Ndanga, É.N., Bradley, R.L. # and Cabral, A.R. (2015). Does Vegetation Affect the Methane Oxidation Efficiency of Passive Biosystems? Waste Management, 38: 240-249. 10.1016/j.wasman.2015.01.031

Does Vegetation Affect the Methane Oxidation Efficiency of Passive Biosystems?

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Abstract

It is often reported in the technical literature that the presence of vegetation improves the methane oxidation efficiency of biosystems; however, the phenomena involved and biosystem performance results are still poorly documented, particularly in the field. This triggered a study to assess the importance of vegetation in methane oxidation efficiency (MOE). In this study, 4 large scale columns, each filled with sand, topsoil and a mixture of compost and topsoil were tested under controlled conditions in the laboratory and partially controlled conditions in the field. Four series of laboratory tests and two series of field tests were performed. 4 different plant

covers were tested for each series: *Trifolium repens L.* (White clover), *Phleum pratense L.* (Timothy grass), a mixture of both, and bare soil as the control biosystem. The study results indicated that up to a loading equal to 100 g $CH_4/m^2/d$, the type of plant cover did not influence the oxidation rates, and the MOE was quite high (≥ 95%) in all columns. Beyond this point, the oxidation rate continued to increase, reaching 253 and 179 g $CH_4/m^2/d$ in laboratory and field tests respectively. In the end, the bare soil achieved as high or higher MOEs than vegetated biosystems. Despite the fact that the findings of this study cannot be generalized to other types of biosystems and plants and that the vegetation types tested were not fully grown, it was shown that for the short-term tests performed and the types of substrates and plants used herein, vegetation does not seem to be a key factor for enhancing biosystem performance. This key conclusion does not corroborate the conclusion of the relatively few studies published in the technical literature assessing the importance of vegetation in MOE.

Keywords: Landfill final covers; Landfill gas emission abatement; Plant cover

1. Introduction

Methane (CH_4) is the main greenhouse gas emitted by landfills and represents 18% of the global anthropogenic CH_4 emissions (Bogner et al., 2007). Passive methane oxidation biosystems (PMOBs) are considered one of the most cost-effective technologies for mitigation of CH_4 emissions from landfills (IPCC, 2007). In recent years, considerable research has focused on improving these biosystems. They are usually made up of a sequence of soil layers, including a gas distribution layer (GDL) and a methane oxidation layer (MOL). The performance of passive methane oxidation biosystems (PMOBs) depends on several environmental factors, including temperature, degree of water saturation within the soils, organic matter content of the MOL, several other soil properties and characteristics and, last but not least, the presence of vegetation.

According to Reay et al. (2005), vegetation is a key determinant of biotic CH_4 oxidation. Despite this finding, its importance on the efficiency of PMOBs is still relatively poorly documented, particularly in the field, where, to the authors' knowledge, no technical papers have been published so far. This paper focuses on evaluating the importance of vegetation on CH_4 oxidation efficiency within engineered biosystems tested on a landfill and in the laboratory.

Documentation on CH_4 oxidation and emissions from several vegetated mediums (wetland rice fields, freshwater marshes, forest soil, grassland or cultivated soil) is widely available (Ding et al., 2004; Jia et al., 2001; Keppler et al., 2006; Nouchi et al., 1990; Reay et al., 2005; Watanabe et al., 1997). The effect of vegetation has been related to several bio-physico-chemical processes such as: diffusion, biological controls and CH_4 transport through the root system. Indeed, transport through vascular plants has been identified as one of the main pathways of CH_4 exchange between the atmosphere and the soil (Chanton, 2005; Chanton et al., 1989; Ding et al.,

2004; Schütz et al., 1989). Chanton (2005) reported methane consumption by the roots of two aquatic plants: pontederia cordata and sagittaria lancifolia. Vascular plants can help promote the diffusion of O_2 from the atmosphere to the rhizosphere through the arenchyma system. In addition, plant roots can produce exudates and release them to the rhizosphere, which may substantially influence chemical or biological soil properties in ways that can help the biogeochemical process of methane oxidation (Hilger et al., 2000; Stralis-Pavese et al., 2004; Tanthachoon et al., 2008). Moreover, in a study of the effect of 3 plant species on the CH_4 oxidation capacity in forest soils, Reay et al. (2005) suggested that the presence of nitrogen-fixing (N-fixing) plants, such as alder, may result in large reductions in potential CH_4 oxidation in soils. Popp et al. (2000) reported on the other hand that there were no significant differences between CH_4 oxidation measured for bulk peat of a non-vegetated site core and the control vegetated site cores for the same time period. Thereby, quantitative estimates of methane oxidation in several vegetated mediums may be related to differences in the systems studied such as the plant species present (King et al., 1990; Van der Nat et al., 1997).

Recent research on engineered biosystems for landfills suggests that plants would positively contribute to CH_4 oxidation (Bohn et al., 2010; Hilger et al., 2000; Reichenauer et al., 2011; Wang et al., 2008). It is reported that vegetation can improve the air-filled capacity of soils through the formation of secondary macro-pores by spreading roots. In addition, vegetation controls moisture infiltration by means of plant evapotranspiration. Finally, plant growth may also provide nutrients for methanotrophs by root exudates and debris of dead plants and thereby increase oxidation efficiency. Some potential negative effects of vegetation on CH_4 oxidation include the potential for plant roots to create preferential channels for CH_4 emissions, and their competition for O_2 due to root respiration (Wang et al., 2008). Plants debris may also lead to O_2

competition with bacteria degrading the debris and thus decreasing methane oxidation efficiency. However, the actual integrated effect of plant species on the methane oxidation process in landfill covers remains poorly documented in the technical literature, particularly in relation to engineered biosystems for landfills tested under field conditions.

In order to verify the validity of the hypothesis that the type of vegetation may affect the CH_4 oxidation efficiency of a biosystem, the following 3 types of plants were tested under the controlled conditions prevailing in the laboratory and under the partially controlled conditions of the Saint-Nicéphore landfill, QC, Canada: 1) White clover (*Trifolium repens L.*), which is a leguminous plant; 2) Timothy grass (*Phleum pratense L.*); and 3) a mixture of White clover and Timothy grass. An unplanted biosystem served as control.

The research reported in this paper included a series of 4 laboratory tests performed in sequence and 2 field tests. Each test was comprised of 4 columns containing the same sequence of materials and one of the 4 vegetation covers presented above. The methane oxidation efficiencies (MOE) of the columns were determined for several methane loadings, while temperature and degree of water saturation profiles were obtained throughout the tests by a data acquisition system.

