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ET Covers: Construction & Tree Development Inside & Outside of Lysimeters

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ABSTRACT: Two evapotranspiration covers pan lysimeters were constructed side by side to two unlined cover test sections in 2004 at the Leon County Solid Waste Management Facility in Tallahassee, Florida. The unlined test sections were constructed in the same manner as the pan lysimeters, but without at a pan, i.e., the soil profile in the unlined test sections was in contact with landfill gas. One objective of this study was to contrast tree growth, soil temperature, and soil water storage inside and outside the pan lysimeter. This paper summarizes the construction of the lysimeters and unlined test sections compares tree development, soil water storage, and temperature inside and outside the lysimeters.

Analysis of variance showed no significant difference between eucalyptus trees inside the lysimeter to those outside. Cottonwood heights were significantly different during the first measurement but not significantly different during the next two measurements. Soil temperature inside the lysimeter was significantly lower than outside the lysimeter. Soil water storage inside the lysimeter was significantly higher than outside. The difference in water storage and temperature did not lead to difference in vegetation growth.

INTRODUCTION

Most field studies use lysimeters to assess performance of alternative landfill covers. Lysimeters provide an opportunity to directly measure percolation rate from alternative covers. Percolation rates can be measured with a precision of 0.5 mm/yr or better using lysimeters (Gee & Hillel, 1988; Benson et al.; 1994; Albright et al., 2004; Ward & Gee, 1997; Benson et al.; 2001). One of the disadvantages of lysimeters is the presence of an artificial no flow boundary induced by the lysimeter at the base of the profile which prevents upward and downward flow of vapor and liquid across the base of the lysimeter. All water that migrates downward to the base of the profile is collected and routed out of the system. Consequently, the collected water as well as the moisture under the lysimeter can never move upward as a result of natural upward gradients induced by evapotranspiration (Benson et al., 2001). Lysimeter and associated monitoring equipment installation disturb the soils inside and outside lysimeters. This disturbance is thought to affect the percolation rate through the soil cover and, consequently, affect the precision with which percolation rate is measured (Liu, 2004). Despite this, few studies have been conducted to assess the effect of the bottom boundary on water flow and solute transport in the lysimeters (Flury et al., 1999; Abdou & Flury, 2004). The effects of the lysimeter lower boundary on the temperature, water content and vegetation is not well known. This paper addresses the effect of the lysimeter lower boundary on the growth of trees, soil temperature and soil water storage. Water balance results are presented in other publications.

LYSIMETERS

Lysimeters are devices used to measure percolation of water infiltrating through soils. Lysimeters are widely used to study water flow and solute transport in soils (e.g. Bergstrom & Jarvis, 1993; Putz et al.., 1998). Lysimeter studies are considered to be an intermediate approach between field studies and small scale laboratory experiments. Because lysimeters are exposed to the same environmental conditions, they are more likely to mimic natural field conditions than laboratory studies (Abdou & Flury, 2004). Lysimeters consists of a base pan with or without sidewalls. The pan acts as a collector of percolation. The pans of most lysimeters used to monitor landfill cover sections are rectangular. The depth of a lysimeter is a critical design parameter and varies with the intended purposes of the tests. Because of the critical role that plants play in removing water from landfill cover, the depth, distribution and density of plant roots have to be taken into account in determining depth of a lysimeter in a landfill cover study. The depth should permit the development of normal rooting density and rooting depth and provide similar available water profiles to the field profile (Van Bavel et al., 1961). The areal extent of lysimeters depends on the spatial variability in the properties of cover soils and vegetation. The length and width are usually 5 times larger than depth to ensure that preferential flow processes (e.g., rapid flow in such features as cracks, fissures, root channels, and worm holes) are captured in the test and that the construction process would mimic full scale conditions (Bews et al., 1999; Benson et al., 2001).

