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In the line of fire: Analyzing burning impacts on air pollution and air quality in an Amazonian city, Brazil

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A R T I C L E I N F O

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A B S T R A C T

Brazil is grappling with escalating wildfire incidents, particularly in the ecotone region of Cerrado-Amazon, attributed to climate change and anthropogenic factors. These wildfires significantly impact air quality, posing health and environmental risks to the population. This study aimed to assess the influence of wildfires on air quality in Sinop, a city located in Northern Mato Grosso, Brazil. The primary focus was on understanding the behavior of air pollutants during and after wildfire events. Air quality data were obtained from modeling dataset, while meteorological data from ground-based monitoring, and wildfire data from the National Institute of Spatial Research of Brazil. Statistical analyses were employed to investigate pollutant variations and their relationships with meteorological parameters and wildfire intensity indicators. The study revealed a significant impact of wildfires on pollutant concentrations, with ozone levels rising immediately after fires and remaining elevated for several days. The particulate matter ($PM_{2.5}$ and PM_{10}) concentrations increased a few days after fire events. Fire radiative power (FRP) correlated with O_3 levels, suggesting it is an intensity indicator. Temperature exhibited a consistent positive correlation with all pollutants, highlighting its role in pollutant dynamics. The findings underscore the multifaceted relationship between wildfires, meteorological conditions, and pollutant concentrations pointing to the importance of holistic air quality management strategies in fire-prone regions. Such studies are crucial for guiding environmental policies, safeguarding public health, and advancing scientific understanding in the face of escalating wildfire challenges.

1. Introduction

Brazil holds a prominent position in terms of wildfires, both in South America and globally, ranking third among countries with the highest occurrence of wildfire hotspots in the last decade (Targino et al., 2024). This perception is concerning, especially because of the increasing frequency of large fires (Cobelo et al., 2023) and their close relationship with climate change and its consequences (Mansoor et al., 2022). In recent years, such as 2019 and 2020, Brazilian biomes have garnered international attention due to the unprecedented frequency and magnitude of fire events (Pivello et al., 2021).

The Cerrado-Amazon ecotone is one of the most vulnerable areas to anthropogenic actions in Brazil. Situated amid the territorial strip known as the “Arc of Deforestation,” this transitional area between the Amazon and the Cerrado (the two largest Brazilian biomes) covers nearly 5% of the national territory (Reis et al., 2021) and encompasses the states of Pará, Maranhão, Tocantins, Rondônia, and Mato Grosso (Maciel et al., 2016). Considered one of the world’s largest agricultural

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frontiers, this region of rich biodiversity has become severely susceptible to fragmentation and environmental pollution, posing risks to local populations and native species (Marques et al., 2019).

The state of Mato Grosso (MT) can be lighted in comparison to the others, since more than 60% of its economic activities are linked to the agricultural sector, as pointed out by the Mato Grosso Institute of Agricultural Economics (IMEA. Instituto Mato-Grossense de Economia Agropecuária, 2023). Temporal and spatial changes associated with agricultural activities, which often include the process of deforestation, contribute to the occurrence of episodes of anthropogenic biomass burning (Pereira et al., 2011; Wu et al., 2023). Sinop is one of the municipalities in the north of the state that plays a leading role in grain production (Wesz Junior, 2022), and was established under Brazil's Plan for National Integration (PIN) for the occupation of the Legal Amazon in the 1970s, with a population of approximately 200,000 inhabitants (IBGE. Instituto Brasileiro de Geografia e Estatística, 2023).

Early in the last decade, Silvestrini et al. (2011) mentioned that fire risk in Brazil could be more directly influenced by climatic factors than by anthropogenically caused fires since favorable weather conditions are a prerequisite for human-caused wildfires. However, recent studies show that, although fires have natural causes, they are now much more strongly linked to anthropogenic activities, with climate change as a background inextricably associated with and modified by these actions (Pivello et al., 2021; Diele Viegas et al., 2022). The study by Brando et al. (2020) projected that due to climate changes, the area burned by wildfires in Amazon will double by 2050, affecting 16% of the biome area.

Scientific evidence also shows that precipitation is decreasing in the southern Amazon region, leading to more dry days (Dubreuil et al., 2017; Leite-Filho et al., 2021). Le Roux et al. (2022) point to a potential vicious circle in which increased fires triggered by prolonged droughts increase vulnerability to new fires, especially in degraded Amazon and Cerrado areas. Shi and Touge (2022) emphasize that most fires in Mato Grosso occur in illegally deforested areas, which contributes to increased fire risk. The complex dynamics of deforestation, despite initiatives such as the soy moratorium, underscore the multifaceted nature of fire risk in Brazil (Kuschnig et al., 2021).

Wildfires are also directly linked to air pollution and low air quality (Sánchez-Balseca and Pérez-Foguet, 2020; Requia et al., 2021a; Scott, 2023). Some of the main pollutants from biomass burning, such as black carbon, particulate matter ($PM_{2.5}$ and PM_{10}), and volatile organic compounds (VOCs) (O'Dell et al., 2020), have the potential to contaminate water bodies. The United Nations Environment Programme (UNEP) asserts that these substances can cause landslides, contribute to global temperature rise, compromise carbon recycling, pose a threat to a wide variety of species, and induce the emergence of storms and electrical discharges that can ignite new fires (UNEP, 2022).

The effects of particulate matter on the reduction of air quality and illness have already been highlighted in Brazil by previous studies (Mataveli et al., 2019; Ye et al., 2022). Tropospheric ozone can also be produced by fires, but indirectly (Lei et al., 2021). The presence of VOCs and nitrogen oxides ($NOx\ [= NO + NO_2]$) during wildfires in combination with sunlight triggers photochemical processes that contribute to the increase in ozone levels (Kanchana et al., 2020). The increase in O_3 concentration itself can also damage vegetation by reducing stomatal conductance and thus dry deposition. The feedback resulting from these reactions is the enhancement of O_3 levels (Lei et al., 2021). However, these processes can be influenced by various factors such as the local temperature and the age of the plume (Jaffe and Widger, 2012; McClure and Jaffe, 2018; Lu et al., 2021).

In this sense, the link between wildfires and the air pollution they generate has been well-established around the world (Vicente et al., 2011; Garcia-Hurtado et al., 2014; Golobokova et al., 2020; Artés et al., 2022; Schneider and Abbatt, 2022). The investigation of deviations in air quality after fire events has attracted the attention of several research groups, whose results indicate, among other things, an increase in hospitalizations, changes in learning, circulatory disease, and premature births as their consequences (Nunes et al., 2013; Reddington et al., 2015; Machado-Silva et al., 2020; Butt et al., 2021; Requia et al., 2021b). At the same time, the poor understanding of prescribed fires, which excludes traditional practices, leads to the accumulation of combustible material, which favors new fires (Hiers et al., 2020). This may limit future urban and agricultural expansion due to resource depletion and climatic changes themselves (Moura and Da Silva Júnior, 2023). Wildfires have far-reaching consequences as pollution spreads thousands of miles from the source (by entering the air column and being transported by the wind) according to the United States Environmental Protection Agency and other authors (Bolaño-Diaz et al., 2022; Brum et al., 2023; Prist et al., 2023; USEPA, 2023). Wu et al. (2023) found that about 0.7% of all deaths and 0.5% of hospitalizations are due to particulate matter generated by wildfires. A recent study by Coker et al. (2022), indicated that with every 10 μg m^3 increase in $PM_{2.5}$, respiratory hospitalizations increased by more than 5%, occurring two to three days after wildfires.

Particularly vulnerable groups such as pregnant women, people with pre-existing conditions, children and the elderly are at increased risk, leading to premature deaths and significant economic losses (Reid et al., 2019; Marlier et al., 2020; Ye et al., 2022; Cobelo et al., 2023; Scott, 2023). To make matters worse, inadequate air quality monitoring in most of the Brazilian territory makes it difficult to accurately assess the exposure of the population, which is a greater challenge in other countries of the Global South (De Moura and Da Silva Junior, 2023).

While Sinop-MT was previously recognized as a major timber center (Nascimento et al., 2019), it has now become an exemplary "agribusiness city" due to the expansion of the production of commodities such as soybeans and maize (Coy et al., 2020), which is associated with significant land use changes and climate impacts (Mello-Théry et al., 2020; Sabino et al., 2020). Although previous studies have pointed to the role of drought as a factor influencing the occurrence of fires in Mato Grosso (Rossi and Santos, 2020), the complex relationship between forest fires and the dynamics of air pollutants has not been assessed. This lack of data makes it impossible to analyze how fires affect the regional atmosphere and represents the knowledge gap under investigation.

Brazil is currently experiencing a fierce conflict between the environmental perspective and land ownership (Shinde et al., 2022). Although progress towards sustainability is evident among decision-makers and stakeholders, for many producers in the Cerrado-Amazon transition zone, environmental issues are primarily analyzed in terms of financial gains or losses before being considered in terms of social impacts or the need for alternatives that enable economic development without harming ecosystems (Mello-Théry et al., 2020).

Considering this scenario, the study of wildfire events in the north of Mato Grosso fulfills the need for research that helps understand the mobilization of pollutants and their sources in small and medium-sized cities (Da Silva Júnior et al., 2023). Therefore, the present study aims to assess the mobilization of air pollutants over a year in Sinop - MT, particularly after forest fire events, to gain a better understanding of their behavior and promote preventive measures that minimize the impact of such events on human health.

