296 Chilean J. Agric. Anim. Sci., (2023) 39(3): 296-304.
https://doi.org/10.29393/CHJAA39-26DCJT60026

ISSN 0719-3890 online

DYNAMICS OF CO_2 EMISSION AND DISPERSION FROM TWO SUGARCANE MILLS IN THE GUAYAS BASIN

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ABSTRACT

Sugarcane (*Saccharum* spp.) is a C4 plant widely cultivated for the production of sugar, energy, and other derivatives. Sugarcane fixes a certain amount of carbon in the biomass but emits variable amounts of carbon dioxide ($CO_{2)}$ into the atmosphere, depending on the technologies used in both field and industrial processes. This study quantified and described the spatial and temporal dispersion of CO_2 emissions generated during the sugarcane harvest period by the San Carlos and Valdez sugarcane mills, in Guayas, Ecuador. Measurements of CO_2 were carried out using a 3M's portable gas analyzer model Monitor 3M-EVM-7, which provides digital readings without requiring any additional procedure. Samples were taken every two weeks during the milling period (June to December). Sampling was carried out at distances of approximately 280, 500, 1000, and 3000 m from the central chimney of the factories. Locations were eventually georeferenced to allow for possible associations to infer spatial and temporal patterns and distributions. The effects associated with dispersion patterns of greenhouse gases released from the industrial chimneys as well as wind direction and speed were considered. The results show that CO_2 emitted by the industrial sugarcane process did not impact surface-level measurements due to natural dispersion, although it decreased with distance. There was a high, negative, and significant correlation between CO_2 concentrations and temperature; and a high, direct, and significant correlation with dew point. CO_2 concentrations were inversely correlated with distances from the factory chimneys.

Keywords: industrial pollution, CO_2, sugar mill, gas dispersion.

Received: July 27, 2023 Accepted: December 4, 2023

INTRODUCTION

The atmosphere is a complex system in which many physical and chemical processes occur, involving transport, dispersion, and mixing with pollutants emitted naturally and anthropogenically. In addition, these pollutants can be partially affected by the meteorological conditions during their emission (Steiner, 2020). Some of the most notorious pollutants related to agricultural processes include greenhouse gases (GHGs) such as carbon monoxide, nitrous oxide, sulfur oxide, ozone, and carbon dioxide, which affect the natural balance of gases that are necessary for the biosphere. In this sense, monitoring this balance is essential for sustainability in agricultural areas where products are subjected to the enforceable competition of good farming practices and carbon footprint (Kweku et al., 2018).

Carbon dioxide is the primary GHG emitted through human activities. In 2017, CO_2 accounted for approximately 81.6% of the total anthropogenic GHG emissions in the U.S. (Yoro and Daramola, 2020). To date, carbon dioxide remains the most significant contributor to these total gases, followed by methane. While the global average abundance of CO_2 in 2022 was 417 parts per million (ppm), the cumulative warming influence of all gases included in the Annual Greenhouse Gases Index (AGGI) was equivalent to 523 ppm CO_2 (Stein, 2023).

Studies on GHGs use equivalent measures in terms of tons of Carbon Dioxide Equivalent (CO_2e) because they include emissions of six gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF_6) (Zheng et al., 2019).

According to US EPA (2016), the primary sources of CO_2 emissions are transportation, electricity, and industry. Carbon dioxide is continually exchanged among the Earth's various surfaces, which include soil, rivers, seas, oceans, and agricultural land. This natural exchange process involves the production and absorption of CO_2 by many microorganisms, plants, and animals, thus maintaining a delicate equilibrium. However, because of the technological advancements dating back to the Industrial Revolution of the 18th century, human activities have introduced CO_2 and other GHGs into the atmosphere, leading to the trapping of heat and subsequent impacts on climate change.

