detritus Multidisciplinary Journal for Waste Resources & Residues

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SPATIAL VARIABILITY OF GAS COMPOSITION AND FLOW IN A LANDFILL UNDER IN-SITU AERATION

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Article Info:
Received:
18 January 2022
Revised:
25 March 2022
Accepted:
12 May 2022
Available online:
30 June 2022

Keywords:
In-situ aeration
Landfill stabilization
Spatial variability
Gas composition
Flow rate

ABSTRACT

In-situ aeration of landfills accelerates biodegradation of waste organic matter and hence advances waste stabilization. The spatial outreach of aeration greatly affects stabilization efficiency. This study analyzed the spatial variability of gas composition and flow in 230 wells spread over four compartments of a Dutch landfill which is under in situ aeration since 2017, as well as the carbon extraction efficiency, temperature, and settlement. Flow rates and gas composition in the extraction wells varied strongly. The highest variability was observed in the compartment with the highest water tables with submerged filter screens for most wells, with low flow rates, and elevated ratios of CH_4 to CO_2, indicating predominance of anaerobic processes (compartment 11Z). The compartment with the most uniform distribution of gas flow rates, composition and lower ratios of CH_4 to CO_2, suggesting a significant share of aerobic carbon mineralization, also showed higher temperatures, a carbon extraction efficiency, and larger cumulative settlement, all indicative of enhanced microbial activity (compartment 11N). In this compartment, the amount of extracted carbon exceeded the carbon generation predicted from landfill gas modeling by the factor of 2 over the hitherto four years aeration. The effect of water tables on gas flow and the correlation between the flow, and the ratio of CH_4 to CO_2 appeared weak, indicating that also other factors than water tables influence gas concentration and flow. Future work includes stable isotope probing to analyze the significance of microbial respiration and microbial CH_4 oxidation for the composition of the final extracted gas mixture.

1. INTRODUCTION

In-situ aeration is considered a possible method for the stabilization of landfills, reducing waste reactivity and the landfill's emission potential faster than under anaerobic conditions and therefore also reducing the time for monitoring during aftercare (Erses et al., 2008; Grossule & Stegmann, 2020; Ritzkowski et al., 2006). On a field scale, an important factor for the efficacy of treatment by in-situ aeration is the spatial distribution of air and gas throughout the waste body (van Turnhout et al., 2020), controlling (a) the reduction of the remaining methane production potential, (b) the desired increase in organic matter decay by microbial respiration and (c) the extent of methane oxidation within the landfill fulfill. However, homogeneous aeration on a field scale is a challenge not easy to reach (Ritzkowski & Stegmann, 2012), and is mainly limited by zones of water saturation and preferential liquid flow paths (Fellner & Brunner, 2010; Hrad et al., 2013). The spatial distribution of gas flow also depends on the operational conditions of aeration. For example, a model developed to find an optimal aeration strategy in a landfill indicated that air injection reaches a larger volume fraction of waste with higher airflow, but extraction appears to achieve a more homogeneous distribution of oxygen throughout the waste body (van Turnhout et al., 2020). Most of the in-situ aeration strategies use low-pressure aeration, which usually considers pressure within the range of 20-80 mbar (Ritzkowski & Stegmann, 2012). For optimal performance of in-situ aeration, the permeability of the waste body to both gas and water has to be considered (Ritzkowski & Stegmann, 2012; Xu et al., 2020).

Within the Dutch sustainable landfilling program iDS (Sustainable Landfill Foundation, n.d.), four compartments of the landfill Braambergen located near the city of Almere (The Netherlands), have been aerated since September 2017 (Cruz et al., 2021; Lammen et al., 2019, 2021). The waste comprises mainly soil and soil decontamination residues and around 15% of organic waste (more detail in section 2.1). Two different aeration strategies were em-

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ployed: over-extraction and combi-aeration (low-pressure aeration). The over-extraction method creates a suction pressure by extracting more gas than gas produced, thereby causing ambient air to intrude into the landfill. Low-pressure aeration combines air injection and gas extraction considering lower pressure for injected air than extracted gas (Vereniging Afvalbedrijven, 2015). This paper researches the spatial variability of landfill gas composition and flow under the operational conditions of combi-aeration. It was hypothesized that based on the variability of the water tables detected in the injection-extraction wells (Gebert et al., this issue), neither the flow of the extracted gas nor the flow of the injected air is distributed uniformly. Consequently, the enhancement of biodegradation would differ spatially, and this would be reflected in the landfill gas (LFG) composition. To better understand which factors cause this spatial variability, data on gas composition was combined with data on gas flow rates and water columns in all compartments. The ratio of CH_4 to CO_2 was used to assess the spatial variability of the impact of aerobic and anaerobic processes on the measured gas composition. Further, this study analyzes the temporal variability of carbon extraction efficiency, temperature, and settlement for the period 2017-2020. It was hypothesized that compartments with higher aeration efficiency would show a higher carbon extraction efficiency, higher temperatures in relation to higher biodegradation rates, and higher settlement rates.

2. MATERIAL AND METHODS

2.1 Description of site and aeration system

The Braambergen landfill is located near the city of Almere in the northern part of the Netherlands, with the four pilot compartments 11North (11N) and South (11Z) and 12 East (12O) and West (12W) in operation from 1999 to 2008 on a surface area of approximately 10 ha. The pilot compartments contain around 1,200,000 tons of waste, mainly composed of soil and soil decontamination residues (80.6%) (Cruz et al., 2021; Lammen et al., 2019). Figure 1 shows a timeline of landfilling considering the different compartments and the main waste components, including soil and soil decontamination residues, construction and demolition waste, commercial waste, shredder, street cleansing waste, coarse household waste, sludge, and household waste. Compartments 12O and 11Z comprise mainly soil and soil decontamination residues (95.8%) and are approximately the same age. The oldest compartment is 12W and has the lowest percentage of soil and soil decontamination residues. This compartment together with compartment 11N are the ones that were filled with commercial waste and household waste (2.7% for compartment 11N). Compartment 11N is also the one with the longest active landfilling period.

Landfill stabilization through in-situ aeration is carried out since September 2017. A network of 230 wells spaced at 15 to 20 m distance over the four compartments (Figure 2, left) can be operated in an over-extraction or combi-aeration mode (Figure 2, lower right). From north to south, each aeration line is denoted by a letter (A to W), and from west to east, each well by a number (1 to 8-11) (Figure 2, top right). All wells are deep filtered with the filter screen over a height of 1.8 m from the bottom of the well, which has been inserted to a total depth of up to 10-12 m below the landfill surface, corresponding to approximately 2 m below the Amsterdam Ordnance Datum (NAP) into the waste body.