2. Material and methods

2.1. Study area

This study was conducted in the city of Sinop (11°50′53″ S, 55°38′57″ W), located in the north of Mato Grosso State, approximately 500 km from the state capital, Cuiabá (Sinop, 2023) (Fig. 1). The municipality has an area of 3990.87 km^2, of which about 70 km^2 are urbanized, with a population density of 49.13 inhabitants/km^2 (IBGE. Instituto Brasileiro de Geografia e Estatística, 2023). According to the Köppen-Geiger classification, the city has a Tropical savanna climate (Aw). It receives an average annual precipitation of over 1900 mm, has an average annual temperature of 24.7 °C, and experiences a very intense and hot dry

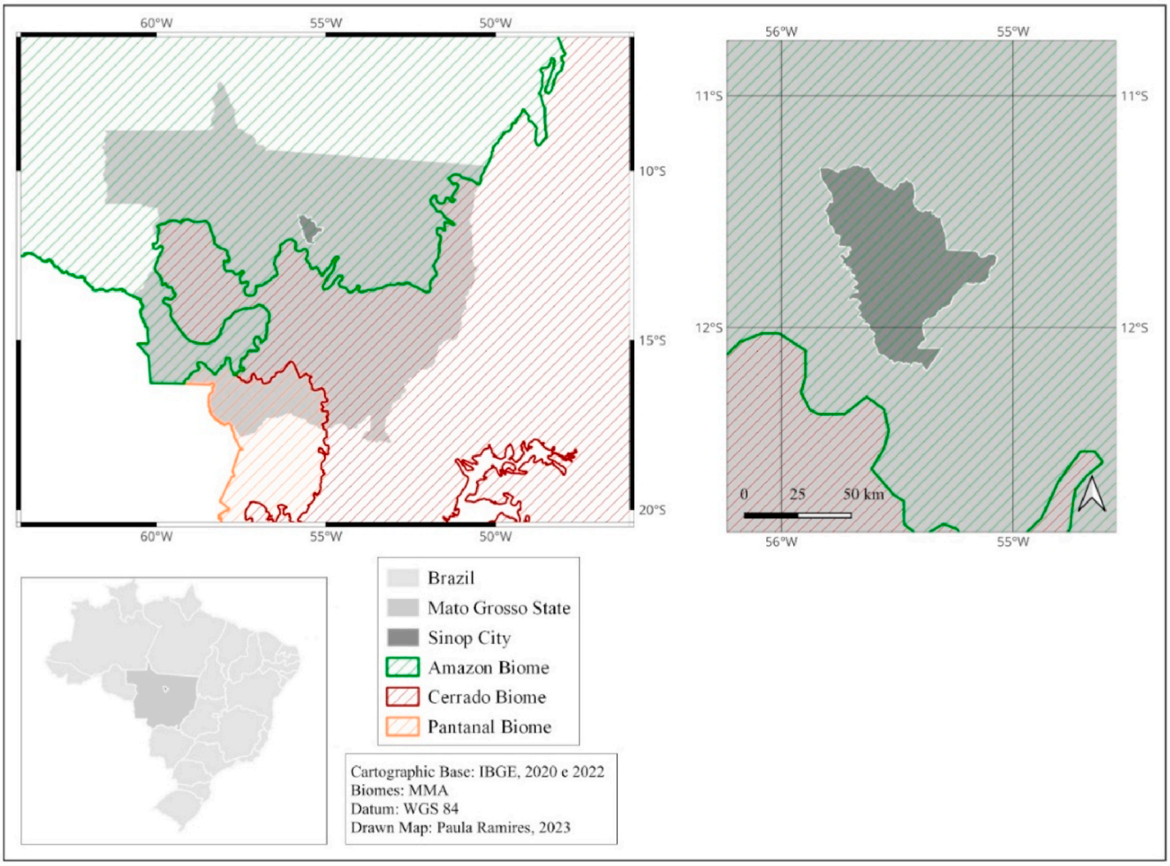

Fig. 1. Map showing the biomes found in Mato Grosso and the geographic location of Sinop.

season between May and September each year, as most cities in the state, and earlier than Acre and Rondonia, for example (Khand et al., 2017; Volpato et al., 2022). Vegetation characteristic of the transition between the Amazon and Cerrado prevails in the region (Biudes et al., 2022). The area is highly modified (changes in land cover) due to the expansion of livestock and grains cultivation, as well as the distribution of land as a result of land reform (Casavecchia et al., 2019), and is frequently affected by fires. Rossi and Santos (2020) found that in the driest years, burned areas in the region are proportionally larger.

2.2. Air quality data

The O_3 (ozone), $PM_{2.5}$ (fine particulate matter), and PM_{10} (coarse particulate matter) levels (all expressed in μg m^3) were derived from the modeling dataset sourced from the European Center for Medium-Range Weather Forecasts (ECMWF), specifically, the Copernicus Atmosphere Monitoring Service (CAMS), which provides daily analyses and forecasts including reactive trace gases, greenhouse gases, and aerosol concentrations (Gardin and Requia, 2023). Despite being developed for studies on the European continent, Inness et al. (2019) presented the global validation of CAMS for $PM_{2.5}$ using ground observations conducted by AERONET - Aerosol Robotic Network.

Given this, its application in the study of air pollution in Brazil has become popular in recent years. Although no direct validation of CAMS data is available in Brazil due to the lack of air quality monitoring in several regions of the country, other Brazilian researchers have used the same tool with consistent data (Carvalho et al., 2022; Castelhano et al., 2022; Oliveira et al., 2023; Requia et al., 2022; Tavella et al., 2022; Tavella et al., 2023). Inness et al. (2019) also emphasized that the CAMS data are quite suitable for reproducing seasonal and monthly variations in pollutants such as ozone (O_3), carbon monoxide (CO), and nitrogen dioxide (NO_2).

The data was extracted every day at around 12 ± 1 p.m., utilizing The Weather Channel application provided by IBM, USA (Leão et al., 2021).

2.3. Weather data

The correlation between climatic variables and air pollutants was also investigated in this study. The climatic data, including daily average temperature (°C), wind velocity (m s^{-1}), humidity (%), atmospheric pressure (hPa), UV radiation index, and precipitation (mm), were collected from an automated station situated in Sinop (11°87’ S, 55°57’ W) at an altitude of 370 m. These data were obtained from the Agrometeorological Monitoring System (Agritempo), developed by the Brazilian Agricultural Research Corporation (EMBRAPA) in partnership with the Brazilian National Institute of Meteorology (INMET) (Agritempo, 2023), which is a web-based platform offering users online access to weather and agrometeorological information from various municipalities and states across Brazil (Carvalho et al., 2017).

2.4. Wildfires data

We collected the wildfire data from the “Queimadas” tool that is maintained by the National Institute of Spatial Research of Brazil—Instituto Nacional de Pesquisas Espaciais - INPE. This data includes the date, latitude, and longitude of each wildfire occurrence (burned pixels) and the number of fire spots (fire foci) identified. Additionally, it supplies the fire radiative power (FRP), a quantifiable gauge of emitted radiant heat. FRP is widely employed to estimate fire intensity, a parameter correlated with the rate of combustion and the emission of smoke. This measurement is expressed in megawatts (MW), as discussed by Vadrevu and Lasko (2018). According to Silva Júnior et al. (2018), FRP can be labeled in four intervals: ≤50 MW (low intensity), 50 to ≤ 500 MW (moderate to high intensity), 500 ≤ 1000 MW (very high intensity), and >1000 MW (extreme intensity).

We accounted for all wildfire records in Sinop between January 1st, 2022, and December 31st, 2022. INPE derived wildfire data from seven satellite observations, which are NOAA-18, NOAA-19, METOP-B, MODIS (NASA TERRA and AQUA), VIIRS (NPP-Suomi and NOAA-20), GOES-16, and MSG-3, as described by Requia et al. (2021a). Table 1 provides a summary of the multisource datasets used in this study.

2.5. Data analyses

We assessed the impact of the fires by calculating the mean ± standard error of mean (SEM) of the concentrations of the three selected pollutants on days without fire, on days with fire outbreaks, and up to five days after the start of the fire episode, resulting in the following groups: non-wildfire day, day 0 (when a fire episode happened), day 1, day 2, day 3, day 4, and day 5. This 5-day lag was considered following Honscha et al. (2023) and Yang et al. (2021) who observed the lagged effects of meteorological variables on air pollutants up to 5 days. Since there were days when consecutive fires were observed, redundancy occurred in the days considered in each group. We performed the Shapiro-Wilk test to confirm the normality of the data and the Levene test to verify homoscedasticity. One-way analysis of variance (ANOVA) followed by Tukey's was used to compare all categories, for O_3, and followed to Dunnett's multiple comparison test was applied to compare all the categories to the non-wildfire day for $PM_{2.5}$ and PM_{10}.

Pearson correlation was also performed between the meteorological variables and air pollutants for each of the previously established categories, to investigate the existence of a relationship between parameters directly related to fires – fire radiative power (FRP) and number of fire foci per day – and pollutants (O_3 and $PM_{2.5}$), as it was already applied by other groups (Liu et al., 2020; Beringui et al., 2023; Yousaf et al., 2024). PM_{10} was excluded due to its high redundancy with $PM_{2.5}$. This redundancy seems to be a feature that is not unique to Sinop, as another study observed a similar pattern in Barão de Melgaço, MT (Santos et al., 2016), and could be a consequence of the main sources of particulate matter in the central-western region of Brazil (Santanna et al., 2016), as the $PM_{2.5}/PM_{10}$ ratio in Sinop is also very stable.