Sugarcane is a C4 plant cultivated in large agricultural areas to produce sucrose, and more recently also used to generate valuable derivatives such as energy, as well as various other products (Nass et al., 2007). This crop has a significant social, economic, and environmental impact worldwide. The primary environmental impact of sugarcane is related to air quality, primarily stemming from the release of CO_2, other gases, and particularly particulate matter. This is associated with the burning of fields before harvesting, either manually or mechanically, as well as CO_2 emissions and particulate matter from the chimneys of sugarcane mills during the sugar manufacturing process.

Most sugarcane mills only use petroleum-based fuels for a start-up but maintain subsequent energy production using the combustion of dry sugarcane fiber, "bagasse", obtained after grinding sugar cane stalks. This fiber represents more than 10\% of the total weight of sugarcane and feeds the boilers that supply steam for the generators. Burning this fiber fuel in boilers produces gases and particles of different sizes, increasing air pollution.

Recent research has provided valuable information regarding the environmental and health damage caused by burning plant fibers. However, conclusions are contradictory and mainly evaluate this technology from an energy and economic perspective. Sugarcane burning in the field and bagasse combustion in sugarcane mills continue to be the predominant technology (Ortiz Laurel et al., 2012).

Pre-harvest crop burning and fiber combustion technologies depends on industrial infrastructure, machinery, agricultural technology, and, to a lesser extent, workers' protection. In Brazil, Rípoli et al. (2000) have pointed out numerous shortcomings of the burned harvesting system in sugarcane (especially environmental), but the manufacturing phase or emissions associated with sugarcane mills were not addressed.

The present study quantified and described the spatial and temporal dispersion of CO_2 emissions generated during the sugar harvest period by two sugarcane mills located in the Guayas River basin in the coastal region of Ecuador.

MATERIALS AND METHODS

The research was carried out in Ecuador in the area around the San Carlos (674030m, 9755872m WGS84 UTM 17S) and Valdez (655772m, 9764825m WGS84 UTM 17S) sugarcane mills, near the cities of Milagro and Marcelino Maridueña, respectively. CO_2 measurements were recorded using a 3M's portable gas analyzer, model Monitor 3M-EVM-7. Each sampling point was monitored for five minutes. Measurements were made every two seconds and automatically averaged by the equipment, generating 150 observations in each sampling. A total of 190 samples from 28500 measurements were obtained from July 2022 to January 2023. Air sampling occurred every two weeks during the milling period, starting in June and ending in mid- or late December when chimney emissions from the mills and crop field burning ceased.

The sampling locations were chosen based on their distance from the sugarcane mill chimney, specifically at approximately 280, 500, 1000, and 3000 m. Additionally, the direction of the CO_2 plume was taken into account. Each sampling location was geo-referenced, allowing for spatial associations; descriptive parameters were calculated to identify patterns of wind and spatial and temporal distributions of gases and particles. Wind direction and speed records at a height of 10 meters were considered throughout the sampling period in both locations. These data were obtained from the website: https://power.larc.nasa.gov/data-access-viewer.

Simultaneously to CO_2 measurements, maximum, minimum, and average temperatures, as well as relative humidity and dew point were obtained from three weather stations located close to the sugarcane mills. March and April had the highest average sunshine hours (heliophany) of 3 hours/day, while the lowest values were recorded in October and November, with 0.38 hours per day. Sugarcane mills started operations in June with an average heliophany of 0.6 hours/day.

According to the 2021 Annual Report of the Sugarcane Research Center of Ecuador, (CINCAE, 2022), the eight most planted sugarcane varieties in Ecuador are mainly those obtained by CINCAE: ECU-01: 9,882.3 ha; EC-02: 3,578.1 ha; EC-05: 2,865.4 ha; EC-08: 1,832.8 ha; EC-07: 1,409.6 ha; EC-09: 936.2 ha and EC06: 977.8 ha; accounting for a total of 39,361.7 ha around the three largest mills.

A Spearman correlation matrix was performed using the psych package (Revelle, 2023). For CO_2 flow direction, the Openair package (Carslaw and Ropkins, 2012) and openairmaps (Davison and Carslaw, 2023) were used. The function used was "polar map" with the statistic "nor", which implements the nonparametric wind regression approach of Henry et al. (2009) that uses kernel smoothers. The outdoor implementation differs because Gaussian kernels are used for wind direction and speed. All the packages mentioned before were run in Rstudio (version 2023.06.0) (RStudio Team, 2023).