2. Materials and Methods

2.1. Experimental set-up

2.1.1. Laboratory set-up

Four columns measuring 0.61 x 0.46 x 0.52 m were built for the laboratory-scale experiment. A schematic of their design is presented in Figure 1. The methane oxidation layer (MOL) of the biosystems was constituted of the following materials, from the bottom up: a 0.30-m layer of fine sand, a 0.075-m layer of topsoil, and a 0.075-m layer of topsoil enriched with compost (5% dry weight). The gas distribution layer (GDL) that is usually constructed under the MOL was substituted by an empty space. The GDL and MOL were separated by a 2-cm thick perforated plastic plate covered by a fine wire mesh. Seepage water was collected at the bottom of the column and evacuated through an outlet.

The columns were set in an explosion-proof laboratory. A lighting system was installed in order to foster plant growth. It consisted of 100-Watt fluorescent lamps controlled by an electronic unit that was set to provide the required number of hours of light per day (14 h/d) and a light intensity of approximately 8000 lx. The temperature of the laboratory was maintained at 19°C by a cooling system. An aeration unit allowed the renewal of air in the laboratory.

Figure 1: Experimental design of laboratory columns

2.1.2. Field set-up

At the Saint-Nicéphore landfill site, in Quebec, Canada, four experimental biosystems measuring 0.9 m x 0.9 m were installed during spring 2013. As shown in Figure 2, their design was quite similar to that adopted for the laboratory columns. The MOL material was the same as for the laboratory. A 0.10-m thick gas distribution layer underlying the MOL was built with 12.7-mm gravel topped by a fine wire mesh to avoid clogging of the gravel pores by the MOL material. The sides of the four columns were thermally insulated by surrounding them with a 0.30-m thick layer of locally-available silt (Figure 2). This insulation helped prevent lateral migration of moisture within the columns due to thermal gradients.

Figure 2: Experimental design of field columns

The cover materials used in both the laboratory and field columns were those widely available on-site. Their characteristics, presented in Table 1, were fixed and the same for all columns. Sand was placed in three 0.10-m layers and compacted to obtain a dry density of 1690 Kg/m^3. The 0.075-m layers of unenriched and enriched topsoil were compacted at a density of 1200 Kg/m^3. These degrees of compaction were chosen to reproduce an existing experimental biosystem at the Saint-Nicéphore landfill site.

Table 1: Characteristics of cover materials

2.2. Experimental procedure

For this study, four series of 4 column tests were performed under controlled laboratory conditions, and two series of 4 column tests were performed under partially controlled field conditions. Each laboratory test was conducted over approximately 5 months, including the acclimatization period and plant germination period. In order to observe the influence of climatic conditions on field results, two field tests were performed each over two different seasons. The first test started in May and ended in August (spring to summer), which corresponds to the best growth period for plants. The second one started in August, a less favourable period for plant growth, and ended in October (summer to fall).

Before the laboratory and field tests, an air tightness test was performed within the columns. A controlled CH_4 loading was introduced at the bottom of the previously emptied columns and the CH_4 flux out of the column was monitored to assess losses due to leaks. The field columns showed a loss of about 6% of the CH_4 loading, while in the laboratory, the loss was 3.5%.

2.2.1. Plant seed

Two different plant species were selected and used in this study, based on their abundance on site. The first one was the *Trifolium repens L.*, White clover, a leguminous and perennial plant. According to the USDA NRCS Plant Materials Program, it is considered to be a beneficial component of seed mixture because of its N-fixing property by converting atmospheric nitrogen - through its root system - into a form that is usable by other plants and microorganisms in the soil. The second one was the *Phleum pratense L.*, Timothy grass. It is a perennial plant that has a shallow, compact, and fibrous root system. Timothy grass has a relatively high demand for

160 nutrients, especially nitrogen, which is often the major limiting nutrient for Timothy growth.
161 However, its competition for N is low at the beginning of its growth.

162 For the experiments, columns were seeded with Timothy grass (TG column), White clover (WC
163 column) and a mixture of 67% Timothy grass and 33% White clover (MIX column). Column 4
164 was the control column and was therefore not seeded (bare soil, BS column). Based on
165 preliminary seeding tests, the seeding density for each column was 6g/m^2.

166

167 2.2.2. Irrigation

168 Field columns were naturally irrigated with rainwater, while laboratory columns were watered
169 manually following approximately the 30-year monthly average rainfall for Drummondville,
170 Quebec. The Environment Canada database was used for this purpose. Due to the intense
171 aeration inside the explosion-proof chamber (6 air renewals per hour) where the columns were
172 installed, the material dried faster than in normal field conditions. As a consequence, the amount
173 of water added to the columns was adjusted to compensate for this condition. Thereby, the
174 protocol may diverge from actual field conditions. Daily irrigation was recorded during the
175 experimental period. The average daily precipitation was 2.7-mm in the laboratory and 1.54-mm
176 in the field.

177

178 2.2.3. Biogas loading

179 After the columns were filled with soil, synthetic biogas (50% CH_4/50% CO_2, v/v) was applied
180 to the bottom of the laboratory columns, whereas raw landfill gas (LFG) was applied to the field

columns. Methane loadings in each column were controlled by flow meters (Gilmont Instruments, Inc. GF 1060). Before injection into the column, the synthetic biogas was moisturized by bubbling through a water-filled bottle to prevent desiccation of soil. The LFG was already sufficiently wet. Columns were kept at the residual landfill gas exposure of 8 g $CH_4/m^2/d$ for one month (two weeks before and after seeding) to allow plants to germinate and methanotrophs to grow as reported in Kightley et al. (1995). Subsequently, the loading was increased gradually from 8 to 270 and 180 g $CH_4/m^2/d$ for laboratory and field tests, respectively, as presented in Figures 3 and 4.

2.2.4. Column instrumentation

Each column was equipped with temperature and water content probes (ECTM-5, from Decagon Devices), placed at 10, 20 and 30 cm below the surface. During the experimental period, daily values were recorded manually in laboratory tests using a ProCheck Decagon Device and automatically in field tests with data loggers. To better visualize the results, the water content was converted into degree of saturation using the usual soil mechanic formulas.

In order to collect gas samples from the headspace and be able to estimate CH_4 surface emissions, 110 L and 300 L PVC caps were constructed respectively for laboratory and field columns, and were installed only when CH_4 surface emission measurements were taken.

In the laboratory, the top of the cap was perforated and four tubes were introduced at 80, 60, 40, and 20% of the total height of the cap to cover its entire surface and volume (Figure 1). The CH_4 concentration in the headspace was measured with a gas chromatograph (Micro GC 3000A, Agilent Technologies). Gas samples were collected from each tube of the headspace with a

syringe at a regular frequency, and immediately analyzed.

In the field columns, only one sampling point was placed at the center of the cap. CH_4 surface emission was measured using a portable flame ionization detector (TVA-1000B, Thermo Scientific) equipped with a data acquisition system.

