Assessment of Black Carbon in Ciudad Valles, San Luis Potosí, México, During Sugarcane Harvest 2020-2021

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Abstract

This work evaluates Black Carbon emissions produced in Ciudad Valles, San Luis Potosí, México, during the harvest 2020–2021 of Ingenio Plan de Ayala and its association with the sugarcane sector in its area of influence. Black Carbon concentrations were measured each hour by the 7-wavelength aethalometer (AE-33) from November 13, 2020, to June 7, 2021, at Tecnológico Nacional de México - Campus Ciudad Valles, located northeast of the city, approximately 1 kilometer from Ingenio and bordered by the sugarcane area. The maximum daily concentration recorded was 4.5 ± 0.072 μg m^{-3} with a daily average of 0.9 ± 0.014 μg m^{-3}, enough to increase the mortality of the long-term exposed population by almost 6.0% moreover, according to the World Health Organization, and to cause environmental and productive effects. The burning of fossil fuels represented 62.9% of the total Black Carbon, indicating that contrary to official statistics, Ingenio Plan de Ayala may continue using fuel oil. Likewise, there was a statistically significant difference in Black Carbon concentrations during harvest and no harvest periods, indicating a direct relationship between its emissions and the sugarcane sector of this region. The highest concentrations were in the surrounding area of Ingenio Plan de Ayala and sugarcane lands, which supports the previous theory. With the results obtained, the bottom line is that evaluating other agricultural burning emissions near the growing cities is necessary to minimize adverse effects on human health and reduce CO_2eq emissions.

Introduction

Pollution is the introduction of a contaminant into a natural environment that causes instability, disorder, damage, or discomfort in an ecosystem, physical environment, or living beings. Although natural sources and human activities generate a significant proportion. Different classes or types of pollution depend on the environment affected and the extent of the source. Air pollution from industries, construction sites, agricultural practices, vehicles, and the combustion of dirty energy sources, is the fourth deadliest health risk in the world, causing one in ten deaths. Anthropogenic air pollution is the leading cause of climate change (UN, 2022). In the last 100 years, the average global temperature has increased by 0.76 ºC, and approximately 87.0% of the world´s population is exposed to pollution levels that exceed air quality guidelines set by World Health Organization (WHO). Premature deaths due to air pollution cost the global economy $225 billion in lost labor income, equivalent to the combined gross domestic product of India, Canada, and Mexico. Because of its severity, pollution control should be a priority for country governments; however, this expenditure always competes with other budget priorities and political interests (IHNME & WB, 2016).

One of the primary air pollutants is Particle Matter (PM); this term describes solid or liquid particles (<100 μm) that are present airborne and dispersed. This complex heterogeneous mixture of chemical compounds (organic and inorganic) can react and change depending on thermodynamic properties, emission sources (natural or anthropogenic), and meteorological conditions (WHO, 2013). For example, $PM_{2.5}$, particles less than or equal to 2.5 μm, are highly produced by anthropogenic sources in urban areas with a residence life in the atmosphere for weeks or days but can travel hundreds of miles. Therefore, it implies that studying them for their local or global effects is very important.

Black carbon (BC) is an air pollutant contained mainly in $PM_{2.5}$. It is a type of carbonaceous material formed primarily from combustion, emitted directly into the atmosphere, and with a unique combination of physical properties. It strongly absorbs visible light, is refractory, and has a vaporization temperature near 4000K. In addition, it is an aggregate of small spheres and insoluble in water and common organic solvents. BC plays a significant role in the Earth´s climate system because it absorbs solar radiation, influences cloud processes, and alters the meltdown of snow and ice sheets. Since a large fraction of its atmospheric concentrations is due to anthropogenic activities, reducing its concentrations could represent an efficient environmental strategy because BC is rapidly removed from the atmosphere by deposition, which could decrease the global climate forced by human activities in the short term and its associated rate of climate change (Bond et al., 2013). Also, it is the second most potent agent of climate change, with a warming potential equivalent to 55.0% of that attributed to CO_2 (Liu et al., 2022).

The direct exposure of humans to BC is associated with health damages such as cardiac arrest and failure (Burroughs-Peña & Rollins, 2018), blood strokes (Mordukhovich et al., 2009), lung cancer (Yong et al., 2019), chronic bronchitis, asthma, emphysema (Paunescu et al., 2019), and low birth weight (Bové et al., 2019); as well as severe dehydration, acute renal dysfunction, and genotoxicity (Chaudhuri et al., 2017). Given the association of its emissions with other highly harmful pollutants, such as polycyclic aromatic hydrocarbons (PAHs), BC is considered the principal indicator of air quality in human health (Casares-Long, Longhurst and Barnes, 2020). Recent research has found that in cities as polluted as Delhi, India, the daily average BC concentrations are 24.4 μg m^{-3}, but with episodes higher than 59.9 μg m^{-3} (Dumka et al., 2018).

As for effects on human health, the WHO indicates that exposure of the population to 10.0 μg m^{-3} of BC, in the short term, can increase mortality by 0.9% from cardiovascular diseases and 0.7% from other causes. Moreover, prolonged exposure to 1.0 μg m^{-3} would increase the risk of death by 6.0% (Janssen, 2012). Additionally, Tobias et al. in 2014 concluded that increments of 1.4 μg m^{-3} increase respiratory mortality risk by 10.0%.

There are two main techniques for quantitative measurement of BC groups: those based on thermal properties and those using the optical properties of the pollutant (Slowik et al., 2007). Optical techniques usually measure light absorption by aerosols, which is then empirically related to BC content (Ahmed et al., 2009). An example is Soot Particle Absorption Photometer which performs a filter-based absorption measurement (Cremer et al., 2022). Similarly, there is a Photoacoustic Spectrometer, which measures sound at different wavelengths to identify its absorbing components (Jin et al., 2021), and a Multi-angle Absorption Photometer, which is capable of simultaneously measuring radiation fields in the front and back hemispheres concerning an aerosol filter system (Abdullah et al., 2022). Among these commercial BC monitors, filter-based absorption photometers, such as aethalometers, are the most widely used in air quality monitoring stations of their robust precision design (Kalbermatter et al., 2022; Srivastava et al., 2021).

Many researchers have conducted several studies with Aethalometers around the world: emissions from fireworks (Rawat et al., 2022), transportation (Minderyté et al., 2022), materials production (Hedmer et al., 2022), and burning of agricultural residues (Sight et al., 2014) and firewood (Li et al., 2022). Also, variations in BC concentrations and composition generated by extraordinary events, such as pandemics caused by COVID-19 (Pandey & Negi, 2022); seasonal (Sharma et al., 2022) or diurnal (Yan et al., 2022), have been observed. In the same way, there were analyzed differences in BC concentrations in rural and urban environments (Kouassi, 2021) or their effects in remote places such as Antarctica (Gonçalves Jr. et al., 2022).

There are also no unified international or national standards or criteria on the effects of BC concentrations at different levels, but studies have shown that deposition of between 100 and 300 ng-BC/g^1-H_2O of BC can reduce the albedo from 2.7% to 6.0%. It may increase when continuously runoff between 70 and 204 millimeters of water (Suárez et al., 2017).

Mexico has a National Black Carbon Monitoring Network that performs intermittent monitoring in 9 cities. In Mexico City, annual average concentrations exceed 2.5 μg m^{-3} (Peralta et al., 2019), In other overriding conurbations in México, such as Guadalajara, Jalisco, the average is 3.1 μg m^{-3} and in Monterrey, Nuevo León, it is 3.6 μg m^{-3} (INECC, 2016). In the case of the city of San Luis Potosí, the annual average concentration for the year 2018 is 1.11 μg m^{-3} in the northern part of the city (Zapata-Ramírez, 2022) and 2.04 μg m^{-3} in the southern one in the year 2020 (Cueto-Delgadillo, 2021).

Mexico has established the Intended Nationally Determined Contribution (INDC) program to reduce national emissions of BC in unconditional mitigation goals for the following years, which México´s Government expects to reduce around 51 % of the BC emissions by 2030. Due to their importance, several techniques have been developed to estimate their emissions, sources, and potential effects. In México, Instituto Nacional de Ecología y Cambio Climático (INECC) estimates the emissions of greenhouse gases (GHGs), including BC, through Inventario Nacional de Gases y Compuestos de Efecto Invernadero (INEGYCEI); and to make it, INECC uses the traditional Emission Factors method.

According to the Emission Factors method in 2016, the emissions from sugarcane burning in San Luis Potosí were 1,059,728 ± 21,194 tCO_2eq, while those from the sugar mills were 658,949 ± 13,178 tCO_2eq, as well as 6,331 ± 126 t of $PM_{2.5}$ and 1,429 ± 28 t of BC (Quintana-Quintalán, 2022).

Currently, seeks to increase the certainty of the estimations of emissions from the agricultural sector by creating specific emission factors for each crop and area (Mugica-Álvarez et al., 2018), as well as using quantitative techniques through direct monitoring of agricultural land where the burning takes place. For instance, Jain et al. (2019) conducted a state inventory of air pollutants from crop residue burning, using the IPCC 2006 inventory preparation guidelines, finding the proportions included in Fig. 1.

The sugarcane zone of San Luis Potosí is part of the northeastern sugarcane region of México, the second largest in the country (CONADESUCA, 2021). Four mills operate in the state that process sugarcane production for industrial purposes, all located in the Huasteca region. Plan de Ayala and Plan de San Luis in Ciudad Valles; Alianza Popular in Tamasopo, and San Miguel del Naranjo in El Naranjo (Fig. 2).

During the sugarcane harvest 2020-2021, the four mills processed more than 5 billion tons of sugarcane from 103 thousand hectares, producing 644 thousand tons of different qualities of sugar (CONADESUCA, 2022). Sugarcane production generated an income of close to 2.5 billion pesos, making it the third most important crop in the state concerning area harvested and the first in respect of production value (SIAP, 2022). In addition to employing 15 thousand of producers (Beta San Miguel, 2016; Grupo PIASA, 2019; Ingenio Santos, 2020), the sugarcane sector in the state required the labor of more than 1,500 workers in the mills and more than 7,000 cutters during the harvest, as well as a significant number of transporters and indirect employees (CONADESUCA, 2021).