In addition, to assess the impact of fire events on the concentration of air pollutants, we divided the daily concentrations of ozone and particulate matter into quartiles (Q1 (lowest), Q2, Q3, and Q4 (highest)) for both days when fires occurred and the days they did not. From this, we calculated the percentage of days (non-wildfire and wildfire) in each of the four quartiles. To analyze whether there was an increase in the number of days in the highest quartiles, the Chi-square test for trend was used. Statistical significance was accepted at $p < 0.05$.

Furthermore, a principal component analysis (PCA) was performed considering meteorological parameters and concentrations of O_3 and $PM_{2.5}$. For this purpose, the average values of all tested concentrations for each pollutant were evaluated. The analysis was based on the correlation between the variables and the graph created considered the two axes (factors) with the greatest contribution to the analysis.

Concerning the methodology of the Air Quality Index (AQI), it involves creating sub-indices for individual pollutants and subsequently aggregating these sub-indices and it varies across the world based on the definitions of different organizations as mentioned by Senthivel and Chidambaranathan (2022). The purpose of this categorization is to communicate and inform the population about the concentrations of monitored pollutants and their possible harmful effects on health. USEPA determined that the AQI would be calculated by the formula:

$$AQI = Iin + \frac{Ifn - Iin}{Cfn - Cin} \times (C - Cin)$$

where.

Iin = the index breakpoint conforming to Cin
Ifn = the index breakpoint conforming to Cfn
Cin = the concentration breakpoints $< C$
Cfn = the concentration breakpoints $\geq C$
C = concentration of pollutants

USEPA categorizes the AQI into six levels according to the standards defined by the World Health Organization (AirNow, 2023). For ozone a conversion was necessary as values in AQI are considered in ppm, so we applied the conversion proposed by Boguski (2006). Table 2 shows the linear segmented relationship for sub-index values, the corresponding pollutant concentrations, and the health effects expected.

3. Results

The occurrence of wildfires was shown to significantly affect the levels of the pollutants analyzed in Sinop. For the pollutant O_3, the mean values of all groups in which there were days with fires (Day 0 to Day 5), differed from the mean values of the non-wildfire days group. On the other hand, for the particulate matter, $PM_{2.5}$ and PM_{10}, significant differences were found only between the group of non-wildfire days, and the groups Day 3, Day 4, and Day 5 (Fig. 2).

The data on the number of fire spots (fire foci) and FRP are shown in Figs. 3 and 4. There were fires throughout the year, but after the first four months of the year, fires became more frequent and peaked between the 236th and 257th days of the year, which are in August and September. At the same time, higher FRP values were also verified, namely 104.5 MW and 342.9 MW, both classified as moderate to high intensity. However, the most critical FRP value collected was measured on June 27th and was 652.2 MW. Both the number of fires and FRP values showed a significant effect on O_3 levels ($p = 0.021$, and $p = 0.02$, respectively). On the particulate matter levels, these indicators had no statistically significant influence.

The existing correlations between the meteorological variables and air pollutants in the presence or absence of fires can be verified in Tables 3–5. Temperature showed a significant positive correlation with the three pollutants, both in the absence of fires and on the days when fires occurred. Wind speed displayed a positive correlation with ozone in most scenarios considered but did not affect $PM_{2.5}$ and PM_{10}. Similarly, O_3 was negatively correlated with precipitation, but neither $PM_{2.5}$ nor PM_{10} were correlated with this variable. Regarding humidity, there was a negative correlation for the three pollutants, but ozone proved to be more affected by this parameter than particulate matter. Moreover, atmospheric pressure and UV radiation index did not show a strong

Table 1
Summary of the various data sources used in this study.

Category	Source product	Temporal resolution	Spatial resolution
Air quality	$PM_{2.5}$, PM_{10}, O_3	hourly	point
Weather	Temperature	monthly	25 km
	Wind velocity	monthly	25 km
	Relative humidity	monthly	25 km
	Atmospheric pressure	monthly	25 km
	UV radiation index	monthly	25 km
	Precipitation	monthly	25 km
Wildfire (fire foci, FRP)	NASA Terra/Aqua MODIS	daily	1 km
	NOAA-18/NOAA-19	daily	1.1 km
	Suomi NPP VIIRS	daily	5 km
	NOAA-20	daily	750 m
	METOP-B	daily	5.5 km
	GOES-16	hourly	4 km
	MSG-3	hourly	3 km

Table 2
Impacts on health verified in conditions of deviations in air quality.

USEPA AQI Level	Index	O_3 (ppm) 8h	$PM_{2.5}$ ($\mu g\ m^3$) 24h	PM_{10} ($\mu g\ m^3$) 24h	Health recommendations (24h exposure)
Good	0-50	0-0.054	0-12	0-54	Air quality is good and poses little to no risk.
Moderate	51-100	0.055-0.07	12.1-35.4	55-154	Air quality is acceptable but is a concern for sensitive people who should avoid outdoor activities.
Unhealthy for sensitive groups	101-150	0.071-0.085	35.5-55.4	155-254	Air quality is unhealthy for many people. Sensitive groups may suffer negative health effects while the general public is less likely to be affected.
Unhealthy	151-200	0.086-0.105	55.5-150.4	255-354	Air quality is bad. The general public may face negative health effects while sensitive groups are likely to have more serious problems. Strenuous outside activities must be avoided.
Very unhealthy	201 - 300	0.106-0.2	150.5-250.4	355-424	Air quality is unhealthy for everyone. The risk of negative health effects is high, especially for people with heart and/or lung diseases.
Hazardous	301 - 500	>0.21	>250.5	>425	Air quality is hazardous. It is an emergency condition: everybody is likely to be affected and people should stay indoors.

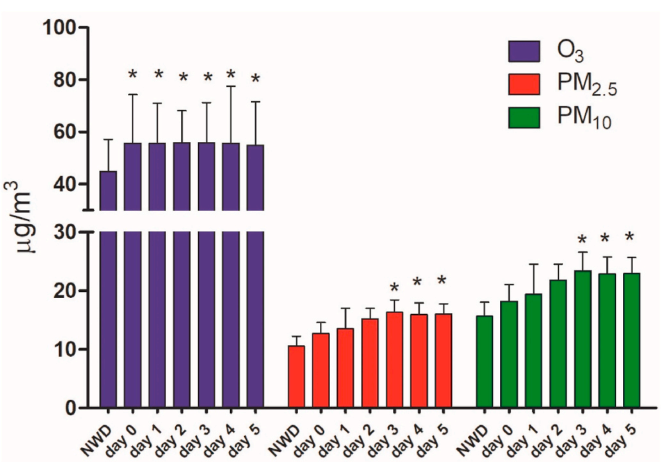

Fig. 2. Air pollutants levels in non-wildfire days (NWD) and from the first day when fires occurred (day 0) to 5 days after (day 5).

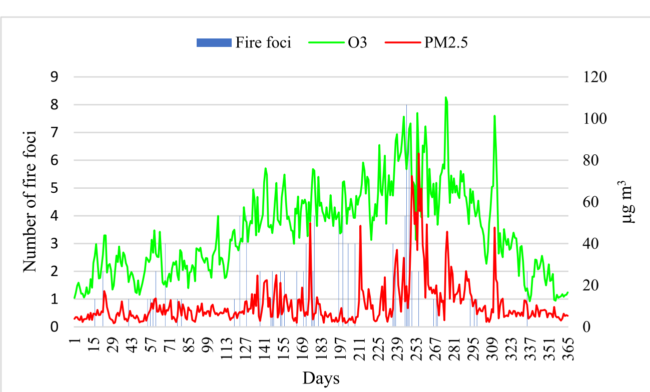

Fig. 3. Occurrence of fire foci and levels of O_3 and $PM_{2.5}$ in Sinop in 2022.

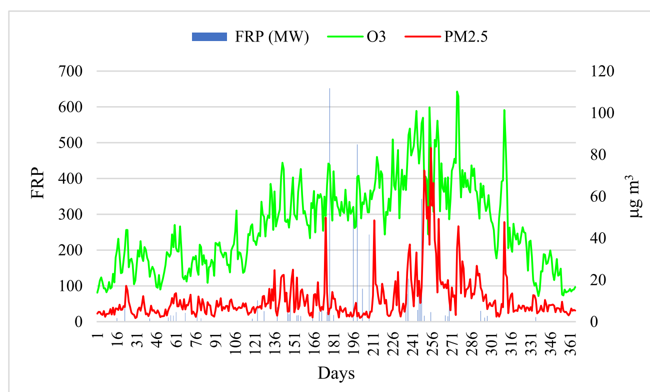

Fig. 4. Fire radiative power (FRP) during wildfire episodes and levels of O_3 and $PM_{2.5}$ in Sinop in 2022.

correlation with any of the pollutants, although significant results were demonstrated. For non-wildfire days, the percentage of days in each of the four quartiles is quite homogeneous for the concentration of the three pollutants, as can be seen in Table 6. Despite that, for O_3 this scenario changes significantly given the days with fire events, where the number of days in Q3 and Q4 increased significantly compared to Q1, denoting that there is a greater number of days when ozone levels were among the highest 50% detected during the evaluated period (Chi-square for tendency test - $\chi^2 = 16.51$ and $p < 0.0001$). For particulate matter this difference almost did not happen and was not significant ($PM_{2.5}$ Chi-square for tendency test - $\chi^2 = 1.14$ and $p = 0.29$/PM_{10} Chi-square for tendency test - $\chi^2 = 0.57$ and $p = 0.45$).