The spatial data were analyzed using the QGIS program (version 3.32) (QGIS Development Team, 2023). Inverse Distance Weighting (IDW) interpolation was used, the raster cell size was 2m, and a buffer was made - to each sugar mill - with the distances required for each sampling. Based on this information, the compositions of the corresponding thematic maps were made.

RESULTS AND DISCUSSION

The maximum, minimum, and average values of CO_2 in the vicinity of the mill chimneys under study are shown in Table 1. Global average CO_2 values were around 415 parts per million (ppm) until September 2021 (Stein, 2023). The results obtained in this study show that average CO_2 near sugarcane mills was 490 ppm which is above the international average values.

The results in the present study refer exclusively to the influence of the sugarcane mills on the variations of CO_2 concentration in urban environments. Measurements extended to 3000 m from the central factory chimney of the Valdez mill, and to 1000 m of the San Carlos mill. It should also be noted that these areas present a confluence of CO_2 emissions from other sources, such as vehicles and socio-economic activities of the population, which means that the values obtained do not exclusively reflect the activity of the sugar industry. This coincides with Shi et al. (2023), who reported a mean CO_2 range of 425-520 ppm near factories in Mongolia and China, attributing these results to the irregular effect of

Table 1. Maximum, minimum, and mean values of CO_2 concentrations measured using a portable gas analyzer at different distances from the central chimneys of the San Carlos and Valdez sugarcane mills.

Distance from the central chimney (m)	CO_2 (ppm)		
	Maximum	Minimum	Mean
280	595	455	498
500	600	449	490
1000	603	455	497
3000	541	441	475

emissions from the population near the sampling points.

The highest CO_2 concentrations were recorded at distances of 500 to 1000 m from the emission source. This coincides with a study conducted by Alvarado (2013), who reported that the maximum point of concentration at surface level was recorded at approximately 400 m in a Mexican sugarcane mill. These data are relevant because of the negative effects on air quality and respiratory health in human settlements in the vicinity of the mill (Jacobson et al., 2019).

Gas emission stack/plume height is determined by the velocity and movement of gases when they exit the stack, which causes a reduction in the probable maximum ground-level concentration of the effluent as it is diluted by an amount close to the square of the effective stack height. The effective height is calculated by adding the actual stack height with the upward velocity and buoyancy of the plume (Cervantes, 2011). This applies to both sugarcane mills in this study and explains the higher values of CO_2 observed at 1000 m from the stack rather than at 280 or 500 m.

When separating CO_2 measurements corresponding to the field harvest and factory rest (non-harvest) periods (Table 2), it is evident that CO_2 values decrease in all cases in the factory rest period. The CO_2 values tend to be lower at greater distances, especially the average values during harvest. CO_2 increase was greater in the maximum values at 280 m (19%) and 1000 m (25%). In this sense, the average values showed a more consistent trend, with an increase of 10% and 7% for distances of 280 m and 500 m, respectively.

Although the sugarcane mills had geographic proximity and shared some common aspects, such as sugarcane varieties, management practices, and harvesting technologies, weather conditions and some technological issues different between the two factories. Because of this, they were characterized (Table 3) based on the CO_2 load of their environments. In the case of the San Carlos mill, the 3000 m sampling site is located within the sugarcane field.

Fig. 1A shows the behavior of CO_2 measurements at the surface level in the San Carlos sugarcane mill from July to December 2022, the maximum values being recorded at 500 and 1000 m from the central factory chimney. Additionally, it can be observed the measurements taken at 500 m are less stable, with peaks in October (close to 600 ppm) and December (close to 750 ppm), in

Table 2. Maximum, minimum, and mean values of CO_2 concentrations at points on the perimeters of two sugarcane mills with each percentual variation between harvest season "Zafra" and factory rest periods (No Zafra).