MATERIALS AND METHODS

Construction of the Lysimeters and Unlined Test Sections

The schematic diagram of the ET cap lysimeters is shown on Fig. 1. The 7 m x 14 m lysimeter consists of a "bath tub" lined with geomembrane and geocomposite. At the down slope, a drainage sump was installed and connected to a drainage monitoring system. A geocomposite drainage layer followed by a thin gravel layer was placed on top of geomembrane in order to collect the percolating water from the cap soil and rapidly transmit to the sump area. This layer also acts as a cushion layer to protect the bottom geomembrane during soil placement. Root barrier (Biobarrier II, Reemay, Inc.) was placed on top of the gravel layer. The root barrier is intended to prevent the roots from reaching the deep drainage collection system. The alternative cap was then placed in three lifts of soils. A thin layer of compost was also added at each lift of soil to improve fertility to aid growth of trees and grasses and to improve the water storage capacity of the soil.. The unlined test sections were constructed to the same dimensions as the lysimeters, except that in the unlined test sections, the soil profile is in direct contact with landfill gas. The unlined test section consisted of a thin gravel layer placed on top of the existing interim cover. Several 8 inches wide holes filled with gravel were drilled through the interim cover (into the waste) to allow direct movement of landfill gas to the gravel layer below the cover.

Vegetation

Two species of trees were planted in the ET cover lysimeters. Eucalyptus trees were planted on one of the lysimeters and cottonwood trees were planted on the other. These species were used because they are native to the study area and their ability to remove water from the soil. Trees were also planted on the buffer area between the test pads to reduce the edge effects. Trees were planted in May 2004 as small containerized plants (300 mm on average). Tree survival during planting was kept to 100% by removing all dead cuttings and replacing with fresh tree cuttings. Grasses were seeded on both ET covers. Tree heights were measured in August 2004, December 2005, and January 2007. Tree height and diameter at breast height (DBH) were measured inside the lysimeter and inside the unlined test sections. The sample size used in this study included 35 and 30 cottonwood trees in unlined test section and lysimeter respectively. The number of eucalyptus trees measured was 36 for unlined test section and 38 for lysimeter.

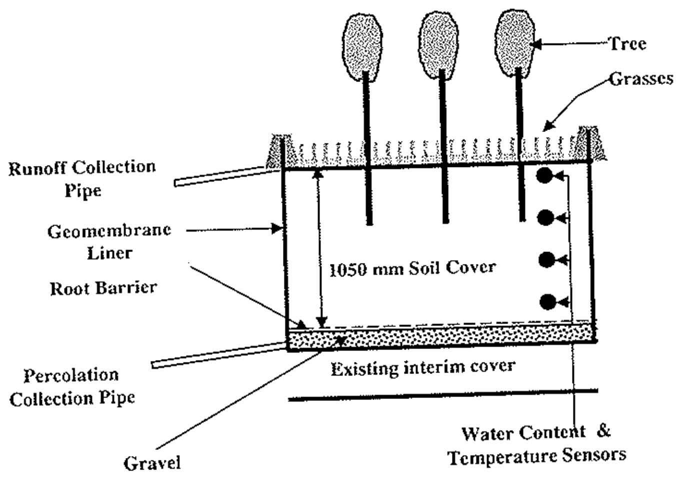

Fig. 1. Schematic of ET cap lysimeter

Water Content and Temperature Sensors

CS616 water content reflectometers (WCR) and CR 23X datalogger were used to record soil moisture at various depths for both the ET cover inside and outside the lysimeters. The CS616 probes are used to measure the probe output periods which were converted to volumetric water content using calibrations equations developed in the laboratory. The probes were installed in two nests at three locations along the center line of the lysimeter and unlined test sections. Each nest contains four probes alligned horizontally as shown on figure 1. Soil water storage was then computed by integrating the volumetric soil water content measured with the probes over the representative volumes of the cover profiles. The volumetric water content recorded by each sensor was multiplied to the thickness of the soil where the sensor is placed. The water storages in each soil layer were then added to obtain the water storage of the entire cover profile.

Thermocouples were used to measure the soil temperature at various depths of the covers. Temperature sensors were co-located with water content sensors at each nest. These sensors were also connected to the CR 23X Campbell Scientific datalogger. Water content and soil temperature data were recorded in the datalogger every two hours for the duration of three years. Soil water storage and soil temperature in the lysimeters were then compared with that in the unlined test sections. Analysis of variance was also carried out to assess the significance of the difference in water storage and soil temperature in the lysimeters as compared to that in the unlined test section.