During the period studied, wildfires were recorded in the region on 47 days. On six occasions, in May (1), June (2), August (1), and September (2), the fires occurred on consecutive days, without interruption. Fig. 5 shows the AQI results by percentage of days within each classification level for the pollutants we evaluated.

According to the AQI classification, O_3 levels on days without fires (318 days) remained predominantly classified as good), with only 1 day classified as moderate. Regarding $PM_{2.5}$, on days without burning occurrences, about 74.2% were classified as good, 21.1% as moderate, and

Table 3
Correlations between meteorological variables and occurrence of wildfires for O_3 levels.

		All days	Non-wildfire days	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5
Temperature (°C)	*r*	**0.60**	**0.59**	**0.59**	**0.61**	**0.59**	**0.59**	**0.62**	**0.59**
	p	<0.01	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Wind speed (m s$^{-1)}$	*r*	**0.21**	**0.18**	**0.43**	**0.51**	**0.49**	**0.32**	ns	**0.56**
	p	<0.001	= 0.01	= 0.003	<0.001	= 0.001	= 0.03		<0.001
Humidity (%)	*r*	**−0.76**	**−0.75**	**−0.78**	**−0.80**	**−0.73**	**−0.77**	**−0.76**	**−0.76**
	p	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Pressure (hPa)	*r*	**0.34**	**0.29**	ns	ns	**0.33**	ns	**0.33**	ns
	p	<0.001	<0.001			= 0.02		= 0.02	
UV radiation index	*r*	**0.23**	**0.25**	ns	ns	ns	ns	**0.33**	ns
	p	<0.001	<0.001					= 0.02	
Precipitation (mm)	*r*	**−0.23**	**−0.21**	**−0.39**	**−0.34**	ns	**−0.37**	**−0.46**	ns
	p	= 0.04	<0.001	= 0.007	= 0.02		= 0.01	= 0.001	

Bold values indicate *r* values with statistical significance ($p < 0.05$).

Table 4
Correlations between meteorological variables and occurrence of wildfires for $PM_{2.5}$ levels.

		All days	Non-wildfire days	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5
Temperature (°C)	*r*	**0.43**	**0.45**	**0.33**	**0.59**	**0.36**	**0.44**	**0.43**	**0.45**
	p	<0.001	<0.001	= 0.03	<0.001	= 0.01	= 0.002	= 0.003	= 0.01
Wind speed (m s$^{-1)}$	*r*	ns	ns	ns	ns	ns	ns	ns	ns
	p								
Humidity (%)	*r*	**−0.31**	**−0.34**	ns	**−0.30**	ns	ns	**−0.37**	**0.29**
	p	<0.001	<0.001		= 0.04			= 0.01	= 0.04
Pressure (mb)	*r*	**0.23**	ns	ns	ns	ns	ns	ns	ns
	p	<0.001							
UV radiation index	*r*	**0.27**	**0.30**	ns	**0.45**	ns	ns	ns	ns
	p	<0.001	<0.001		= 0.002				
Precipitation (mm)	*r*	ns	ns	ns	ns	ns	Ns	ns	ns
	p								

Bold values indicate *r* values with statistical significance ($p < 0.05$).

Table 5
Correlations between meteorological variables and occurrence of wildfires for PM_{10} levels.

		All days	Non-wildfire days	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5
Temperature (°C)	*r*	**0.39**	**0.41**	**0.33**	**0.59**	**0.36**	**0.45**	**0.43**	**0.45**
	p	<0.001	<0.001	= 0.03	<0.001	= 0.01	= 0.002	= 0.003	= 0.01
Wind speed (m s$^{-1)}$	*r*	ns	ns	ns	ns	ns	ns	ns	ns
	p								
Humidity (%)	*r*	**−0.28**	**−0.29**	ns	**−0.30**	ns	ns	**−0.38**	**0.29**
	p	<0.001	<0.001		= 0.04			= 0.01	= 0.04
Pressure (mb)	*r*	**0.23**	ns	ns	ns	ns	ns	ns	ns
	p	<0.001							
UV radiation index	*r*	**0.27**	**0.29**	ns	**0.45**	ns	ns	ns	ns
	p	<0.001	<0.001		= 0.002				
Precipitation (mm)	*r*	ns	ns	ns	ns	ns	ns	ns	ns
	p								

Bold values indicate *r* values with statistical significance ($p < 0.05$).

3.7% as unhealthy for sensitive groups. PM_{10} levels were classified as good on 306 days and normal on the remaining 12 days. On the other hand, the AQI results on days with burning showed a slight increase in the number of days classified as moderate for $PM_{2.5}$ and PM_{10}. For $PM_{2.5}$, moderate days increased by 0.5 percentage points, and days classified as unhealthy increased by 2.69 percentage points.

Principal component analysis (PCA) was used to reveal patterns and correlations within the data. The PCA results for days with and without wildfires can be seen in Supplementary 1 and 2, respectively. In both cases, the contribution of the two axes explains more than 60% of the data variance. In this sense, it can be observed that regardless of the occurrence of forest fires, humidity, and precipitation show a negative correlation with O_3, while the temperature and UV index are positively correlated with both O_3 and $PM_{2.5}$.

4. Discussion

The present study aimed to investigate the multiple effects and consequences of fires on the dynamics of air pollutants in Sinop, a reference center in the North of Mato Grosso (Vieira et al., 2015), on the border between the Brazilian Amazon and Cerrado. Throughout its history, the State of Mato Grosso has undergone transformations that drastically modified its land coverage, and the economic activities that predominate in the region, are recognized for having environmental impacts (Simões et al., 2020), with wildfires being a frequent occurrence.

To the best of our knowledge, this is also the first research to date to investigate the implications of fires on air pollution in this city. Despite the severity of the scenario, Sinop, as well as the other cities in Mato Grosso, do not have an integrated system for monitoring air quality (Vormittag et al., 2021), compromising data collection and making it

Table 6
Differences in the frequency of days according to air pollutants concentrations (in quartiles) during wildfire or non-wildfire days.

Classification	Air pollutants					
	O_3		$PM_{2.5}$		PM_{10}	
Non-wildfire days	n	%	n	%	n	%
Q1	87	27.4	82	25.8	82	25.8
Q2	83	26.1	81	25.5	79	24.8
Q3	76	23.9	78	24.5	81	25.5
Q4	72	22.6	77	24.2	76	23.9
p for trend		ns		ns		ns
Wildfire days						
Q1	4	8.5	9	19.1	11	23.4
Q2	9	19.1	13	27.7	11	23.4
Q3	15	31.9	11	23.4	11	23.4
Q4	19	40.4	14	29.8	14	29.8
p for trend		a		ns		ns

[a] *p* for trend showed statistical significance. [ns]*p* for trend showed no statistical significance.

difficult to measure the actual levels of pollution and their impacts on health. Hence, three central aspects can be highlighted from the results we obtained: 1) the dynamic influence of wildfires on pollutant levels; 2) the temporal patterns of fire occurrence and FRP, and 3) the interplay of meteorological factors and pollutant mobility and concentration.

Concerning the effects of wildfires on atmospheric mobilizations and composition, notably, the temporal patterns of O_3 levels post-fire events reveal a complex interrelationship that merits thorough examination. In Sinop, the O_3 levels rose immediately after the occurrence of wildfires and remained high for the next five days. This is consistent with the study by Targino et al. (2019), which emphasizes that up to 41% of the O_3 found in air pollution in Brazil may originate from forest fires. Similarly, Kalashnikov et al., (2022) pointed out that the occurrence of elevated ozone levels in urban areas in the western United States is related to the occurrence of wildfires. It is common for ozone to be depleted near the fire site by the formation of new NO molecules, while downwind the NO_2 + VOCs cycle is established, contributing to the increase in O_3 (Langford et al., 2023). This also helps to explain why elevated levels of ground-level ozone can persist longer, as more stable compounds formed from NO_x, such as peroxyacyl nitrates (PANs), are eventually degraded (Bourgeois et al., 2021).

Our results corroborate previous works that underlined the intricate connection between wildfires and heightened O_3 levels (McClure and Jaffe, 2018; Pope et al., 2020). Such heightened O_3 concentrations during and following the first days after fire events may be attributed to the photochemical reactions involving the compounds released during combustion processes (Targino et al., 2019) that can induce such raises even out of O_3 season peaks. Despite that, this relationship is still the subject of investigation by the scientific community (Lei et al., 2021).

The effects were somewhat different for $PM_{2.5}$ and PM_{10}. For these pollutants, the response occurred slightly later than for ozone, and it was not until the third day after the fires that there was a significant increase in particulate matter concentrations, which persisted on days 4 and 5. McClure and Jaffe (2018) also described high levels of O_3 preceding significant increases in particulate matter concentrations, and in conditions with heavy smoke formation, O_3 levels tend to decrease. Variations in emissions result from different combustion conditions, which include factors such as fuel properties, combustion temperature, combustion phase (whether flaming or smoldering), moisture content, and weather variables (Kalogridis et al., 2018). An example of this is the study by Yang et al. (2021), which demonstrated that the effects of meteorological variables on air pollutants can be persistent. Under the conditions investigated in their research, precipitation and wind speed influenced $PM_{2.5}$ levels for up to four days.

