This satellite equipped with this type of camera provides the standard RGB (red, green, and blue), Near Infrared bands, and the Panchromatic band which through geoprocessing techniques, allows a spatial resolution of two meters (INPE, 2022). In the present study, this procedure was carried out using ArcGIS software (license number ESU918728411) to obtain the best possible spatial resolution to evaluate the studied fragment vegetation.

Three scenes covering the study area were selected to observe the vegetation patterns. The first dated before the burning, in the rainy season (March 4, 2020), the second at the beginning of the dry period (June 6, 2020), and the third shortly after the burning (October 7, 2020). After selecting and downloading the bands (RGB and Panchromatic) from the INPE Image Catalog, they were imported into ArcGIS, to compose and merge the bands and create the maps.

The drone mapping was carried out in the fragment area one year after the burning. The model used was the MAVIC 2 Pro. The flights were at a height of 100 meters with no control and verification points, on the 20th and 21st of August 2021 between 10 am and 2 pm. The flights were in autonomous mode using a flight plan created in the DroneDeploy software with a frontal overlap of the images of 60% and a lateral overlap of 65%, the flight speed was 13m/s, with a direction of 98º. Seven flights and approximately 1800 photos were necessary to cover the entire area.

The image processing to generate the ortho-photomosaic was also carried out in DroneDeploy using the trial license provided by the software. The orthophotomosaic was then exported to ArcGIS, with a final pixel resolution of 4.4cm. The ortho-photomosaic was used to evaluate vegetation dynamics one year after burning and to analyze the effect of fire using high-resolution images.

Evaluation of Post-Fire Mortality

On-site inventory data

Data from area sampling inventory, before the burning, were collected between October 2017 and February 2018, where all tree individuals ≥ 3 meters in height and diameter ≥ 5 centimeters (cm) at 1.30 meters height above the ground (DBH – diameter at breast height) were inventoried. In this paper, the abundance, diameter at DBH, and total height (th) data of the inventoried trees were used. Dead individuals found in on-site inventory were not included in the analysis, to evaluate only post-fire mortality.

The total survey area was two hectares, sampled in two plots of one hectare each (100m x 100m). These larger plots in the survey were subdivided into subplots of 20x20 meters, facilitating field work. The data in the plots was collected following the protocols of RAINFOR (Rede Amazônica de Inventários Florestais - Amazonian Forest Inventory Network) (PHILLIPS *et al*., 2016), which is a method used in many research around the world, allowing the creation of a database with standardized methodology and comparison between global native vegetation areas. The respective data make up the database of the long-term ecological project (Projeto Ecológico de Longa Duração – PELD-III/IV) Site 15: Cerrado-Amazon Forest Transition.

After the burning, in June 2021, a survey was carried out on the plots to identify the dead individuals. After identifying the dead individuals using data from the survey before the burning, the relative density (RD%), abundance (number of individuals – NI), basal area (G) of living and dead trees volume, and plots' dead and live volume were calculated. The method of Scolforo *et al*. (2008) was used to estimate the total volume of wood in the Semideciduous Seasonal Forest (Equation 1).

$$\mathrm{Ln}\,(Vol) = -9{,}7394993677 + 2{,}3219001043 * \mathrm{Ln}(DBH) + 0{,}5645027997 * \mathrm{Ln}(th)$$

where: Vol = Volume; DBH = diameter at breast height; th= trees' total height.

Based on these data the estimates of evaluated metrics for the total area of the studied fragment and all the calculations were conducted in R software, using the *Florestal* package (FERREIRA, 2020).

Data obtained from the drone

To analyze the tree mortality, the DroneDeploy software was used, and the *PlantHealth* generated using the Atmospherically Resistant Visible Index (ARVI) method based on the ortho-photomosaic, was used to evaluate the post-fire vegetation dynamics. This method uses the image's RGB bands to generate the vegetation index and ARVI measures the vegetation reflectance versus soil. It is a measure of "how green" an image is, making it possible to identify areas of healthy or dead vegetation in an image (DRONEDEPLOY, 2022).

In ArcGIS, the *PlantHealth* raster was reclassified in a supervised manner based on the ortho-photomosaic into two classes (live vegetation and dead vegetation). From this reclassification, the area corresponding to each class in the studied fragment was calculated. The class area proportion was considered as the relative density (RD%) of living and dead trees.