2.2.5. Mass balance calculation of CH_4 oxidation efficiencies

The CH_4 oxidation efficiency (MOE) was calculated using the mass balance method in the headspace. This method is based on the CH_4 loading and the CH_4 surface emission of the biosystem. The MOE was calculated as follows:

$$\mathbf{MOE} = \frac{\mathbf{Flux_{in}} - \mathbf{Flux_{out}}}{\mathbf{Flux_{in}}} \times 100 \qquad (1)$$

where MOE is expressed as the percentage of CH_4 loading oxidized, $\mathbf{Flux_{in}}$ and $\mathbf{Flux_{out}}$ are the CH_4 inlet and outlet fluxes respectively (g $CH_4/m^2/d$). CH_4 outlet flux of the column was determined from the linear regression analysis of the temporal increase in chamber CH_4 concentration. The oxidation rate was calculated by multiplying the MOE by the CH_4 loading.

2.2.6. Statistical analysis

A two-factor analysis of variance (ANOVA) was used to assess the effect of plant type and CH_4 loading on the methane oxidation efficiency of biosystems. Because of the substantial database obtained in the laboratory (4 replicates of each treatment), the significance threshold was

accepted at a level of $p < 0.05$, this level was also maintained for field results. Knowing the significant effect of gas loading on efficiency, and to isolate the effect of plant cover on the latter, a quadratic model was used. This model was also the one suggested when maximizing the predicted and adjusted R-squared values. In order to evaluate the effects of plant cover on depth profiles of temperature and degree of saturation of biosystems, another two-way ANOVA was performed. The significance threshold was maintained at $p < 0.05$.

3. Results and discussion

3.1. Methane oxidation efficiencies under laboratory conditions

The methane oxidation efficiency (MOE) and oxidation rate values for different CH_4 loadings under laboratory conditions are presented in Figure 3. The results presented herein represent the average of the values obtained from the four perforated tubes on the top of the PVC cap. Since the MOE values calculated - based on the data obtained from those four sampling points - did not show a significant difference (< 0.5% at all times), it was concluded that the gas within the headspace was uniformly distributed.

Throughout the present study, MOEs were 100% for loadings up to 125 g $CH_4/m^2/d$. Differences in MOEs of the biosystems became appreciable above this value. In spite of that, the maximum difference in MOEs between biosystems did not exceed 8% for the higher loading values.

As can be observed in Figure 3A-D, the oxidation rates of the 4 columns continued to increase with increasing CH_4 loadings for the four tests and the oxidation rates of the WC and TG columns were quite similar. Furthermore, except for test 1, the highest efficiency was obtained

for the BS columns, whose average oxidation rate was 240 g $CH_4/m^2/d$ (± 2.8 g $CH_4/m^2/d$). For test 1, the maximum oxidation rate (255 g $CH_4/m^2/d$) was obtained for the WC column. The MOE of the BS column remained close to 90% for all laboratory tests. The constant values obtained for this control test confirm the good reproducibility of the adopted protocol.

For the TG WC and MIX columns, when the loading became greater than 125 g $CH_4/m^2/d$, the oxidation rates (and associated MOEs) started to differ from one test to another. A definite explanation cannot be provided herein considering the limited test result database. Variations observed in plant root density from one test to another may partly explain why oxidation rates did not remain constant for all columns (Ndanga et al., 2013). In fact, it could be hypothesized that preferential pathways, usually associated with the root system (Bohn et al., 2010; Scheutz et al., 2009; Wang et al., 2008), led to the increasing differences in MOEs between the columns for loadings greater than 125 g $CH_4/m^2/d$.

Despite the differences observed for loadings greater than 125 g $CH_4/m^2/d$, the MOE remained greater than 80% up to a loading of 225 g $CH_4/m^2/d$, irrespective of plant cover. The lowest oxidation rate was 180 g $CH_4/m^2/d$, which was obtained for the WC column at the end of test 4. This oxidation rate is nonetheless very high considering that it far exceeds what is considered the average methane loading applied to cover systems, in several landfills with gas collection systems in the U.S. and Canada, i.e., 28 g $CH_4/m^2/d$ (Capanema and Cabral, 2012).

In order to assess possible variations of MOE within the same loading, 3 MOE measurements were taken for each loading during the third laboratory test. Figure 3C presents the mean oxidation rates and MOEs for each loading increment. The first measurement was taken at least 7 days after increasing the loading. For all loadings and all columns, there was never a significant

variation in MOE between the 3 measurements. The standard error generally did not exceed 3%. Therefore, values obtained with one measurement in other laboratory tests were considered representative of the real efficiency of columns.

Figure 3: Methane oxidation efficiency and oxidation rates at different CH_4 loadings under laboratory conditions. A - Lab test 1; B - Lab test 2; C - Lab test 3; D - Lab test 4

3.2. Methane oxidation efficiencies under field conditions

Figure 4 presents the MOEs and oxidation rates of the field column tests performed during "spring to summer" (field test 2; Figure 4A) and "summer to fall" (field test 3; Figure 4B). The MOEs during field test 2 remained at ~100% up to a loading equal to 95 g $CH_4/m^2/d$, irrelevant of plant cover. At the end of this test, MOE values remained greater than 80%. Similarly to what was obtained for the laboratory tests, the BS column was the most efficient at the end of the test and the oxidation rate reached 179 g $CH_4/m^2/d$. During field test 3, the MOEs were greater than 95% for all columns up to a loading equal to 95 g $CH_4/m^2/d$. Until near the end of this test MOEs remained greater than 80% but, at the last measurement, the efficiencies dropped drastically when the air temperature reached the freezing point (≤ 0°C) before this last measurement. Nevertheless, in spite of colder weather, oxidation rate values remained high (between 100 and 115 g $CH_4/m^2/d$). Probably due to decreasing air temperatures (as fall approached), MOEs in field test 2 were generally greater than MOEs in field test 3.

285 Repeatability of field measurements was verified by performing at least 2 MOE measurements
286 for each loading during the field tests. In this case, the disparity in MOE values was greater than
287 the disparity obtained during the laboratory tests. Indeed, for WC it reached a peak of 16% for a
288 loading equal to 180 g $CH_4/m^2/d$, and 12% at 95 and 125 g $CH_4/m^2/d$. For all the other loadings
289 and types of plants, the disparity remained less than 5%. For sake of presentation in Figure 4,
290 only the mean oxidation rates and MOEs for each loading increment were retained.

291

292 Figure 4: Methane oxidation efficiency and oxidation rates at different CH4 loadings under field
293 conditions. A - Field test 1; B - Field test 2

294

295 **3.3. Discussion about methane oxidation efficiencies**

296 A two-factor ANOVA of all the MOE values of all columns was performed to further assess the
297 level of influence of vegetation on methane oxidation. The analyses were split into two: the first
298 one for loadings up to 100 g $CH_4/m^2/d$; and the second for loadings greater than this value. For
299 both laboratory and field tests submitted to loadings lower than 100 g $CH_4/m^2/d$, the difference in
300 MOE values was not significant (p<0.05). This means that the type – or absence – of plant cover
301 does not influence the performance of a PMOB up to 100 g $CH_4/m^2/d$, which, as mentioned
302 before, is a much greater value than what can be expected as far as residual CH_4 emissions from
303 landfills are concerned.