Despite its economic and social importance, this sector´s productive and industrial processes have a high environmental impact. First, in 90.0% of the sugarcane area, one or more cultivation tasks do mechanically, which implies the use of diesel fuel. Furthermore, zafra (the sugarcane harvest) takes place approximately six months yearly. During this period, the double-burning method harvests 73.3% of sugarcane production, and 1,800 vehicles are used to transport cane from farms to mills and then the processed sugar from mills to distribution or processing centers. Regarding the industrialization process, San Luis Potosí is the sugarcane producer state in the country that uses the most fuel oil (13.69 million liters, equivalent to 56.3% of that used nationally), as well as 11,700 tons of bagasse (CONADESUCA, 2022).

There have been efforts to reduce sugarcane burning. However, this practice is still common in almost the producing countries, causing effects at different scales, from the local level, such as the diseases caused to the population directly exposed to the global level, such as global warming.

In Mexico, as of 2012, air pollutant monitoring is mandatory only for big cities (NOM-156-SEMARNAT-2012), considering that they are the main emission sites. San Luis Potosí has four monitoring stations that measure criteria pollutants, and in the case of Ciudad Valles, this is the first direct monitoring.

This research is the first to be carried out in the country, with direct monitoring of BC, in a small agro-city of Mexico and associating it with agricultural activity. Its purpose is to evaluate BC concentrations in Ciudad Valles, San Luis Potosí, México, during the 2020-2021 Ingenio Plan de Ayala harvest season. As a result, following the WHO guidelines, it verified the health risk to the exposed population and to find elements that show their possible relationship with activities carried out by the sugarcane sector in this region.

Materials And Methods

Ciudad Valles is the capital of the municipality of the same name, in San Luis Potosí, México. It is in the eastern part of the state, in the Huasteca region, on the banks of the Tampaón River. With a population of 180 thousand inhabitants, it is a major commercial, tourist, agricultural, and livestock center and the second most important city in the state. Moreover, relevant sugar and cement industries are within it (Fig. 3) (INEGI, 2021).

Grupo Santos is the fourth largest sugar corporation in México, with five mills that industrialize the production of 52 thousand hectares, representing 7.7% of the national sugarcane area (CONADESUCA, 2022). Its mills produce sugar of different qualities for the food industry in the domestic market and the United States, as well as molasses for the livestock and pharmaceutical industry, on a smaller scale. These mills are in the process of certifications and approvals for healthy, safe, and innocuous production, such as Kosher, FDA, ISO:9001, and ISO:22000, and clean production (Industria Limpia México).

In the specific case of Ingenio Plan de Ayala (Fig. 3), it has certifications referring to the quality of its processes and, in 2021, obtained BONSUCRO certification for sustainable sugarcane production. Moreover, the population near Ingenio and authorities affirm that these certifications have not impacted visibly on improvements in the pollution emitted and social problems caused by the company (Quadratín SLP, 2018). Ingenio Plan de Ayala has certifications because of the quality of its processes. Also, in 2021, obtained BONSUCRO certification for the sustainable production of sugarcane, even if the population near Ingenio and authorities affirm that these certifications have not impacted visibly the pollution emitted and social problems caused by the company (Quadratín SLP, 2018).

The equipment used for monitoring was an AE33 aethalometer (Magee Scientific, Berkeley, U.S.A.) was installed inside Tecnológico Nacional de México - Campus Ciudad Valles (TecNM - Ciudad Valles), located at northwest of the city (22°01'19"N, 99°02'11"W). The sampling site is approximately one-kilometer northeast of Ingenio Plan de Ayala and is surrounded from northeast to west by sugarcane fields. Model AE33 aethalometer is a filter-based absorption photometer that measures seven wavelengths (370-950 nm). It continuously captures particles by drawing the aerosol-laden air stream through a spot on the filter tape. The analysis has done by measuring the light transmission through a portion of filter tape containing the sample versus the transmission through an unloaded tape portion that acts as a reference area (Drinovec et al., 2015). This equipment can differentiate BC from fossil fuels and biomass burning, which in this case will be very useful in explaining the proportion of contamination attributable to sugarcane and bagasse burning, which comes from the use of fuel oil in the agroindustrial process at the mill (Fig. 4a).

Uncertainty calculation is a relevant factor to consider when measuring atmospheric pollutants such as BC, according to Intergovernmental Panel on Climate Change (IPCC). In this case, was used the *Expanded Uncertainty* formula. Expanded Uncertainty is a measure that defines, around the result, an interval within which it can find a large part of the distribution of values that can attribute reasonably to the measurand. For this purpose, first, the Combined Uncertainty is calculated using Formula (1). Then finally, Expanded Uncertainty was determined with formula (2) (CEM, 2008). With the corresponding calculations, the uncertainty for this case was 0.016, which corresponds to the results obtained by Cuesta-Mosquera. (2020).

$$u_c = \sqrt{\sum_i [c_i \cdot u(x_i)]^2} \quad (1)$$

$$U = k u_c(y) \quad (2)$$

where: u_c = Combined Uncertainty, c_i = sensitivity coefficient, $u(x_i)$ = component uncertainty, U = Expanded Uncertainty, k = coverage factor, and y = factor.

In addition, a Vantage Pro2 mobile weather station had installed (Davis Instruments, Davis, USA) to obtain meteorological data from the site. The station can obtain continuous data in 15-minute intervals on wind direction and speed (anemometer), temperature (thermometer), relative humidity (hygrometer), atmospheric pressure (barometer), and precipitation (rain gauge), among others (Fig. 4b), of which hourly got averages subsequently.

RStudio, a free statistical and graphing software for the R programming language, was used for the data analysis. In addition, customized graphs were done with Openair (a package developed to analyze air quality data) and other packages to show BC behavior during the analysis period. Finally, arc Map, version 10.2, was also used to graph pollutant concentration distribution to analyze the dispersion ranges and the different BC concentrations.

Results And Discussion

The BC monitoring started on November 13, 2020, and ended on June 7, 2021, covering the entire period of the 2020-2021 sugarcane harvest of the Ingenio Plan de Ayala. Additionally, it was monitored 20 days after the end of the harvest to have a period of concentrations to serve as a control. The Aethalometer AE33 software provided by Magee Scientific processed and classified more than 4,300 data in BC total, BC from fossil fuels, and BC from biomass burning.

The maximum daily average concentration of total BC was 2. 2 ± 0.035 µg m^{-3} however, some episodes exceeded 4.5 ± 0.072 µg m^{-3}. A fraction from fossil fuel burning exceeded 3.5 ± 0.056 µg m^{-3}, while that from biomass burning was 2.3 ± 0.037 µg m^{-3}. In 34.2% of cases, observations were higher than 1 µg m^{-3} and 12.9% higher than 1.4 µg m^{-3}. The entire period average was 0.9 µg m^{-3}. Also, the 95^{th} percentile is 1.7, which implies that 95.0% of the observations reach up to 1.7 µg m^{-3}.

Concentrations from fossil fuel burning (blue line) represented 62.9% of total concentrations (black line), compared to those from biomass burning (green line), which represented, on average, 37.1%. The proportion remains almost unchanged at all BC levels (Fig. 5). According to the Emissions Factors method, BC concentrations in a sugarcane area from biomass combustion should be much higher than those in oil derivatives.

Daily average concentrations showed a bell-shaped behavior, increasing during the months when the harvest was in full swing. On 74 occasions daily average exceeded 1 μg m^{-3} and on 22 occasions excelled at 1.4 μg m^{-3}. As can be seen, December had the highest concentrations, exceeding the WHO reference 23 times. Furthermore, on the days following the harvest ended, the concentrations were reduced to near zero for several days (Table 1).

Table 1 Average daily BC concentrations

Season	Month	Days	Averages		
			BC concentration (μg m^{-3})	Temperature (°C)	Wind speed (km h^{-1})
Winter	Nov	18	0.8 ± 0.013	22.6	0.3
	Dec	31	1.1 ± 0.018	18.3	0.5
	Jan	31	0.9 ± 0.014	18.5	0.4
	Febr	28	0.9 ± 0.014	23.8	1.5
Spring	Mar	31	1.0 ± 0.016	27.4	2.1
	Apr	30	0.8 ± 0.013	31.1	ND
	May	18	0.6 ± 0.010	30.4	ND
No harvest	May-Jun	20	0.5 ± 0.010	30.7	ND

* ND = No data available

A Kolmogorov-Smirnov test proved the data do not fit a normal distribution (p .01). Due to this reason, the Mann-Whitney U test, a non-parametric test that does not require a specific distribution to compare two sample means from the same population and test whether they are equal or not, was used (Ramírez-Ríos & Polack-Peña, 2020).

In this case, in the three types of BC detected (total, biomass, and fossil fuels), it was found that there is a statistically significant difference between the concentrations found in the harvest season and the non-harvest season (Pr > |Z| <.0001). Additionally, the previous results were supported with the Kruskal-Wallis test, obtaining a significant difference between the two groups of data (Pr > Chi-square <.0001) for all cases.

Concerning variation of concentrations between days of the week, concentration levels begin to increase on Mondays, reaching their peak on Tuesdays and then decreasing until Sunday by up 20.0%, even though the Ingenio Plan de Ayala protocols indicate that during harvest season, milling should be constant and by the availability of sugarcane.

As regards changes during the day, there are two peaks with subsequent drops. The first occurs at noon, after a prolonged drop near 20:00 hours. (Fig. 6); some possible explanations are related to times of more significant vehicular traffic because of sugarcane received or sugar shipped, as well as the beginning of processing shifts at the mill, where a more significant amount of fuel must probably be due to the machinery starting.