RESULTS

Tree Growth

Eucalyptus trees grew to an average height of 830 mm (lysimeter) and 940 mm (unlined section) in August 2004 and to 5230 mm (lysimeter) and 5490 mm (unlined section) in December 2005 (Table 1). The eucalyptus trees further grew to an average height of 8040 mm (lysimeter) and 8820 (unlined section) in January 2007. ANOVA ($\alpha = 0.01$) of the tree height data and DBH (Table 3) data showed no significant difference between tree height and DBH inside and outside the lysimeter, suggesting that neither landfill gases nor the presence of the bottom pan impacted the eucalyptus tree growth rates.

The cottonwood trees grew to an average height of 1270 mm (lysimeter) and 1710 mm (unlined section) in August 2004 (Table 2). The difference is tree height was not significantly different outside and inside the lysimeter during this period. In December 2005, the cottonwood trees grew to an average height of 6350 mm (lysimeter) and 6310 mm (unlined section). In January 2007, the cottonwood trees reached an average height of 7110 mm (lysimeter) and was not significantly different than outside the lysimeter (8010 mm). The early growth of cottonwood trees was higher than that of the eucalyptus trees. Later on however, the eucalyptus trees grew to an average final height of 8420 mm whereas the cottonwood had a final average height of 7560 mm.

ANOVA of eucalyptus trees and cottonwood trees revealed no significant difference between DBH inside the lysimeter to that outside the lysimeter (December 2005 data). However, ANOVA of DBH measured on January 2007 showed a significant difference between trees inside the lysimeter to those outside the lysimeter for cottonwood trees. Additional monitoring is being performed to monitor the long term growth and tree development in all test sections.

Table 1. Eucalyptus Test Section Mean Tree Height Summary

Date	Note	Lysimeter		Unlined Section		P-Value
		Height (mm)	St Dev (mm)	Height (mm)	St Dev (mm)	
May-04	Planting	300	-	300	-	-
Aug-04	-	830	240	940	220	0.061
Dec-05	-	5230	1130	5490	1100	0.311
Jan-07	-	8040	1780	8820	790	0.019

Table 2. Cottonwood Test Section Mean Tree Height Summary

Date	Note	Lysimeter		Unlined Section		P-Value
		Height (mm)	St Dev (mm)	Height (mm)	St Dev (mm)	
May-2004	Planting	300	-	300	-	-
Aug-2004	-	1270	480	1710	360	-
Dec-2005	-	6350	630	6310	1450	0.877
Jan-2007	-	7110	1090	8010	1590	0.014

Table 3. Mean Diameter at Breast Height (DBH) of Trees

Date	Trees Type	Lysimeter		Unlined Section		P-Value
		DBH (mm)	Std Dev (mm)	DBH (mm)	Std Dev (mm)	
Dec-2005	Eucalyptus	14	4.6	16	5.1	0.082
	Cottonwood	14	3.4	17	5.6	0.061
Jan-2007	Eucalyptus	67	22.2	78	18.6	0.019
	Cottonwood	53	14.8	68	23.3	0.004

Soil Water Storage and Soil Temperature

Fig. 2 shows soil water storage inside and outside the lysimeter. Generally, the soil water storage in the lysimeter was slightly higher than the storage in the unlined test section. The average soil water storage in the lysimeter was 429 mm while that of the unlined test section was 408 mm and these values were significantly different ($P<0.001$). The higher soil water storage in the lysimeter may be due to the presence of the geocomposite at the bottom boundary. The presence of geocomposite may induce capillary effects and increase the water content right above it. The soil temperature inside the lysimeter was slightly lower than soil temperature in the unlined section (Fig. 3). The decreased temperature inside the lysimeter might be caused by the fact that the lysimeter act as a container for the soil with the liner acting as a thermal separation layer between the outside and the inside of the lysimeter. Analysis of variance (Table 4) indicates that there is a significant difference between the soil temperature in the lysimeters and in the unlined test sections.

