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Some findings on the spatial and temporal distribution of methane emissions in landfills

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ABSTRACT

The purpose of this article is to present some facts of interest for the quantification of gas emissions in active landfills obtained from a series of field campaigns in a case study landfill where spatial and temporal patterns of methane emissions were analyzed. Nine campaigns were carried out to measure diffuse surface methane emissions at an European municipal waste landfill in operation using the static flow chamber technique in different seasons over three years. Results obtained show a global annual diffuse flux of 733.26 t CH_4/year for the year 2020. Certain points on the surface, where concentrations reached values above 1000 ppm, were observed during the campaigns. These points, called "hotspots", represented only 10% of all the points measured but accounted for 73% of the total diffuse methane emissions (506 t CH_4/year). Furthermore, localized emissions, such as those from landfill gas extraction wells, which were not connected to the general extraction network, were also analyzed. These localized emissions represent more than twice the total diffuse emissions measured on the surface (1500 t CH_4/year). These results highlight the importance of identifying high emission points to design effective mitigation measures. Moreover, the influence of certain meteorological conditions such as atmospheric pressure, temperature or rainfall was also studied. A new particular effect has been detected regarding precipitation, which favors or hinders methane emissions depending on the volume accumulated during the previous weeks. Pressure was found to be the factor that most affects methane emission variations in the case studied, presenting a clear inverse correlation with the field data that was collected. This suggests the need to consider the meteorological fluctuations over time to calculate the field emission estimates. Correcting the annual estimation in the case studied by considering the atmospheric pressure fluctuations over the year led to a 14% change in the estimate, obtaining a final result of 836.73 t CH_4/year for the total diffuse emissions.

1. Introduction

Landfill gas (LFG), consisting of methane (55–60% v/v) and carbon dioxide (40–45% v/v), is produced by microbial anaerobic degradation of the organic fraction in landfills (Scheutz et al., 2009). Methane is one of the greenhouse gases (GHG) of concern, with a global warming potential (GWP) of 81.2 over 20 years and 27.9 over 100 years (IPCC, 2021). Landfills are the third largest anthropogenic source of methane, accounting for approximately 11% of estimated global methane emissions, which are expected to increase by around 6% by the year 2030 (Global Methane Initiative, 2020).

Currently, most landfills have mitigation measures to reduce the effects of superficial GHG emissions. The most common are the collection of LFG through an extraction system and later burning or using it (Ciuła et al., 2018), or the installation of clay covers on the surface of the landfill. Some authors mention other types of measures such as aeration or leachate recirculation (Huang et al., 2022). However, these measures are not enough to avoid part of the diffuse emissions. The quantification of these diffuse emissions can be carried out by means of field measurements, as in the present study, or through estimation models (Nikkhah et al., 2018; Ciuła et al., 2020; Ciuła, 2021).

It is evident, from the literature, that LFG emissions measured in landfills vary significantly, in terms of both space and time (McBain et al., 2005; Kissas et al., 2022) and these emissions into the atmosphere are influenced by numerous factors. These variations could be affected by the elements of the landfill topography, such as slopes and ridges (Rachor et al., 2013) or the properties of the cover soil, such as its thickness, porosity or oxidation potential (Abushammala et al., 2014).

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Some other factors are related to meteorological conditions (Scheutz et al., 2009), like precipitation, barometric pressure or air temperature, or operational aspects such as LFG extraction.

There are certain specific points where the methane emission flux significantly exceeds the mean values of the landfill. When CH_4 concentration at these particular areas exceeds 1000 ppm, they are called “hotspots” (Huber-Humer and Gebert, 2021). Several studies have reported that emissions from hotspots are responsible of a large portion of total diffuse emissions and some techniques have been developed for its detection (Gonzalez-Valencia et al., 2016; Jeong et al., 2019; Karimi et al., 2021; Reinelt et al., 2022). In measuring campaigns using ground techniques carried out to estimate the amount of emissions, hotspots could have a negative effect by altering the average values. Knowing how these high emission points behave would make it possible to obtain more accurate estimates and to create appropriate mitigation measures.

The influence of meteorological factors on landfill emissions has been studied for many years but no common conclusion has been agreed on by all authors. Barometric pressure is one of the most studied meteorological factors. McBain et al. (2005) reported that barometric pressure had the most influence on CH_4 emission rates within a given site. Rachor et al. (2013) showed a very strong and negative correlation between barometric pressure and CH_4 emissions in all the hotspots examined, which was later corroborated by other authors (Nwachukwu and Anonye, 2013; Xu et al., 2014; Kissas et al., 2022). Air temperature seems to have less influence on the rate of emissions. Aghdam et al. (2019) and Kissas et al. (2022) reported a weak correlation between methane flux and air temperature in their studies.