Similarly, Tavella et al. (2022) observed that PM_{10} and $PM_{2.5}$ levels decreased dramatically in the case of the mini-lockdown in the city of Pelotas–RS, and even after the resumption of activities, these levels remained reduced for several days, also suggesting a time lag in the dynamics of these pollutants. Although soybean-growing areas in the Amazon biome are known to produce high levels of particulate matter during fires (Cobelo et al., 2023), the complexity of factors leading to the formation of these compounds in the atmosphere could contribute to the

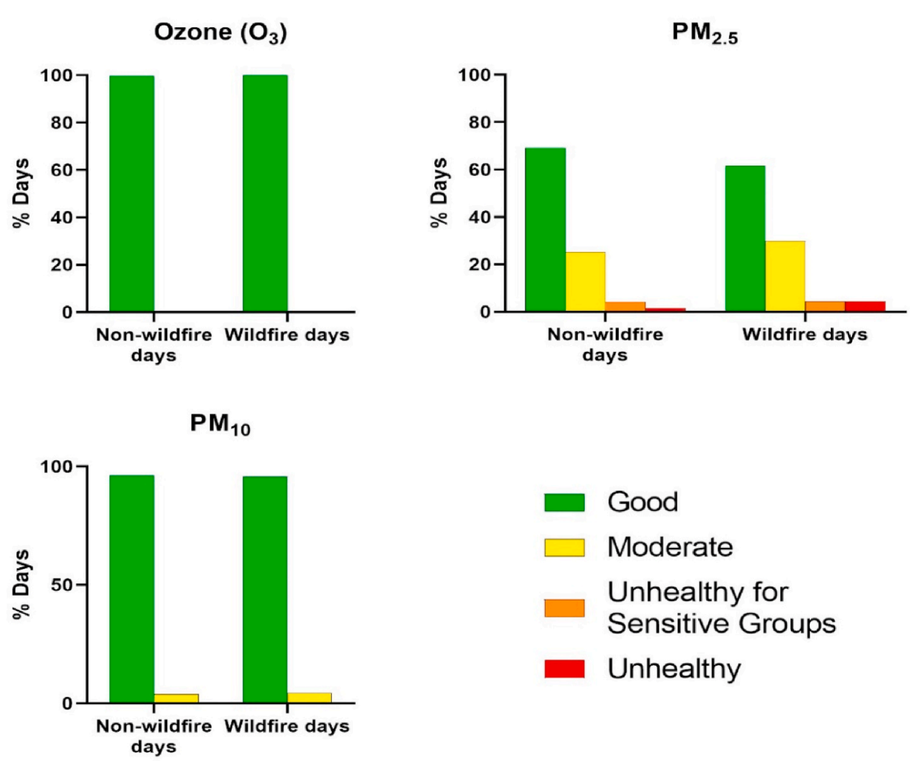

Fig. 5. Air quality index variations for O_3, $PM_{2.5}$, and PM_{10} on wildfire and non-wildfire days.

lagged increase we verified. In addition, the study by Costa et al. (2022) is valuable as it shows that in the initial stages of a forest fire (flaming), submicrometric size particles (size <1 μm) tend to predominate, which are more difficult to detect, and when the fire moves into the smoldering phase, the smoke aging process leads to an increase in particle size. Taking into account the new air quality standards recently established by the World Health Organization (WHO. World Health Organization, 2021) which predict daily averages of 15 μg m^3 and 45 μg m^3 for $PM_{2.5}$ and PM_{10}, respectively, and 100 μg m^3 for O_3 every 8 h, and up to 60 μg m^3 in the peak season, the levels verified in Sinop went above the recommendation in various occasions, especially during wildfire days.

Figs. 3 and 4 provide a vivid depiction of temporal fire patterns and their synergy with FRP values. The concentration of fire incidents during August and September, coupled with the identification of moderate to high FRP values, reinforces the potential for intense combustion and consequential heat release. Markedly, the correlation between FRP values and ozone levels demonstrates FRP's utility as an indicator of fire intensity and its subsequent ramifications for air quality (Fisher et al., 2020). One of the hypotheses that may help explain this relationship is the apparent positive correlation between the increase in FRP and the increase in NO_2 and nitrous acid (HONO) levels, both compounds released during combustion that can participate in the chemical reactions that take place in the atmosphere in the presence of sunlight and act as precursors of ground-level O_3 and particulate matter, as Fredrickson et al. (2023) mentioned. In particular, for fires with FRP <400 MW, which include most of the episodes that occurred in Sinop in 2022, this relationship appears to be consistent worldwide.

The fire radiative power can also positively correlate with the particulate matter, as shown by Ohashi et al. (2021) and Son et al. (2023). The lack of correlation between FRP and particulate matter in our study may be due to the short time series examined, as according to Price et al. (2012), data from several decades may be required to verify the relationship between FRP and the level of air pollutants. Son et al. (2023) also emphasized that fires alone cannot always be the direct cause of the elevated $PM_{2.5}$ levels, as periods of high particulate matter concentrations in the atmosphere can occur while low FRP levels are detected. This linkage is still very little explored in Brazil's investigations on air pollution, however, this indicator seems to be a very interesting method in biomass burning emissions estimation (Li et al., 2020).

The temporal progression of fire incidents holds implications that extend beyond statistical observations, as fires can be considered an essential climatic variable (Laurent et al., 2019) with undeniable impacts on heat wave formation, and climate change (Oliveira et al., 2022). These patterns suggest the need for preparedness during the months of increased fire activity. Additionally, these findings prompt a closer examination of underlying drivers—climatic, ecological, or anthropogenic—that contribute to the observed temporal trends, as this region is continuously described as of high density of fire foci (Oliveira-Júnior et al., 2021).

Regarding the analysis of correlations between meteorological variables and pollutants, it helps to elucidate the interdependencies between atmospheric parameters and pollutant levels. Temperature's persistent positive correlation with all three pollutants emphasizes its role in reactions and emissions. This scenario points to the disastrous consequences of global warming associated with increased atmospheric pollution (Moura and Da Silva Júnior, 2023). Also, the positive relationship between wind speed and ozone concurs with the dispersal of pollutants over larger areas during fire events (Urrutia-Pereira et al., 2021). Humidity's negative correlation with pollutants is probably related to its influence on chemical transformations and deposition processes (Kavassalis and Murphy, 2017). Despite this considered positive effect, increased humidity levels in fire episodes can be problematic both by dragging pollutants such as particulate matter closer to the ground, facilitating its inhalation (Airly, 2023), as well as by triggering a phenomenon called "superfog" which causes visibility to be extremely impaired and may lead to transportation hazards (O'Neil et al., 2017). Yet, the complexity of these relationships necessitates further investigation, potentially encompassing detailed chemical kinetics simulations and field campaigns to tease apart the underlying mechanisms.

About the AQI results, it should be noted that when converting the ozone values to ppm, values corresponding to the classification "moderate" were only achieved on one day (October 10th), while the $PM_{2.5}$ standards changed only slightly, but not significantly. Intriguingly, the quartile analysis further enriches our understanding of the observed AQI variations. The homogeneity in the distribution of pollutant concentrations during non-wildfire days across quartiles demonstrates quite stable air quality conditions. However, for ozone this pattern shifted during wildfire events, with a noticeable increase in days falling within the third and fourth quartiles even though no differences were seen in AQI index. This reinforces the greater occurrence of elevated pollutant levels during wildfire episodes. The juxtaposition of AQI trends and quartile illustrates how wildfire-induced variations disrupt the distribution of pollutant concentrations (Son et al., 2023).

These integrated findings provide a comprehensive perspective on the multiple impacts of wildfires on air quality, from the underlying atmospheric processes to their tangible implications for public health and urban environments, which are usually difficult to control and predict. This approach fosters a deeper understanding of the dynamic interplay between wildfires, meteorology, and pollutant concentrations, empowering policymakers and researchers alike to develop more effective strategies for managing air quality during and after wildfire events.

Some limitations of this study must be acknowledged. First, the variables on wildfires, air pollution, and weather were either determined by satellite remote sensing or derived from models using satellite data, especially the air pollution data for which there is also no local monitoring information. This can lead to certain inaccuracies in the measurements. All fire data provided by the INPE were calculated as wildfires, making it impossible to determine their origin or if they were deliberately lit fires. Furthermore, as this is a relatively short study covering one year, the data we reviewed may be singular and a larger data set collected over a broader study period could corroborate the results obtained or even provide new insights that we were unable to verify. Although it is known that the emission of pollutants from fires is usually limited to hours or days, the constancy of their occurrence and the long-term effects of exposure to high levels of air pollutants underline the importance of studies such as this one.

5. Conclusions

In this study, the impact of wildfires on air quality in Sinop was investigated, revealing significant findings with implications for the field. The analysis demonstrated that wildfires had an important influence on pollutant levels, particularly for ozone, where mean values during days with fires significantly differed from non-wildfire days. The occurrence of fires and their intensity, measured through FRP, peaked in August and September, coinciding with the highest O_3 levels. However, particulate matter exhibited significant differences only between non-wildfire days and specific wildfire days. Meteorological factors like temperature, wind speed, humidity, and precipitation exhibited varying correlations with pollutants, with temperature displaying a consistent positive correlation. Additionally, the AQI revealed a degradation in air quality on days with wildfires, particularly for O_3, emphasizing the environmental impact of these events.

The findings collectively call attention to the significance of interdisciplinary approaches in understanding and addressing the complex relations between wildfires and atmospheric pollutants. These insights unveil the variety of parameters that must be considered in devising holistic air quality management strategies, particularly in regions vulnerable to frequent and intense fire events, such as the Cerrado-Amazon ecotone.