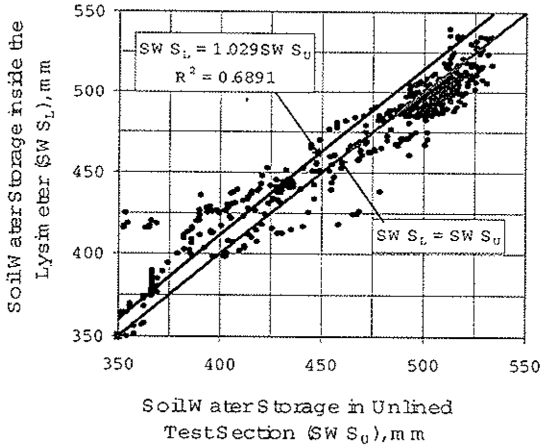

Fig. 2. Comparison of soil water storage inside and outside the lysimeter

Table 4. Soil Temperature in the Lysimeter and Unlined Section

Trees	Depth (mm)	Lysimeter		Unlined Test Section		P-Value
		Soil Temp. (^oC)	St Dev (^oC)	Soil Temp. (^oC)	St Dev (^oC)	
Eucalyptus	75	22.14	5.92	23.21	6.30	<0.01
	950	24.91	4.36	25.48	4.55	<0.01
Cottonwood	150	22.93	6.14	26.17	5.61	<0.01
	750	26.19	4.89	27.20	5.08	<0.01

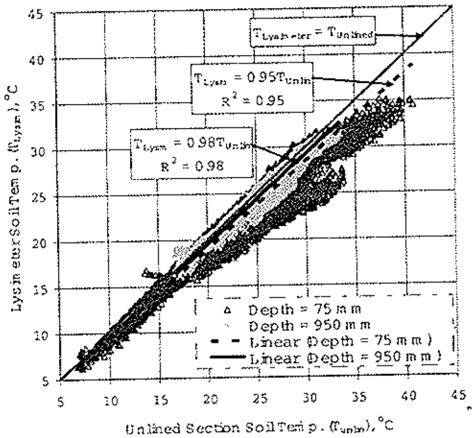

Fig. 3. Soil temperature inside and outside the eucalyptus trees lysimeter

SUMMARY AND CONCLUSIONS

Two ET cover lysimeters and two ET unlined test section were constructed in Tallahassee, Florida to assess the effect of bottom boundary on the performance of lysimeters. Assessment of the effect of the bottom boundary on the performance is achieved by comparing water storage, soil temperature, and trees growth in lysimeters to those measured in unlined test sections. Generally, the average heights of trees inside the lysimeters were slightly less that those outside the lysimeters. The diameters at breast height (DBH) inside the lysimeters were also smaller than those of the trees outside the lysimeters. Analysis of variance of tree growth inside and outside lysimeters, however, indicated that there is no significant difference in tree height for eucalyptus trees for all three measurement events. The growth rate of eucalyptus trees inside the lysimeter also showed no significant difference to that of trees outside the lysimeter. ANOVA of both eucalyptus trees and cottonwood trees revealed no significant difference between DBH inside the lysimeter to that outside the lysimeter (December 2005 data). However, ANOVA of DBH measured on January 2007 showed a significant difference between trees inside the lysimeter to those outside the lysimeter for cottonwood trees. Additional monitoring is being performed to monitor the long term growth and tree development in all test sections.

The soil water storage in the lysimeter is slightly higher than the storage in the unlined test section. The higher soil water storage in the lysimeter may be due to the presence of the geocomposite at the bottom boundary. However, ANOVA comparison of the soil water storage inside and outside the lysimeter showed no significant difference between them. The soil temperature inside the lysimeter seems to be slightly lower than the soil temperature in the unlined test section. ANOVA comparison of the soil temperature inside and outside the lysimeter also showed that there is a significant difference temperature inside and outside the lysimeter.

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ESTIMATING METHANE EMISSION AND OXIDATION FROM EARTHEN LANDFILL COVERS

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ABSTRACT: Measuring methane emission and oxidation through landfill covers has been well studied. However, numerical methods to estimate methane emission and oxidation are very limited. A simulation model was developed that combined water and heat flow model and a gas transport and oxidation model. The gas transport and oxidation model is able to use dynamic parameters associated with water content and temperature and incorporate into dynamic methanotrophic activity. Four sites were selected to showcase how emissions and oxidation can be estimated knowing cover design, management practices, and climatic conditions. Simulations were performed for scenarios with and without an active gas collection system. Different simulations were performed with and without organic amendments to the soil cover. Thirty-two simulations were conducted under different locations, climate conditions, bottom pressure boundaries, and soil oxidation capacities.