304 For loadings greater than 100 g $CH_4/m^2/d$, the difference between the MOEs was statistically
305 significant ($F_{3,101} = 4.67$, $p < .01$ and $F_{3,31} = 4.82$, $p < .01$ respectively for laboratory and field

306 tests). As can be clearly observed in Figure 3 and Figure 4, the performance of the BS column
307 during the test was the highest. Hypothetically, soil diffusivity and macro-pore formation
308 associated with vegetation may have facilitated the escape of CH_4 to the atmosphere (Bohn et al.,
309 2010; Scheutz et al., 2009). However, the average deviation between the MOE of the vegetated
310 columns and the BS column was only 4%. This small difference could be attributed either to
311 vegetation or to incomplete air tightness of the columns (Section 2.2).

312 It is relevant to note that the increase in CH_4 loading during the laboratory and field tests resulted
313 in ever greater oxidation rates for all columns and the maximum oxidation capacity was probably
314 never achieved. A drop in efficiency was observed only in field test 3, when the air temperature
315 was below the freezing point. The other tests were stopped at relatively high loadings (270 and
316 180 g $CH_4/m^2/d$ for laboratory and field tests, respectively), and high CH_4 oxidation rates were
317 obtained.

318 All results considered, the differences between observed methane oxidation rates obtained for
319 each type of vegetation tested were not significant ($p < 0.05$). Robertson et al. (2000) compared
320 two perennial crops, alfalfa (Medicago sativa) and poplar (Populus sp.) trees in a field study.
321 They also observed no difference in the rates of CH_4 oxidation among any of the cropped sites.

322 Therefore, one can conclude that the 3 biosystems with plant covers showed MOE values
323 comparable to those obtained for the unplanted biosystem, both in the laboratory and in the field.
324 The findings above clearly diverge from what has been often reported in the technical literature
325 relating to the positive impact of vegetation on methane oxidation in landfill covers Table 2.

326 In a column study, Bohn (2010) compared the methane oxidation potential of one column with
327 compost material planted with a mixture of different types of grasses and herbages and three

columns with a mixture of clayey silt and greencut compost, unplanted, planted with Canadian goldenrod (*Solidago canadensis* L.) and planted with a mixture of leguminous plants. Submitted to a loading equal to 90.0 g $CH_4/m^2/d$, Bohn (2010) observed high methane oxidation in grass (90.0 g $CH_4/m^2/d$), S canadensis (63 g $CH_4/m^2/d$) and leguminous plants (37 g $CH_4/m^2/d$). Only the control column showed a negative oxidation rate, i.e. methane production or temporal methane storage due to a clogged surface.

According to Bohn (2010), vegetation improved the soil's diffusivity and physical properties, which led to a significant and positive effect of vegetation on methane oxidation. Moreover, all the studies in Table 2 found a positive effect of vegetation on methane oxidation regardless of soil material used. Several mechanisms were proposed to explain this positive effect, such as regulation of soil moisture through water uptake and evapotranspiration, and oxigenation of the soil by plant roots, which create macro-pores therefore enhancing gas diffusion. Another mechanism is related to root exudates, which serve as selective substrates and promote the growth of methanotrophs.

In comparison with the study herein, the studies presented in Table 2 used different soil materials to constitute the CH_4 oxidation biosystem. With the exception of the studies by Hilger et al. (2000) and Wang et al. (2008), who used sandy loam and a red soil, all the others cited in Table 2 used mature compost – mixed or not with soils. Composts are considered by several as the most suitable material for methane oxidation and plant growth (e.g. Huber-Humer and Lechner, 2003). In the present study, the biosystems tested were made up of sand dominated materials: fine sand, top soil and enriched top soil. In other words, the materials tested were not – in principle - as favorable as those used elsewhere to evaluate the impact of vegetation on methane oxidation in landfill covers.

Test duration was an important constraint of this experimental study. At the end of the testing period (5 months), plants were not fully grown and their root systems were not fully established. It can be presumed that the microbial community was not fully developed either. In the case of the studies in Table 2, tests lasted from 6 to 18 months. Test duration might therefore explain – at least in part - the differences in outcomes between this study and those in Table 2. However, according to Habekost et al. (2008), 18 months may not be long enough for the vegetation to fully develop thereby limiting its capacity to influence CH_4 oxidation.

Table 2: Comparison with results from other studies

3.4. Temperature and degree of water saturation monitoring

During each field and laboratory test, temperature and degree of water saturation (Sr) values were recorded periodically. Figure 5 shows the maximum and minimum temperature values within the columns, and the average temperatures during two arbitrary loading applications in field (95 and 125 g $CH_4/m^2/d$) and laboratory tests (70 and 225 g $CH_4/m^2/d$). Averages here were determined for each depth.

3.4.1. Temperature variations

In the beginning of the laboratory test, the temperature within the profiles remained quite similar to the room temperature (~ 19°C), which was finally the minimum value observed within the columns (T min in Figure 5a-d). Generally, the temperature within the biosystem remained

372 higher than the air temperature. When the CH_4 loading was increased, the temperature also
373 increased. This is in agreement with the observation made by Einola et al. (2007), Börjesson et
374 al. (2004) and Gebert et al. (2003), who observed that temperature increases within biosystems
375 were attributed to CH_4 oxidation activity. The typical profiles in Figure 5c and Figure 5e show
376 maximum variations of 5°C of the average temperature values for CH_4 loadings ranging from
377 70 g $CH_4/m^2/d$ to 225 g $CH_4/m^2/d$ in laboratory tests, and 13°C for loadings ranging from
378 95 g $CH_4/m^2/d$ to 125 g $CH_4/m^2/d$ in field tests at 10-cm depth.

379 Field test 3 (summer to fall) showed lower temperatures at 10 and 20 cm than field test 2 (spring
380 to summer) throughout the testing period. Despite the fact that near the end of field test 3 the air
381 temperature dropped below 0°C during the night, the average temperature within the soil
382 remained higher than 5°C. This suggests that there might still have been oxidation activity within
383 the columns (Figure 5f) (Einola et al., 2007).

384 However, for laboratory and field studies, there were no significant differences between
385 temperatures within the profiles, regardless of plant cover (or column). The temperature profiles
386 were generally quite similar for all columns (SD < 1°C). Furthermore, although the temperatures
387 were generally lower in the deepest layers (20 and 30 cm depth; Figure 5a-d) of the biosystems
388 tested, there were noticeable increases in temperature as CH_4 loadings were raised, indicating
389 that bacterial activity was also occurring at these depths.

