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ASSESSING THE EFFICIENCY OF LANDFILL AERATION WITH A CARBON MASS BALANCE APPROACH

Julia Gebert[1], Nathali Meza[1], Carmen Cruz Osorio[2], Hans Lammen[2]

[1] *Department of Geoscience & Engineering, Delft University of Technology, Stevinweg 1, 2628 CN Delft, Netherlands*

[2] *Afvalzorg Holding, Nauerna 1, 1566 PB Assendelft, Netherlands*

ABSTRACT: This study quantifies the share of aerobically produced carbon (aeration efficiency) during six years of a full scale landfill aeration project using the balance between methane and carbon dioxide in the bulk extracted gas. Aeration was realized by overextraction. Aeration enhanced carbon release in comparison to the anaerobic ‘base case’, as predicted by the Afvalzorg multiphase model, by a factor of 3.7. Aeration efficiency, averaging around 44%, varied seasonally, and was lower in periods of low or no evapotranspiration and hence higher moisture content in the landfill cover soil (winter). Higher aeration efficiencies were observed when evapotranspiration enables increased cover soil permeability (summer). Correspondingly, aeration efficiency was linearly related to the concentration of N_2 in the bulk extracted gas. To a lesser extent, condensate and its removal also affected flow and hence the aeration efficiency. Except for the modulation by seasonal effects, the cumulative amount of extracted ‘aerobic carbon’ increased linearly over time, independent of changes in the blower pressure and flow. This suggests that below the cover soil, within the waste body, flow is chanelled in preferential pathways, limiting the intrusion of oxygen into the bulk waste. Aeration can hence only be enhanced by reducing well spacing. The blower efficiency, assessed by the ratio of flow to pressure, decreased markedly over time, likely indicating diminishing waste permeability as a result of waste consolidation.

Keywords: In-situ stabilization, aeration, over-extraction

1. INTRODUCTION

Landfill in-situ aeration aims to accelerate waste stabilization by introducing oxygen as electron acceptor, thereby enhancing biodegradation of waste organic matter and enable an earlier transition into and eventually release from aftercare (Ritzkowski & Stegmann, 2012; Laner et al., 2012; Dijkstra et al., 2018), provided that site-specific completion criteria for leachate quality are met (Brand et al., 2016). As part of the Dutch Sustainable Landfill Management Project iDS (https://duurzaamstortbeheer.nl/), compartment 6 of landfill Wieringermeer is aerated by over-extraction since 2017, with atmospheric air ingressing through the cover soil (1 to > 2 m thick) into the waste body. The aeration infrastructure comprises 109 wells distributed over ~2.6 ha, filtered over the bottom 1.8 m of an average well depth of 12 m b. s., that intercept 281,083 t of mostly commercial waste with an estimated carbon content of 10%, deposited in the period 1992-1998 (van Vossen et al., 2009). Over-extraction is realized with negative pressures of -20 to -40 hPa, with mean flow rates between 2 and 5 m^3/h per well and bulk flow ranging between 200 and 900 m^3/h. Bulk gas flow, pressure, temperature and composition are monitored continuously.

Under aerobic conditions, carbon dioxide (CO_2) is the terminal carbon product of biodegradation of waste organic matter, increasing the ratio of CO_2 to CH_4 in the gas mixture as compared to strictly anaerobic conditions. The ratio is therefore indicative of the desired aerobic processes. The efficiency of aeration can be assessed in various ways, for example by solid waste sampling and analysis of its gas potential, chemical or biological oxygen demand before and after the stabilization measure (Ritzkowski et al., 2016; Brandstaetter et al., 2020). While these methods offer the opportunity to study the effects of in-situ stabilisation directly on physical samples, their informative value may be limited by high heterogeneity within the waste body. This study uses the share excess CO_2 in the bulk extracted gas to assess the efficiency of aeration and thereby integrates the range of stabilisation efficiencies for the entire waste body under study.