Simulations showed that soil covers in subhumid areas can prevent high methane emission with blockage and decent oxidation capacity. In semiarid sites, higher emission was obtained due to the higher air filled void space of the soil. Oxidation capacities in semiarid sites are higher than those in subhumid sites since influxes of methane are higher in semiarid sites. High pressure underneath the cover caused higher emission in all sites. Even with active gas collection system (vacuum pressure), emissions were significant in semiarid climates. Soil oxidation is not only dependent on the potential methane oxidation capacity (Vmaxmax), but also depends on methane availability.

INTRODUCTION

The global annual input of methane to the atmosphere is estimated to be 535±125 Tg (IPCC, 1995), of which about half is considered to be both anthropogenic and originating from biospheric processes, particularly anaerobic bacterial fermentation. Decomposition of refuse in municipal landfills is believed to be one of the major components of this biogenic methane, but past estimates of the emissions from this source have varied greatly, from 9 to 70 Tg per year. More reliable estimates are clearly needed, but it appears that landfills are the largest anthropogenic source of atmospheric methane in the United States and European countries. Rates for both methane production and oxidation can exceed observed rates for other terrestrial ecosystems by large factors. Field flux measurements (net emissions) vary over 7 orders of magnitude, from less than 0.0004 to about 4,000 grams per square meter per day (Bogner et al., 1997). These net emissions, of course, are the result of methane production, oxidation, and gaseous transport processes in the cover soil. Hence, it is difficult to predict emission rates at sites with various cover types, climatic regimes, and management practices. Oxidation rates in these soils range up to over 100 g m^{-2} d^{-1}, and in some cases, the landfill can be a net sink for atmospheric methane oxidation. Emission data can be obtained by chamber, inert tracer, and micrometeorological methods.

Water content is a very important factor affecting CH_4 transport and oxidation in landfill cover soils. Boeckx et al. (1996) used a multiple linear regression analysis under different incubation conditions and concluded that water content has more influence on CH_4 oxidation than temperature. Christophersen et al. (2000) used statistical methods to analyze the effect of soil water content on CH_4 oxidation. They also concluded that water content can explain most of the variation observed in CH_4 emission data. Water plays three important roles. First, the optimum environment for CH_4 oxidizing bacteria (methanotrophy) is obtained at certain water content. Second, water content affects the penetration of oxygen (O_2) into the soils, which is the main reactor for CH_4 oxidation. As the water content increases in the soil, the O_2 diffusion into the soil is hindered. Thirdly, water content affects the air filled porosity of the soil and influences gas transport through the soil. As water fills the pores in the soil, it blocks the flow of gas upward. At the same time, the blocking of flow might lead to CH_4 emission due to the excess pressure built-up in the landfill (Boeckx et al., 1996).

Generally, CH_4 oxidation rate increases with increasing temperature (De Visscher and Van Cleemput, 2003). Low temperatures inhibit CH_4 oxidation (Whalen et al. 1990; Nozhevnikova et al., 1993; Borjesson and Svensson, 1997; Visvanathan et al., 1999). Borjesson and Svensson (1997) even reported that soil temperature is the controlling factor of CH_4 oxidation, and can explain 85% of the variation in measured CH_4 oxidation. Methanotrophic bacteria favor a certain range of temperatures. Czepiel et al. (1996) reported that oxidation rate increased as temperature increased to 36°C. They also reported that CH_4 oxidation essentially stopped when temperature reached 45°C. Humer and Lechner (2001) reported that CH_4 oxidation rate was 70-80% at 18°C. At a lower temperature of 4°C, little oxidation was observed. Borjesson and Svensson (1997) reported that the optimum temperatures for CH_4 oxidation were ~25 to 35°C.

This paper present a numerical model which combines water balance, heat transport models with a gas transport and oxidation model to estimate methane emission and oxidation from landfills with different climates. Four sites were selected to showcase how emissions and oxidation can be estimated knowing cover design, management practices, and climatic conditions. Simulations were performed for scenarios with and without an active gas collection system. Different simulations was performed with and without organic amendments to the soil cover.

MATERIALS AND METHODS

Four sites were selected to run the model for typical subhumid-warm weather at Florida (FL), subhumid-cold weather at Iowa (IA), semiarid-warm weather at California (CA), and semiarid-cold weather at Montana (MT). In the wet areas (FL and IA), the covers were built thicker, 135 cm and 165 cm, respectively, to limit percolation , while in the dry areas, the covers were build thinner of 120cm thick each. All the covers are well vegetated.