Estimates comparative

Based on the results obtained from the two classes generated using the drone and geoprocessing tools and using the results obtained from abundance, basal area (G), and volume from the on-site sampling inventory, these same parameters were calculated, based on the area percentage of each class, using the following equations:

$$\text{Estimated dead volume} = \text{Total value in loco per ha}*\left(\frac{\%\text{ of dead vegetation}}{100}\right)$$

$$\text{Estimated live value} = \text{Total value in loco per ha}*\left(\frac{\%\text{ of live vegetation}}{100}\right)$$

To compare the results of the two estimates, the Chi-square test of dependence was conducted. It is possible to observe whether there is a significant difference between the values observed in the field with the inventory and the estimates made using the ortho-photomosaic generated by the drone images. The analyses were carried out using R software.

It was considered that what is expected for the total area are the parameter estimates based on the on-site sampling inventory, while the values obtained by the drone are the results of the previous equations that consider the inventory results but use the percentage of area of each class (living vegetation and dead vegetation) to obtain the estimates.

RESULTS

Vegetation dynamics

The vegetation dynamics evaluation showed that the fragment has homogeneous vegetation (Figure 2A) with regions with characteristics of vegetation that respond more severely to the hydrological cycle, coinciding with the presence of intermittent watercourses, forming areas of drier vegetation (fuel biomass) in the dry period that accompanies the watercourses (Figure 2B). These drier areas favored the fire movement through the fragment (Figure 2C) and were the most affected as regards vegetation mortality (Figure 2D).

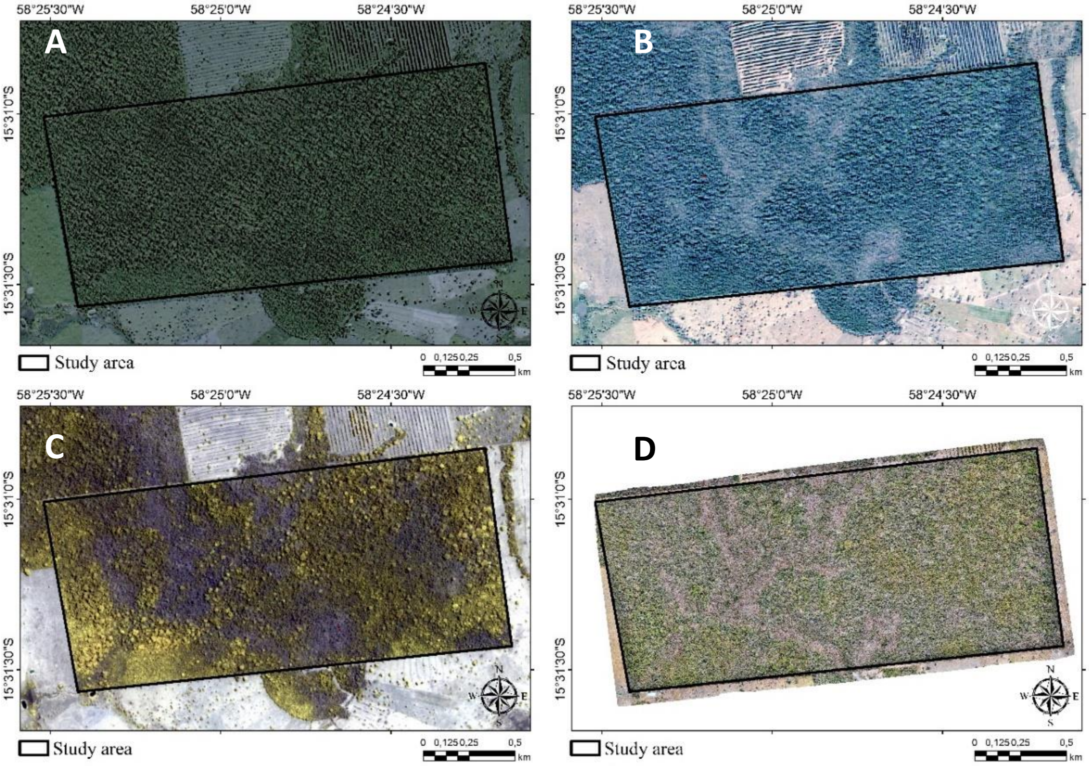

Figure 1. Vegetation dynamics. A – Satellite image of the studied area in the rainy period before the fire; B - satellite image of the study area in the dry period before the fire; C - satellite image of the study area one month after the fire; D - ortho-photomosaic of the study area one month after the fire.