2. METHODS

Flow rate, pressure, temperature and concentrations of CH_4, CO_2 and O_2 in the extracted bulk landfill gas were continuously measured at the suction line of the gas blower and data stored every 15 minutes. After removal of erronous data (e.g., in relation to sensor failure or maintenance shutdowns) all data were aggregated to hourly averages before further analysis. As no other gas component was present in relevant concentrations, the concentration of N_2 in the extracted landfill gas could be calculated as:

$$[N_{2\_LFG}] = 100 - \sum[CH_{4\_LFG}], [CO_{2\_LFG}], [O_{2\_LFG}] \qquad [1]$$

With $[N_{2\_LFG}]$ = concentration of N_2 in extracted landfill gas (vol.%) and $[CH_{4\_LFG}]$, $[CO_{2\_LFG}]$, $[O_{2\_LFG}]$ = concentrations of CH_4, CO_2 and O_2 (vol.%) measured in the extracted landfill gas mixture, respectively.

Measured flow rates were normalised to standard temperature (273 K) and pressure (101.325 kPa) by applying the ideal gas law:

$$Flow\_norm = \frac{P \times Flow\_meas \times 1000 \times MV}{R \times T} \qquad [2]$$

With P = pressure, calculated from the sum of atmospheric pressure and blower pressure (kPa), Flow_meas = measured flow rate (m^3/h) MV = molar gas volume at STP (22.414 l/mol), R = universal gas constant (8.3144 J/mol.K), T = temperature (K).

In this study, aeration efficiency (AE) is defined as the percentage of carbon resulting from aerobic processes, assessed by the share of aerobically produced CO_2 related to the concentration of total CO_2 and CH_4 in the extracted bulk gas mixture. Adapting the approach to calculate the percentage of anaerobic activity by Yasani et al. (2010), aeration efficiency was calculated as follows:

$$AE = \frac{[CO_{2\_LFG}] - [CO_{2\_AN}]}{[CO_{2\_LFG}] + [CH_{4\_LFG}]} \times 100 \qquad [3]$$

With AE = aeration efficiency (%), $[CO_{2\_LFG}]$ = concentration of total CO_2 measured in the extracted landfill gas mixture (vol.%), $[CO_{2\_AN}]$ = concentration of anaerobically produced CO_2 (vol.%), which is equal to the concentration of CH_4 (vol.%), $[CH_{4\_LFG}]$ = concentration of CH_4 measured in the extracted landfill gas mixture (vol.%).

By equaling the concentration of anaerobically produced CO_2 with the concentration of CH_4, this approach assumes that CH_4 and CO_2 are generated by acetotrophic methanogenesis in the ratio of 1:1, representing a conservative estimate of the share of aerobically produced CO_2 in the total gas mixture.

The concentration of original atmospheric O_2 in the extracted gas was calculated from the concentration of N_2 (calculated from eq. 1) according to the nominal atmospheric ratio of 79% N_2 to 21%

O_2, after subtracting an average of 4.8% of the total N_2 that is estimated to be produced by net denitrification on this aeration pilot (Yi et al., 2023):

$$[O_{2\_original}] = ([N_{2\_LFG}] - [N_{2_{LFG}}] \times F_{DN}) \times \frac{[O_{2\_Atm}]}{[N_{2\_Atm}]} \qquad [4]$$

With $[O_{2\_original}]$ = concentration of O_2 that would have been present in the extracted landfill gas mixture would it not have been consumed, $[N_{2\_LFG}]$ = concentration of N_2 in the extracted landfill gas mixture (calculated according to Eq. 1), $F_{\_DN}$ = Fraction of N_2 originating from denitrification (0.048 = 4.8%), O_{2_Atm} = concentration of O_2 in atmosphere (21 vol.%), N_{2_Atm} = concentration of N_2 in atmosphere (79 vol.%).