HYDRUS1D Modeling Description

The investigation of the volumetric water content and temperature profile of landfill cover on their performance involved simulations of water and heat flow in variably saturated soils using the computer program HYDRUS1D v3.0 (Simunek et al. 2005). The program numerically solves the Richards' equation for saturated–unsaturated water flow as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x} + \cos\alpha\right)\right] - S \qquad (1)$$

where θ is volumetric water content, h is pressure head [L], x are the spatial coordinates [L], t is time [T], S is the sink term $[L^3L^{-3}T^{-1}]$, α is the angle between the flow direction and the vertical axis (i.e., $\alpha = 0$ for vertical flow, 90 for horizontal flow, and $0 < \alpha < 90$ for inclined flow), The hydraulic properties K [m s^{-1}] were represented by the Mualem-van Genuchten function (Van Genuchten, 1980).

$$S_e = [1 + (ah)^n]^{(1/n-1)} \qquad (2)$$

$$K_r = K_s S_e^l [1 - (1 - S_e^{1/(1-1/n)})^{(1-1/n)}]^2 \qquad (3)$$

where Ks is saturated hydraulic conductivity, Kr is relative hydraulic conductivity. *l* is a hydraulic conductivity parameter. *a* is related to the air-entry value [m^{-1}], and n is a pore size distribution parameter. *Se* in Eq. 2 is expressed by Eq. 4

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (4)$$

where Θ_r is the residual water content [m^3 m^{-3}]. Θ_s is the saturated water content [m^3 m^{-3}]

S in Eq. 1 is a sink term to account for water uptake by plant roots and is defined as:

$$S(h) = \alpha(h) T_p / L_R \qquad (5)$$

where, $\alpha(h)$ is the plant water stress function, T_p is the potential transpiration rate[LT^{-1}], L_R the depth [L] of the root zone.

Heat transport through the cover was coupled to water transport and is described with a convection-dispersion equation of the form:

$$\frac{\partial C_p(\theta)T}{\partial t} = \frac{\partial}{\partial x}[\lambda(\theta)\frac{\partial T}{\partial x}] - C_w \frac{\partial qT}{\partial x} - C_w ST \qquad (6)$$

where $\lambda(\theta)$ is the coefficient of the apparent thermal conductivity of the soil [M m s^{-3} K^{-1}]. $C_p(\theta)$ and *Cw* is the volumetric heat capacities [M m^{-1}s^{-2} K^{-1}] of the porous medium and the liquid phase, respectively. q is Darcian fluid flux density [m s^{-1}]

Gas Transport Modeling

Volumetric water content and temperature were generated at each node each day by HYDRUS1D. The gas transport model used these dynamic results to simulate methane emission and oxidation at each day.

A continuity equation and a mass balance equation were used to describe the gas flow and reaction within the porous media.

$$\varepsilon \frac{dC_i}{dt} = -\frac{dJ_i}{dx} + r_i \qquad (7)$$

where ε is the air filled porosity [m$^{-3}_{gas}$ m$^{-3}_{soil}$], C_i, the molar gas concentration [mol m^{-3}], J_i is the flux of gas component *i* including the diffusive and advective flux (mol m^{-2} s^{-1}), r_i is the reaction rate of gas component *i* [mol kg$^{-1}_{dry\ soil}$ s^{-1}], and dt [s] and dx [m], are time and vertical distance coordinates.

The flux of the gas, J_i, has two components: diffusion and advection. Gas diffusion in porous media is governed by Fick's law and gas advection is governed by Darcy's law, the total flux can then be expressed as follows:

$$J_i = -D_{soil,i}\frac{dC_i}{dx} - \frac{k}{\mu}\frac{dP}{dx}C_i \qquad (8)$$

where the diffusion coefficient of gas component i, $D_{soil,i}$, in soil [m^2 s^{-1}]. k is the intrinsic permeability of the soil (m^2), μ is the gas mixture viscosity [N s m^{-2}] and P is the pressure [Pa].The pressure P is obtained by the ideal gas law:

$$P = \sum_{i=1}^{4} C_i RT \qquad (9)$$

where T is the absolute temperature (K) and R is universal gas constant [8.314 J K^{-1} mol^{-1}].