Distance from the central chimney (m)	CO_2 (ppm)								
	Maximum			Minimum			Mean		
	Zafra	No Zafra	%	Zafra	No Zafra	%	Zafra	No Zafra	%
280	633	531	19	463	439	5	514	468	10
500	592	508	17	464	435	7	507	475	7
1000	621	495	25	454	445	2	486	465	5
3000	562	488	15	447	428	4	483	453	7

Table 3. Maximum and mean values of CO_2 concentrations measured at different distances from the central chimneys of the San Carlos and Valdez sugarcane mills during the harvest period.

Distance from the central chimney (m)	CO_2 values in ppm			
	Maximum values		Mean values	
	San Carlos	Valdez	San Carlos	Valdez
280	575	707	474	669
500	723	572	543	501
1000	563	651	461	479
3000	640	554	448	487

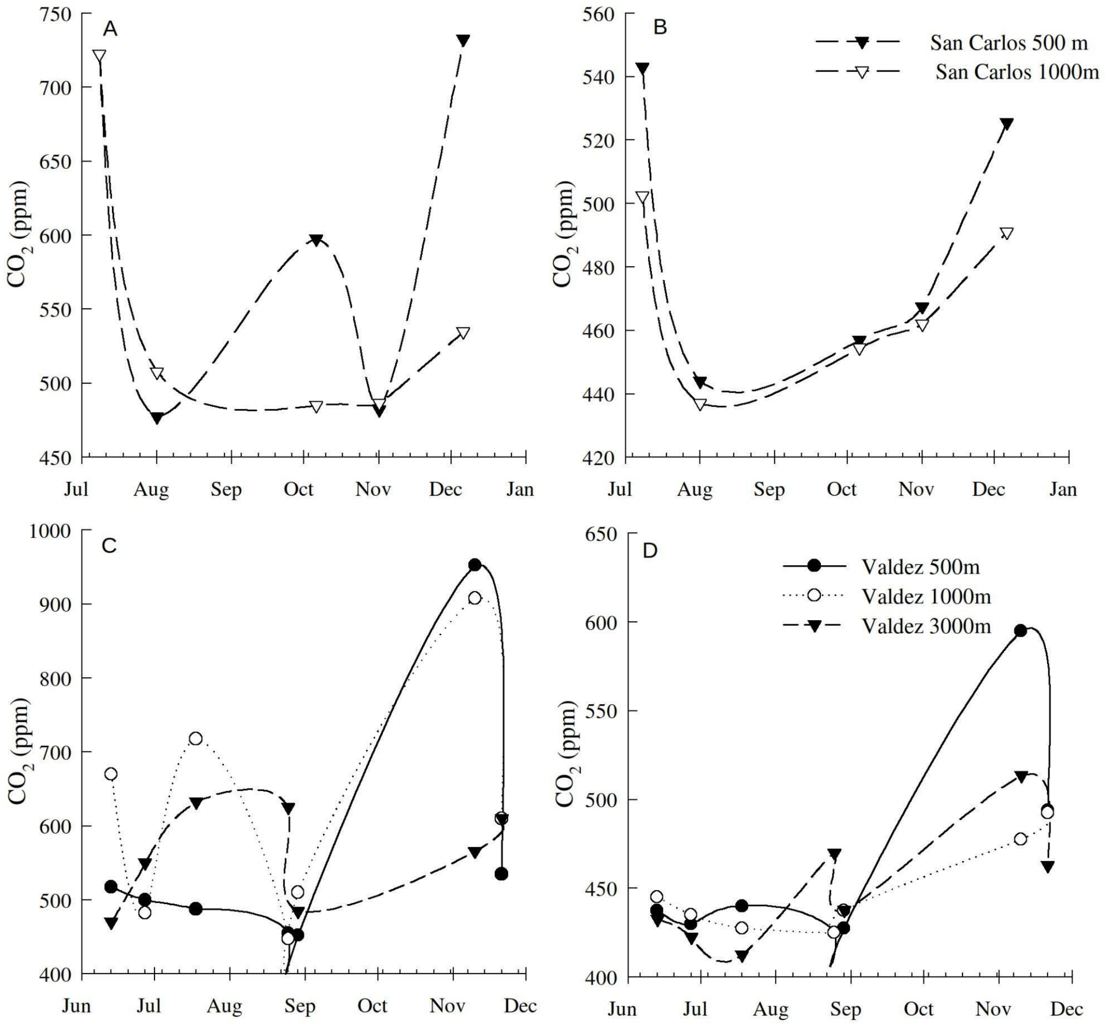

Fig. 1. CO_2 dynamics curves between June and December 2022 (harvest period) at three concentric distances from the (A,B) San Carlos and (C,D) Valdez sugarcane mills. (A, C) Maximum values for the San Carlos and Valdez mills. (B, D) Mean values for the San Carlos and Valdez mills.

addition to reflecting a value at the beginning of the measurements in July similar to those at both distances. There is a similarity in the dynamics of CO_2 concentrations at different levels, being higher at 500 m and lower at 1000 m (Fig. 1B).

The measurements recorded at 1000 m from the central factory chimney are more stable, starting from a value identical to that taken at 500 m in July. However, values decrease from August to November, dropping below 500 ppm and then showing a slight increase in December. It should be noted that sugarcane mills are generally in operation during the milling period (Zafra), according to a technical program. At this stage, they consume diesel and generate black smoke. After start-up, the factories use energy from the steam generated by the burning of bagasse produced during the milling of sugarcane stalks, which generates white smoke, evidencing a decrease in CO_2 emissions. In this sense, a study conducted by Gunawan et al. (2019) showed that CO_2 emissions can be reduced by 25 to 45% with the use of sugarcane bagasse. This temporary energy fuel consumption has a significant influence on CO_2 emissions which generated an initial peak at the beginning of the harvest season (Fig. 1A). Fig. 1C shows CO_2 measurements (also maximum values) at surface level at Valdez mill from July to December 2022, at distances of 500, 1000, and 3000 m from the central factory chimney since the urban area of the city of Milagro, where the factory is located, is much larger. In this case, the maximum values of CO_2 at the beginning of the harvest are similar at 500 and 3000 m. The values at a distance of 500 m exhibit a declining trend until September, followed by a subsequent increase during October and November. However, values decline again in December.