Figura 2. Dinâmica da Vegetação. A – Imagem de Satélite da área do estudo no período chuvoso anterior ao incêndio; B - Imagem de Satélite da área do estudo no período seco anterior ao incêndio; C - Imagem de Satélite da área do estudo um mês após ao incêndio; D - Ortofotomosaico da área do estudo um mês após ao incêndio.

Post-fire mortality

From the total area, and the results obtained with the drone, it was possible to observe that 37.37% (RD%) of the vegetation in the fragment was dead (Figure 3A and Figure 3B). In the on-site evaluation of the permanent plots, this total was 41.91%.

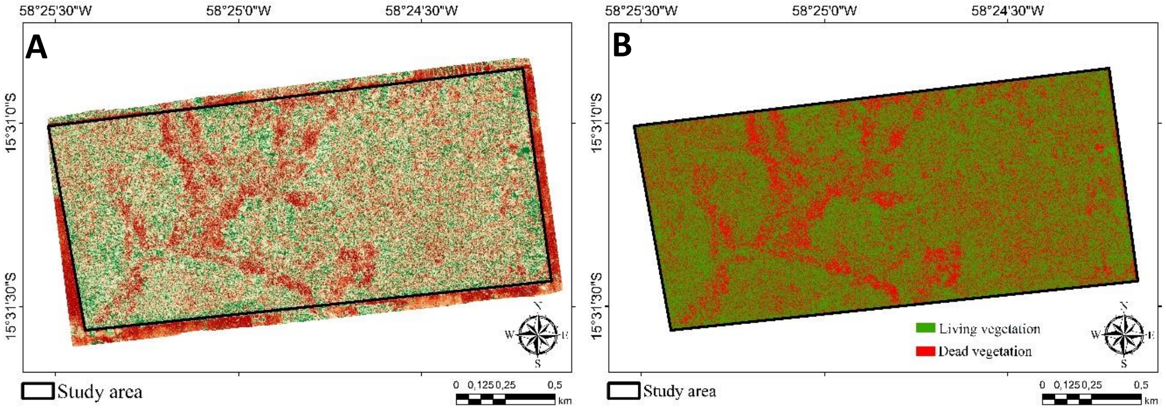

Figure 2. Mortality evaluation with the drone in the study area. A – PlantHealth generated in DroneDeploy; B – Dead and living vegetation.

Figura 3. Avaliação da mortalidade com o Drone na área do estudo. A – PlantHealth gerado no DroneDeploy; B – Vegetação morta e viva.

Comparison between estimates

The results based on the on-site sampling inventory registered a total of 782 ind/ha, a basal area equal to 19.8715 m^2/ha, and a volume equal to 253.5652 m^3/ha. The sampling of mortality of individuals in the permanent plots after the burning showed there was estimated mortality of 328 ind/ha, the dead basal area found was 5.4196 m^2/ha and the dead volume was equal to 54, 3177 m^3/ha.

Based on the results from the ortho-photomosaic, using the total values obtained in the on-site plots evaluation, the estimates indicated a total of 292 dead individuals/ha, dead basal area equal to 7.4260 m^2/ha, and dead volume of 94.7573 m^3/ha.

The results of the applied statistical analyses showed that for the abundance and volume data, there is a significant difference in the estimates. In other words, the on-site inventory and the estimates made based on high-resolution aerial images are not similar. As for the basal area, the result showed that the two methods do not differ in the estimates for the study area, therefore they are equal.

Table 1. Results of the estimates based on the on-site inventory (1) and from the high-resolution aerial images taken with the drone (2).

Tabela 1. Resultados das estimativas baseado no inventário in loco (1) e a partir das imagens aéreas de alta resolução realizadas com Drone (2).

	ind/ha^1	**ind/ha^2**	**G/ha^1 (m^2)**	**G/ha^2 (m^2)**	**Volume/ha^1 (m3)**	**Volume/ha^2 (m3)**
Dead	454	489*	14,4518	12,4455■	199,2475	158,8079*
Live	328	292*	5,4196	7,4260■	54,3177	94,7573*

Legend: *values of the estimates based on data obtained in loco differ significantly at 95% confidence level; ■ values of the estimates based on the data obtained in loco do not differ significantly at 95% confidence level.

Legenda: *valores diferem significativamente ao nível de 95% de confiabilidade das estimativas baseadas nos dados obtidos *in loco*; ■ valores não diferem significativamente ao nível de 95% de confiabilidade das estimativas baseadas nos dados obtidos *in* loco.