Precipitations are closely linked to soil moisture. Rachor et al. (2013) explained that moisture can have a double effect on emissions. On the one hand, an increase in soil moisture can reduce the diffusive ingress of oxygen, thus impeding methane oxidation. Yet, on the other, if the water content is large enough, it can completely prevent gas exchange between the landfill and the atmosphere, stopping emissions altogether. Likewise, McBain et al. (2005) reported that landfill biogas fluxes are reduced during precipitation events, among other things, because rainwater temporarily occupies the majority of pores in the near-surface cover soil. Nevertheless, methane emissions increase after precipitation events, probably because of the drainage of macro pores, which allow vertical diffusion and mass flux of CH_4.

The purpose of this article is to present some facts of interest for the quantification of gas emissions in landfills in operation. The conclusions of this investigation were obtained from a series of field campaigns for the evaluation of methane emissions in a case study landfill. The following paragraphs describe the experimental methodology used and analyze the results obtained. Based on these results, new ideas are suggested on methods for quantifying the landfill emissions, information processing and mitigation measures.

2. Materials and methods

2.1. Description of the site studied

The municipal waste landfill under study is located in the north of Spain, where a temperate-wet climate is predominant. The landfill opened in the year 1989. Since then, more than 2 million metric tons of waste have been deposited over a surface of 19 ha. The landfill is composed of 4 m waste layers with 0.3 m intermediate clayey covers. Each layer has its own leachate collection system, and LFG collection wells are built as the landfill grows in height. These wells run through all the waste layers and are connected to the same system of LFG collectors. The LFG management system involves 71 vertical gas wells, a flare system, and electrical equipment consisting of a set of generators with a total generation capacity of 2,862 kW.

During the first years of operation, until 1991, waste was deposited in *Cell A*, located in the northern part of the disposal area, which was then sealed with clay materials and topsoil. The current section, *Cell B*, has received waste since then. It is divided into two phases of operation. In 2010 *Phase B1* was sealed with a double layer of clay and geomembrane (in accordance with specifications from European Union (1999), later modified by European Union (2018)), to start the operation of *Phase B2*, as a vertical expansion, which is completely hydraulic and gas insulated from the previous phase.

Fig. 1 shows the disposition of the different areas of the landfill, including the *Closing ridge*, composed of a mineral wall, which is built as the landfill grows. To facilitate the study of surface emissions and the taking of measurements, *Phase B2* was divided into five subzones: *Recent operation plain*, an area temporarily covered by 0.4 m of clay, where waste was recently deposited; *Plain next to slopes* and *Recent operation slopes*, both of which are areas temporarily covered by a 0.4 m layer of clay, where waste was deposited between the years 2016 and 2017; *Compacted zone*, an area with the oldest waste from *Phase B2*, which was deposited approximately 10 years ago, and is covered by a clay layer; and *Tipping area*, which is an operating area where waste is being deposited and compacted. Due to safety reasons, no measures were taken in the *Tipping area*. As an example, since the area of each subzone changed from the first campaign to the last one due to operation work, the different *Phase B2* subzones of the landfill during the last campaign in June 2021 are also shown in Fig. 1. Currently, *Phase B1* is almost totally covered by *Phase B2*, and only a small portion of the surface is still uncovered. Moreover, the layout of the biogas extraction wells is represented in this figure.

2.2. Field campaigns

To quantify the landfill surface emissions experimentally, nine field measurement campaigns were carried out using the static flux chamber method (Pihlatie et al., 2013; Jeong et al., 2019; Mønster et al., 2019; Reinelt et al., 2022). This method estimates the total LFG emissions drawn from measures at a certain number of points by analyzing on-site the rate of increase in LFG concentration inside the chamber. It is easily adaptable to different types of landfills, with the disadvantage of requiring a labor-intensive fieldwork, since a minimum number of points must be measured per unit area to achieve an adequate accuracy for the estimation of the global landfill surface emissions.

A customized static chamber was developed by the research group, with a surface of 50 × 50 cm and a height of 10 cm. To facilitate its handling, the chamber was built of aluminum and colored white to reflect solar rays and prevent excessive warming. Two centimeters below the lower edge of the chamber there is a 2 cm strip that runs along the whole perimeter in order to increase the precision of the useful volume of the chamber. Under this strip there is a neoprene sheet to ensure the sealing of the chamber. It has three external connections through valves allowing different monitoring devices to be connected. A schematic diagram and an image of the chamber used, which was the same throughout the study, is included in the supplementary material (Fig. S1).