390 The highest temperature increase is expected to occur at the oxidation front, which is where
391 oxidation activity is optimal within a biosystem. In the case of the laboratory and field tests
392 presented herein, the oxidation front was located between 0 and 10-cm from the surface. In
393 particular for laboratory test 3, the temperature at 10-cm depth (topsoil layer enriched with

394 compost; within the root zone) reached 33°C, which represented a thermal amplitude of 14°C
395 compared to the air temperature. The upper 7.5-cm of this 10-cm layer was the most oxygenated
396 and nutrient-rich part of the biosystems tested compared to the deepest layers (top soil and sand
397 layers). Jugnia et al. (2008) also observed, during a field test in an organic matter-rich layer of an
398 experimental landfill cover, an oxidation zone situated between 0 – 10-cm. Therefore, the
399 nutrient content as well as climatic conditions, O_2 supply, precipitation and physical property of
400 the soil cover affect the depth of the oxidation front (Berger, 2005; Humer and Lechner, 2001;
401 Jugnia et al., 2008).

402

403 Figure 5: Temperature profiles within the columns and air temperature in field and lab tests

404

405 3.4.2. Degree of water saturation

406 The degrees of water saturation Sr in Table 3 represent the average and standard deviations of all
407 recorded values for each test. Since the upper parts of the soil columns were probably the most
408 affected by precipitation and evapotranspiration, Sr variations were greater at a depth of 10 cm.
409 Under field conditions, the drier regions of the biosystems were located at a depth of 20 cm.
410 Moisturized gas from the bottom provided humidity to the soil at 30 cm depth. Consequently Sr
411 values were the highest where biogas was injected. Despite the fact that the raw biogas was very
412 wet, Sr values never reached 85%, which is the critical value above which there is pore
413 occlusion, leading to a substantial decrease in gas migration through a porous system (Aachib et
414 al., 2004; Cabral et al., 2004; Nagaraj et al., 2006). In the laboratory, the synthetic biogas was

415 also moisturized by bubbling through water-filled bottles before injection into the column;
416 however, Sr values also remained well below 85% at the bottom of the columns.

417 According to the data obtained, vegetation seems to have a significant effect on Sr values for all
418 biosystems ($p < 0.05$). Despite the fact that the columns were submitted to the same watering
419 conditions, the upper layer of the BS column was generally wetter than the vegetated columns,
420 for both laboratory and field tests. Although evapotranspiration was not monitored, it is probable
421 that it was the main cause for the lower Sr values within the root zone (first 10 cm). Indeed,
422 plants are important contributors to reduction of soil moisture by water uptake and transpiration
423 (Bohn et al., 2010; Reichenauer et al., 2011). Drying of the pores may lead to the formation of
424 macro pores that eventually facilitate gas migration. Accordingly, the greater efficiency of the
425 BS column at high loadings might be at least partly attributed to the absence of drier pores.

426 As observed for the MOEs, the variations of Sr values within the BS column were generally less
427 than those observed for the vegetated columns (Table 3). This confirmed the good
428 reproducibility of the adopted protocol and is in agreement with the observed significant effect of
429 the vegetation on Sr values.

430

431 Table 3: Average values of degree of saturation in % and standard deviation for lab and field
432 tests

433

434 ## 4. Limitations

435 One of the limitations of the study presented herein concerns the duration of the tests, which had
436 to be limited to approximately five months for each repetition. Some vegetated biotic systems,

may take several years to completely develop their root system. According to an experimental study by Habekost et al. (2008), the first effects of the aboveground plant community on the microbial community composition becomes detectable at least four years after establishing the grassland systems. According to Habekost et al. (2008), these differences would presumably increase with time. Considering this, it is probable (but not verified) that the tests in this study were terminated before full root growth; and, for that matter, the same might have happened in all the studies referred to in Table 2. Therefore, one cannot ascertain that different types of fully grown vegetation would not lead to greater differences in MOEs than those obtained herein. This study showed that there were no perceptible differences in MOE values for loadings lower than 100 g $CH_4/m^2/d$ and relatively minimal differences for loadings greater than 100 g $CH_4/m^2/d$.

A second limitation is that the present tests only compared 4 types of plant covers (including bare soil). A third limitation concerns the space available for the laboratory testing program, which required an explosion-proof chamber. The only such laboratory available could only hold 1 replicate of each of the 4 columns containing a different plant cover. As a consequence, the same tests had to be repeated 4 times over time, as explained above. This sequence of testing allowed a minimal statistical analysis of the results and revealed a significance level of 0.05.

Finally, the present study did not examine microbial activity and other bio-chemical processes involving plants exposed to biogas fluxes, such as the study of the influence of root exudates (over time or otherwise), evapotranspiration, etc.

5. Conclusion

This study evaluated whether the use of different types of common plants, including a N-fixing plant (White clover; WC), a non N-fixing plant (Timothy grass; TG) and a mixture of both (MIX), would affect CH_4 oxidation within passive biosystems.

An important conclusion – and contribution - from this study was the observation that high oxidation rates were obtained regardless of plant cover. In fact, up to a loading equal to 100 g $CH_4/m^2/d$, the type of plant cover did not influence performance, herein expressed by the methane oxidation efficiency (MOE). The MOEs in the laboratory and field columns remained greater than 95%.

Until the highest CH_4 loading was applied, the oxidation rate increased following increases in CH_4 loading. The continuous increase in oxidation rates suggests that the maximum oxidation capacity of the biosystems tested may have never been fully attained. The oxidation rates obtained in the laboratory for the high end loadings varied between 191 and 253 g $CH_4/m^2/d$ (MOEs = 71% – 94%). In the field, these oxidation rates were 179 and 105 g $CH_4/m^2/d$ (MOEs = 99% and 84%, respectively).

For higher loadings (270 and 180 g $CH_4/m^2/d$ for laboratory and field tests, respectively), the plant cover that had the least effect on MOEs and oxidation rates was the MIX column in the laboratory, whereas the WC column was the least effective in the field. MOEs in the field may also be affected by climatic conditions.

Another noteworthy result of the present study is that unplanted biosystems achieved as high (if not higher) MOEs as planted biosystems. In other words, for the short-term test results presented,

vegetation may not necessarily be a key factor in biosystem performance. Nevertheless, despite the important database generated, this study has its limitations; accordingly, one cannot generalize the results obtained to all other types of biosystems and plants. In fact, for every case, one must take into account several other parameters and – possibly – phenomena, such as climatic conditions, physical characteristics of the cover soil (texture, compaction etc.) plant species, influence of root exudates, plant growth stage and plant maturity, etc.