In the graph, 1 μg m^{-3} was established as the limit since it is the WHO reference for increasing the risk of premature death due to prolonged exposure to BC. During November, December, and January, the highest concentrations occurred between 18:00 and 23:00 hours, while from February to May, they occurred between 10:00 and 14:00 hours. Concentrations are considerably lower at the beginning and end of the harvest. The lowest concentrations of the entire period were during June, when the harvest had already concluded (Fig. 7). A relevant fact is that nearly the entire December concentrations exceeded 1 μg m^{-3}, becoming the most polluted month.

The highest concentrations occurred at low wind speeds, so a large part of the emissions must remain and be deposited in the surrounding areas where they are generated. Joining the distribution BC concentrations graph with the map of Ciudad Valles is possible to observe that the highest concentrations are found in the location of Ingenio Plan de Ayala and its surroundings, as well as to the north and northwest of the sampling point where there is a large area cultivated with sugarcane (Fig. 8).

These results are consistent with trajectory models obtained from Global Data Assimilation System data of the National Oceanic and Atmospheric Administration (NOAA), which show no substantial variations in wind trajectories at different times of the day or between the months of the year. Furthermore, up to 87.0% of the winds come from the Gulf of Mexico. Therefore, it implies that the predominant winds blow from west to east. Still, when they meet the Sierra Madre Oriental, a natural barrier that delimits the Huasteca Potosina, an essential fraction of the particles they contain are deposited in this zone (Fig. 9).

On this matter, during the sugarcane harvest season, the naked eye can see the smoke generated by the burning of the sugarcane fields and the sugar mill (Fig. 10). Moreover, the deposition of black dust (BC) is present on the surfaces of houses and vehicles in much of the city. As a result, many people feel discomfort in the respiratory tract.

Sugarcane is one of the most important economic activities in Ciudad Valles and other municipalities of the Huasteca Potosina that depend heavily on it. However, despite its economic and social importance, since decades ago, it has been facing severe problems that threaten the sustainability of the activity. Although for several years, it remained the main crop in San Luis Potosí, recently, some more profitable products have become uppermost, displacing sugarcane. Currently, it ranks fourth in cultivated area, with 11.5% of the agricultural area, and second in production value, with 17.3% of the agricultural income generated.

Notwithstanding, the sector has managed to maintain its importance due to the addition of surfaces to production areas, which has necessarily implied massive land clearing (SIAP, 2022). Nevertheless, on the other hand, it has serious problems of low and decreasing productivity, and dependence on rainfall since only 22.3% of sugarcane land has an irrigation system (CONADESUCA, 2022).

On the other hand, the sugarcane sector's production and industrialization process lead to activities involving the combustion of both biomass and fossil fuels. For this reason, BC concentrations can increase to more than double during the sugarcane harvest season, causing severe environmental, productive, and human health effects, among others.

In Ciudad Valles, hourly mean concentrations for the entire period were 0.9 ± 0.014 μg m^{-3}, with episodes exceeding 4.5 ± 0.072 μg m^{-3}. During one-third of the sampling time, concentrations exceeded the WHO guidelines (1.0 μg m^{-3}) for increases in human mortality from prolonged exposure to BC. This fact is grave for the population of Ciudad Valles (180,000 inhabitants) and surrounding communities since they are exposed to BC and other air pollutants emitted during the harvest six months yearly.

In addition, emissions from this sector could have a direct relationship with sugarcane production. That is because both productive and industrial systems involve several activities with fossil fuels and biomass combustion.

Considering that sugarcane milled by Ingenio Plan de Ayala has increased by 42.3% over the last 15 years, it is foreseeable that concentrations to which the population is exposed have also increased. Furthermore, as mentioned, the environment is affected, as well as agriculture itself, since part of BC is deposited on the crops, reducing the sunlight they receive and thus their productivity.

Concerning the BC composition, there was an unexpected result since, according to CONADESUCA figures, during the 2020-2021 harvest, Ingenio Plan de Ayala did not use petroleum in its processes. Nevertheless, the aethalometer data are conclusive and consistent: concentrations from fossil fuel combustion represent two-thirds of the total BC found. Furthermore, other temporal variations indicate that processing patterns decrease concentration during weekends and at night, although this may also be related to other social or natural factors. What is a fact is, during the cold months, the highest concentrations were in the evenings, between 18:00 and 23:00 hours. On the other side, during the warm months, they were in the mornings, between 9:00 and 13:00 hours.

The wind speed was low (average of 0.6 km h^{-1}) during the monitoring. This fact in addition to the high humidity (80.0%) triggers the scarce BC dispersion; in other words, a large part of the contamination remains where it was emitted. That is why the Hysplit model indicated the highest concentrations are distributed mainly around Ingenio Plan de Ayala and to the north-northwest of TecNM - Ciudad Valles, where the sugarcane area is.

Likewise, a decrease in BC concentrations practically until zero was detected when the harvest ended (there is a statistical difference during harvest and non-harvest seasons). So, it is very likely that they are directly related to emissions from the factory and the sugarcane growing area in the region, and that Ingenio Plan de Ayala continues to use fuel oil as fuel, in addition to not using filters.

Despite the limitations that this research contains, it is an important antecedent for future works of greater depth, time, and completeness, which include complimentary techniques such as scanning microscopy to corroborate the composition of the particles, as well as PM monitoring.

BC is the leading indicator of air quality (Janssen et al., 2011) since its emission is associated with those other air pollutants that are highly toxic to humans and environmental contaminants. Therefore, although the evaluation of BC concentrations is the focus of this study, it has been found that, at the same time, a significant amount of air pollutants is emitted by the sugarcane sector, mainly in the harvest season.

In addition, the burning of agricultural residues is a widespread practice throughout Mexico and many countries in the world, especially in grain-producing crops such as corn, rice, sorghum, and wheat, among others (Santiago-De la Rosa et al., 2017). That is why the problem of air pollution from agricultural activities is not limited to sugarcane areas but many other agricultural lands. Despite this, until now, it has not been awarded the corresponding importance, which is why the data from direct monitoring in areas where agricultural burning is scarce and temporary.

The weak environmental legislation in Mexico is only limited to a draft standard to regulate emissions from sugar mills, without being consolidated from 2017 to date. Regarding agricultural burnings, producers only need to follow a regulation to elaborate guardrails to prevent the fire from spreading uncontrolled and notify Environmental Ministry to be able to carry them out.

Despite its economic and social relevance, the sugarcane sector activities adversely affect the local population and the global environment. The sugarcane sector emissions also affect the BC reduction goals of 51% to 2030, signed by Mexico in COP21. That is because it is crucial to establish accurate air quality monitoring systems that provide information to implement fairer agricultural policies according to reality to sanction those responsible for the effects and even inhibit the activities that produce such contamination.

Conclusions

The BC concentrations found in this research show that contamination generated during the harvest season can be equal to or higher than those reported in the largest cities in Mexico, despite Ciudad Valles having less than 200,000 inhabitants. Furthermore, these concentrations are high enough to increase the risk of disease and premature death in the exposed population and cause harmful environmental and productive impacts.

The results showed that concentrations are significantly higher during the sugarcane harvesting season than during the rest of the year, so there are elements to think that this sector is the growth generator. Additionally, the highest concentrations were between the sugar mill and cultivation areas, reaffirming the previous idea.

There have been efforts to measure and evaluate air pollutants in San Luis Potosí. Still, the time and the contaminants monitored have yielded valuable but limited results to establish better control strategies and improve air quality. Therefore, it is highly desirable to continue research related to these issues, extending the time and resources used, such as a more significant amount of equipment and the use of technologies such as geographic information systems and remote sensing to expand and improve the information generated.

In this regard, as it is known, the reduction of BC emissions is an effective measure to reduce global warming and improve the health of the exposed population. The sugarcane sector could contribute to this reduction with actions such as green harvesting and the installation of filters in the chimneys of sugar mills. It is possible to quantify these improvements with the implementation of monitoring systems. This is fundamental to aspiring the agricultural sector to reduce their emissions and contributes to achieving the goals proposed by México for The 2030 Agenda for Sustainable Development concerning emissions reduction.

Declarations

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Data availability

The datasets generated during and analyzed during the current study are available from the corresponding author and Pedro Pérez Medina (first author) on reasonable request.

Competing interests

All authors certify that we have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Author contributions

The undersigned, authors of this manuscript, state that we collaborated in the present research work by performing the following roles (according to CRediT's classification):

[1] Pedro Pérez Medina – Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review and editing.

[2] María Guadalupe Galindo Mendoza – Conceptualization, Funding Acquisition, Methodology, Supervision, Writing - review and editing.

[3] Valter A. Barrera - Conceptualization, Formal Analysis, Methodology, Resources, Software, Writing - review and editing.

Ethics

The undersigned, authors of the manuscript, state that the research presented did not involve experimentation or manipulation of humans or any other living being, so we considered that the authorization of an Ethics or Bioethics Committee is not required.