For the field measurements and the monitoring protocol two standards were considered: Guidance on monitoring landfill gas surface emissions (LFTGN07) (Environment Agency Wales, 2010) and Air Guidance Note 6 Surface VOC Emissions Monitoring on Landfill Facilities (AG6) (Environmental Protection Agency, 2011), which nowadays constitute some of the most important references for monitoring landfill emissions (Mønster et al., 2019; Jeong et al., 2019; Scheutz and Kjeldsen, 2019).

As a preliminary step to quantifying surface emissions, the standards recommend carrying out a surface walkover to determine the general conditions of the landfill. The surface walkover consists in slowly traveling across the surface of the landfill (at a speed lower than 0.5 m/s) with the measuring instrument adapted for taking surface samples and continuously recording the concentration of gases. Samples should be taken at a height of approximately 5 cm above the surface to avoid the effects of wind and surface roughness. To do this, an adapted sampling

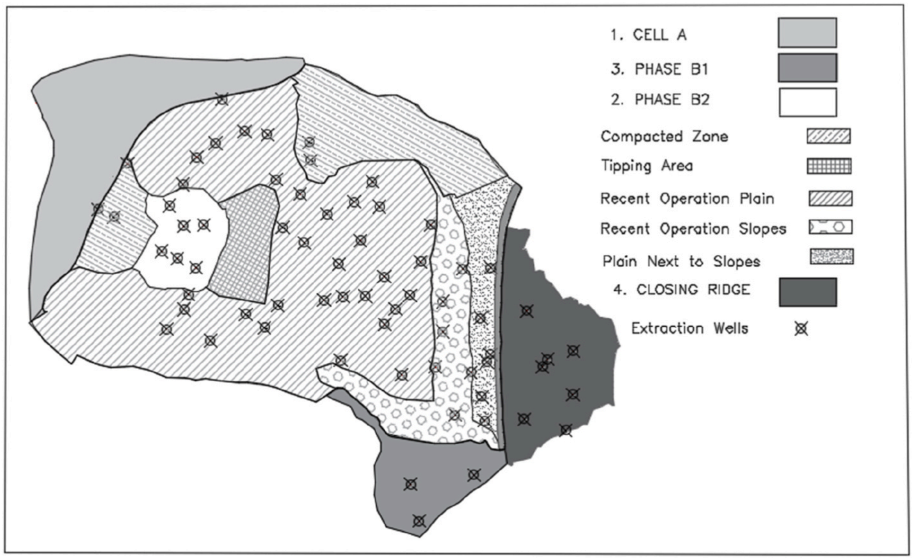

Fig. 1. Differentiated areas in the landfill for this study and disposition of the biogas extraction wells.

device with a probe is attached to the sensor.

With the concentrations observed on the surface during the walk-over, the area with the highest emissions is determined, in this case *Phase B2*. Environment Agency Wales (2010) established the number of points at which to measure the emission rate according to the zone size. Following these recommendations for the zone in which the highest flux is expected, *Phase B2*, 57 points were obtained. To distribute them evenly over the surface area of 113,796 m^2, this number supposes a grid with 45 m sides. Once in the field, the measurement points are placed within each grid randomly. As the tipping front of the landfill progressed, the surfaces of the different areas varied but the same grid size was maintained for each area.

Anticipating emissions of a lower magnitude, fewer points were selected for the rest of the zones, as shown in Table 1.

Due to the strong influence of atmospheric conditions (McBain et al., 2005; Rachor et al., 2013), field campaigns were not performed in adverse conditions such as rainfall, high winds, high temperature or high pressure. They were carried out when there had been no rain for at least two consecutive days prior to starting them. The determination of the dates to carry out the campaigns has been subject to weather conditions, as well as the availability of access to the landfill, staff and equipment.

The main instrument used was the LASER ONE digital gas detection equipment manufactured by HUBERG. This is a selective device for detecting methane gas in low concentrations using laser technology. Its measurement range is 0–10,000 ppm and it achieves a resolution of 1 ppm. This equipment also has a built-in GPS system and measurement log, so samples can be located on a map.

At each measurement point, the LASER ONE equipment was connected to the static chamber and stuck into the surface. At points where this is impossible due to the ground conditions, the chamber is sealed with clay material to minimize gas leaks during measurement. The measurements of CH_4 concentration inside the chamber were registered for approximately 5 min. Since the device takes concentration measurements every second, approximately 300 concentration values are obtained for each sampling point.

Table 1
Surface and number of sampling points in each zone of the landfill.