The results also indicated a significant effect of vegetation on the values of degree of water saturation (Sr), most probably due to water uptake by the plant root system. There was no noticeable effect of vegetation on soil temperature. As expected, temperature was affected by the biotic oxidation activity occurring within the biosystem. The effects were greater with increasing CH_4 loadings.

Acknowledgements

This study received financial support from the Natural Science and Engineering Research Council of Canada (NSERC) and Waste Management (WM Quebec Inc.), under the collaborative research and development grant # CRD 379885-08 and from the Consortium de recherche et innovations en bioprocédés industriels du Québec (CRIBIQ). The invaluable help of Jean-Guy Lemelin, technician, in setting up the laboratory and field cells must also be acknowledged.

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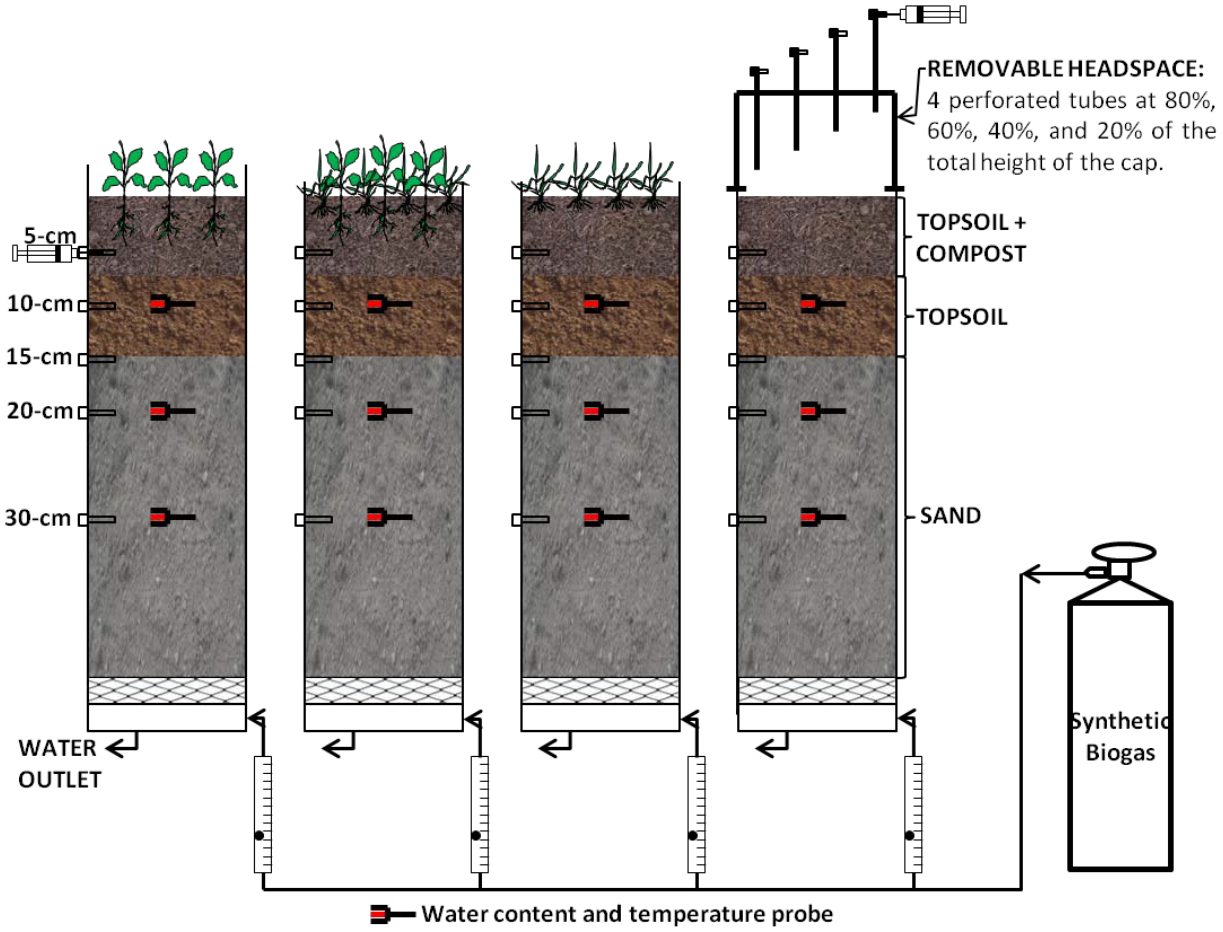