The share of consumed oxygen (O_2) was calculated from the difference between atmospheric O_2 and residual O_2 measured in the extracted landfill gas mixture:

$$[O_{2\_consumed}] = [O_{2\_original}] - [O_{2\_LFG}] \qquad [5]$$

With $[O_{2\_consumed}]$ = O_2 consumed by aerobic processes (vol.%), $[O_{2\_original}]$ = concentration of O_2 that would have been present in the extracted landfill gas mixture would it not have been consumed (Eq. 4), $[O_{2\_LFG}]$ = concentration of O_2 measured in the extracted landfill gas mixture.

Mid December 2019, blower pressure was decreased from a level of -25 hPa to -40 hPa. In relation to monthly manual gas concentration measurements on individual wells, the plant is shut down and condensate in the distributors is removed manually. Starting from 13 January 2022, an automated daily process was introduced. This new process involves a 20-minute period of flow reversal and air injection in addition to the monthly condensate removal.

3. RESULTS AND DISCUSSION

Aeration efficiency, here defined as the share of aerobically produced carbon in relation to total LFG carbon (Eq. 3) of Wieringermeer compartment 6 varied between 10% and 80% (excluding outliers) with an average of 44% and was subject to strong seasonal variation (Figure 1). Higher efficiencies were observed in the summer months and lower efficiencies in the winter months. Correspondingly, the share of O_2 consumed (Eq. 5) and the residual O_2 measured in the extracted gas mixture were higher and lower, respectively, in the summer period and vice versa in winter (Figure 2). As precipitation during the investigation period was more or less evenly distributed over the year (data not shown), this pattern is assumed to reflect higher permeability of the cover soil due to higher evapotranspiration and hence lower soil moisture during summer. Higher cover soil permeability allows for higher intrusion of atmospheric air at a given underpressure gradient from landfill gas overextraction. In addition, condensation in the aeration piping infrastructure limits flow from the aeration wells. It is also seen that after June 2022, the share of residual O_2 in the extracted gas increases, indicating short-circuiting of atmospheric air to the blower by leakage in aeration piping and/or preferential pathways alongside wells or within the waste body.

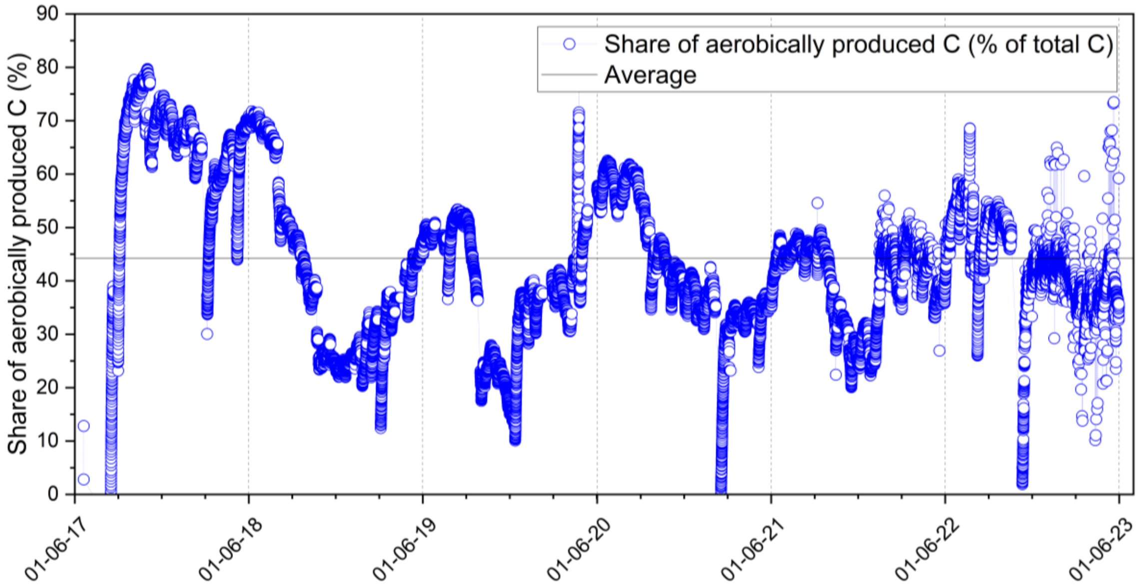

Figure 1. Aeration efficiency as quantified from the carbon mass balance of the bulk extracted gas (Eq. 3) over time, hourly data.