Areas	m^2	n	Grid Side (m)
1. Cell A	28,659	3	98
2. Phase B2	113,796	57	45
3. Phase B1	45,168	4	106
4. Closing Ridge	21,862	3	88
TOTAL	**209,485**	**67**	

2.3. Data analysis

Once all the points have been registered in the device, the data is processed. The average rate of increase in the CH_4 concentration (mg/m^3/s) is the slope of concentration line that can be obtained through lineal regression of the measurements registered. The slope is measured in the upward stretch of the curve. This approximation is only considered valid if the regression coefficient R^2 is higher than 0.8, the graph has more than 5 points, and the change in concentration registered is more than zero (Environment Agency Wales, 2010). If any of these values are not fulfilled, a flux of 0.00005 mg/m^2/s is assumed by default. To obtain the emission rate per surface unit (mg/m^2/s), the value obtained is multiplied by the chamber volume and it is divided by its surface area. As an example, the linear regression of one of the measured points is attached as supplementary material (Fig. S2).

In accordance with the standard, an arithmetic average of the emissions of the points measured in each zone was carried out and the global emission of the landfill was the sum of the emissions in each zone.

To analyze the influence of meteorological and operating conditions, for each measurement campaign, the LFG wealth and capture, and the precipitation, temperature, and pressure on the days of measurement and the previous weeks were all used as input data. Meteorological data was taken from the meteorological station located in the landfill, which records daily hourly data on wind direction, temperature, humidity, pressure, solar radiation, precipitation and dew point. Once the nine campaigns had been completed (a total of 663 points measured), the correlation between the average methane fluxes obtained in each campaign and the operating conditions and meteorological fluctuations was studied. The correlation analysis of the different variables was performed according to the Spearman Method (Eq. (1)), previously applied by other authors (Aghdam et al., 2019; Abushammala et al., 2013). This method results in a number between −1 and 1, where the higher the absolute numerical value, the greater the degree of correlation is, and positive or negative correlation coefficients show a direct (+) or inverse (−) relationship.

$$\rho = 1 - \frac{6\sum D^2}{N(N^2 - 1)} \quad \text{Eq. 1}$$

where:

D = Difference between corresponding statistics of the order of pairs of variables.

N = Number of data pairs

3. Results and discussion

3.1. Field campaign results

Over the years 2019–2021 nine campaigns were carried out. To obtain a collection of measures in different climatic and operating conditions they were performed in May and July 2019, January, May, July, November and October 2020 and February and June 2021. Table 2 summarizes the results obtained, showing the average methane flux for each zone in the nine campaigns.

In keeping with Environment Agency Wales (2010), a reference limit of 0.001 mg/m^2/s was used for the emission flux in areas with intermediate cover and 0.1 mg/m^2/s in areas with final cover. Table 2 shows that the highest fluxes are concentrated in *Phase B2* due to its recent operation and its temporary cover. On the other hand, surface emissions in *Phase B1* are negligible, since it has a liner that prevents gas migration through it. *Cell A* also has lower fluxes than *Phase B2*, even though the final cover in this zone is not as thick as in *Phase B1* and does not include a liner. Furthermore, the waste deposited in *Cell A* is older than that in other areas, about 30 years, and therefore the waste is more degraded and the expected CH_4 generation rate is lower.

Results obtained show an average annual emission of 690 t CH_4/year with a 95% confidence interval of ±164 t CH_4/year. This wide interval range (±24%) is related to various factors. Some of them are meteorological, such as temperature, pressure or precipitation (McBain et al., 2005; Rachor et al., 2013), and other variations may be attributed to operational and technical effects.

Since the landfill tipping front is continuously moving and the surface areas change in each campaign, the best way to compare emissions over time is to consider average fluxes, as in Table 2. Considering only the surface flux in *Phase B2*, the range obtained is 0.16348 ± 0.04193 mg/m^2/s (±26%).

3.2. Hotspots

Gases generated in the waste mass try to escape into the atmosphere through the cover. Sometimes these gases find preferential paths that facilitate their escape, which, along with other causes, give rise to what are known as hotspots. In most cases, these points do not present any particularity on the surface, so it is impossible to detect them before measurement. In *Phase B2*, which is the most representative area of the landfill studied, hotspots alter the average of the measured emissions due to their high concentration fluxes. Even though these points make up less than 10% of the total number of points measured in *Phase B2*, they account for approximately 73% of the emissions in this phase (Table 3). Since the emissions measured in the rest of the phases are well below those of *Phase B2*, the ratio between hotspots emissions (506 t CH_4/year) and total landfill emissions is also 73%. These results corroborate the observations of other authors such as Gonzalez-Valencia et al. (2016) who reported that 50% of CH_4 emissions came from 0.4 to 5.6% of the total landfill area. Jeong et al. (2019) also observed that the 20% of the areas with the highest emission fluxes were responsible for more than 68% of the total CH_4 emissions.