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References

1. Abdullah, N. A., Latif, M. T., Juneng, L., Uning, R., Hassan, H., Azhari, A., Tuch, T., & Wiedensohler, A. (2022). Aerosol particle properties at a remote tropical rainforest in Borneo. *Atmospheric Pollution Research*, *13*(4), 101383. https://doi.org/10.1016/j.apr.2022.101383
2. Ahmed, T., Dutkiewicz, V. A., Shareef, A., Tuncel, G., Tuncel, S., & Husain, L. (2009). Measurement of black carbon (BC) by an optical method and a thermal-optical method: Intercomparison for four sites. *Atmospheric*

Environment, *43*(40), 6305–6311. https://doi.org/10.1016/j.atmosenv.2009.09.031

3. Beta San Miguel. (2016, August 8). *San Miguel del Naranjo*. BSM Beta San Miguel. Retrieved April 21, 2022, from https://www.bsm.com.mx/naranjo.html
4. Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., . . . Zender, C. S. (2013). Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres*, *118*(11), 5380–5552. https://doi.org/10.1002/jgrd.5017 1
5. Bové, H., Bongaerts, E., Slenders, E., Bijnens, E. M., Saenen, N. D., Gyselaers, W., Van Eyken, P., Plusquin, M., Roeffaers, M. B. J., Ameloot, M., & Nawrot, T. S. (2019, September 17). Ambient black carbon particles reach the fetal side of human placenta. *Nature Communications, 10*(1). https://doi.org/10.1038/s41467-019-11654-3
6. Burroughs Peña, M. S., & Rollins, A. (2017, February). Environmental Exposures and Cardiovascular Disease. *Cardiology Clinics, 35*(1), 71–86. https://doi.org/10.1016/j.ccl.2016.09.001
7. Casares Long, J. J., Longhurst, J. W. S., & Barnes, J. (2020). *Air Pollution XXVIII (Wit Transactions on Ecology and the Environment, Vol 244): 28*. WIT Press / Computational Mechanics.
8. Centro Español de Metrología (CEM). (2008). *Evaluación de datos de medición. Guía para la Expresión de la Incertidumbre de Medida* (1st ed.). Madrid, España. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.cem.es/sites/default/files/gum20digital1202010_0.pdf
9. Chaudhuri, I., Fruijtier-Pölloth, C., Ngiewih, Y., & Levy, L. (2017, November 2). Evaluating the evidence on genotoxicity and reproductive toxicity of carbon black: a critical review. *Critical Reviews in Toxicology, 48*(2), 143–169. https://doi.org/10.1080/10408444.2017.1391746
10. Comité Nacional para el Desarrollo Sustentable de la Caña de Azúcar (CONADESUCA). (2021, October). *Informe Estadístico del Sector Agroindustrial de la Caña de Azúcar en México Zafras 2011–2012 / 2020–2021* (No. 8). https://siiba.conadesuca.gob.mx/infocana/informe/informe.html
11. Comité Nacional para el Desarrollo Sustentable de la Caña de Azúcar (CONADESUCA). (2022). *Reportes*. Sistema Sinfocaña. Retrieved December 15, 2021, from https://www.gob.mx/conadesuca/acciones-y-programas/sistema-infocana
12. Cremer, R. S., Tunved, P., & Ström, J. (2022). Airmass Analysis of Size-Resolved Black Carbon Particles Observed in the Arctic Based on Cluster Analysis. *Atmosphere*, *13*(5), 648. https://doi.org/10.3390/atmos13050648
13. Cuesta-Mosquera, A., Močnik, G., Drinovec, L., Müller, T., Pfeifer, S., Minguillón, M. C., Björn, B., Buckley, P., Dudoitis, V., Fernández-García, J., Fernández-Amado, M., Ferreira De Brito, J., Flentje, H., Heffernan, E., Kalivitis, N., Kalogridis, A. C., Keernik, H., Marmureanu, L., Luoma, K., . . . Wiedensohler, A. (2020, August 28). Intercomparison and characterization of 23 Aethalometers under laboratory and ambient air conditions: Procedures and unit-to-unit variabilities. Atmospheric Measurement Techniques. https://doi.org/10.5194/amt-2020-344
14. Cueto-Delgadillo, A. (2021). *Evaluación de carbono negro en la zona sur de San Luis Potosí en el año 2020* [Tesis de licenciatura]. Universidad Autónoma de San Luis Potosí.

15. Drinovec, L., Močnik, G., Zotter, P., Prévôt, A. S. H., Ruckstuhl, C., Coz, E., Rupakheti, M., Sciare, J., Müller, T., Wiedensohler, A., & Hansen, A. D. A. (2015). The "dual-spot" Aethalometer: an improved measurement of aerosol black carbon with real-time loading compensation. *Atmospheric Measurement Techniques*, *8*(5), 1965–1979. https://doi.org/10.5194/amt-8-1965-2015
16. Dumka, U., Kaskaoutis, D., Tiwari, S., Safai, P., Attri, S., Soni, V., Singh, N., & Mihalopoulos, N. (2018). Assessment of biomass burning and fossil fuel contribution to black carbon concentrations in Delhi during winter. *Atmospheric Environment*, *194*, 93–109. https://doi.org/10.1016/j.atmosenv.2018.09.033
17. Gobierno de Aragón. (2022, August 4). *El cambio climático*. Portal de Aragon. Retrieved July 15, 2022, from https:// www.ara gon.es/-/el-cambio climatico#:%7E:text=La%20temperatura%20del%20planeta%20sube%3ª%20es%20el%20calentamiento%20global,-Las%20temperaturas%20de&text=En%20los%20%C3%BAltimos% 20100%20ª%C3%B1os,el%20%C3%81rtico%2C%20hasta%205%20%C2%BAC
18. Gonçalves JR, S. J., Magalhães, N., Charello, R. C., Evangelista, H., & Godoi, R. H. (2022). Relative contributions of fossil fuel and biomass burning sources to black carbon aerosol on the Southern Atlantic Ocean Coast and King George Island (Antarctic Peninsula). *Anais da Academia Brasileira de Ciências*, *94*(suppl 1). https://doi.org/10.1590/0001-3765202220210805
19. Grupo PIASA. (2019, April 30). *Ingenio Plan de San Luis*. Retrieved April 21, 2022, from https://grupopiasa.com/site/index.php/u-o-perativas/ingenio-plan-de-san-luis
20. Hedmer, M., Lovén, K., Martinsson, J., Messing, M. E., Gudmundsson, A., & Pagels, J. (2022). Real-Time Emission and Exposure Measurements of Multi-walled Carbon Nanotubes during Production, Power Sawing, and Testing of Epoxy-Based Nanocomposites. *Annals of Work Exposures and Health*. https://doi.org/10.1093/annweh/wxac015
21. Ingenios Santos. (2020, February 18). *Unidades Estratégicas*. Retrieved April 21, 2022, from https://www.santos.com.mx/
22. Institute for Health Metrics and Evaluation (IHME) & World Bank (WB). (2016). *The Cost of Air Pollution*. World Bank Group, IHME.
23. Instituto Nacional de Ecología y Cambio Climático (INECC). (2016). *Políticas de mitigación de contaminantes climáticos de vida corta Perspectivas desde México sobre la implementación Mitigación de Carbono Negro* [En línea]. https://https://www.inecc.gob.mx/dialogos/dialogos1/images/documentos/Dialogo6/Abraham_Residuos.pdf
24. Instituto Nacional de Estadística y Geografía (INEGI). (2021). *Censo de Población y Vivienda* (Version 2020) [Dataset]. INEGI. https://www.inegi.org.mx/default.html
25. Jain, N., Bhatia, A., & Pathak, H. (2014). Emission of Air Pollutants from Crop Residue Burning in India. *Aerosol and Air Quality Research, 14*(1), 422–430. https://doi.org/10.4209/aaqr.2013.01.0031
26. Janssen, N. A., Hoek, G., Simic-Lawson, M., Fischer, P., van Bree, L., ten Brink, H., Keuken, M., Atkinson, R. W., Anderson, H. R., Brunekreef, B., & Cassee, F. R. (2011, December). Black Carbon as an Additional Indicator of the Adverse Health Effects of Airborne Particles Compared with PM_{10} and $PM_{2.5}$. *Environmental Health Perspectives, 119*(12), 1691–1699. https://doi.org/10.1289/ehp.1003369
27. Janssen, N. A. H., World Health Organization. Regional Office for Europe, & Weltgesundheitsorganisation Regionalbüro für Europa. (2012). *Health Effects of Black Carbon*. World Health Organization, Regional Office for Europe.

28. Jin, H. W., Hu, R. Z., Pin-hua, X., & Ping, L. (2021). Synchronous detection of multiple optical characteristics of atmospheric aerosol by coupled photoacoustic cavity. *Chinese Physics B*. https://doi.org/10.1088/1674-1056/ac43ad
29. Kalbermatter, D. M., Močnik, G., Drinovec, L., Visser, B., Röhrbein, J., Oscity, M., Weingartner, E., Hyvärinen, A. P., & Vasilatou, K. (2022). Comparing black-carbon- and aerosol-absorption-measuring instruments – a new system using lab-generated soot coated with controlled amounts of secondary organic matter. *Atmospheric Measurement Techniques*, *15*(2), 561–572. https://doi.org/10.5194/amt-15-561-2022
30. Kouassi, A. A., Doumbia, M., Silue, S., Yao, E. M., Dajuma, A., Adon, M., Touré, N. E., & Yoboue, V. (2021). Measurement of Atmospheric Black Carbon Concentration in Rural and Urban Environments: Cases of Lamto and Abidjan. *Journal of Environmental Protection*, *12*(11), 855–872. https://doi.org/10.4236/jep.2021.1211050
31. Li, A. F., Zhang, K. M., Allen, G., Zhang, S., Yang, B., Gu, J., Hashad, K., Sward, J., Felton, D., & Rattigan, O. (2022). Ambient sampling of real-world residential wood combustion plumes. *Journal of the Air & Waste Management Association*. https://doi.org/10.1080/10962247.2022.2044410
32. Liu, X., Zheng, M., Liu, Y., Jin, Y., Liu, J., Zhang, B., Yang, X., Wu, Y., Zhang, T., Xiang, Y., Liu, B., & Yan, C. (2022). Intercomparison of equivalent black carbon (eBC) and elemental carbon (EC) concentrations with three-year continuous measurement in Beijing, China. *Environmental Research*, *209*, 112791. https://doi.org/10.1016/j.envres.2022.112791
33. Minderytė, A., Pauraite, J., Dudoitis, V., Plauškaitė, K., Kilikevičius, A., Matijošius, J., Rimkus, A., Kilikevičienė, K., Vainorius, D., & Byčenkienė, S. (2022). Carbonaceous aerosol source apportionment and assessment of transport-related pollution. *Atmospheric Environment*, *279*, 119043. https://doi.org/10.1016/j.atmosenv.2022.119043
34. Mordukhovich, I., Wilker, E., Suh, H., Wright, R., Sparrow, D., Vokonas, P. S., & Schwartz, J. (2009, November). Black Carbon Exposure, Oxidative Stress Genes, and Blood Pressure in a Repeated-Measures Study. *Environmental Health Perspectives, 117*(11), 1767–1772. https://doi.org/10.1289/ehp.0900591
35. Mugica-Álvarez, V., Hernández-Rosas, F., Magaña-Reyes, M., Herrera-Murillo, J., Santiago-De La Rosa, N., Gutiérrez-Arzaluz, M., de Jesús Figueroa-Lara, J., & González-Cardoso, G. (2018b, November). Sugarcane burning emissions: Characterization and emission factors. *Atmospheric Environment, 193*, 262–272. https://doi.org/10.1016/j.atmosenv.2018.09.013
36. Pandey, C. P., & Negi, P. S. (2022). Characteristics of equivalent black carbon aerosols over Doon Valley in NW Indian Himalaya during COVID-19 lockdown 2020. *Environmental Monitoring and Assessment*, *194*(3). https://doi.org/10.1007/s10661-022-09879-9
37. Paunescu, A. C., Casas, M., Ferrero, A., Pañella, P., Bougas, N., Beydon, N., Just, J., Lezmi, G., Sunyer, J., Ballester, F., & Momas, I. (2019, October). Associations of black carbon with lung function and airway inflammation in schoolchildren. *Environment International, 131*, 104984. https://doi.org/10.1016/j.envint.2019.104984
38. Peralta, O., Ortínez-Alvarez, A., Basaldud, R., Santiago, N., Alvarez-Ospina, H., de la Cruz, K., Barrera, V., de la Luz Espinosa, M., Saavedra, I., Castro, T., Martínez-Arroyo, A., Páramo, V. H., Ruíz-Suárez, L. G., Vazquez-Galvez, F. A., & Gavilán, A. (2019). Atmospheric black carbon concentrations in Mexico. *Atmospheric Research*, *230*, 104626. https://doi.org/10.1016/j.atmosres.2019.104626
39. Quadratín SLP. (2018, December 25). *Provoca cáncer Ingenio Plan de Ayala en Valles: funcionario municipal* [Press release]. https://sanluispotosi.quadratin.com.mx/san-luis-potosi/provoca-cancer-ingenio-plan-de-ayala-