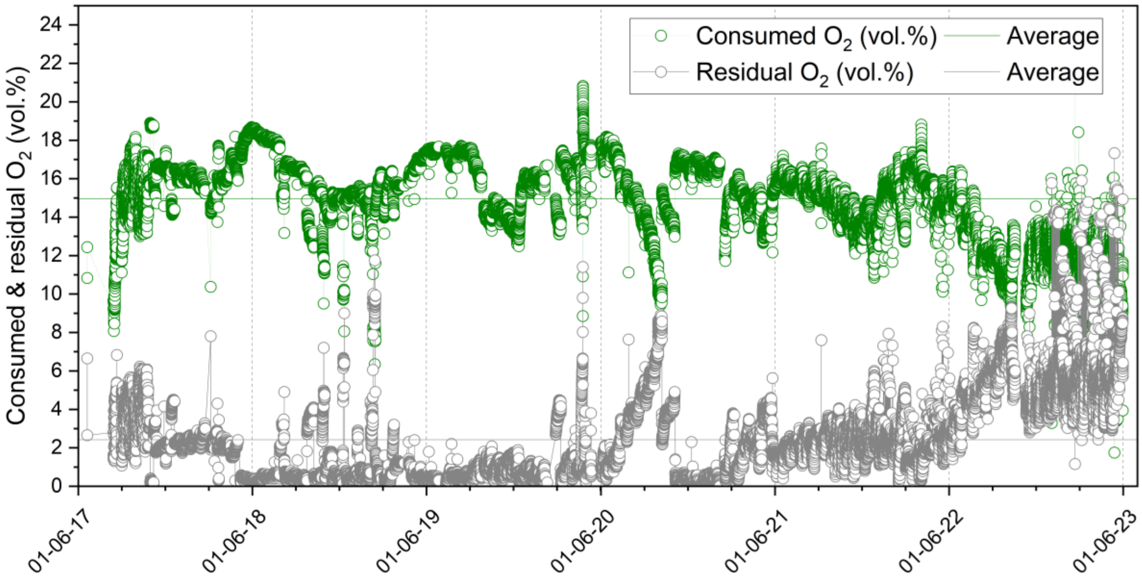

Figure 2. Consumed O_2 (Eq. 5) and residual O_2 over time, hourly data.

In order to separate effects of condensation in the aeration infrastructure from seasonal effects of cover soil saturation, data were examined with regard to the effect of the monthly removal of condensate. Figure 3 shows this by example of the year 2020. It is seen that condensate affects the aeration efficiency significantly, with sometimes > 15 %-points, e.g. in May 2020. However, the seasonal variability of cover soil permeability is responsible for the largest part of the variation, in 2020 for up to ~35 %-points.