The distribution of these points across the surface of the landfill was heterogeneous. However, thanks to the zoning of the surface, it is seen that some zones apparently had a higher density of hotspots. As Fig. 2 shows, the *Recent operation slopes* area, where the extension, compaction and maintenance of the intermediate covers is difficult, presents a higher concentration of hotspots. In addition, in this area there are small leachate emanations and streams that form furrows in the coverage that favor biogas leaks. The density of hotspots found was also high in the *Recent operation plain*. This area has a temporary clayey cover that often has desiccation cracks. Conversely, the *Compacted Zone* presents the lowest concentrations of hotspots probably due to its old landfilling age, high level of compaction and the vegetation cover that can favor methane oxidation.

3.3. Extraction wells

Due to operational reasons, some of the extraction wells, those

Table 3
Number of hotspots across the nine campaigns and percentage of emissions they represent in Phase B2.

Campaign	No. Points measured	No. Hotspots	Total emissions (t CH_4/year)	% Hotspot emissions
May 2019	55	7	570.25	78
July 2019	54	9	893.24	84
January 2020	55	4	807.84	94
May 2020	63	4	360.09	41
July 2020	56	4	670.10	68
October 2020	65	10	1131.26	74
November 2020	65	7	644.04	65
February 2021	68	4	449.72	60
June 2021	55	6	403.87	65

Table 2
Average methane fluxes of field campaigns, extraction well emissions and total emissions per year.

Zone	Average CH_4 Flux (mg/m^2/s)								
	May (2019)	July (2019)	January (2020)	May (2020)	July (2020)	October (2020)	November (2020)	February (2021)	June (2021)
TOTALPhase B2	0.17420	0.25261	0.20280	0.08750	0.16000	0.25645	0.14602	0.10010	0.09603
Plain Next to Slopes	0.09430	0.05952	0.00440	0.09013	0.09964	0.26747	0.00324	0.00496	0.00000
Recent Operation Slopes	0.31580	0.25699	0.79837	0.09918	0.23207	0.37609	0.13852	0.33280	0.20267
Recent Operation Plain	0.37520	0.55421	0.20539	0.10983	0.18726	0.33524	0.21484	0.07469	0.08522
Compacted Zone	0.01360	0.08283	0.00647	0.05085	0.0978	0.04700	0.05083	0.07178	0.06903
Cell A	0.23130	0.00585	0.09131	0.02916	0.00615	0.01637	0.00140	0.00226	0.00201
Phase B1	0.00350	0.00456	0.00005	0.01369	0.00587	0.00005	0.00005	0.00005	0.00005
Closing Ridge	0.00099	0.00005	0.00005	0.00047	0.0001	0.00038	0.00005	0.00005	0.00372
TOTAL diffuse (t CH_4/year)	**784.91**	**905.05**	**817.56**	**385.66**	**676.73**	**1141.41**	**644.94**	**451.15**	**407.67**
Extraction Wells (t CH_4/year)	1927.1	607.24	0	0	303.62	303.62	303.62	607.24	0
TOTAL (t CH_4/year)	**2712.0**	**1512.29**	**817.56**	**385.66**	**980.35**	**1445.03**	**948.56**	**1058.39**	**407.67**

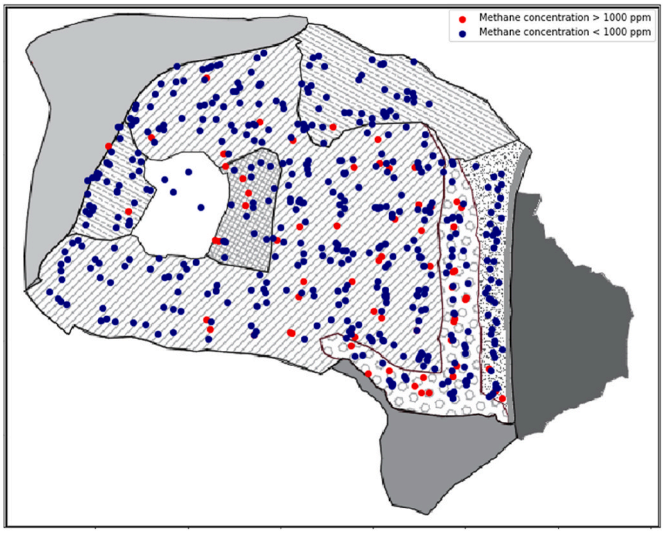

Fig. 2. Distribution of points measured over the nine campaigns. Areas marked with different patterns correspond to those detailed in Fig. 1.

within and around the *Tipping area*, remained disconnected from the extraction system for some time. Thus, they became localized sources of biogas emission. These localized emissions were also quantified during the measurement campaigns, proving to be one of the most important emission sources in the landfill under study.