Moreover, our results help to set the stage for future research endeavors. The temporal patterns of fire occurrences demand a nuanced exploration of the factors that act over fire activity during peak months. The role of FRP as an intensity indicator shows the potential for its integration into predictive models for fire-related air quality degradation. The meteorological-pollutant relationships call for an approach that combines numerical simulations, remote sensing, and ground-based observations to unravel the underlying mechanisms which are still very scarce in the region.

In conclusion, the current study offers a foundation for decision-makers in considering new politics for facing and better-managing air quality during fire events, with far-reaching implications for environmental policy, public health, and scientific advancement.

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CRediT authorship contribution statement

Fernando Rafael de Moura: Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Petter Djeison Witte Machado:** Writing - review & editing. **Paula Florêncio Ramires:** Writing - review & editing. **Ronan Adler Tavella:** Writing - review & editing. **Helotonio Carvalho:** Writing - review & editing. **Flávio Manoel Rodrigues da Silva Júnior:** Visualization, Methodology, Software, Formal analysis, Resources, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Agritempo, 2023. Agritempo, Brasília. Available at: https://www.agritempo.gov.br/agritempo/sobre.jsp. (Accessed 1 February 2023).

Airly, 2023. Airly, Palo Alto. Available at: https://airly.org/en/how-does-humidity-affect-air-quality-all-you-need-to-know/. (Accessed 1 February 2023).

AirNow, 2023. AirNow. Durham. Available at: https://www.airnow.gov/aqi/aqi-basics/. (Accessed 10 June 2023).

Artés, T., Castellnou, M., Durrant, T.H., San-Miguel, J., 2022. Wildfire-atmosphere interaction index for extreme-fire behaviour. Nat. Hazards Earth Syst. Sci. 22, 509–522.

Beringui, K., Justo, E.P.S., Ventura, L.M.B., Gomes, R.G.S., Lionel-Mateus, V., De La Cruz, A.H., et al., 2023. The contribution of meteorological parameters and the COVID-19 partial lockdown on air quality in Rio de Janeiro, Brazil. J. Braz. Chem. Soc. 34 (1), 69–82.

Biudes, M.S., Geli, H.M.E., Vourlitis, G.L., Machado, N.G., Pavão, V.M., Santos, L.O.F., et al., 2022. Evapotranspiration seasonality over tropical ecosystems in Mato Grosso, Brazil. Rem. Sens. 14 (10), 2482.

Bolaño-Diaz, S., Camargo-Caicedo, Y., Bernal, F.T., Bolaño-Ortiz, T.R., 2022. The effect of forest fire events on air quality: a case study of northern Colombia. Fire 5, 191.

Boguski, T.K., 2006. Center for Hazardous Substance Research. Kansas State University, Manhattan. Available at: https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.files/fileid/14285. (Accessed 1 December 2023).

Bourgeois, I., Peischl, J., Neuman, J.A., Brown, S.S., Thompson, C.R., Aikin, K.C., et al., 2021. Large contribution of biomass burning emissions to ozone throughout the global remote troposphere. Proc. Natl. Acad. Sci. U.S.A. 118 (52), e2109628118.

Brando, P.M., Soares-Filho, B., Rodrigues, L., Assunção, A., Morton, D., et al., 2020. Sci. Adv. 6 (2), eaay1632.

Brum, R.L., Tavella, R.A., Ramires, P.F., Santos, J.E.K., Klein, R.D., Da Silva Júnior, F.M.R., 2023. Ozone and $PM_{2.5}$ behavior in small cities in southern Brazil. Vittalle - Rev. Ciências Saúde 35 (1), 62–72.

Butt, E.W., Conibear, L., Knote, C., Spracklen, D.V., 2021. Large air quality and public health impacts due to amazonian deforestation fires in 2019. Geohealth 5 (7), e2021GH000429.

Carvalho, J.R.P., Almeida Monteiro, J.E.B., Nakai, A.M., Assad, E.D., 2017. Model for multiple imputation to estimate daily rainfall data and filling of faults. Rev. Bras. Meteorol. 32, 575–583.

Carvalho, R.B., Marmett, B., Dorneles, G.P., da Silva, I.M., Romão, P.R.T., da Silva Júnior, F.M.R., et al., 2022. O_3 concentration and duration of exposure are factors influencing the environmental health risk of exercising in Rio Grande, Brazil. Environ. Geochem. Health 44 (8), 2733–2742.

Casavecchia, B.H., De Souza, A.P., Stangerlin, D.M., Uliana, E.M., Melo, R.R., 2019. Índices de perigo de incêndios em uma área de transição Cerrado-Amazônia. Rev. Ciencias Agrar. 42 (3), 842–854.

Castelhano, F.J., Pedroso, A.C.N., Cobelo, I., Borge, R., Roig, H.L., Adams, M., et al., 2022. The impact of long-term weather changes on air quality in Brazil. Atmos. Environ. 283, 119182.

Cobelo, I., Castelhano, F.J., Borge, R., Roig, H.L., Adams, M., Amini, H., et al., 2023. The impact of wildfires on air pollution and health across land use categories in Brazil over a 16-year period. Environ. Res. 224, 115522.

Coker, E.S., Buralli, R., Manrique, A.F., Kanai, C.M., Amegah, A.K., Gouveia, N., 2022. Association between PM2.5 and respiratory hospitalization in Rio Branco, Brazil: demonstrating the potential of low-cost air quality sensor for epidemiologic research. Environ. Res. 214 (Part 1), 113738.

Costa, M.A.M., Amaral, S.S., Soares Neto, T.G., Cardoso, A.A., Santos, J.C., Souza, M.L., et al., 2022. Forest fires in the Brazilian Amazon and their effects on particulate matter concentration, size distribution, and chemical composition. Combust. Sci. Technol. 195 (13), 3045–3071.

Coy, M., Töpfer, T., Zirkl, F., Dorn, F.M., 2020. Agribusiness and rural-urban linkages - the case of Sinop in northern Mato Grosso, Brazil. In: Kratzer, A., Kister, J. (Eds.), Rural-Urban Linkages for Sustainable Development. Routledge, London, pp. 49–63.

Da Silva Júnior, F.M.R., De Moura, F.R., De Lima Brum, R., Tavella, R.A., 2023. Air pollution-A look beyond big cities. Integrated Environ. Assess. Manag. 19 (2), 295–297.

Letter to the editor De Moura, F.R., Da Silva Júnior, F.M.R., 2023. Gaps and future directions in research on health effects of air pollution. EBioMedicine, 104786.

Diele Viegas, L.M., Sales, L., Hipólito, J., Amorim, C., Johnson de Pereira, E., Ferreira, P., et al., 2022. We're building it up to burn it down: fire occurrence and fire-related climatic patterns in Brazilian biomes. PeerJ 10, e14276.

Dubreuil, V., Funatsu, B.M., Michot, V., Nasuti, S., Debortoli, N., Mello-Thery, N.A., et al., 2017. Local rainfall trends and their perceptions by Amazonian communities. Clim. Change 143 (3–4), 461–472.

Fisher, D., Wooster, M.J., Xu, W., Thomas, G., Lestari, P., 2020. Top-Down estimation of particulate matter emissions from extreme tropical peatland fires using geostationary satellite fire radiative power observations. Sensors 20 (24), 7075.

Fredrickson, C.D., Theys, N., Thornton, J.A., 2023. Satellite evidence of $HONO/NO_2$ increase with fire radiative power. Geophys. Res. Lett. 50, e2023GL103836.

Garcia-Hurtado, E., Pey, J., Borrás, E., Sánchez, P., Vera, T., Carratalá, A., et al., 2014. Atmospheric PM and volatile organic compounds released from Mediterranean shrubland wildfires. Atmos. Environ. 89, 85–92.

Gardin, T.N., Requia, W.J., 2023. Air quality and individual-level academic performance in Brazil: a nationwide study of more than 15 million students between 2000 and 2020. Environ. Res. 226, 115689.

Golobokova, L., Khodzher, T., Khuriganova, O., Marinayte, I., Onishchuk, N., Rusanova, P., et al., 2020. Variability of chemical properties of the atmospheric aerosol above lake baikal during large wildfires in Siberia. Atmosphere 11 (11), 1230.

Hiers, J.K., O'Brien, J.J., Varner, J.M., Butler, B.W., Dickinson, M., Furman, J., et al., 2020. Prescribed fire science: the case for a refined research agenda. Fire Ecol 16 (11), 1–15.

Honscha, L.C., Reis, F.O., Aikawa, P., Coronas, M.V., Muccillo-Baisch, A.L., Baisch, P.R.M., et al., 2023. Human health risk assessment of air pollutants in the largest coal mining area in Brazil. Environ. Sci. Pollut. Res. Int. 30 (21), 59499–59509.

IBGE. Instituto Brasileiro de Geografia e Estatística, 2023. Ibge – cidades. IBGE, Rio de Janeiro. Available at: https://cidades.ibge.gov.br/brasil/mt/sinop/panorama. (Accessed 15 May 2023).

IMEA. Instituto Mato-Grossense de Economia Agropecuária, 2023. IMEA, Cuiabá. Available at: https://www.imea.com.br/imea-site/view/uploads/estudos-customizados/AgroMT2025.pdf. (Accessed 10 May 2023).