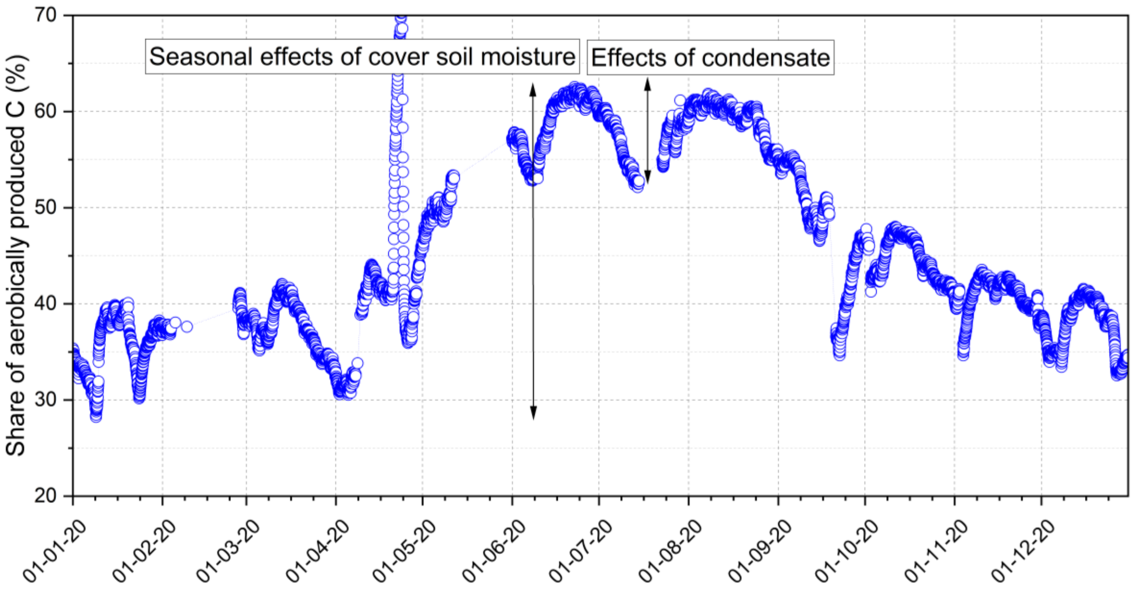

Figure 3. Aeration efficiency as quantified from the carbon mass balance of the bulk extracted gas (Eq. 3) in the year 2020, hourly data. Arrows indicate the variability from seasonal effects of cover soil permeability and from condensate removal in aeration piping.

Obviously, the possible extent of aerobic processes is governed by the intrusion of atmospheric air into the waste body, which can be assessed by the concentration of N_2 in the extracted gas mixture. Indeed, aeration efficiency was near-linearly related to the share of N_2, which usually exceeded 50 vol.% (Figure 4). Concentrations exceeding 79%, especially observed for the the year 2020 which was characterised by an exceptionally dry spring and early summer, are likely related to net production of N_2 by denitrification, which contributed with up to 13% to the N_2 in the total extracted gas mixture (Nagamori et al., 2016; Yi et al., 2023). The linear relationship suggests that the rate of aerobic waste biodegradation is limited by the intrusion of atmospheric air and thereby by all processes that act thereupon.

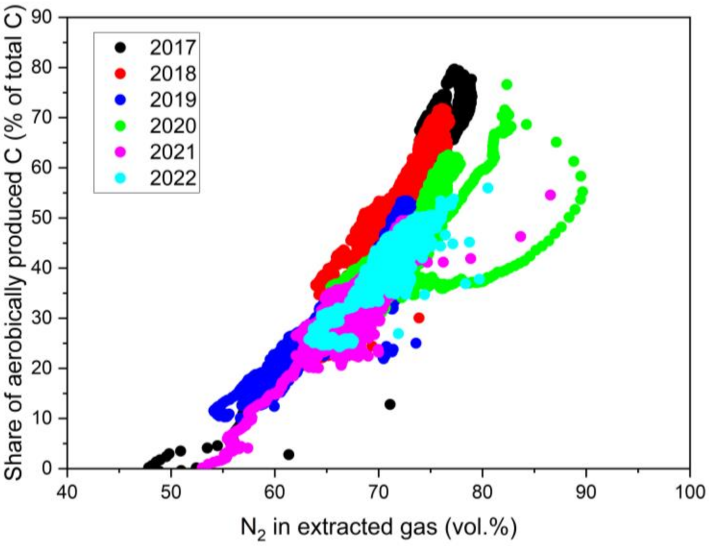

Figure 4. Aeration efficiency as a function of the concentration of N_2 in the extracted gas mixture. Data from June 2022 onwards omitted due to the suspected inluence of leakage or preferential pathways.