en-valles-funcionario -municipal/

40. Quintana-Quintalán, O. M. (2021, March). *Análisis y elaboración del Inventario de Emisiones de Gases y Compuestos de Efecto Invernadero (GYCEI) del sector azucarero de San Luis Potosí*. Facultad de Ingeniería, Universidad Autónoma de San Luis Potosí.
41. Ramírez-Ríos, A., & Polack-Peña, A. M. (2020). Estadística inferencial. Elección de una prueba estadística no paramétrica en investigación científica. *Horizonte de La Ciencia, 10*(19). https://doi.org/10.26490/uncp.horizonteciencia.2020.1 9.597
42. Rawat, P., Sharma, B., Dey, S., Rana, A., Mukherjee, A., Polana, A. J., Mao, J., Jia, S., Yadav, A. K., Khillare, P. S., & Sarkar, S. (2022). Are fireworks a significant episodic source of brown carbon? *Environmental Science and Pollution Research*, *29*(26), 40252–40261. https://doi.org/10.1007/s11356-022-20183-4
43. Santiago-De la Rosa, N., Mugica-Álvarez, V., Cereceda-Balic, F., Guerrero, F., Yáñez, K., & Lapuerta, M. (2017, September 9). Emission factors from different burning stages of agriculture wastes in Mexico. *Environmental Science and Pollution Research, 24*(31), 24297–24310. https://doi.org/10.1007/s11356-017-0049-4
44. Sharma, K., Ranjan, R. K., Lohar, S., Sharma, J., Rajak, R., Gupta, A., Prakash, A., & Pandey, A. K. (2022). Black Carbon Concentration during Spring Season at High Altitude Urban Center in Eastern Himalayan Region of India. *Asian Journal of Atmospheric Environment*, *16*(1), 100–112. https://doi.org/10.5572/ajae.2021.149
45. Singh, A., Rajput, P., Sharma, D., Sarin, M. M., & Singh, D. (2014). Black Carbon and Elemental Carbon from Postharvest Agricultural-Waste Burning Emissions in the Indo-Gangetic Plain. *Advances in Meteorology*, *2014*, 1–10. https://doi.org/10.1155/2014/179301
46. Sistema de Información Agroalimentaria y Pesquera (SIAP). (2022). *Producción Agrícola*. Cierre de la producción agrícola. Retrieved July 8, 2022, from https://nube.siap.gob.mx/cierreagricola/
47. Slowik, J. G., Cross, E. S., Han, J. H., Davidovits, P., Onasch, T. B., Jayne, J. T., Williams, L. R., Canagaratna, M. R., Worsnop, D. R., Chakrabarty, R. K., Moosmüller, H., Arnott, W. P., Schwarz, J. P., Gao, R. S., Fahey, D. W., Kok, G. L., & Petzold, A. (2007). An Inter-Comparison of Instruments Measuring Black Carbon Content of Soot Particles. *Aerosol Science and Technology*, *41*(3), 295–314. https://doi.org/10.1080/02786820701197078
48. Srivastava, P., Naja, M., Seshadri, T. R., Joshi, H., Dumka, U. C., Gogoi, M. M., & Babu, S. S. (2021). Implications of Site-specific Mass Absorption Cross-section (MAC) to Black Carbon Observations at a High-altitude Site in the Central Himalaya. *Asia-Pacific Journal of Atmospheric Sciences*, *58*(1), 83–96. https://doi.org/10.1007/s13143-021-00241-6
49. Suárez, L., Torres, C., Helmig, D., & Hueber, J. (2017). Medición y análisis del aerosol de carbono negro en el observatorio de Huancayo, Perú. *Revista Boliviana de Física*, *30*, 7–15. http://www.scielo.org.bo/scielo.php?script=sci_arttext&p id=S1562-38232017000100003&lng=en&tlng=es
50. Tobias, A., Karanasiou, A., Reche, C., Amato, F., Alastuey, A., & Querol, X. (2014). Efectos del carbón negro sobre la salud respiratoria en la ciudad de Barcelona. *European Respiratory Journal*, *44*, 2923. https://erj.ersjournals.com/content/44/Suppl_58/2923.short
51. United Nations (UN). (2022, September 9). *Pollution and climate change upsurge the risk of “climate penalty”.* UN News. Retrieved September 26, 2022, from https://news.un.org/en/story/2022/09/1126141
52. World Health organization (WHO). (2013). *Health effects of particulate matter. Policy implications for countries in eastern Europe, Caucasus and central Asia*. https://pm10.kormany.hu/download/1/e6/80000/Health-effects-of-particulate-matter-final-Eng.pdf

53. Yan, Q., Kong, S., Yan, Y., Liu, X., Zheng, S., Qin, S., Wu, F., Niu, Z., Zheng, H., Cheng, Y., Zeng, X., Wu, J., Yao, L., Liu, D., & Qi, S. (2022). Hourly emission estimation of black carbon and brown carbon absorption from domestic coal burning in China. *Science of The Total Environment*, *814*, 151950. https://doi.org/10.1016/j.scitotenv.2021.151950
54. Yong, M., Anderle, L., Levy, L., & McCunney, R. J. (2019, November). Carbon Black and Lung Cancer Mortality—A Meta-regression Analysis Based on Three Occupational Cohort Studies. Journal of Occupational &Amp; *Environmental Medicine, 61*(11), 949–00. https://doi.org/10.1097/jom.0000000000001713
55. Zapata Ramírez, J. D. (2022). *Evaluación de Carbono Negro en la zona norte de la ciudad de San Luis Potosí durante los años 2018-2019* [Tesis de licenciatura]. Universidad Autónoma de San Luis Potosí.

