Does Vegetation Affect the Methane Oxidation Efficiency of Passive Biosystems?

Éliane M. Ndanga, Robert L. Bradley and Alexandre R. Cabral,.*

a Geoenvironmental Group, Department of Civil Engineering, University of Sherbrooke, Sherbrooke, Quebec, Canada J1K 2R1.
b Dept. of Biology, University of Sherbrooke, Sherbrooke, Quebec, Canada J1K 2R1.

*Corresponding author: Tel.: +1 819 821-7906. Postal address: 2500, boul. de l’Université, Sherbrooke, Quebec, Canada J1K 2R1.

E-mail addresses: alexandre.cabral@usherbrooke.ca (A. R. Cabral); e.ndanga@usherbrooke.ca (É. M. Ndanga); Robert.Bradley@usherbrooke.ca (R. L. Bradley).

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 (CH₄) is the main greenhouse gas emitted by landfills and represents 18% of the global anthropogenic CH₄ emissions (Bogner et al., 2007). Passive methane oxidation biosystems (PMOBs) are considered one of the most cost-effective technologies for mitigation of CH₄ 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 CH₄ 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 CH₄ oxidation efficiency within engineered biosystems tested on a landfill and in the laboratory.

Documentation on CH₄ 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 CH₄ transport through the root system. Indeed, transport through vascular plants has been identified as one of the main pathways of CH₄ 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 O₂ from the atmosphere to the rhizosphere through the arechnema 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 CH₄ 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 CH₄ oxidation in soils. Popp et al. (2000) reported on the other hand that there were no significant differences between CH₄ 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 CH₄ oxidation (Bohn et al., 2010; Hilger et al., 2000; Reichenaier 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 CH₄ oxidation include the potential for plant roots to create preferential channels for CH₄ emissions, and their competition for O₂ due to root respiration (Wang et al., 2008). Plants debris may also lead to O₂
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.
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/m³. The 0.075-m layers of unenriched and enriched topsoil were compacted at a density of 1200 Kg/m³. 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
nutrients, especially nitrogen, which is often the major limiting nutrient for Timothy growth. However, its competition for N is low at the beginning of its growth.

For the experiments, columns were seeded with Timothy grass (TG column), White clover (WC column) and a mixture of 67% Timothy grass and 33% White clover (MIX column). Column 4 was the control column and was therefore not seeded (bare soil, BS column). Based on preliminary seeding tests, the seeding density for each column was 6g/m².

2.2.2. Irrigation

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

2.2.3. Biogas loading

After the columns were filled with soil, synthetic biogas (50% CH₄/50% CO₂, v/v) was applied 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 CH₄/m²/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 CH₄/m²/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 CH₄ surface emissions, 110 L and 300 L PVC caps were constructed respectively for laboratory and field columns, and were installed only when CH₄ 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 CH₄ 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:

\[
MOE = \frac{Flux_{in} - Flux_{out}}{Flux_{in}} \times 100
\]  \hspace{1cm} (1)

where MOE is expressed as the percentage of CH$_4$ loading oxidized, Flux$_{in}$ and 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 CH₄ 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 CH₄/m²/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 CH₄/m²/d. During field test 3, the MOEs were greater than 95% for all columns up to a loading equal to 95 g CH₄/m²/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 CH₄/m²/d). Probably due to decreasing air temperatures (as fall approached), MOEs in field test 2 were generally greater than MOEs in field test 3.
Repeatability of field measurements was verified by performing at least 2 MOE measurements for each loading during the field tests. In this case, the disparity in MOE values was greater than the disparity obtained during the laboratory tests. Indeed, for WC it reached a peak of 16% for a loading equal to 180 g CH₄/m²/d, and 12% at 95 and 125 g CH₄/m²/d. For all the other loadings and types of plants, the disparity remained less than 5%. For sake of presentation in Figure 4, only the mean oxidation rates and MOEs for each loading increment were retained.

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

3.3. Discussion about methane oxidation efficiencies

A two-factor ANOVA of all the MOE values of all columns was performed to further assess the level of influence of vegetation on methane oxidation. The analyses were split into two: the first one for loadings up to 100 g CH₄/m²/d; and the second for loadings greater than this value. For both laboratory and field tests submitted to loadings lower than 100 g CH₄/m²/d, the difference in MOE values was not significant ($p<0.05$). This means that the type – or absence – of plant cover does not influence the performance of a PMOB up to 100 g CH₄/m²/d, which, as mentioned before, is a much greater value than what can be expected as far as residual CH₄ emissions from landfills are concerned.