2.2 Data acquisition, selection and processing

Flow velocity and temperature (multifunctional handheld unit, Höntzsch U426, TA-10 probe), gas composition (Geotech Gas Analyzer GA2000; detection limit 0.1%), and the pressure (pressure gauge by Blue line S4600) were measured manually on a monthly interval. At the gas blower station, landfill gas (LFG) flow rate (Proline Prosonic Flow B 200 Ultrasonic flowmeter for gas extraction, and Proline 65i T-mass flowmeter for air injection; both Endress+Hauser),

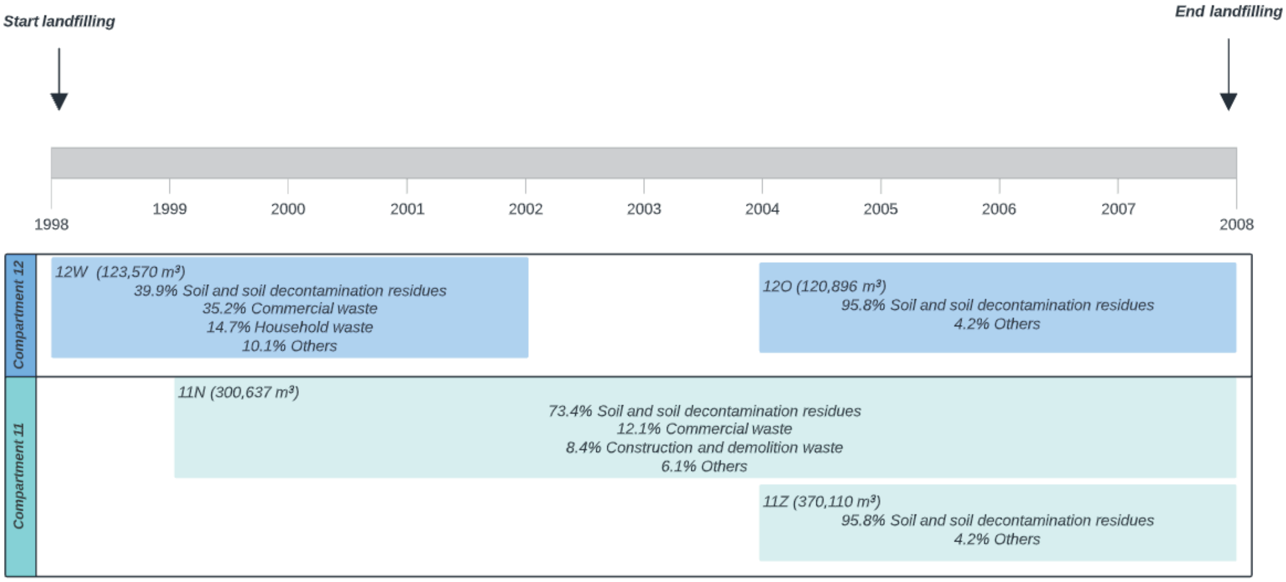

FIGURE 1: Timeline of waste landfilling per compartment.

pressure (PMC51-R8K2/0; Endress+Hausser), gas composition (CH_4, CO_2, and O_2, Biotech Gas Analyzer 3000), and temperature (iTEMP TMT181; Endress+Hausser) were continuously measured and recorded every fifteen minutes. The data from the gas blower station with the same collection time as the individual well sampling was selected for analysis. To obtain the flow rate for each well, the normalized flow (at standard temperature and pressure) from the gas extraction blower were averaged over the period in which the manual measurements were carried out, then divided by the individual wells in proportion to the velocity measured at each well. This study presents data from March 2020.

Using Python, MS Excel, and Origin software packages, the spatial variability of gas composition, flow, and water columns were visualized and analyzed. Based on the gas composition and the ratio of CH_4 to CO_2, the percentage of anaerobic activity (PAA) was calculated for each well (Yazdani et al., 2010) as follows:

$$PAA = \frac{2[CH_4]}{2[CH_4]+([CO_2]-[CH_4])} \, x\, 100 \quad (1)$$

where $[CH_4]$ and $[CO_2]$ are the measured concentrations (% v/v) of CH_4 and CO_2. PAA was then normalized to the maximum observed value to obtain the normalized anaerobic activity. The difference of 1 was considered as the normalized aerobic activity (NAA, Equation 2):

$$NAA = 1 - \frac{\mathrm{PAA}}{PAA_{max}} \quad (2)$$

where PAA_{max} is the highest percentage of anaerobic activity.

The coefficient of variation for gas composition and flow was calculated by dividing the standard deviation and the mean for all the datasets in each compartment. The spatial variability was analyzed using the Rijks-Driehoek (RD) coordinate system from the Dutch Geographical service in EPSG projection 28992 (Amersfoort datum). The relationship between the individual parameters was tested using Pearson's coefficient r. The number of observations, the variability of the parameters, and the confidence level determined the significance of this correlation.

Using the ideal gas law, the gas concentration, flow rate, pressure, and temperature, the extracted carbon in kilograms of carbon per hour was calculated. The carbon extraction efficiency was calculated using the amount of extracted carbon normalized to the number of wells and tons of waste in each compartment.

The temperature in compartments 11N and 11Z was obtained using a Silixa Ultima XT-DTS distributed temperature sensor which performed a double-ended measurement every 0.5 m using a long section of glass fiber distributed over 12 wells in each compartment (11N and 11Z) between -2 m and 9 m with respect to the NAP. For data configuration and collection, Silixa software was used. The height of the landfill surface and hence landfill settlement was measured twice per year on a network of 43 settlement beacons distributed over the four compartments using a TRIMBLE R8-2 rover GNSS Receiver.

3. RESULTS AND DISCUSSION

The following sections present the spatial variability of CH_4 concentrations, the ratios between CO_2 and CH_4, methane and total gas flow rates, and temperature in the individual wells. Gas-related parameters are only taken into account for the 110 wells that are operating in extraction mode during simultaneous air injection and gas extraction on alternative wells (combi-aeration) in March 2020.