During the first campaign, in July 2019, 13 wells were not connected to the extraction system, and generated very significant emissions that represented more than twice the total diffuse emissions measured on the surface (Table 2). Landfill operators were recommended to cover the outlets of unconnected wells to prevent these emissions, and this resulted in a considerable decrease in the amount of methane emitted. On average, five wells remain unconnected to the network throughout the year. Taking measurements of the gas output in several wells, a unit flow of around 300 t CH_4/year has been estimated, and emissions from all the wells not connected to the grid would be around 1500 t CH_4/year. Some of these wells, generally 1 or 2, are located in the *Tipping area* and must go through a regrowth phase to adapt them to the new level of the waste layer. Since the new stretches are perforated, covering these wells makes no sense. For this reason, in the following campaigns, reductions in this source ranged from 68% to 100% (when no well was in the regrowth phase).

3.4. Influence of meteorological and operating conditions

Meteorological conditions in the area of study vary significantly from one season of the year to another. Precipitations registered in the region are approximately 1,200 l/m^2 per year. In general, November and January are the rainiest months and July and August are the driest. Daily mean temperatures range from 9 °C in the coldest months to 20 °C in the warmest. Figures S3, S4 and S5, included in supplementary material, show the variation in pressure and temperature, the monthly collection of biogas and methane, and the variations in daily precipitation over the years the research was being conducted.

The operating conditions vary according to the needs of the landfill and do not present a specific variation pattern throughout the year.

Each of the areas that make up the landfill has a different coverage, so that meteorological and operational factors can affect each of them in different ways. For this reason, the effects of these factors were analyzed separately in each of the areas.

Table 4 shows the results of the statistical analysis described in the methodology section, which was performed considering all the measurement campaigns. The higher intensity of the color of the cells represents a higher correlation.

The atmospheric pressure is seen to have the highest impact on the measured values in four zones. In these areas a greater number of points with significant emissions (higher than the minimum value of 0.00005 mg/m^2/s (Environment Agency Wales, 2010)) were measured, and therefore the absolute variations in the emission flux were easier to observe. Fig. 3 shows the linear equation that relates the average flux results of the campaigns obtained for each zone to the atmospheric pressure values, so as to be able to visualize the correlation. Likewise, it can be seen in Fig. 4 how the atmospheric pressure and the CH_4 flux vary inversely throughout the campaigns, especially in the *Recent operation slopes* and *Recent operation plain* areas.

Probably due to the high level of compaction in the *Compacted zone*, pressure variations did not influence the emissions flux in this area. Furthermore, its vegetated surface provides the waste with more isolation from weather conditions.

The high inverse correlation highlights the fact that pressure increases the entry of air into the surface layers and thus hinders the escape of methane into the atmosphere. This coincides with the

Table 4
Spearman correlation coefficients between meteorological and operational factors and the average methane emission flux. *AP: Accumulated Precipitation.

	Plain next to slopes	Recent operation slopes	Recent operation plain	Compacted zone	Cell A	Phase B1	Closing ridge
Pressure	-0.62	-0.70	-0.70	0.30	-0.65	-0.27	-0.06
AP* (3 days)	-0.05	0.30	0.27	-0.08	0.32	-0.27	-0.44
AP (7 days)	-0.86	0.00	-0.12	0.03	-0.33	-0.56	0.44
AP (21 days)	0.12	-0.10	-0.28	-0.18	-0.40	-0.53	-0.04
AP (21 days) <100 l/m^2	0.50	-0.66	-0.83	-0.09	-0.14	-0.17	-0.17
AP (21 days) >100 l/m^2	0.50	-0.50	1.00	-1.00	-0.50	-0.25	-0.25
Temperature	0.38	-0.52	0.08	0.52	-0.15	0.08	-0.08
CH_4 wealth	0.02	0.68	0.28	-0.03			
CH_4 captured	-0.07	0.21	-0.28	0.05			