Inness, A., Ades, M., Agustí-Panareda, A., Barré, J., Benedictow, A., Blechschmidt, A.M., et al., 2019. The CAMS reanalysis of atmospheric composition. Atmos. Chem. Phys. 19, 3515–3556.
Jaffe, D.A., Widger, N.L., 2012. Ozone production from wildfires: a critical review. Atmos. Environ. 51, 1–10.
Kalashnikov, D.A., Schnell, J.L., Abatzoglou, J.T., Swain, D.L., Singh, D., 2022. Increasing co-occurrence of fine particulate matter and ground-level ozone extremes in the western United States. Sci. Adv. 8 (1), eabi9386.
Kalogridis, A.C., Popovicheva, O.B., Engling, G., Diapouli, E., Kawamura, K., Tachibana, E., et al., 2018. Smoke aerosol chemistry and aging of Siberian biomass burning emissions in a large aerosol chamber. Atmos. Environ. 185, 15–28.
Kanchana, A.L., Sagar, V.K., Pathakoti, M., Mahalakshmi, D.V., Mallikarjun, K., Gharai, B., 2020. Ozone variability: influence by its precursors and meteorological parameters- an investigation. J. Atmos. Sol. Terr. Phys. 211, 105468.
Kavassalis, S.C., Murphy, J.G., 2017. Understanding ozone-meteorology correlations: a role for dry deposition. Geophys. Res. Lett. 44, 2922–2931.
Khand, K., Numata, I., Kjaersgaard, J., Vourlitis, G.L., 2017. Dry season evapotranspiration dynamics over human-impacted landscapes in the southern Amazon using the landsat-based METRIC model. Rem. Sens. 9 (7), 706.
Kuschnig, N., Cuaresma, J.C., Krisztin, T., Giljum, S., 2021. Spatial spillover effects from agriculture drive deforestation in Mato Grosso, Brazil. Sci. Rep. 11, 21804.
Langford, A.O., Senff, C.J., Alvarez II, R.J., Aikin, K.C., Ahmadov, R., Angevine, W.M., et al., 2023. Were wildfires responsible for the unusually high surface ozone in Colorado during 2021? J. Geophys. Res. Atmos. 128 (12), e2022JD037700.
Laurent, P., Mouillot, F., Moreno, M.V., Yue, C., Ciais, P., 2019. Varying relationships between fire radiative power and fire size at a global scale. Biogeosciences 16, 275–288.
Leão, M.L.P., Penteado, J.O., Ulguim, S.M., Gabriel, R.R., Dos Santos, M., Brum, A.N., Zhang, L., da Silva Júnior, F.M.R., 2021. Health impact assessment of air pollutants during the COVID-19 pandemic in a Brazilian metropolis. Environ. Sci. Pollut. Res. Int. 28 (31), 41843–41850.
Lei, Y., Yue, X., Liao, H., Zhang, L., Yang, Y., Zhou, et al., 2021. Indirect contributions of global fires to surface ozone through ozone–vegetation feedback. Atmos. Chem. Phys. 21, 11531–11543.
Le Roux, R., Wagner, F., Blanc, L., Betbeder, J., Gond, V., Dessard, H., et al., 2022. How wildfires increase sensitivity of Amazon forests to droughts. Environ. Res. Lett. 17 (4), 044031.
Leite-Filho, A.T., Soares-Filho, B.S., Davis, J.L., Abrahão, G.M., Börner, J., 2021. Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. Nat. Commun. 12, 2591.
Li, F., Zhang, X., Kondragunta, S., Lu, X., 2020. An evaluation of advanced baseline imager fire radiative power based wildfire emissions using carbon monoxide observed by the Tropospheric Monitoring Instrument across the conterminous United States. Environ. Res. Lett. 15, 094049.
Liu, Y., Zhou, Y., Lu, J., 2020. Exploring the relationship between air pollution and meteorological conditions in China under environmental governance. Sci. Rep. 10, 14518.
Lu, X., Crounse, J.H., Vasquez, K.T., Allen, H., Wennberg, P.O., Bourgeois, I., et al., 2021. Ozone chemistry in western U.S. wildfire plumes. Sci. Adv. 7 (50), eabl3648.
Machado-Silva, F., Libonati, R., Lima, T.F.M., Peixoto, R.B., França, J.R.A., Magalhães, M.A.F.M., et al., 2020. Drought and fires influence the respiratory diseases hospitalizations in the Amazon. Ecol. Indicat. 109, 105817.
Maciel, E.A., Oliveira-Filho, A.T., Eisenlohr, P.V., 2016. Prioritizing rare tree species of the Cerrado-Amazon ecotone: warnings and insights emerging from a comprehensive transitional zone of South America. Nat. Conserv. 14 (2), 74–82.
Mansoor, S., Farooq, I., Kachroo, M.M., Mahmoud, A.E.D., Fawzy, M., Popescu, S.M., et al., 2022. Elevation in wildfire frequencies with respect to the climate change. J. Environ. Manag. 301, 113769.
Marlier, M.E., Bonilla, E.X., Mickley, L.J., 2020. How do Brazilian fires affect air pollution and public health? GeoHealth 4 (12), e2020GH000331.
Marques, E.Q., Marimon-Junior, B.H., Marimon, B.S., Matricardi, E.A.T., Mews, H.A., Colli, G.R., 2019. Redefining the Cerrado-Amazonia transition: implications for conservation. Biodivers. Conserv. 29, 1501–1517.
Mataveli, G.A.V., Silva, M.E.S., França, D.A., Brunsell, N.A., Oliveira, G., Cardozo, F.S., et al., 2019. Characterization and trends of fine particulate matter (PM2.5) fire emissions in the Brazilian Cerrado during 2002–2017. Rem. Sens. 11 (19), 2254.
McClure, C.D., Jaffe, D.A., 2018. Investigation of high ozone events due to wildfire smoke in an urban area. Atmos. Environ. 194, 146–157.
Mello-Théry, N.A., Caldas, E.L., Funatsu, B.M., Arvor, D., Dubreuil, V., 2020. Climate change and public policies in the Brazilian Amazon state of Mato Grosso: perceptions and challenges. Sustainability 12 (12), 5093.
Moura, F.R., Da Silva Júnior, F.M.R., 2023. 2030 Agenda: discussion on Brazilian priorities facing air pollution and climate change challenges. Environ. Sci. Pollut. Res. Int. 30 (3), 8376–8390.
Nascimento, N., West, T.A.P., Börner, J., Ometto, J., 2019. What drives intensification of land use at agricultural frontiers in the Brazilian Amazon? Evidence from a decision game. Forests 10 (6), 464.
Nunes, K.V.R., Ignotti, E., Hacon, S.S., 2013. Circulatory disease mortality rates in the elderly and exposure to $PM_{2.5}$ generated by biomass burning in the Brazilian Amazon in 2005. Cad. Saúde Pública 29 (3), 589–598.
O'Dell, K., Hornbrook, R.S., Permar, W., Levin, E.J.T., Garofalo, L.A., Apel, E.C., et al., 2020. Hazardous air pollutants in fresh and aged western US wildfire smoke and implications for long-term exposure. Environ. Sci. Technol. 54 (19), 11838–11847.
Ohashi, M., Kameda, A., Kozan, O., Kawasaki, M., Iriana, W., Tonokura, K., et al., 2021. Correlation of publication frequency of newspaper articles with environment and public health issues in fire-prone peatland regions of Riau in Sumatra, Indonesia. Humanit. Soc. Sci. Commun. 8, 307.
O'Neil, S.M., Urbanski, S., Goodrick, S., Larkin, N.K., 2017. Smoke plumes: emissions and effects. Fire manag. Today Off. 75 (1), 10–15.
Oliveira, I.N., Oliveira, B.F.A., Silveira, I.H., Machado, L.M.G., Villardi, J.W.R., Ignotti, E., 2023. Air pollution from forest burning as environmental risk for millions of inhabitants of the Brazilian Amazon: an exposure indicator for human health. Cad. Saúde Pública 39 (6), e00131422.
Oliveira, U., Soares-Filho, B., Bustamante, M., Gomes, L., Ometto, J.P., Rajão, R., 2022. Determinants of fire impact in the Brazilian biomes. Front. For. Glob. Change 5, 735017.
Oliveira-Júnior, J.F., Mendes, D., Correia Filho, W.L.F., Silva Junior, C.A., Gois, G., Jardim, A.M.R.F., 2021. Fire foci in South America: impact and causes, fire hazard and future scenarios. J. South Am. Earth Sci. 112 (Part 2), 103623.
Pereira, G., Shimabukuro, Y.E., Moraes, E.C., Freitas, S.R., Cardozo, F.S., Longo, K.M., 2011. Monitoring the transport of biomass burning emission in South America. Atmos. Pollut. Res. 2, 247–254.
Pivello, V.R., Vieira, I., Christianini, A.V., Ribeiro, D.B., Menezes, L.S., Berlinck, C.N., et al., 2021. Understanding Brazil's catastrophic fires: causes, consequences and policy needed to prevent future tragedies. Perspect. Ecol. Conserv. 19 (3), 233–255.
Pope, R.J., Arnold, S.R., Chippefield, M.P., Reddington, C.L.S., Butt, E.W., Keslake, T.D., et al., 2020. Substantial increases in Eastern Amazon and Cerrado biomass burning-sourced tropospheric ozone. Geophys. Res. Lett. 17 (3), e2019GL084143.
Price, O.F., Williamson, G.J., Henderson, S.B., Johnston, F., Bowman, D.M.J.S., 2012. The relationship between particulate pollution levels in Australian cities, meteorology, and landscape fire activity detected from MODIS hotspots. PLoS One 7 (10), e47327.
Prist, P.R., Sangermano, F., Bailey, A., Bugni, V., Villalobos-Segura, M.C., Pimiento-Quiroga, N., et al., 2023. Protecting Brazilian Amazon Indigenous territories reduces atmospheric particulates and avoids associated health impacts and costs. Commun. Earth Environ. 4, 34.
Reddington, C.L., Butt, E.W., Ridley, D.A., Artaxo, P., Morgan, W.T., Coe, H., et al., 2015. Air quality and human health improvements from reductions in deforestation-related fire in Brazil. Nat. Geosci. 8, 768–771.
Reid, C.E., Considine, E.M., Watson, G.L., Telesca, D., Pfister, G.G., Jerrett, M., 2019. Associations between respiratory health and ozone and fine particulate matter during a wildfire event. Environ. Int. 129, 291–298.
Requia, W.J., Amini, H., Mukherjee, R., Gold, D.R., Schwartz, J.D., 2021a. Health impacts of wildfire-related air pollution in Brazil: a nationwide study of more than 2 million hospital admissions between 2008 and 2018. Nat. Commun. 12, 6555.
Requia, W.J., Roig, H.L., Schwartz, J.D., 2021b. Schools exposure to air pollution sources in Brazil: a nationwide assessment of more than 180 thousand schools. Sci. Total Environ. 763, 143027.
Reis, A.S., Leite, R.C., Soares, G.O.S., Soares, J.L.S., Gonçalves, F.B., Fidelis, R.R., 2021. Soil Chemical attributes under different management systems in Cerrado-Amazon ecotone. Res. Soc. Dev. 10 (7), e36210716045.
Rossi, F.S., Santos, G.A.A., 2020. Fire dynamics in Mato Grosso State, Brazil: the relative roles of gross primary productivity. Big Earth Data 4 (1), 23–44.
Sabino, M., Silva, J.B., Costa, R.O., Duarte, L.G., Souza, A.P., 2020. Biophysical parameters and extreme air temperature indices in the Cerrado-Amazonia transition. Soc. Nat. 32, 490–500.
Sánchez-Balseca, J., Pérez-Foguet, A., 2020. Modelling hourly spatio-temporal PM 2.5 concentration in wildfire scenarios using dynamic linear models. Atmos. Res. 242, 104999.
Santanna, F.B., Almeida Filho, E.O., Vourlitis, G.L., Arruda, P.H.Z., Palácios, R.S., Nogueira, J.S., 2016. Elemental composition of PM10 and PM2.5 for a savanna (Cerrado) region of southern Amazonia. Quim. Nova 39 (10), 1170–1176.
Santos, A.C.A., Finger, A., Nogueira, J.S., Curado, L.F.A., Palácios, R.S., Pereira, V.M.R., 2016. Análise da concentração e composição de aerossóis de queimadas no pantanal Mato-Grosso. Quim. Nova 39 (8), 919–924.
Scott, E., 2023. Brazilian forest fires cause toxic air pollution. Nat. Rev. Earth Environ. 4, 431.
Schneider, S.R., Abbatt, J.P.D., 2022. Wildfire atmospheric chemistry: climate anda ir quality impacts. Trends Chem 4 (4), 255–257.
Senthivel, S., Chidambaranathan, M., 2022. Machine learning approaches used for air quality forecast: a review. Rev. IIntell. Artif. 36 (1), 73–78.
Shi, K., Touge, Y., 2022. Characterization of global wildfire burned area spatiotemporal patterns and underlying climatic causes. Sci. Rep. 12, 644.
Shinde, N.N., Do Valle, S.Z.S., Maia, A.G., Amacher, G.S., 2022. Can an environmental policy contribute to the reduction of land conflict? Evidence from the Rural Environmental Registry (CAR) in the Brazilian Amazon. In: Proceedings of 22 Agricultural & Applied Economics Association Annual Meeting. Anaheim, Canada, pp. 1–64. July 31 - August 2, 2022.
Silva Júnior, C.H.L., Aragão, L.E.O.C., Fonseca, M.G., Almeida, C.T., Vedovato, L.B., Anderson, L.O., 2018. Deforestation-induced fragmentation increases forest fire occurrence in central Brazilian Amazonia. Forests 9 (6), 305.
Silvestrini, R.A., Soares-Filho, B.S., Nepstad, D., Coe, M., Rodrigues, H., Assunção, R., 2011. Simulating fire regimes in the Amazon in response to climate change and deforestation. Ecol. Appl. 21 (5), 1573–1590.
Simões, R., Picoli, M.C.A., Camara, G., Maciel, A., Santos, L., Andrade, P.R., et al., 2020. Land use and cover maps for Mato Grosso state in Brazil from 2001 to 2017. Sci. Data 7, 34.
Sinop, 2023. Prefeitura de Sinop – geografia. Available at: https://www.sinop.mt.gov.br/A-Cidade/Geografia/. (Accessed 14 May 2023).
Son, R., Stratoulias, D., Kim, H.C., Yoon, J.H., 2023. Estimation of surface PM2.5 concentrations from atmospheric gas species retrieved from TROPOMI using deep