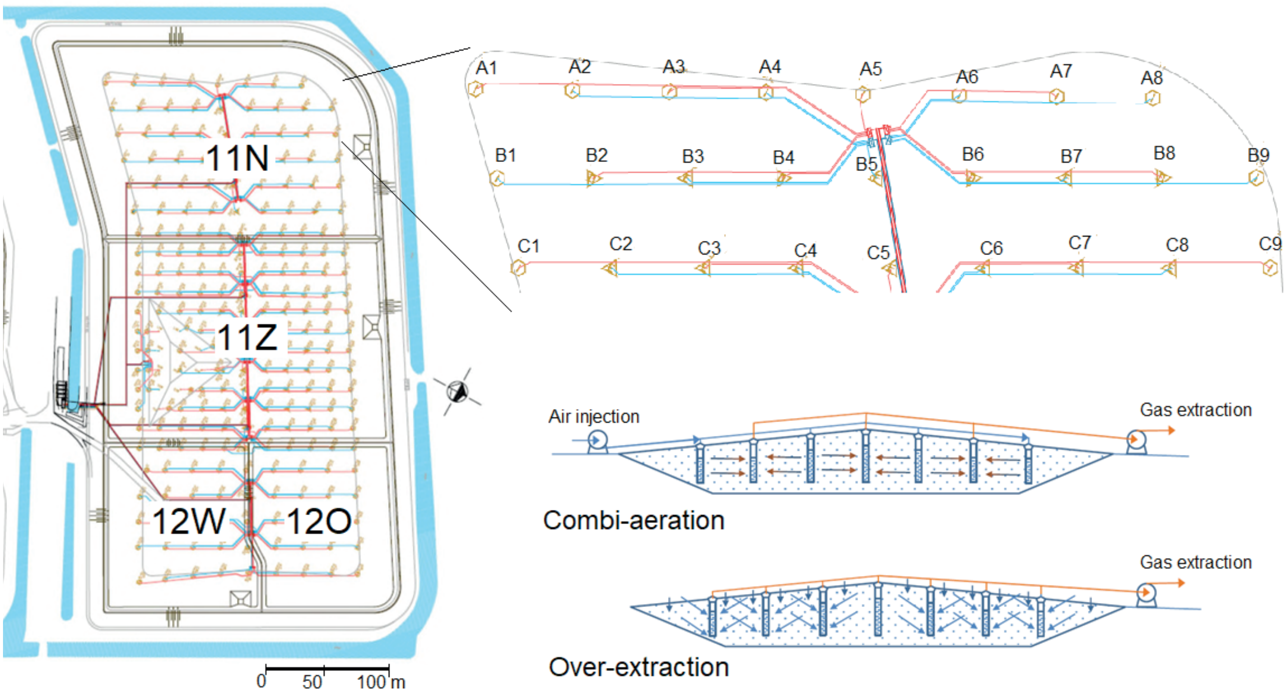

FIGURE 2: Network of aeration wells, systematics of well labeling and a schematic representation of combi-aeration and over-extraction.

3.1 Variability of gas composition

The CH_4 concentration in aeration wells of the compartments 11N, 11Z, 12W, and 12O of Braambergen landfill in March 2020 was not spatially uniform, with the largest range observed in compartments 11N, 11Z, and 12O (Figure 3). In those three compartments, CH_4 concentration varied between close to zero and higher than 40%. High CH_4 concentrations are related to anaerobic waste degradation processes, whereas low CH_4 concentrations are related to CH_4 oxidation processes, as well as to non-existent or reduced (anaerobic) landfill gas formation, for example as a result of aeration. Little information is available from the literature regarding the variability of CH_4 concentrations in waste bodies. However, high variability in CH_4 concentrations in 90 cm depth of an old municipal solid waste landfill (Röwer et al., 2011) have been reported, and the high variability of surface CH_4 emissions is well known (Giani et al., 2002; Mønster et al., 2019; Rachor et al., 2013; Spokas et al., 2003). As the spatial patterns in surface CH_4 emissions are not only impacted by the heterogeneity of waste composition and flow paths within the waste, but also by the variability of cover soil permeability. The comparability between the dynamics of the waste body's gas phase and surface emission is limited.

The ratio of CH_4 to CO_2 and the normalized aerobic activity (NAA) in the extracted gas (Figure 4) provides information about the share of aerobic to anaerobic processes occurring in the waste body. In compartment 11N most of the wells produced more CO_2 than CH_4 (ratios CH_4:CO_2 below 1), indicating the dominance of aerobic activity in most of its wells compared to the other compartments. Aeration in this compartment is likely to be more efficient due to the lower water tables (Gebert et al., this issue), allowing for an increased level of aeration and therefore increased CO_2 production from both, respiration of waste organic matter and CH_4 oxidation. For an old municipal solid waste landfill, it showed that the onset of aeration led to a decline of the ratio of CH_4 to CO_2 to values below 1 in most of the control wells. However, in many of the monitoring wells, especially those intercepting the deeper layers, this ratio increased again after the three year aeration period was terminated, suggesting that the effect of aeration on waste stabilization was limited by the vertical distribution of the injected air and that therefore stabilization had not been completed (Hrad & Huber-Humer, 2017).

Compartment 11Z had the highest water tables and the largest spread with the ratios of CH_4 to CO_2 ranging between 0 and 7, and the NAA varied between 0 and 0.8, as was also observed in compartment 12O.

In compartment 12W most wells produced the same or higher concentration of CH_4 than CO_2, indicating a predominance of anaerobic waste degradation. This was consistent with the low aerobic activity found in 8 out of 12 wells (NAA<0.5, Figure 4 right). Overall aeration appeared to be most effective and uniform (Figure 5) in compartment 11N.

The spatial distribution of CO_2 follows a similar behavior, with the highest variability in compartment 11Z (Figure 5). The fraction of CO_2 increases under conditions of aerobic waste degradation (respiration) compared to anaerobic conditions when also CH_4 is produced besides CO_2. On the other hand, the O_2 concentration in compartment 11Z was more homogeneous than other compartments, with a coefficient of variability of 0.3. Higher O_2 concentrations were found in compartment 11Z, with most of the values close to 21%, reflecting near-atmospheric concentrations. The fact that the extracted gas has a similar percentage of O_2 as the injected air suggests short-circuiting of atmospheric air along with the wells and consequently a reduced extent of aeration of the waste body in the area of influence of the well, likely maintaining the anaerobic conditions. In general, the N_2 concentration varies the least, in line with the fact that N_2 is non-reactive and therefore only affected by variability in transport processes. The observed spatial variability in the gas composition is likely to be closely related to water content and water tables in the landfill, increasing the resistivity to the airflow, hence limiting the aeration efficiency (Hrad et al., 2013).

Although the CH_4-CO_2 ratio and the calculated share of aerobic activity (NAA) give an estimation of aerobic activity, the contribution of the individual processes (respiration, CH_4 oxidation) to the final value is unclear and shall be further investigated using stable isotope probing that could elucidate the significance of anaerobic and aerobic processes for gas composition in the wells. Those wells producing a mixture significantly impacted by CH_4 oxidation should show enrichment in ^{13}C (Cabral et al., 2010; Chanton et al., 2008; Gebert & Streese-Kleeberg, 2017) whereas wells with low gas generation, or in wells where LFG is diluted by air short-circuiting, the isotopic signature of CH_4 should be similar to that of the original landfill gas.