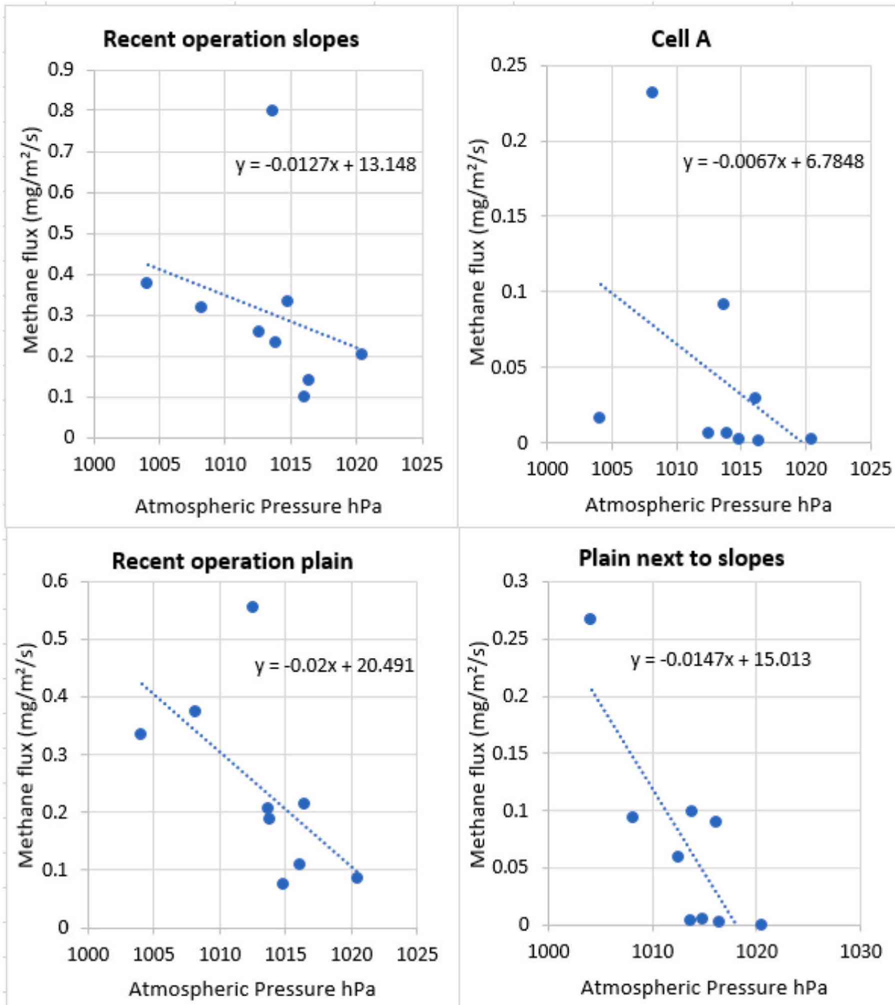

Fig. 3. Linear regression lines and equations of the four zones influenced by pressure variations.

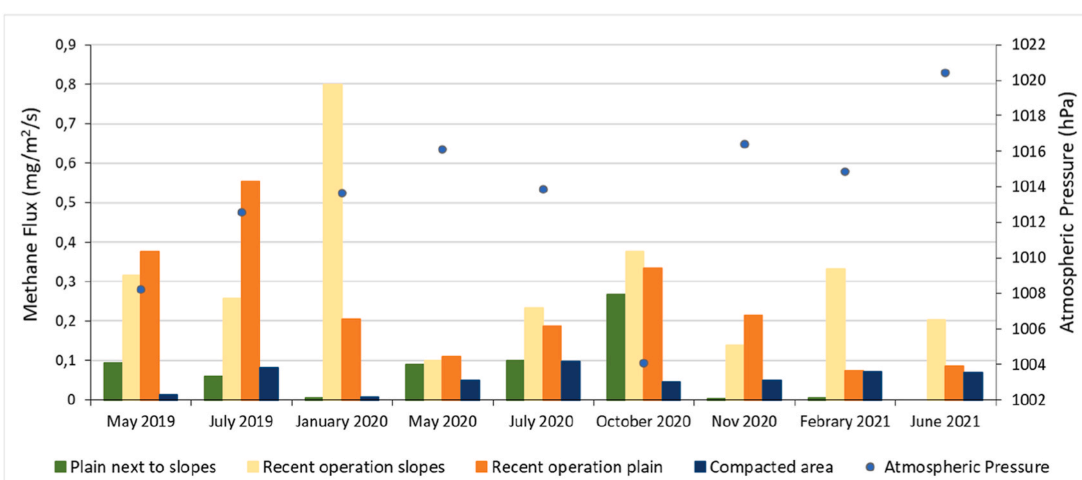

Fig. 4. Comparison of pressure fluctuations and field campaign results.

observations of several authors (McBain et al., 2005; Christophersen et al., 2001; Aghdam et al., 2019), who have claimed that when the atmospheric pressure falls, the methane fluxes can be higher than normal and vice versa.

The rest of the meteorological factors analyzed do not show a clear influence on the emission flux.

Accumulated precipitation has been analyzed in different periods to establish for how long prior to carrying out the campaign the amount of accumulated precipitation can have an influence on the emissions. In the case of accumulated precipitation at 21 days, a peculiarity, which has not been reported in previous works, has been observed. A different behavior was observed between the campaigns with a 21-day accumulated precipitation smaller than 100 l/m^2 (May 2019, July 2019, January 2020, May 2020, July 2020 and June 2021) and those that exceed this value (October 2020, November 2020 and February 2021). A high correlation was observed in two areas, but the first case presents an inverse correlation, while the correlation in the second case is direct (Table 4). This seems to show that, when the precipitation is abundant enough to reach the waste layers, degradation is favored, thus increasing the degradation rate and methane generation. It is possible that in the studied landfill, for this effect to be noticeable, it would take 21 days for the water to reach the waste and degradation to occur. In the short term, there is no time for pore drainage and this effect cannot be appreciated, since the drainage of macro pores is necessary to allow vertical diffusion and mass flux of CH_4 (Christophersen et al., 2001). However, when precipitations are not abundant enough to reach the waste mass, the only effect of the precipitation is the partial or total saturation of the pores of the cover, thus reducing the escape of methane.