learning: impacts of fire on air pollution over Thailand. Atmos. Pollut. Res. 14 (10), 101875.
Targino, A.C., Harrison, R.M., Krecl, P., Glantz, P., Lima, C.H., Beddows, D., 2019. Surface ozone climatology of South Eastern Brazil and the impact of biomass burning events. J. Environ. Manag. 252, 109645.
Targino, A.C., Krecl, P., Oukawa, G.Y., Mollinedo, E.V., 2024. A short climatology of black and brown carbon and their sources at a suburban site impacted by smoke in Brazil. J. Environ. Sci. 136, 498–511.
Tavella, R.A., El Koury Santos, J., de Moura, F.R., da Silva Júnior, F.M.R., 2022. Better understanding the behavior of air pollutants at shutdown times - results of a short full lockdown. Int. J. Environ. Health Res. 2, 1–8.
Tavella, R.A., Galeao da Rosa Moraes, N., Maciel Aick, C.D., Ramires, P.F., Pereira, N., Soares, A.G., et al., 2023. Weekend effect of air pollutants in small and medium-sized cities: the role of policies stringency to COVID-19 containment. Atmos. Pollut. Res. 14 (2), 101662.
Unep (United Nations Environment Programme), 2022. Spreading like Wildfire – the Rising Threat of Extraordinary Landscape Fires. A UNEP Rapid Response Assessment, Nairobi, p. 126.
Urrutia-Pereira, M., Rizzo, L.V., Chong-Neto, J., Solé, D., 2021. Impact of exposure to smoke from biomass burning in the Amazon rain forest on human health. J. Bras. Pneumol. 47 (5), e20210219.
USEPA, 2023. USEPA, Washington D.C. Available at:. United States Environmental Protection Agency https://www.epa.gov/interstate-air-pollution-transport/interstate-air-pollution-transport. (Accessed 10 June 2023).
Vadrevu, K., Lasko, K., 2018. Intercomparison of MODIS AQUA and VIIRS I-band fires and emissions in an agricultural landscape-implications for air pollution research. Rem. Sens. 10 (7), 978.
Vicente, A., Alves, C., Monteiro, C., Nunes, T., Mirante, F., Evtyugina, M., et al., 2011. Measurement of trace gases and organic compounds in the smoke plume from a wildfire in Penedono (central Portugal). Atmos. Environ. 45 (29), 5172–5182.
Vieira, C.J.S.P., Silva, D.J.F., Barreto, E.S., Siqueira, C.E.H., Colombo, T.E., Ozanic, K., et al., 2015. Detection of Mayaro virus infections during a dengue outbreak in Mato Grosso, Brazil. Acta Trop. 147, 12–16.
Volpato, M., Andrade, C.F., Silva, E.L., Barbosa, M.L., Andrade, M.D., Rocha, P.V., 2022. Fire foci and their spatiotemporal relations to weather variables and land uses in the state of Mato Grosso. Environ. Dev. Sustain. 1–20.
Vormittag, E.M.P.A., Cirqueira, S.S.R., Wicher Neto, H., Saldiva, P.H.N., 2021. Análise do monitoramento da qualidade do ar no Brasil. Estud. Avançados 35 (102), 7–30.
Wezs Junior, V.J., 2022. Transformations and characteristics of soybean production chain in Mato Grosso (Brazil). Redes 27, 1–28.
WHO. World Health Organization, 2021. WHO, Geneva. WHO global air quality guidelines: particulate matter (PM2. 5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Available at: https://apps.who.int/iris/handle/10665/345329. (Accessed 1 December 2022).
Wu, Y., Li, S., Xu, R., Chen, G., Yue, X., Yu, P., et al., 2023. Wildfire-related $PM_{2.5}$ and health economic loss of mortality in Brazil. Environ. Int. 174, 107906.
Yang, Z., Yang, J., Li, M., Chen, J., Ou, C.Q., 2021. Nonlinear and lagged meteorological effects on daily levels of ambient $PM_{2.5}$ and O_3: evidence from 284 Chinese cities. J. Clean. Prod. 278, 123931.
Ye, T., Xu, R., Yue, X., Chen, G., Yu, P., Coêlho, M.S.Z.S., et al., 2022. Short-term exposure to wildfire-related PM2.5 increases mortality risks and burdens in Brazil. Nat. Commun. 13 (1), 7651.
Yousaf, H.S., Abbas, M., Ghani, N., Chaudhary, H., Fatima, A., Ahmad, Z., et al., 2024. A comparative assessment of air pollutants of smog in wagah border and other sites in Lahore, Pakistan. Braz. J. Biol. 84, e252471.