For loadings greater than 100 g CH₄/m²/d, the difference between the MOEs was statistically significant ($F_{3,101} = 4.67, p < .01$ and $F_{3,31} = 4.82, p < .01$ respectively for laboratory and field
As can be clearly observed in Figure 3 and Figure 4, the performance of the BS column during the test was the highest. Hypothetically, soil diffusivity and macro-pore formation associated with vegetation may have facilitated the escape of CH₄ to the atmosphere (Bohn et al., 2010; Scheutz et al., 2009). However, the average deviation between the MOE of the vegetated columns and the BS column was only 4%. This small difference could be attributed either to vegetation or to incomplete air tightness of the columns (Section 2.2).

It is relevant to note that the increase in CH₄ loading during the laboratory and field tests resulted in ever greater oxidation rates for all columns and the maximum oxidation capacity was probably never achieved. A drop in efficiency was observed only in field test 3, when the air temperature was below the freezing point. The other tests were stopped at relatively high loadings (270 and 180 g CH₄/m²/d for laboratory and field tests, respectively), and high CH₄ oxidation rates were obtained.

All results considered, the differences between observed methane oxidation rates obtained for each type of vegetation tested were not significant ($p < 0.05$). Robertson et al. (2000) compared two perennial crops, alfalfa (Medicago sativa) and poplar (Populus sp.) trees in a field study. They also observed no difference in the rates of CH₄ oxidation among any of the cropped sites. Therefore, one can conclude that the 3 biosystems with plant covers showed MOE values comparable to those obtained for the unplanted biosystem, both in the laboratory and in the field. The findings above clearly diverge from what has been often reported in the technical literature relating to the positive impact of vegetation on methane oxidation in landfill covers Table 2.

In a column study, Bohn (2010) compared the methane oxidation potential of one column with 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 CH₄/m²/d, Bohn (2010) observed high methane oxidation in grass
(90.0 g CH₄/m²/d), S canadensis (63 g CH₄/m²/d) and leguminous plants (37 g CH₄/m²/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 oxygenation 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 CH₄ 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 CH₄ 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 CH₄/m²/d) and laboratory tests (70 and 225 g CH₄/m²/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
higher than the air temperature. When the CH$_4$ loading was increased, the temperature also increased. This is in agreement with the observation made by Einola et al. (2007), Börjesson et al. (2004) and Gebert et al. (2003), who observed that temperature increases within biosystems were attributed to CH$_4$ oxidation activity. The typical profiles in Figure 5c and Figure 5e show maximum variations of 5°C of the average temperature values for CH$_4$ loadings ranging from 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 95 g CH$_4$/m$^2$/d to 125 g CH$_4$/m$^2$/d in field tests at 10-cm depth.

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

However, for laboratory and field studies, there were no significant differences between temperatures within the profiles, regardless of plant cover (or column). The temperature profiles were generally quite similar for all columns (SD < 1°C). Furthermore, although the temperatures were generally lower in the deepest layers (20 and 30 cm depth; Figure 5a-d) of the biosystems tested, there were noticeable increases in temperature as CH$_4$ loadings were raised, indicating that bacterial activity was also occurring at these depths.

The highest temperature increase is expected to occur at the oxidation front, which is where oxidation activity is optimal within a biosystem. In the case of the laboratory and field tests presented herein, the oxidation front was located between 0 and 10-cm from the surface. In particular for laboratory test 3, the temperature at 10-cm depth (topsoil layer enriched with
compost; within the root zone) reached 33°C, which represented a thermal amplitude of 14°C compared to the air temperature. The upper 7.5-cm of this 10-cm layer was the most oxygenated and nutrient-rich part of the biosystems tested compared to the deepest layers (top soil and sand layers). Jugnia et al. (2008) also observed, during a field test in an organic matter-rich layer of an experimental landfill cover, an oxidation zone situated between 0 – 10-cm. Therefore, the nutrient content as well as climatic conditions, O₂ supply, precipitation and physical property of the soil cover affect the depth of the oxidation front (Berger, 2005; Humer and Lechner, 2001; Jugnia et al., 2008).

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

3.4.2. Degree of water saturation

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

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

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

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

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### 4. Limitations

One of the limitations of the study presented herein concerns the duration of the tests, which had 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 CH₄/m²/d and relatively minimal differences for loadings greater than 100 g CH₄/m²/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
CH₄ loadings.

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REMovable HEADSPACE: 4 perforated tubes at 80%, 60%, 40%, and 20% of the total height of the cap.
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