3.2 Variability of gas flow

Compartment 11N showed both higher total flow rates and higher CH_4 flow rates (Figure 6). Gas flow rates in com-

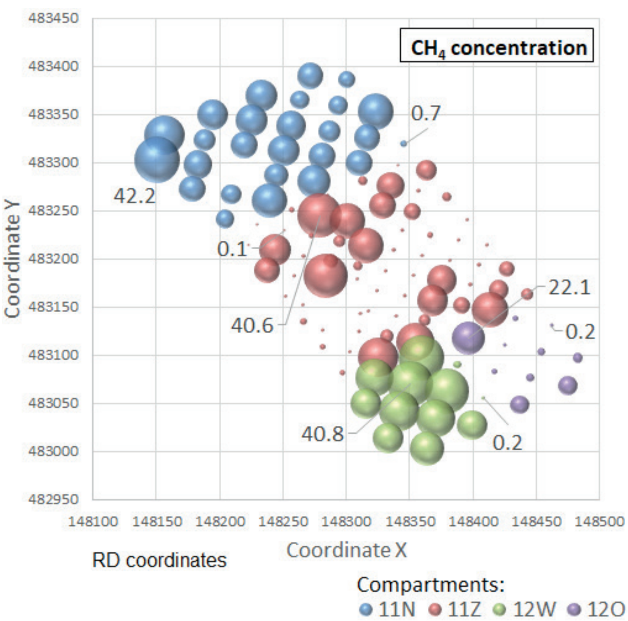

FIGURE 3: Spatial distribution of CH_4 concentration (vol.%) in the extraction wells - March 2020. The size of the symbol is indicative of CH_4 concentration.

partment 11Z were significantly lower, with 35 out of 64 wells showing no flow, presumably in connection with high water tables (Gebert et al., this issue). Compartments 12W and 12O seem to be more homogeneous despite the outliers in wells W2, W4, and S8. The spatial pattern of total flow rate and CH_4 flow rate is similar for compartments 11N and 11Z, but similarities are less for compartments 12W and 12O, in which some wells produce a high total flow rate at low CH_4 concentration and vice versa.

The variability of CH_4 flow rates was similar to the gas concentration variability in each compartment, i.e. compartments 11N and 12W showing a lower variability and compartments 11Z and 12O a higher variability (Figure 5). Considering the waste composition and age, the similarity in gas composition and flow between 11N and 12W and between 12O and 11Z was expected. The highest values for the variability of CH_4 and CO_2 flow rates and concentrations were found in compartment 11Z.

To analyze possible correlations between the flow rate (for conditions of flow > 0) and the ratio of CH_4 to CO_2 in the extraction wells, Pearson's coefficient was calculated. In the case of airflow limiting the aerobic processes, an inverse correlation should be visible, i.e. higher flow rates correlating with higher CO_2 concentrations and therefore a lower ratio of CH_4 to CO_2 in extracted gas. On a confidence level of 99.95%, the flow and the ratio of CH_4 to CO_2 for the total dataset (n=73) were indeed negatively correlated (-0.23), albeit on a low level. With some variation between the compartments (12W: n=12, -0.74; 12O: n=10, 0.01; 11N: n=24, -0.29; 11Z: n=27, -0.10) indicating that the relation-

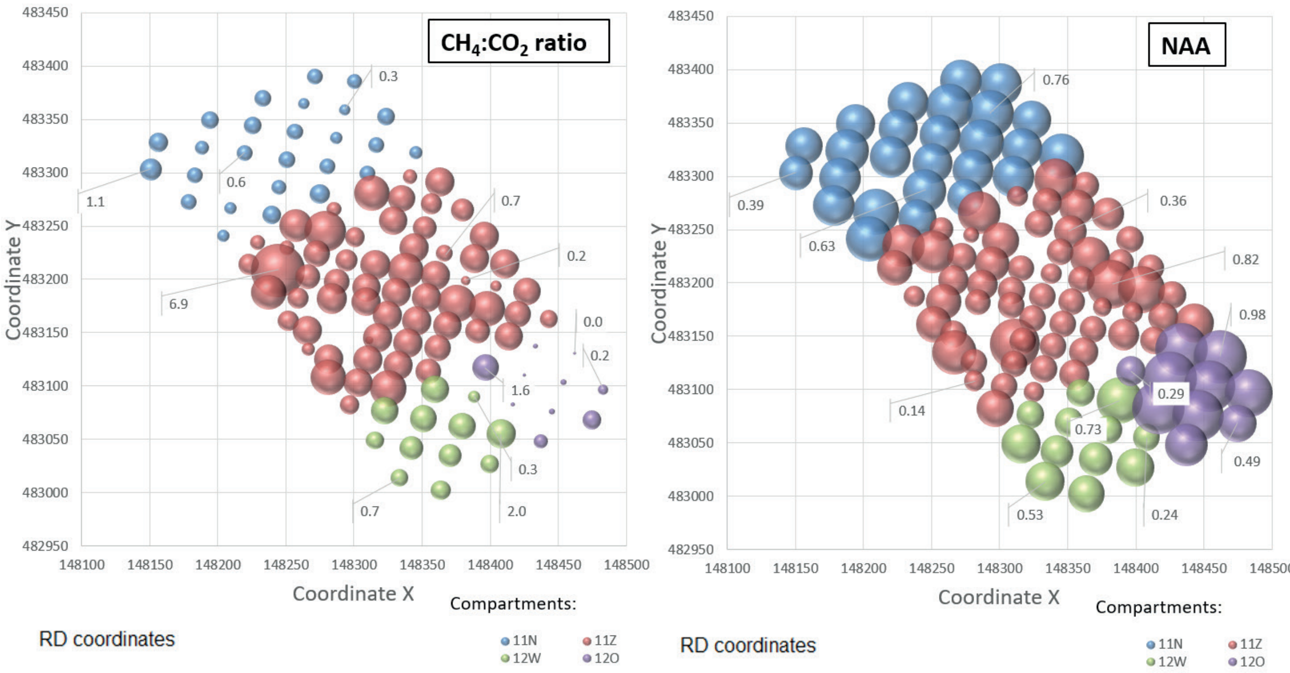

FIGURE 4: Spatial distribution of the ratio CH_4 to CO_2 in the extraction wells (left) and percent of anaerobic activity (right) - March 2020. The size of the symbol is indicative of the ratio CH_4 to CO_2.