Figures

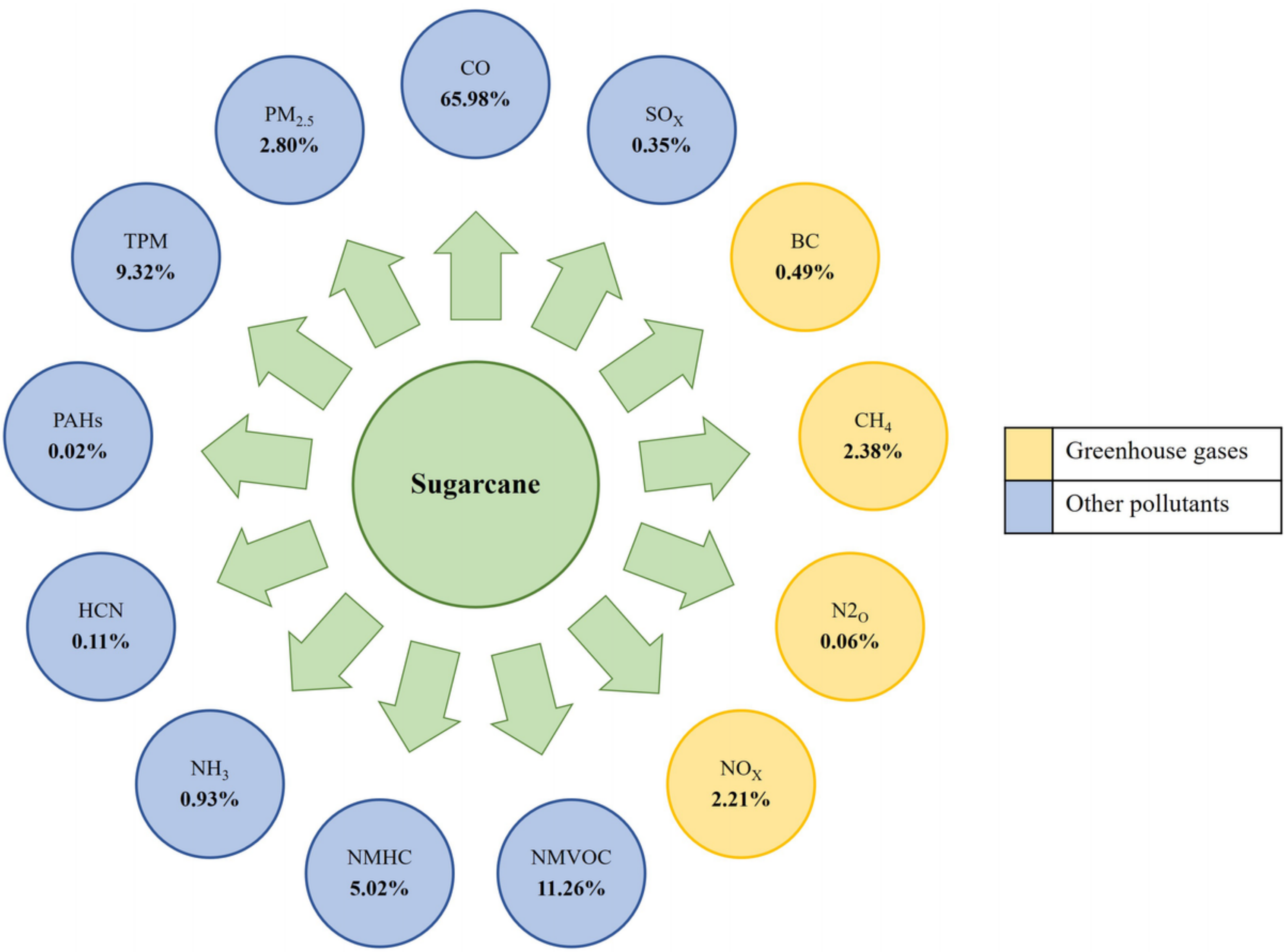

Figure 1

Air pollutants emitted by the burning of crop residues.