The CO_2 values at 1000 m are variable and do not show a trend according to any industrial explanation. However, in November, the highest values were recorded at 500 and 1000 m (close to 900 ppm), with lower values at 3000 m (below 500 ppm). Regarding average values of CO_2 (Fig. 1D), the trend is less confusing. In general, the lowest CO_2 values were recorded at greater distances in most of the harvest months. In this case, values for the three distances increased from June to November and then decreased in December, at least at 500 and 3000 m distances. At 1000 m, the curve is more stable, and the values only increase in the last two months.

In general, mean CO_2 values tended to decrease in the areas close to the sugarcane mills as the distance from them increases. This is much more unstable for the maximum values, which are observed at specific points in time and presumably amplified by factors that are attenuated in the average values. It is important to note that the maximum peaks for both maximum and average values of CO_2 occurred in different months: June and December in the San Carlos mill, and November in the Valdez mill. This could be associated with differences in the beginning and end of the industrial activity period and differences in energy performance.

Fig. 2 shows the degree of association of CO_2 concentrations with three climatic variables; relative humidity, temperature, and dew point, measured simultaneously at distances of 280, 500, and 1000 m from the central chimney of the two sugarcane mills involved in this study and covering exclusively the urban area surrounding the factories. The analysis also correlates the CO_2 concentration with the distance from the chimney, where the sample was taken.

The correlation values were highly significant between climatic variables temperature, dew point, and relative humidity (Fig. 2). These significant correlations are explained by the relationship between dew point, relative humidity, and water vapor saturation pressure, which is also influenced by temperature. CO_2 concentrations were inversely correlated with distances from the chimney since CO_2 concentrations initially increase with decreasing distances.