Figure 1: Experimental design of laboratory columns

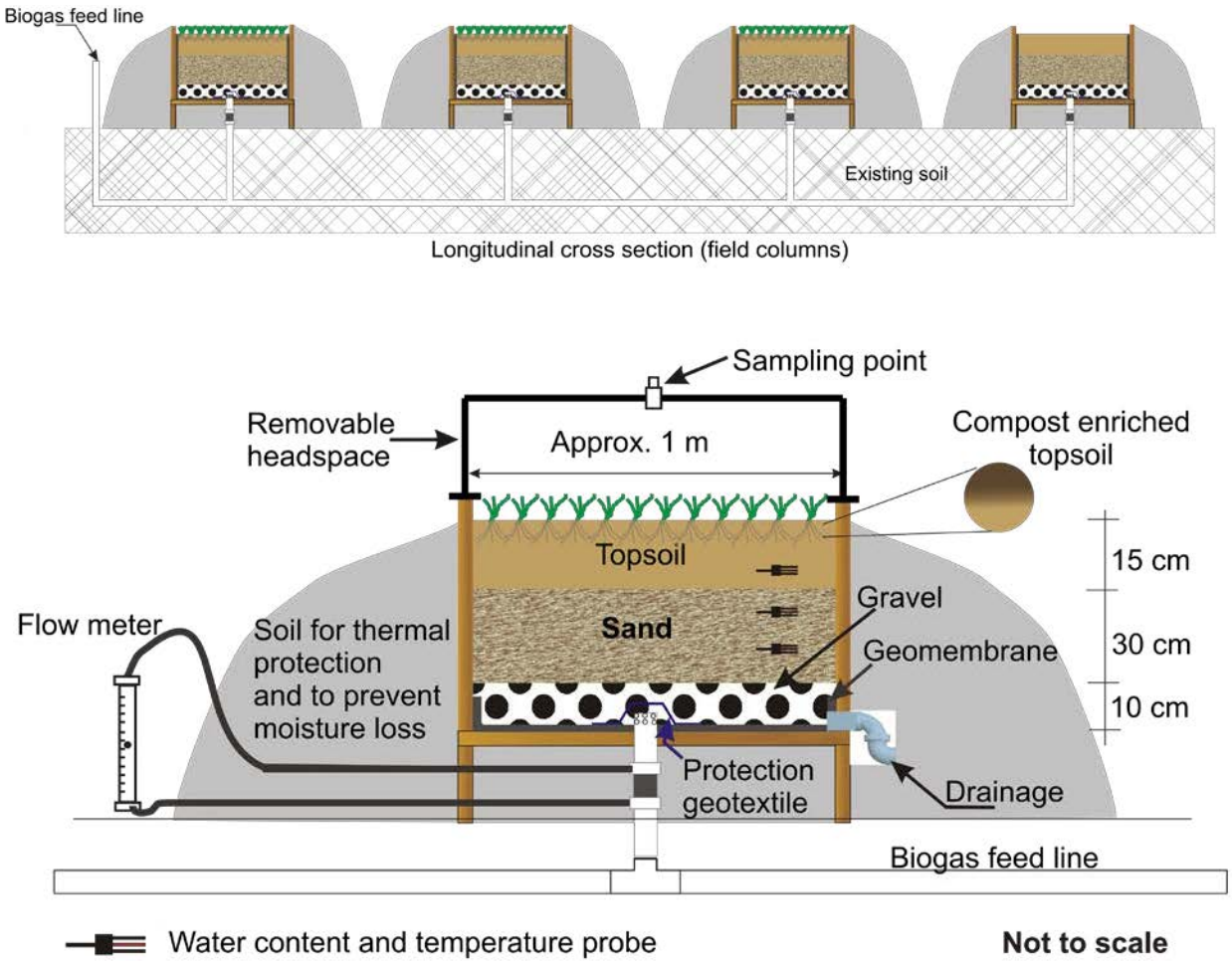

Figure 2: Experimental design of field columns

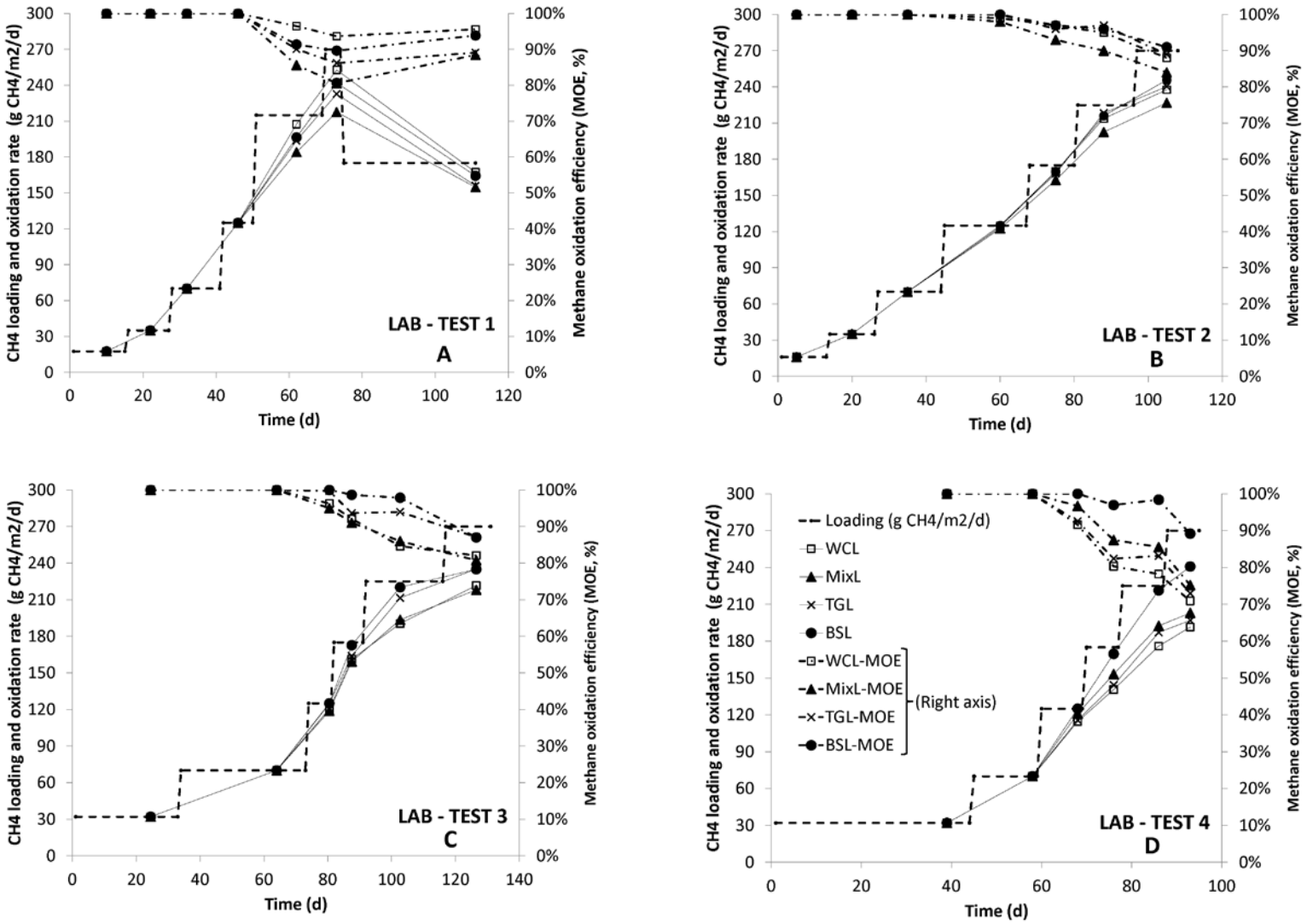

Figure 3: Methane oxidation efficiency and oxidation rates at different CH_4 loadings under laboratory conditions. A - Lab test 1; B - Lab test 2; C - Lab test 3; D - Lab test 4