After six years of in-situ aeration of compartment 6, ~3300 t of carbon have been extracted, of which ~1500 t are estimated to result from aerobic processes (Figure 5). It is seen that the cumulative amount of extracted carbon increases linearly over time. By June 2023, the extracted total carbon exceeded the amount of carbon predicted by the anaerobic ‘base case’ by a factor of 3.7 (average base case, Vereniging Afvalbedrijven, 2014). The linear increase of the cumulative amount of aerobically produced carbon over time suggests that inspite of the close well spacing aerobic processes are limited by the bulk of the flow occurring through preferential pathways.

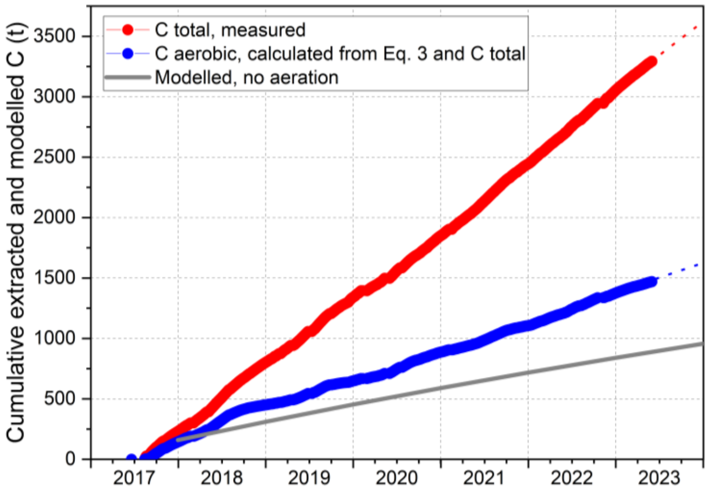

Figure 5. Extracted cumulative total carbon and aerobically produced carbon, and cumulative total carbon predicted with the Afvalzorg multiphase model. Dotted lines = extrapolation from measured and calculated data.

The relationship between flow and pressure of the gas blower can be used to infer changes in the waste body that affect waste permeability, such as settlement, which change as a result of progressing waste degradation and hence stabilization. In the beginning of the aeration period, the ratios of flow to pressure where highest, meaning that at a given (negative) pressure the resulting flow rates were highest (Figure 6). The ratio declined over time, suggesting that waste permeability decreased and hence resistance to flow increased. Currently, the ratio is about a third of the initial ratio, which is likely due the observed waste settlement (data not shown) as a result of waste biodegradation. Also, well clogging contribtes to decreased ratios, as is visible from the positive effect of cleaning and maintenance around begin June 2022. Further, the ratio showed a pronounced seasonal variability with higher values in the summer months and lower values in the winter months, again pointing to the seasonal varaibility of cover soil saturation strongly regulating gas flow. However, it is also seen that the intra-annual range of the ratio and therefore the difference between the seasons is decreasing over time, which would suggest that gas flow is increasingly limited by waste and/or piping permeability and seasonal variations in cover soil permeability play less and less of a role.

Around June 2022, the aeration infrastructure underwent maintenance and clogging of wells was removed, enabling higher flows to pressure ratios again. However, Figure 2 also inidcated higher residual O_2 content in the extracted LFG, which can be intrepreted as increased short-circuiting. Alternatively, it could be that if the maximum level of aerobic processes along the reactive surfaces accessible through waste preferential pathways is reached, increasing flow will not further increase aerobic organic matter conversion and hence lead to an increase in residual (not consumed) oxygen. Most recent data show a renewed decrease of the flow-to-pressure ratio after the maintenance.