As shown in Fig. 3, CO_2 concentrations at the San Carlos mill tend to increase in the same direction as the gas flow from the chimney,

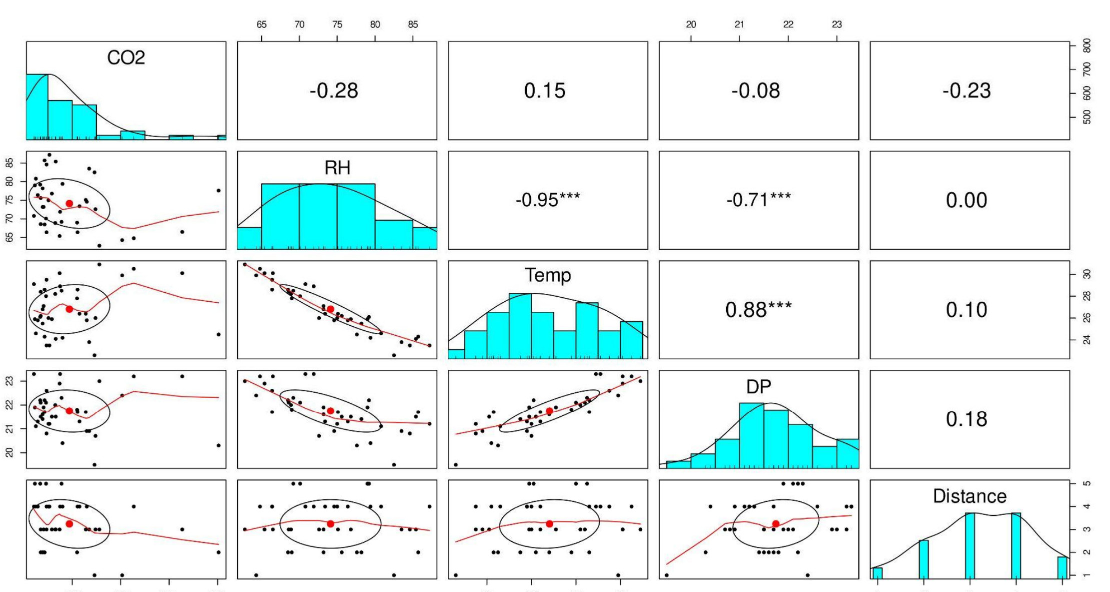

Fig. 2. Correlation matrix between CO_2 concentration and climatic variables measured simultaneously in urban areas at concentric distances between 280 and 1000 m from the central chimney of sugarcane mills. CO_2: ppm concentration, RH: relative humidity, Temp: temperature, DP: dew point,* indicates $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

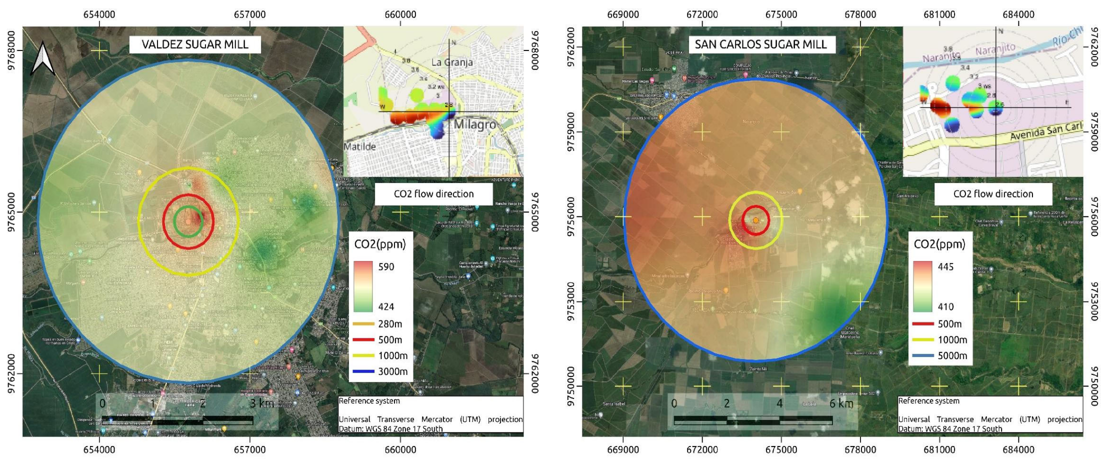

Fig. 3. CO_2 concentrations and flow dynamics at different distances from the central chimney of the Valdez and San Carlos sugarcane mills and direction of gas flow.