Operational factors have only been studied in *Phase B2* since this is the only area where biogas extraction is currently being carried out. Therefore, the rest of the areas should not be affected by variations in the catchment. Table 4 shows that no clear correlations are obtained between the operation of the LFG extraction system and the CH_4 fluxes.

3.5. Annual estimation

Since meteorological variables such as atmospheric pressure or rainfall may have a considerable impact on the emission fluxes, estimating the emissions generated during a period of time based on the results of a number of discrete measuring campaigns should consider the fluctuations of such variables throughout the corresponding period.

In the case under study, given the tight relation between emissions and atmospheric pressure, the total emission values for 2020 were adjusted by considering the pressure and surface area variations throughout the year. Four areas, *Plain next to slopes*, *Recent operation slopes*, *Recent operation plain* and *Cell A*, show a clear relationship between emissions and pressure, and pressure correction was only applied in those.

By entering the daily pressure values for the year 2020 in the regression equations (Fig. 3), the emissions flux value of each day is obtained for the corresponding area. Since the surface area of the landfill changes throughout the year, a linear change was also considered for the surface with which the value of the total annual emissions is obtained.

The first approximation, carried out by means of the average of the results obtained in the campaigns without applying any pressure corrections, shows a total flux of 733.26 t CH_4/year for the year 2020. When applying the corrections in the four areas significantly affected by pressure variations, the result obtained is 836.73 t CH_4/year. This difference in the estimation might be due to the criteria followed to perform the measuring campaigns, which are carried out on days with no rainfall. These normally coincide with anticyclonic events and therefore with high atmospheric pressures, which lead to lower emissions. Neglecting this effect when extrapolating the values measured for the whole year could thus lead to significant underestimation of the actual emissions (14% in the case presented here).

4. Conclusions

This study shows the usefulness of the methodology used for the measurement of surface methane emissions from the studied landfill. Based on the static flux chamber technique, the method can be adapted for the assessment of gas emissions in different facilities. As a disadvantage, it requires an intensive fieldwork (measuring a large number of points) to achieve an adequate accuracy.

The results obtained in the case study throughout nine measuring campaigns show a global diffuse flux of 733.26 t CH_4/year for the year 2020. Moreover, several aspects have been shown to be relevant when quantifying gas surface emissions from landfills.

The most striking finding to emerge from this study, which has not been mentioned by other authors, is the importance of localized emissions from open wells that are not connected to the extraction network. Even in landfills with an active gas extraction system, these emissions can represent a high percentage of total methane flux, around 71% in the case studied (1500 t CH_4/year). Fortunately, they can be easily avoided by covering them if the landfill has an active extraction system, as in the case studied, or by burning the gas in the wells, in passive systems.

The second major finding, which is consistent with the results of other researchers, is the quantitative relevance of hotspots, which in the case studied account for around 73% (506 t CH_4/year) of the diffuse emissions measured in the field. Since methane fluxes vary over time, monitoring some points of this type could help characterizing the variability of the total emissions in the landfill. In addition, measures to reduce diffuse emissions in landfills, such as the one studied, should focus, in a first stage, on these types of points, perhaps proposing local solutions such as oxidation windows.

As described by other authors, in this case study a strong influence of meteorological conditions on the landfill surface emissions has been observed, especially of atmospheric pressure, with which a clear inverse correlation has been obtained. In addition, a novel particular effect has been detected with regard to precipitation, which favors or hinders the CH_4 emissions depending on the volume accumulated during the previous weeks. When estimating the global emissions based on measuring campaigns, the experimental results should be processed to incorporate the continuous variation of the principal influencing factors during the period of time under consideration, such as atmospheric pressure in the case presented here. Correcting the annual estimation by considering these impacts in the studied landfill led to a 14% change in the estimate, obtaining a final result of 836.73 t CH_4/year for the total diffuse emissions.

Finally, these findings will be of interest to improve the interpretation of the results obtained in field campaigns and to design and plan mitigation measures in other facilities.

CRediT authorship contribution statement

Mónica Delgado: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft. **Ana López:** Investigation, Resources, Data curation. **Ana Lorena Esteban:** Resources, Writing – review & editing. **Amaya Lobo:** Conceptualization, Validation, Supervision, Writing – review & editing.

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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.132334.

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