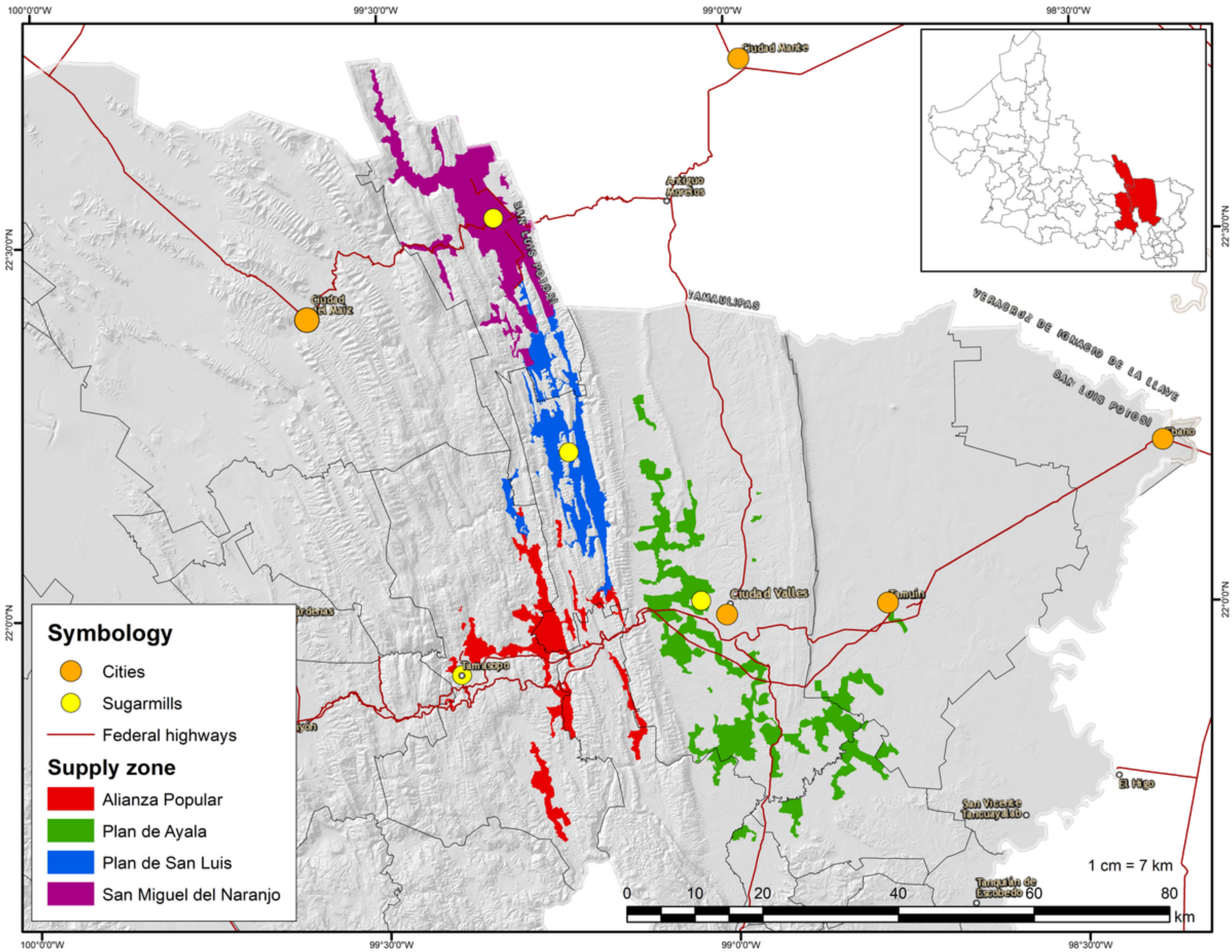

Figure 2

Sugar mills and sugarcane areas of San Luis Potosí, México

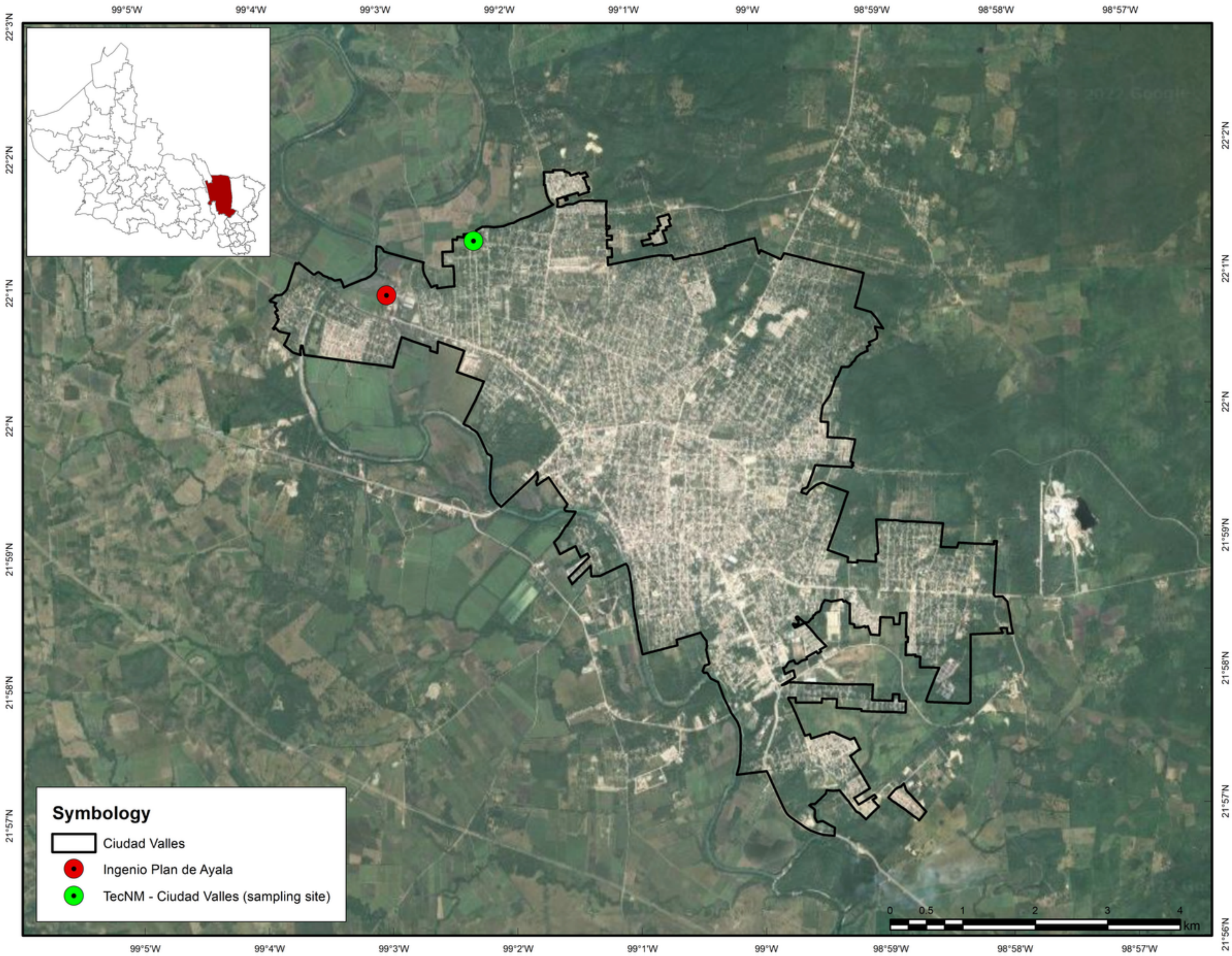

Figure 3

Measurement site location

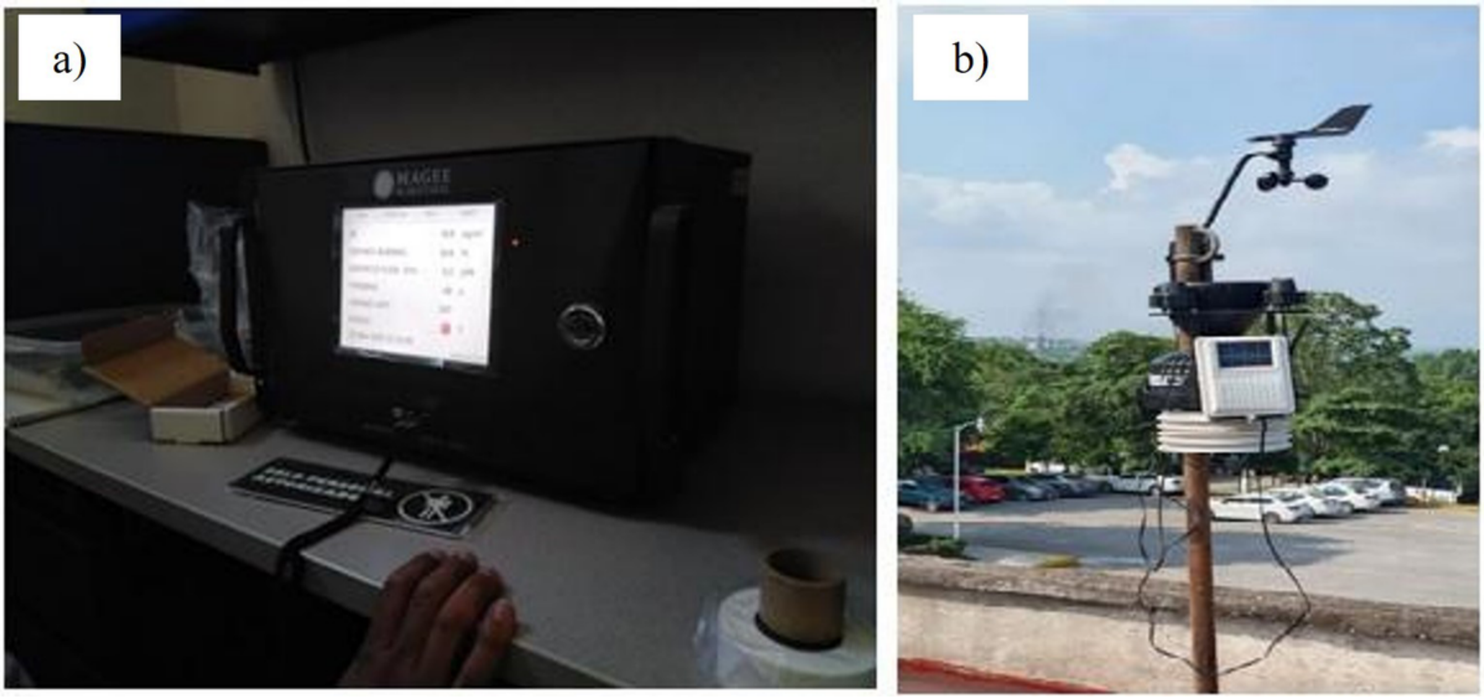

Figure 4

Measuring equipment a) Aethalometer AE33 b) Mobile weather station Vantage Pro2

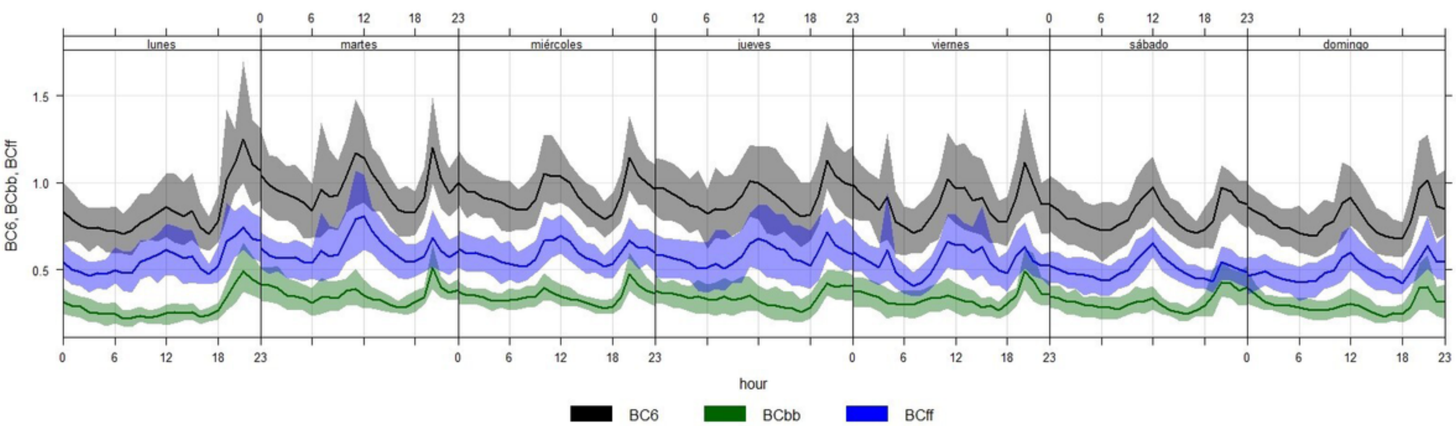

Figure 5

Composition of BC concentrations

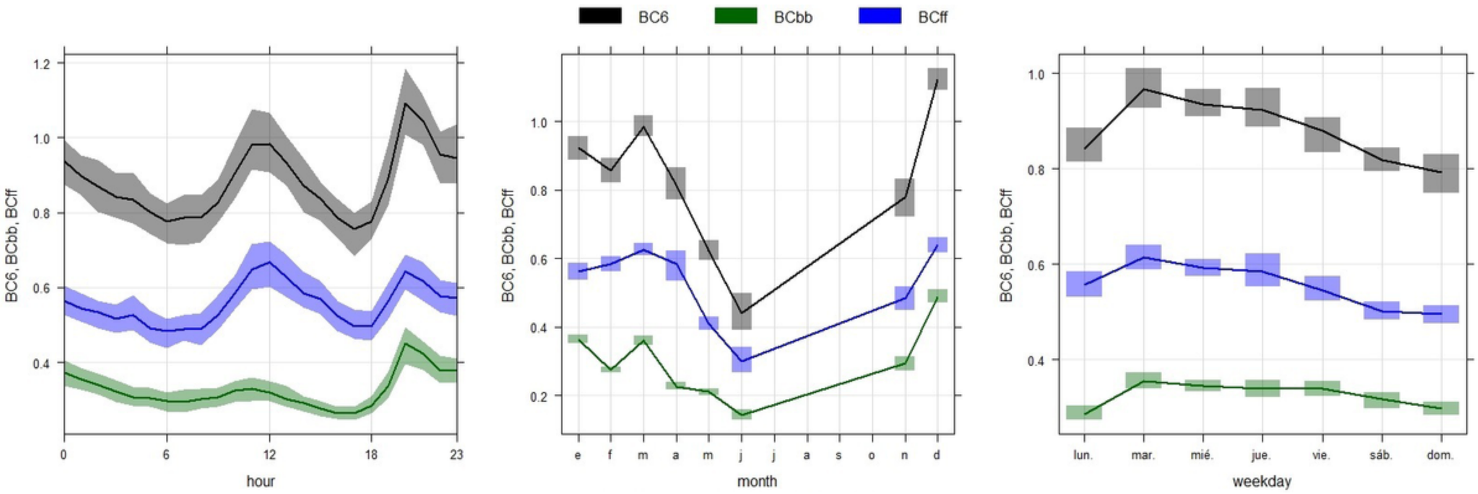

Figure 6

Variation in BC concentrations by day and by hour