ultimately determined by the direction and speed of the wind. Nevertheless, the red zone can extend from the emission point up to 5000 m if it is in the flow direction. On the contrary, low CO_2 concentrations denoted by the green zone which initiates at the mill, outside the urban area, and in the agricultural zone are determined by upwind direction.

In the San Carlos and Valdez mills (Fig. 3), the predominant wind direction is to the west. For Valdez mill, however, the image does not identify an increase in CO_2 concentrations beyond a distance of 1000 m from the chimneys, which is consistent with the values shown in Table 3. The emission of a pollutant into the atmosphere is transported in the direction of the prevailing wind and simultaneously dispersed following vertical air movements and turbulence. The prediction of the CO_2 concentration in the area around the emission point can follow different models. The pollutant is emitted by a stack usually located in flat terrain and flows (Fig. 3). It should be noted that most of the pollutant dispersion problems are found in the atmospheric boundary layer, which is the area of the atmosphere in contact with the Earth's surface up to a height of about 1,000 meters (Manzur et al., 2013).

In addition, there is a significant effect of the type of locality on the dispersion of gases. In Valdez mill, there are maximum values of CO_2 towards the interior of the city of Milagro, even though it does not follow a wind direction pattern. On the contrary, there was no significant incidence of gases originated by other anthropogenic activities at the San Carlos mill, which implies that the amount of gases originated by population settlements is an essential factor in the dynamics of this type of gas. These results agree with the study conducted by Shi et al. (2018), who indicated that the growth of population settlements contributes to an increase in CO_2 emissions, closely related to the GPD of each locality. It is also observed that, for wind flow, the gas has a direction towards the exterior of the population; in both localities, similar trends are evidenced. A study of Toja-Silva et al. (2017) suggests a specific model for pollutant sources near cities since Gaussian plume models present considerable errors in these environments. The authors analyzed CO_2 generated by a power plant located 4 km from the population, and compared the standard Gaussian model with a Gaussian model; the former obtained maximum results of approximately 1500 ppm at 100 m distance, while the latter recorded 820 ppm. It is suggested to use machine learning models to obtain more consistent models that reflect more effectively the reality of gas dispersion in the field, mainly in sites with high human and industrial activity incidences.

CONCLUSIONS

Average CO_2 concentrations around the Valdez and San Carlos sugarcane mills remained constant during the sugarcane harvest season "zafra" at distance between 280 and 3000 m from the central factory chimney, being higher than the global average values of 417 parts per million (ppm) in 2022. There was no significant association between CO_2 concentrations and climate variables. However, relative humidity and distance from the chimney were negatively correlated with CO_2 concentrations. The vicinity of the city influenced CO_2 measurements, indicating that this is a crucial aspect to consider in the analysis of CO_2 concentrations in urban areas. The CO_2 measurements recorded at 1000 m from the central factory chimney were more stable than those at 280, and 500 m or 3000 m. Maximum mean values for CO_2 are reduced at larger distances from the emission source, but this did not apply to the absolute maximum values obtained in this study. The maximum peaks for both the maximum and average values of CO_2 occurred in different months, June and December in the San Carlos mill and November in the Valdez mill, which could be associated with differences in the beginning and end of harvest season and energy performance. CO_2 concentrations tend to increase in the same direction as the gas flow from the chimney, ultimately determined by the direction and speed of the wind, which in this case is to the west. However, the dissipation distances are more significant at the San Carlos mill.

ACKNOWLEDGEMENTS

This research was funded thanks to the Agrarian University of Ecuador (Resolution 042-2022), Ecuador.

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