DISCUSSION

Assessing the dynamics of the vegetation, it was possible to observe that the fire was enhanced by the biomass from drier vegetation, arranged in a meander shape in the fragment (Figure 2B). However, as observed shortly after burning (Figure 2C), the fire reached the entire area, with greater intensity in regions with greater burning potential. Drier and more open areas within an environment allow greater light entry and drying increasing the deposited combustible material (leaves and branches, for example) (BRANDO *et al*., 2014; MEIRA JÚNIOR et al., 2020). This drought-fire interaction increases tree mortality (BERENGUER *et al*., 2021).

In the ortho-photomosaic (Figure 2D), which allows a precise assessment depending on the spatial resolution, it is possible to see that tree mortality occurred throughout the evaluated area, but in drier regions where the combustible material was more flammable, there was greater tree mortality, demonstrating that the fire intensity in these regions amplified the vegetation death. This result is in line with the findings of Berenguer *et al*. (2021), in which tree mortality is influenced by the intensity of the fire, and that trees exposed to higher levels of fire intensity exhibited elevated mortality.

As in previous discussions, the high-resolution aerial image showed “corridors” of dead trees (Figure 2D) approximately one year after the fire in the forest area. These corridors occur precisely due to the fire intensity, which was greater in these regions of the fragment (Berenguer *et al*., 2021). The fire in this area precisely coincided with the historical peak period of fires in Brazil (PINTO *et al*., 2021), caused mainly by the more abundant drier combustible material, typical of this period of the year and the characteristic of the vegetation in the studied fragment (MEIRA JÚNIOR *et al*., 2020).

The expected mortality rate for a region like the one studied is 2.8% per year (ESQUIVEL-MUELBERT *et al*., 2020). As the elapsed time from the on-site inventory, until the mortality assessment was approximately 3.5 years, a mortality rate of around 10% was expected, much lower than those found on-site and with the aerial survey, evidencing the effect of fire under the trees in the studied fragment.

The results of the present study, both in the drone evaluation and in the plots, are superior to those found by Santos *et al*. (2019), in the Tapajós National Forest, registering a 28.4% mortality rate in an area affected by fire. Medeiros and Miranda (2005), after the first controlled burning carried out in the IBGE Ecological Reserve in a *cerradão* area, reported 22.5% mortality. However, the mortality increased to 37% after burnings that occurred in three consecutive years, a value that is closer to those found in the present study, after a single burning event.

Additionally, Peixoto *et al*. (2012), studying a region of Semideciduous Seasonal Forest in the Serra Azul State Park (SAEP), municipality of Barra do Garças-MT, registered a mortality rate of 4.59% after the fire. According to the authors, the low mortality occurred due to constant fire disturbance and hence, increased resilience that shapes and selects individuals more adapted to multiple burning events, unlike the area of the present study. The results of Peixoto *et al*. (2012), in addition to the resistance, might be discrepant from the present study due to the accumulation of combustible material, as it suffers multiple burning events, and there is less accumulated material to be burned.

Another fact that may justify the high post-fire mortality is that areas that have suffered high human intervention are susceptible to more severe fires and consequently higher tree mortality (BERENGUER *et al*., 2021). This fact, combined with drier regions within the area - a forest fragment, with historical logging for timber extraction, inserted in an agricultural landscape matrix, increases the fire severity and explains the high mortality percentage in the present study.

The high mortality rate may also have been increased by the dry period, when a load of combustible material and temperature are higher and the relative air humidity is lower, potentially increasing fire intensity and consequently tree mortality (BRANDO *et al*., 2014). Therefore, the low resilience of the plant community to fire, the history of anthropization combined with the environmental conditions in which the fire occurred, led to the high mortality rate, both detected by the drone and inventoried in the permanent plots.

The big problem with the fire effect is that it makes it more susceptible to new events of this type, as it causes forest impoverishment, and increases forest clearings (NEPSTAD *et al*., 1999), which presents a tendency to change the structure and forest fragment composition throughout time (MEIRA JÚNIOR *et al*., 2020; SILVA et al., 2020a), and affects directly specimens with smaller diameters, reducing the number of individuals and enhancing the establishment of lianas and invasive species (PEREIRA *et al*., 2016).

The results of the statistical analysis comparing the estimates made with on-site sampling and with the drone, allow us to understand that to estimate the basal area, the use of the drone was equally efficient as the field sampling. Therefore, as long as you have an on-site sampling inventory and the objective is to estimate the loss of basal area caused by fire, the drone is an important tool for evaluating the impact suffered by these areas. It is also noteworthy that the percentage of mortality obtained from the survey on the plots and from aerial data was close.