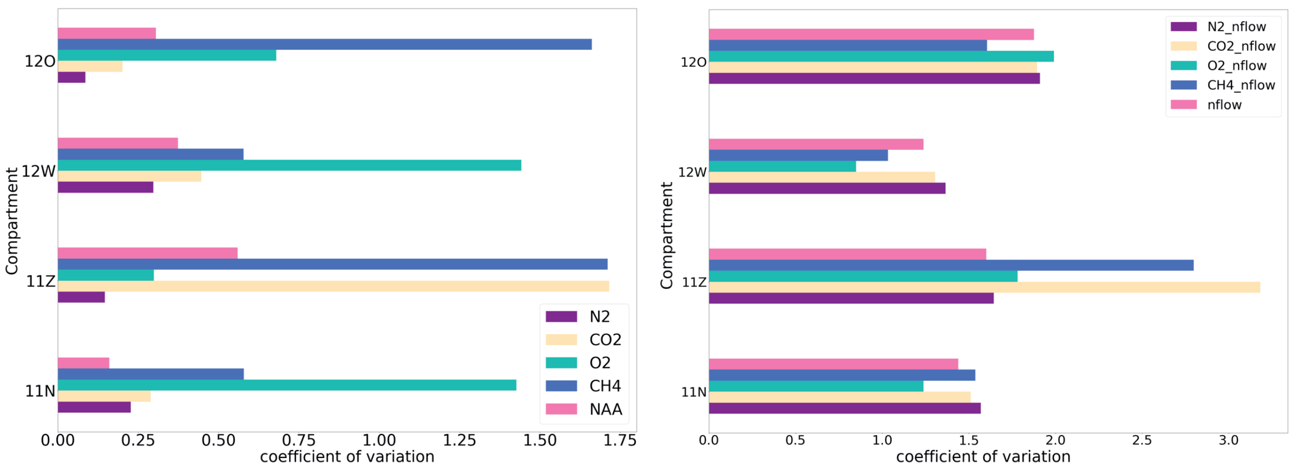

FIGURE 5: Coefficient of variation for the concentration of CH_4, CO_2, O_2, and N_2, and normalized aerobic activity (NAA) (left) and for flow rate, and flow rates of CH_4, CO_2, O_2, and N_2 in the gas extraction wells - March 2020.

ship between the two parameters is confounded, for example, by short-circuiting or near-well differences in waste permeability and hence efficiency of aeration.

The gas prognosis for the aeration pilot (total of all four compartments), carried out with the Afvalzorg Multiphase Model (available from https://www.afvalzorg.com/landfill-gas/lfg-models), estimated the total carbon generation (CH_4-C + CO_2-C) of ~1010 t C for the years 2017 to 2020 if the compartments would not have been aerated (Table 1). Overall compartments, the extracted C exceeded this estimate by a factor of 1.5. A more detailed look at predicted C generation versus realized C extraction reveals that for the wells aerated in compartment 11N, showed the highest C extraction efficiency and highest cumulative settlement, 436 t C more were extracted than predicted to be generated, increasing the factor to > 2, while C extraction in the other compartments remained more or less in the order of magnitude of predicted (anaerobic) C generation. C generation was only modeled for compartment 12 as a whole; hence it is possible that the higher C extraction efficiency calculated for 12W was masked by the less efficient compartment 12O.

While the measured C extraction is deemed accurate, gas generation modeling is subject to high uncertainty (e.g., Scharff & Jacobs, 2006). For example, due to often insufficient data on the waste composition and/or model assumptions on the degradable fraction or kinetic parameters that do not match the deposited waste. The comparison of absolute differences between predicted C generation and extracted C should thus be undertaken with caution. Further, the extracted carbon relates strictly to the gas phase and does not include carbon released from waste biodegradation that leaves the waste body as dissolved organic or inorganic carbon with the leachate. Adding this fraction would increase the share of carbon released in comparison to the predicted carbon generation (landfill gas modeling).

3.2.1 Effect of water tables on gas flow

Analysis of the spatial distribution of water tables over the four compartments showed that most of the wells in compartment 11Z have water tables over the screened part of the aeration well (1.8 m; Gebert et al., this issue). Compartment 11Z is also the one with lower flow rates, higher variability in CH_4 concentrations, and higher ratios of CH_4 to CO_2 (Figures 3 to 6), the latter two suggesting a higher share of anaerobic processes.

The water tables in the waste impede landfill gas and airflow through the wells. It is expected to have a decrease in the flow while the water table gets closer to the top of the screening part of the aeration well. Figure 7 on the far right shows the theoretical relationship between gas flow and height of the water table in the wells, given the location of the filter screen in the lower 1.8 m. For all compartments, the outer boundary of the data approximates this relationship. However, in all compartments also lower gas flow rates were measured than would have been expected from the observed water table, indicating that other factors than the height of the water table, such as the (variable) permeability of the surrounding waste body (Gebert et al., this issue; Xu et al., 2020) also impact aeration efficiency. This was especially pronounced for compartment 11Z in which a high number (98 out of 132 wells) of 'no flow' wells were detected. It can also be seen that the magnitude of gas flow varied per compartment, with at comparable pressures compartment 11N achieving the highest gas velocities.