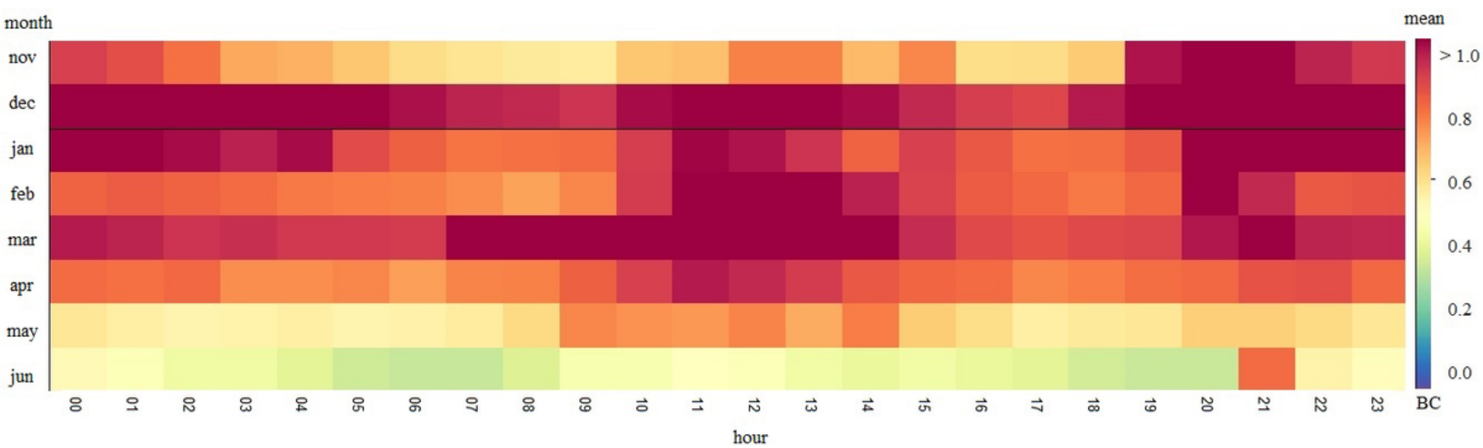

Figure 7

Variation in BC concentrations by hour, during the monitoring months

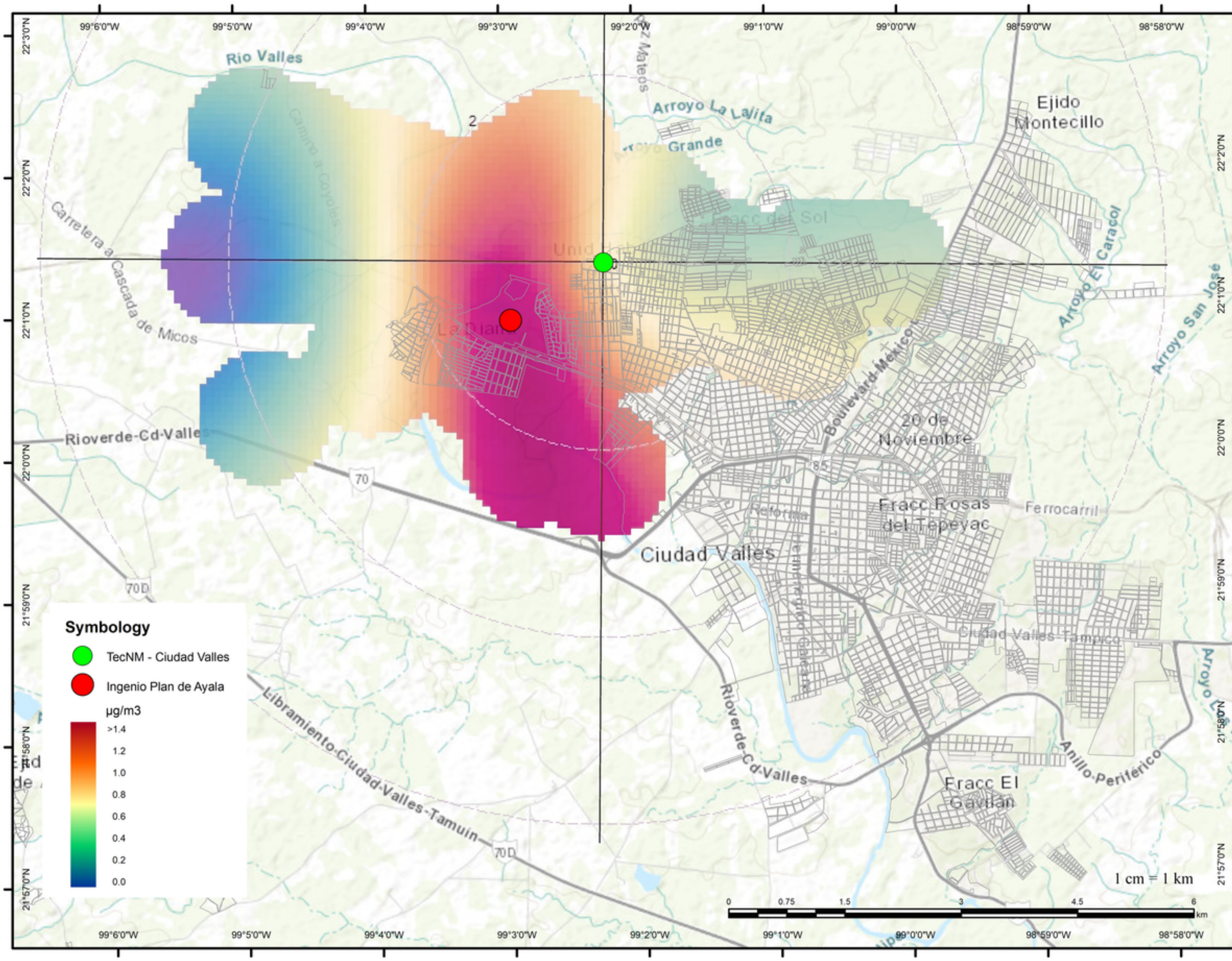

Figure 8

Spatial distribution of BC concentrations

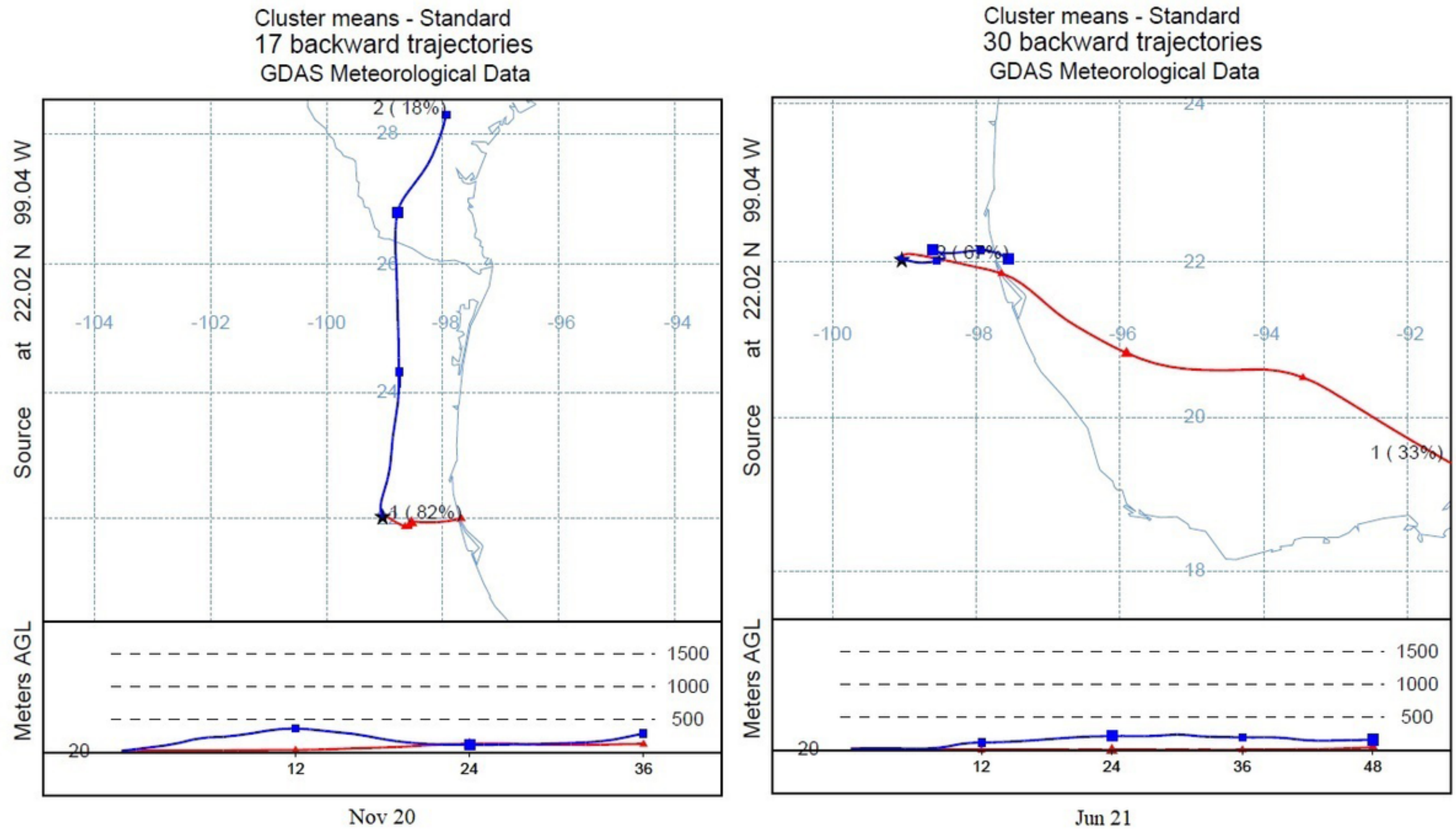

Figure 9

Monthly Provenance paths of winds. November 2020 (left), June 2021 (right)

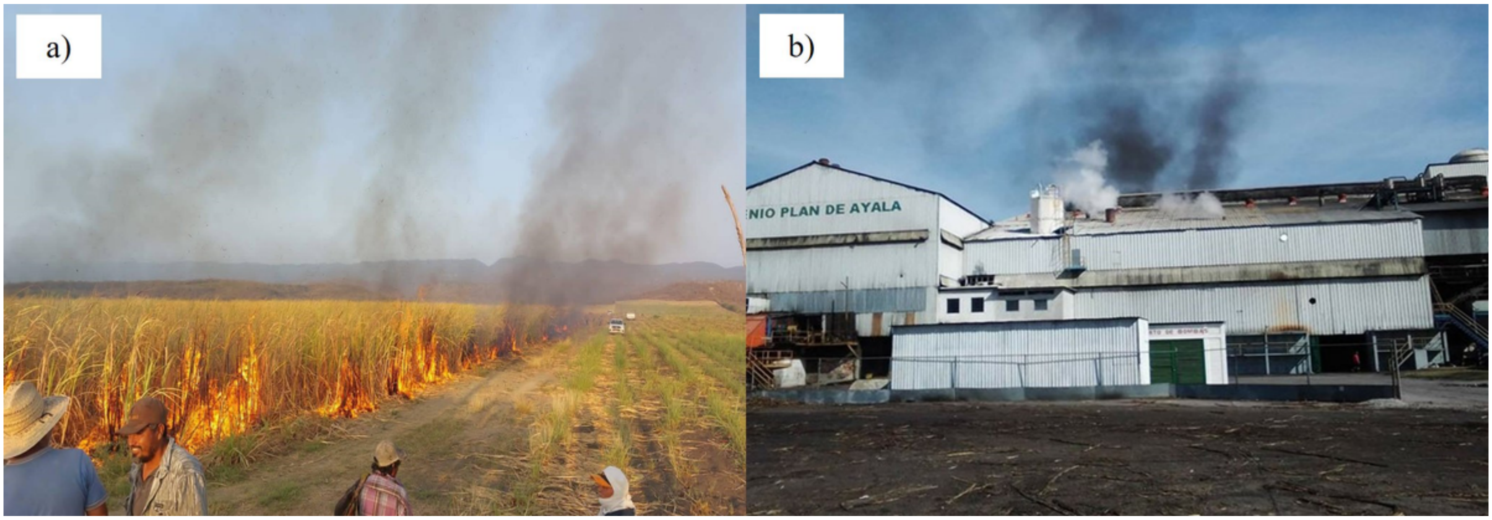

Figure 10

BC emissions produced by sugarcane sector in Ciudad Valles. a) Cane fields b) Sugarmill.