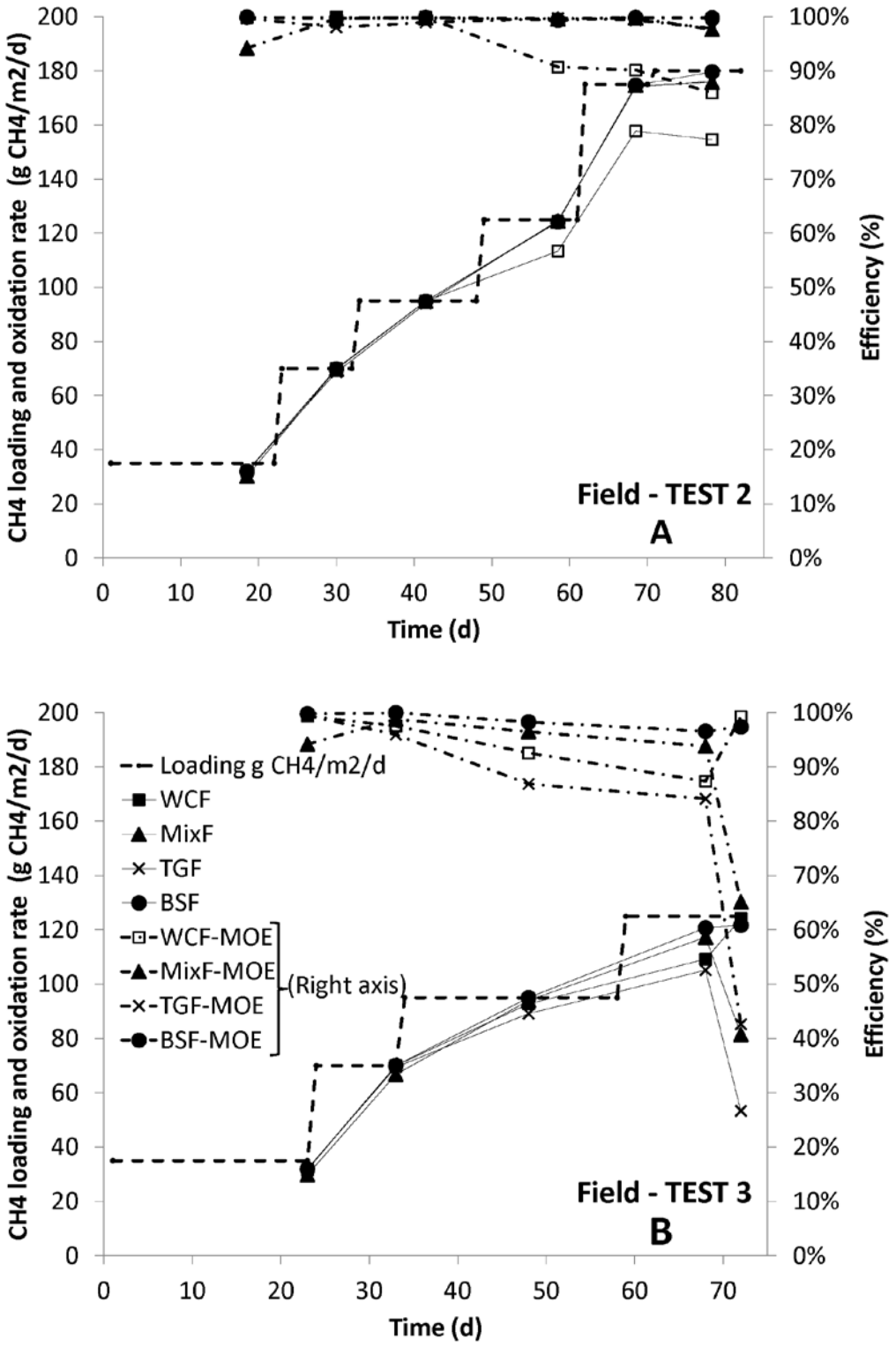

Figure 4: Methane oxidation efficiency and oxidation rates at different CH4 loadings under field conditions. A - Field test 1; B - Field test 2

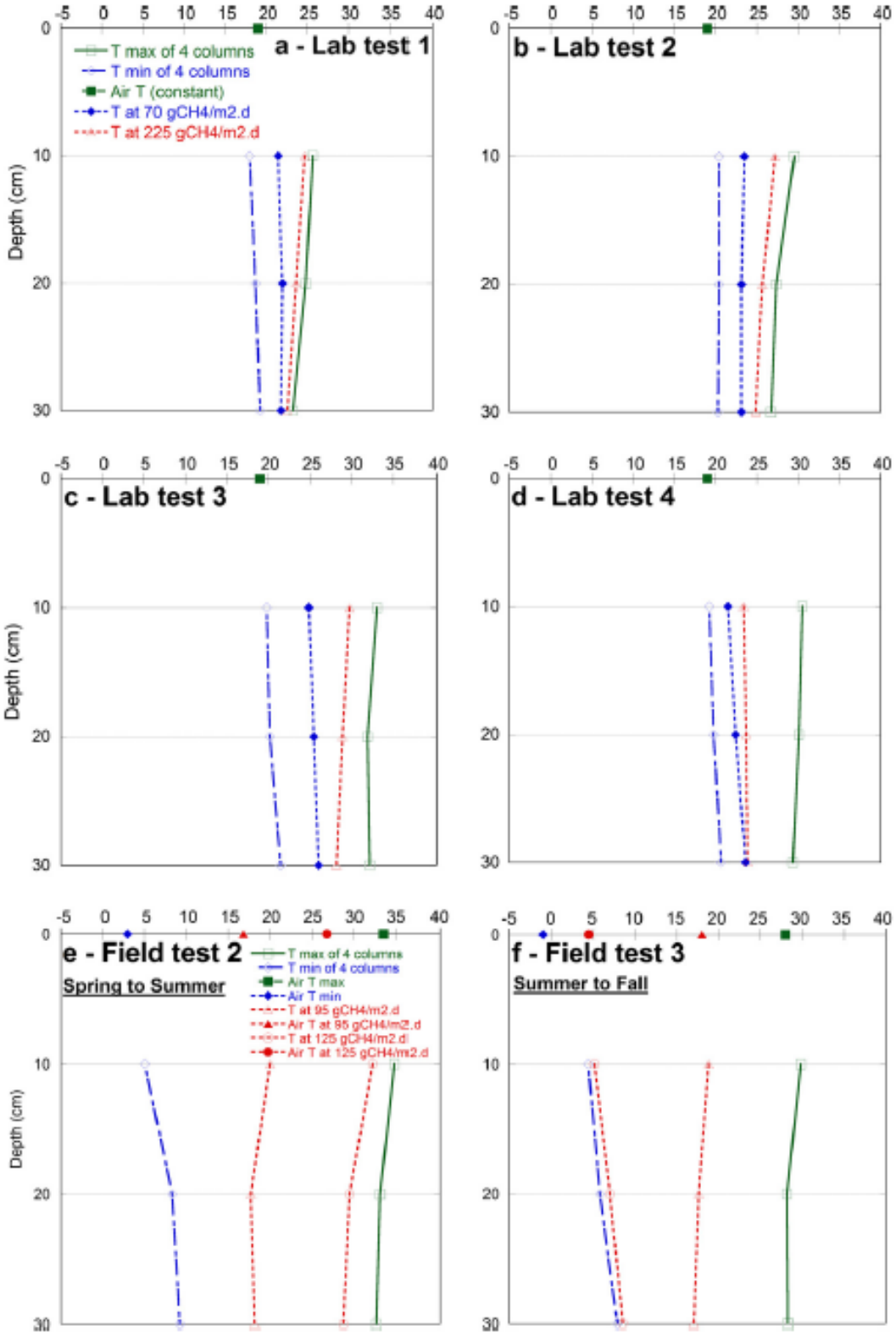

Fig. 5. Temperature profiles within the columns and air temperature in field and lab tests.

Figure 5: Temperature profiles within the columns and air temperature in field and lab tests