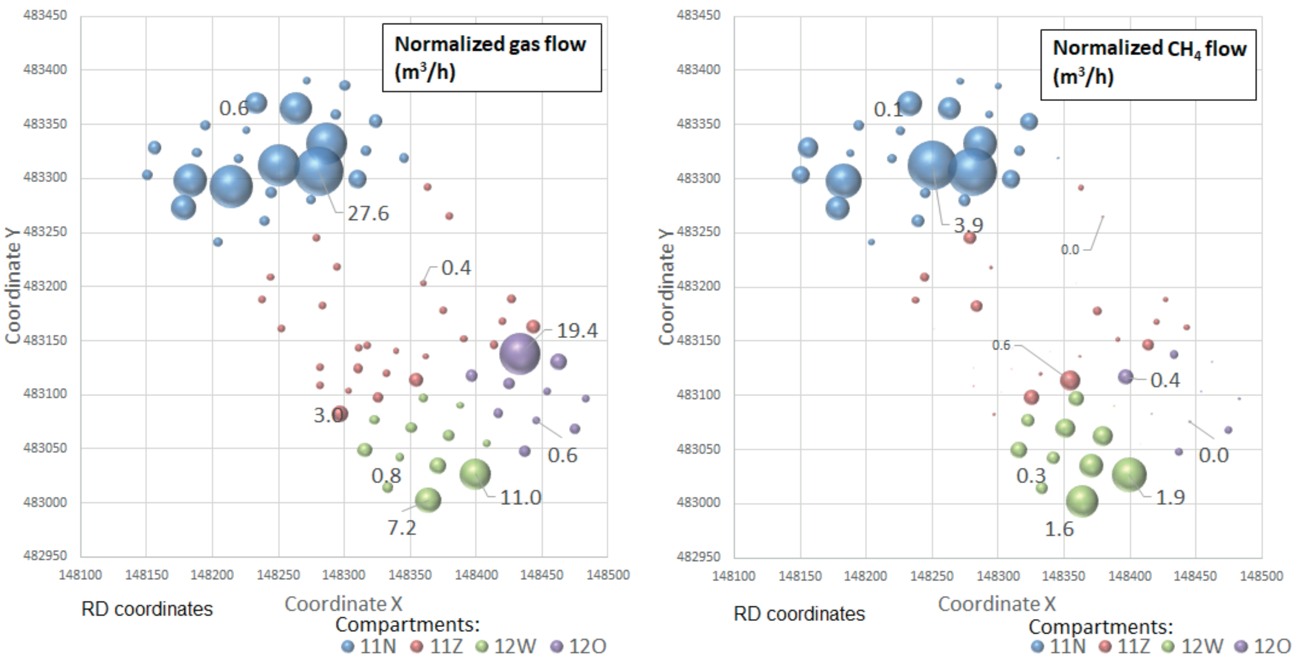

FIGURE 6: Spatial distribution of normalized flow rates (m_3/h) (left) and CH4 flow rates (right) - March 2020. The size of the symbol is indicative of (CH_4) flow rate. Data in graph = exemplary flow rates and CH_4 flow rates.

TABLE 1: Predicted average landfill gas generation and measured average landfill gas extraction for 2017-2020.

Compartment	Predicted cumulative carbon generation (CH_4-C + CO_2-C) 2017-2020 (tons C)	Measured cumulative carbon extraction (CH_4-C + CO_2-C) 2017-2020 (tons C)
11N	382.36	817.82
11Z	193.01	291.60
12W + 12O	435.12	398.87
Total	1010.48	1508.29

3.3 Temporal variability of carbon extraction efficiency, temperature and settlement

As seen from Figure 6 (data for March 2020), compartment 11N showed higher carbon flow rates than the other three compartments. To analyze whether this enhanced performance is consistent over time, the carbon extraction efficiency (carbon flux per compartment normalized to the number of wells and waste volume), waste temperature, and cumulative settlement were analyzed. The carbon extraction efficiency was calculated for the four compartments from the beginning of the aeration in 2017 to 2020 (Figure 8). It is seen that, plausibly, the compartment with the higher aeration efficiency, i.e. the higher share of aerobic processes (NAA, Figure 4) also showed by far the highest carbon extraction efficiency. Compartment 12W showed the second highest carbon extraction efficiency, followed by 11Z and 12O, reflecting the order already seen from the CH_4 flow (Figure 6, right). The differences between the compartments were consistent over the four years since the onset of aeration in 2017.

Figure 9 shows the temperature in compartments 11N and 11Z at +9 m, +6 m, +2 m, and -2 m with respect to the NAP. The landfill surface is between +8 m to +10 m NAP, hence the temperature at +9 m NAP reflects near-surface effects in the landfill, showing the expected seasonal variability with lower temperatures at the beginning of the year and higher temperatures during summer (Figure 9, top left). In the underlying layers, the temperature is influenced by processes within the waste body. The higher aeration efficiency and hence the higher carbon removal efficiency in compartment 11N, as discussed above, reflects clearly the higher waste temperatures due to enhanced biodegradation rates, releasing more heat. Although both com-

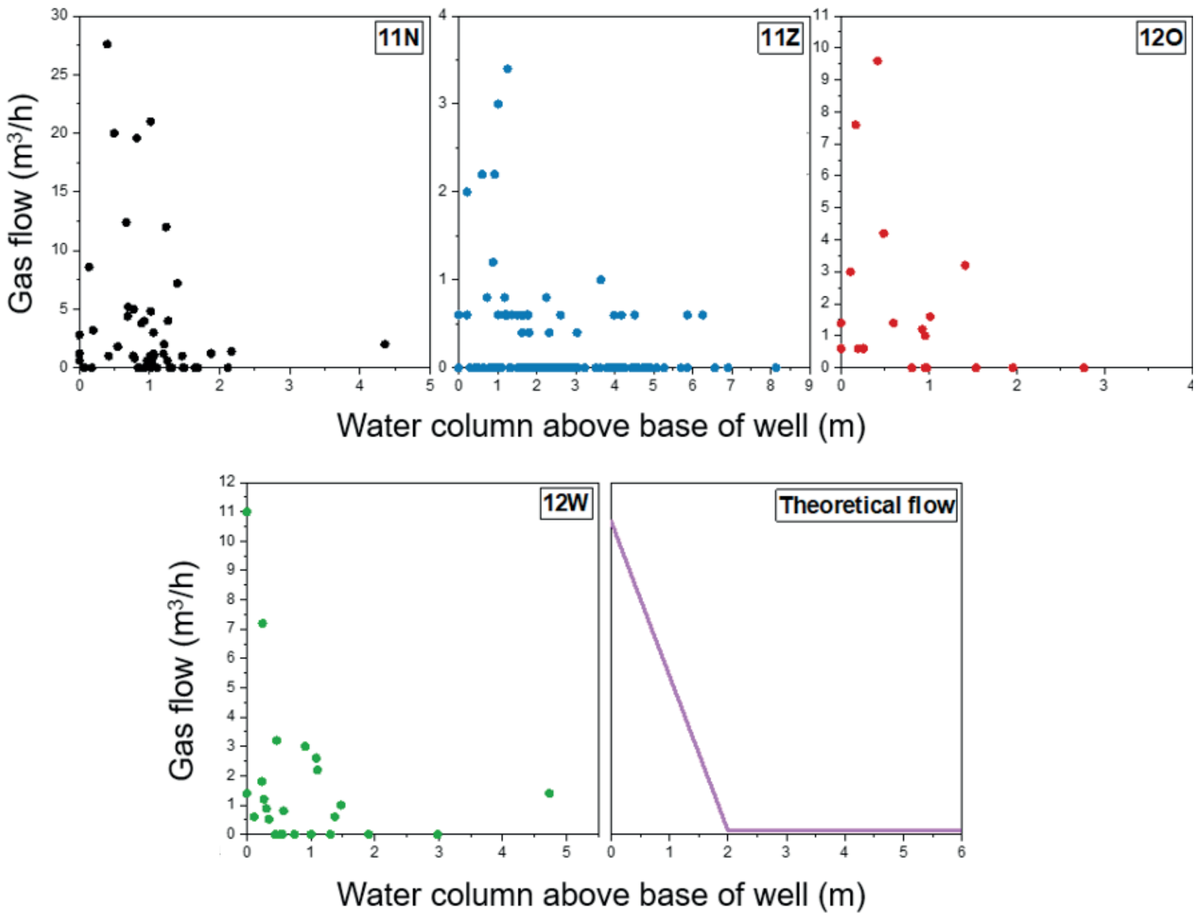

FIGURE 7: Measured normalized gas flow in relation to the height of the water table above the base of the well for compartments 11N, 11Z, 12O, and 12W, expected relationship (far right).