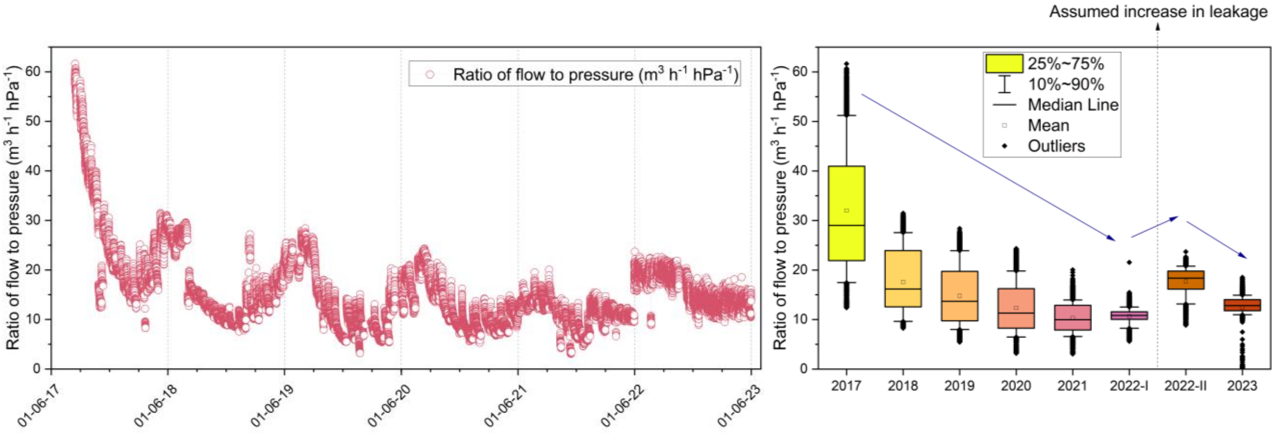

Figure 6. Normalised blower flow rates divided by the blower pressure (absolute values) over time. Left: Hourly data, right: data aggregated per year in box and whisker plots.

It is noteworthy that the cumulative amount of extracted carbon (Figure 5) increases linearly and inspite of the declining blower efficiency, i.e. the declining ratio of blower flow to blower pressure (Figure 6). This re-iterates the assumption that carbon production is strongly impacted by channeling of flow in the waste body (after air has passed through the landfill cover soil) and that the current blower efficiency is not limiting the aeration efficiency but that instead, the aeration efficiency is limited by the intrinsic waste permeability, which is low and anisotropic (Powrie and Beaven, 1999). Vice versa this suggests that investments targeted at increasing the suction and increasing flow would not result in an increase of aeration efficiency. This can only be achieved by decreasing well spacing to further reduce transport limitations, as also predicted by van Turnhout et al. (2020) for the same aeration pilot.

4. SUMMARY AND CONCLUSIONS

This investigation into the aeration efficiency within six years of full scale in situ aeration reveals that

- Waste aeration increased carbon extraction by a factor of 3.7
- The aeration efficiency, estimated at a conservative average of 44%, was linearly related to the ingress of atmospheric air, represented by the concentration of N_2 in the extracted gas
- The ingress of atmospheric air is strongly governed by air flow, with air flow being limited by seasonal changes in cover soil moisture, by clogging up of aeration infrastructure and by transport channeling within the waste body
- Due to channeled flow within the waste body, aeration efficiency cannot be increased by further decreasing negative pressures
- Increasing waste biodegradation was visible not only from settlement but also from decreasing ratio of blower flow to blower pressure over time and hence from an increased resistance to flow. Further, resistance to flow is affected by clogging and trapped water in wells.
- Condensate in the aeration infrastructure impedes flow to some extent, but that the largest part of the variation is caused by seasonal variability in cover soil moisture, affecting cover soil permeability.

Overall, the data suggest that aerobic carbon extraction can only be increased by further increasing the number of wells in order to overcome transport limitations within the waste body. Further research will quantify the spatial outreach of aeration within the waste body using gas tracer and pressure field testing to derive information on waste permeability (also see Duarte Campos et al., 2023).

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