According to Torresan *et al*. (2020), the drone application to estimate aerial biomass is satisfactory, following the results of the present study. The drone maps the tree canopy in forested areas and establishes the relationship between the canopy size, tree diameter, and detects trees with larger crowns (dominant and codominant). These larger trees significantly contribute to the basal area of the population, as highlighted by FIGUEIREDO *et al*. (2020). This contribution explains the equal statistical results observed in the estimated values between the two methods.

It is noteworthy that the individuals' number was not statistically similar between the estimates by the analysis applied, and within the plots, the number of dead trees was greater than that estimated by the drone, this may have occurred due to the drone's incapacity to identify trees of smaller diameters, found in the lower extracts of the forest (TORRESAN *et al.*, 2020; MARTINS NETO; BREUNIG, 2019). Additionally, individuals with smaller diameters tend to be more impacted by fire (SANTOS et al., 2019) explaining the high number of dead individuals found on-site sampling than those estimated with drones.

As for volume, the drone makes an assessment only of the tree canopy, even though there is a relationship between the canopy size and the tree diameter (FIGUEIREDO et al., 2020) for volume, the use of height in the calculation and aerial mapping did not prove to be sufficient for this issue. Kameyama and Sugiura (2020) also obtained results similar to the present study, even testing 80 flight conditions with UAVs, the results demonstrated low precision in relation to real volume values, mainly due to the restrictions of the method for estimating the trees' height.

The on-site inventory may have contributed to the difference between the methods. Even though it is an international protocol that provides important data for ecological studies, it aims to monitor the biomass and dynamics of forests (PHILLIPS *et al*., 2016), and can therefore be considered a sufficient inventory procedure for recognizing the area and monitoring the dynamics of vegetation and biomass. However, it ends up having a high coefficient of variation to estimate values for the entire area (FLORIANO, 2021), which can explain the difference in the values of volume and number of individuals. It is also in line with the similar results found for the basal area between the methods, mainly due to the inventory sampling methodology focusing on forest biomass and the drone demonstrating efficiency in estimating biomass (TORRESAN *et al*., 2020).

It is worth noting that the results presented here regarding the significance of estimates of volume and number of individuals may vary if obtained using inventory data using other approaches that achieve sample sufficiency for the area. This is because it would make the estimates more precise, as discussed by Floriano (2021). Additionally, it is highlighted that the drone is an important tool to assist in monitoring the impact of fires on forest biomass. This is particularly relevant in areas with permanent plots following the sampling method of the RAINFOR network (PHILLIPS et al., 2016), as indicated by the results found for the basal area.

With this study, it was possible to observe the importance of local vegetation studies with the monitoring of permanent plots, as using the drone alone would not be possible to infer dendrometric or phytophysiognomic parameters. However, by combining the two methods compared in the present study, it was possible to estimate some parameters that can provide answers and assist in the restoration of areas similar to the one studied, mainly after being impacted by fires.

The drone allowed a comprehensive assessment of the entire fragment area, extending beyond the specific region covered by the field-installed plots. Consequently, the integration of drone technology with forest inventory data emerges as a crucial tool for monitoring the impact of fires in forested areas, particularly in evaluating the basal area, as indicated by this study's findings. The results suggest that post-fire drone mapping is valuable in estimating the loss or increase in forest carbon stock resulting from fire effects. By providing estimations of basal area data, the drone contributes to carbon stock calculations, as highlighted by SOARES *et al*. (2016). Furthermore, the use of high-resolution aerial images can enhance the monitoring of carbon dynamics.

CONCLUSION

- The area of the studied fragment had its vegetation changed due to the effect of the recorded forest fire.
- There was a high level of tree mortality, verified both in the on-site evaluation and the evaluation using high-resolution aerial images, which showed corridors with a higher incidence of mortality that coincided with regions where environmental conditions favored the spread of fire due to the presence of fuel material availability and consequently its intensity was greater.
- The use of drones to evaluate the mortality of tree vegetation proved to be an important tool for evaluating the effect of fires in forest areas when reconciled with data from sampling inventories carried out in the field.
- The mortality/survival rates observed in the field and by the drone were close and to estimate the dead/alive basal area, no statistically significant difference was found between the estimates based on data collected in the field and aerial data.

- The drone demonstrated limitations in estimating the number of dead/alive individuals and the dead/alive volume when compared with the plot inventory, underestimating the number of dead trees, and overestimating the Dead Volume.

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