partments are filled with approximately the same amount of waste (11N: 300,637 m^3, 11Z: 370,110 m^3), they differ slightly with respect to waste composition: 11N contains almost 20% of waste with potential organic material in it, compared to the only 2.93% in 11Z. This waste body includes commercial waste (11N: 12.1%; 11Z: 2.3%), shredded waste (11N: 2.2%; 11Z: 0.33%), street cleansing waste (11N: 0.2%; 11Z: 0.0%), coarse household waste (11N: 0.5%; 11Z: 0.28%), sludge (11N: 0.4%; 11Z: 0.02%) and household waste (11N: 2.7%; ; 11Z: 0.0%), suggesting a higher potential for microbial degradation of waste organic matter. It is likely, however, that the difference in aeration efficiency and therefore the difference in temperature is due to the differences in water tables (Figure 7), limiting aeration efficiency in compartment 11Z.

The cumulative settlement with respect to the first measurement (2017) until 2020 is shown in Figure 10. In line with the increased extent of aeration and increased carbon extraction efficiency, compartment 11N stood out with the highest cumulative settlement of on average 0.3 m in the period 2017-2020. Also, the range of cumulative settlement in 11N increased over time, indicating that individual areas are subject to higher biodegradation rates than others.

The higher carbon extraction efficiency, temperature, and cumulative settlement suggest a higher microbial activity in compartment 11N, which corroborates the better performance of the aeration system, evidenced by a higher share of CO_2 in the extracted gas compared to CH_4, higher flow rates, lower water tables and higher amount of organic waste.

4. CONCLUSIONS AND OUTLOOK

The dense network of wells installed for in-situ aeration of four compartments of the Braambergen landfill provided a unique opportunity to study the small-scale spatial variability of gas flow, composition, and water columns in the wells. So far, the following conclusions can be drawn:

Gas composition and gas flow rates are subject to high spatial variability, both within one compartment and between compartments.

Particularly in compartment 11Z, considerable perched water tables, impede gas flow and hence aeration efficiency, as also from high ratios of CH_4 to CO_2, indicating predominantly anaerobic conditions. This is consistent with the estimated low aerobic activity. However, high water columns alone can not explain the difference in flow rates. Other factors need also to be considered such as the spatial variability of the gas permeability within the waste body.

The detected short-circuiting of atmospheric air along wells will limit the efficient aeration of the zone of influence of the respective well.

The highest difference between the measured cumulative C extraction and the predicted cumulative C generation (by landfill gas modeling) between 2017 and 2020 was found in compartment 11N, with more than double the extracted carbon with respect to the predicted value.

Higher aeration efficiency (11N) enables higher organic matter degradation, evidenced by higher carbon extraction efficiency, higher temperature, and higher cumulative settlement. Future investigations will include liquid and gas tracer tests to analyze the spatial variability of permeability within the waste package and the sphere of influence of the aeration wells. Further, stable isotope probing of the gas in the aeration wells will be carried out to identify wells influenced by processes of CH_4 oxidation, respiration, anaerobic landfill gas production, and dilution.

ACKNOWLEDGEMENTS

This research is part of the CURE project supported by the Dutch National Science Foundation (NWO) under project no. OCENW.GROOT.2019.092. The research is also

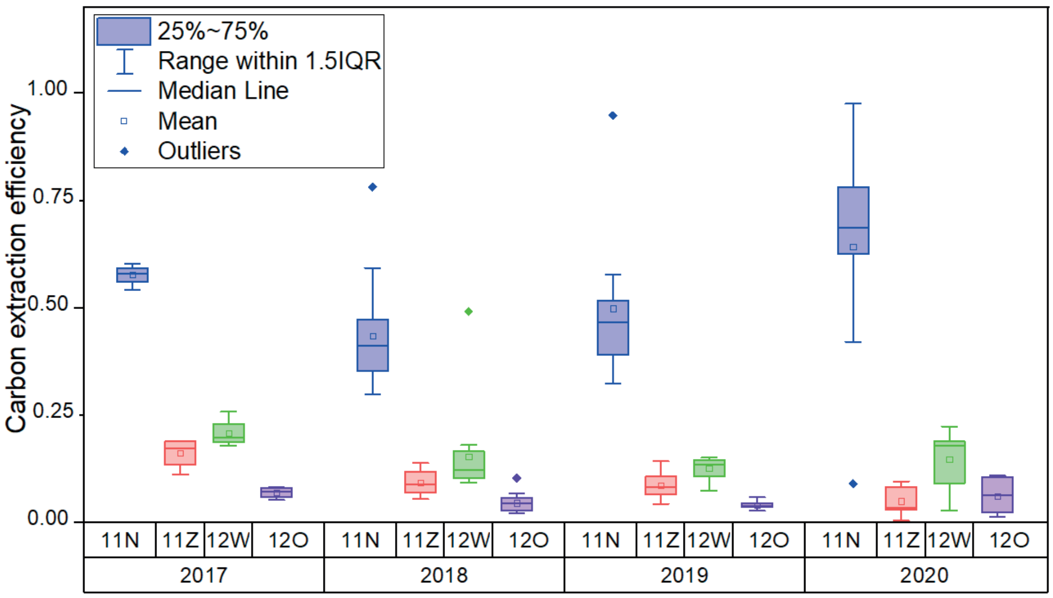

FIGURE 8: Carbon extraction efficiency for compartments 11N, 11Z, 12O, and 12W over the years 2017- 2020.

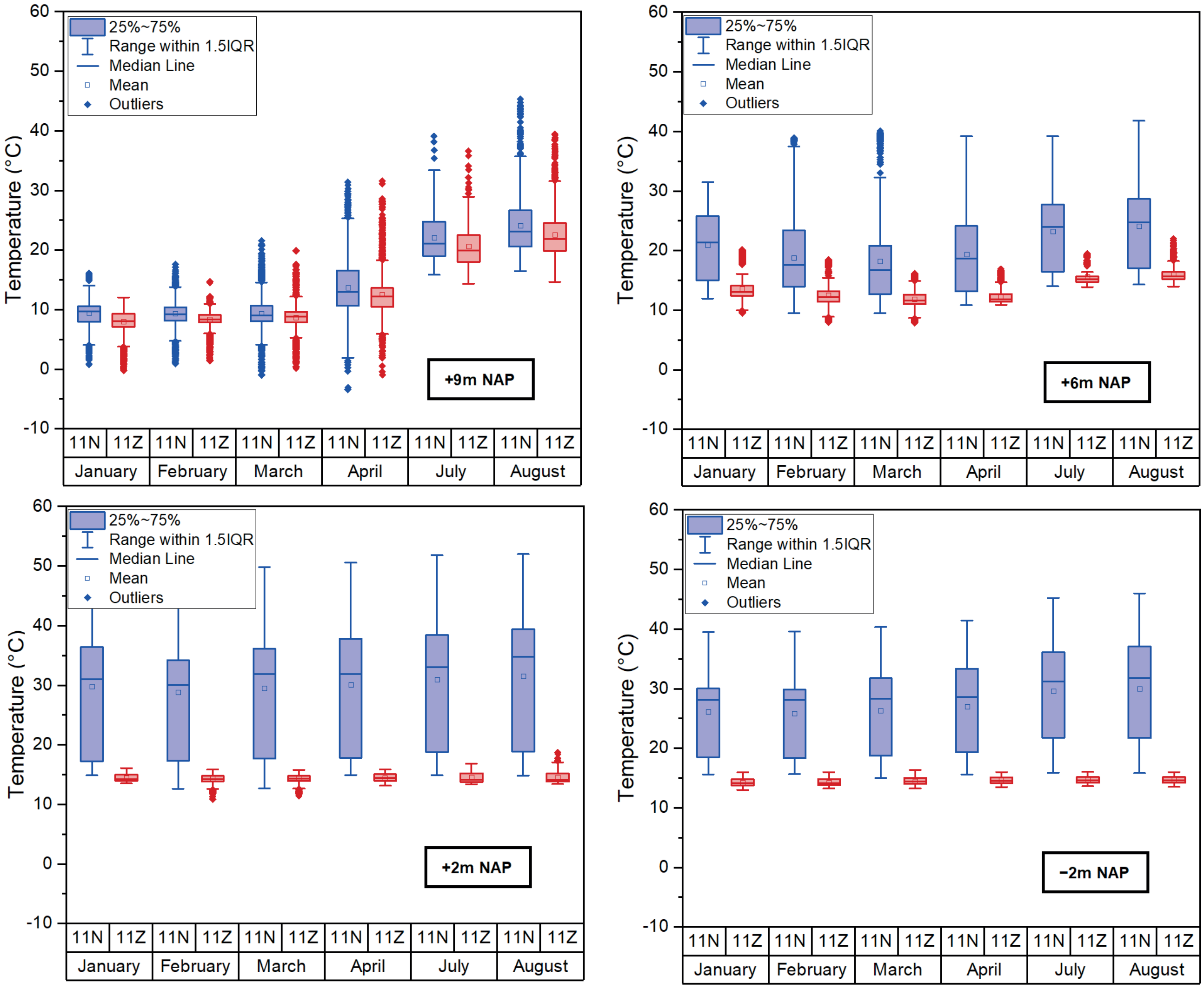

FIGURE 9: Temporal variability in temperature at +9m NAP (top left), +6m NAP (top right), +2m NAP (down left), -2m NAP (down right) – January-August 2020.

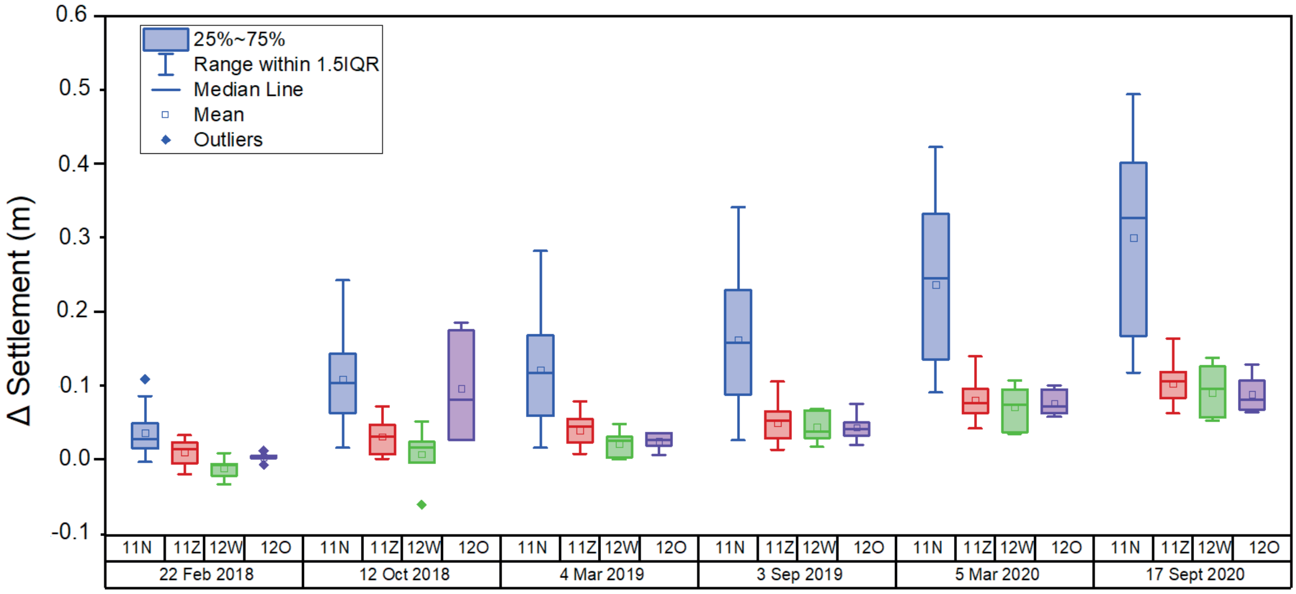

FIGURE 10: Cumulative settlement for compartments 11N, 11Z, 12O, and 12W over the years 2017 to 2020.

supported by the Dutch Sustainable Landfill Foundation via the iDS project.

We thank Dr. Susan Buisma-Yi for proofreading the manuscript.

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