Methanotrophic Reaction

The reaction component of the gas transport equation was assumed to be the following (De Visscher and Van Cleemput 2003):

$$CH_4 + aO_2 \rightarrow bCO_2 \qquad (10)$$

where a, b are the stoichiometric factors for oxygen and carbon dioxide, and were assumed to be 1.5 and 0.5. This leads to the following reaction equation:

$$CH_4 + 1.5O_2 \rightarrow 0.5CO_2 + 0.5CH_2O + 1.5H_2O \qquad (11)$$

where CH_2O represents biomass. r_i in Eq. 7 is the reaction rate of methanotrophic bacteria, which is calculated by Michaelis-Menton kinetics from the incubation experiment.

$$r_{CH_4} = V_{\max}\frac{C_{CH_4}}{K_{m[CH_4]} + C_{CH_4}}\frac{C_{O_2}}{K_{m[O_2]} + C_{O_2}} \qquad (12)$$

where $V_{\max}$ is the maximum methane consumption rate [nmol s^{-1} kg$^{-1}_{dry\ soil}$] and K_m is the half saturation constants [mol m^{-3}]. The Combined model simulation scheme is shown a flow chart (Fig. 1).

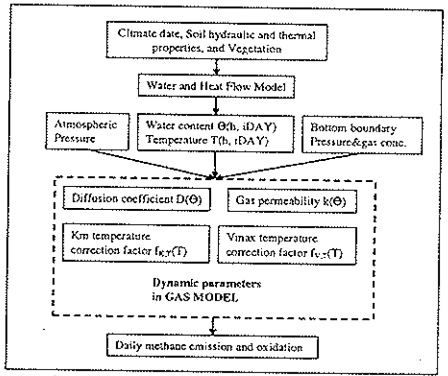

Fig. 1. Flow chart of model algorithm.

Boundary, Initial Conditions, and Input Assumptions

The gas composition at the surface node of the model was assumed to be the atmospheric gas compositions, which are 21.21% oxygen, 1.8 ppmv methane, 370 ppmv carbon dioxide and 78.75% nitrogen. For the bottom boundary, different constant pressures were used to describe the different situation of landfill pressure (as described below). Constant gas concentration boundary condition (60% methane and 40% carbon dioxide) was selected.

Climatic input data for FL site was obtained from a weatherstation build nearby the site. Other sites' historical data were obtained from regional climate centers. The data included daily precipitation, potential evapotranspiration (PET), Maximum temperature, minimum temperature, and average temperature. These climate data were used as a time-variable atmospheric boundary condition. The soil properties for HYDRUS1D were measured for IA, MT, and CA sites. The soil properties for the FL site were estimated based on soil classification. In order to minimize the influence of initial condition, a period of ten consecutive cycles of fourteen months period was modeled by HYDRUS1D code. At the end of this period, daily water content and temperature in each node were obtained for the input of gas transport and oxidation model. Thirty-two gas transport and oxidation simulations were conducted for different bottom pressure boundary condition and different soil oxidation capacity. Four kinds of pressure boundaries were used to represent different landfill conditions. (1) *High* pressure underneath the cover equal to constant 1.1 atm; (2) *Medium* pressure underneath the cover equal to constant 1.04 atm; (3) *Zero* pressure at bottom boundary equal to atmospheric pressure; (4) *Vacuum* pressure at the bottom boundary equal to -10 inches of water (2.49 kPa) as a typical vacuum pressure underneath cover when active landfill gas collection system is on. Two types of soil oxidation capacity were selected as: (1) High oxidation capacities as Vmaxmax=2000 nmol kg^{-1} s^{-1}; (2) low oxidation capacity as Vmaxmax=500 nmol kg^{-1} s^{-1}, where Vmaxmax is the maximum value that Vmax can be reached (De Visscher and Van Cleemput, 2003)

RESULTS AND DISCUSSION

Water Balance

Water balance results are shown in Table 1. The total water applied to the cover (precipitation) was divided into four parts: runoff, evaporation, transpiration, and percolation. For semiarid areas (CA and MT), the cumulative precipitation for the entire period was 503 and 357.9 cm, respectively. In these semiarid areas, the runoffs were zeros since the precipitation was low and no heavy density of rainfall event exist. The transpiration of MT site was only 140.5 cm compared to 217.9 of CA site since the vegetation grow season of MT is shorter than CA. Overall percolation ratio over precipitation for CA and MT were 5.78% and 4.36%. For the subhumid areas (FL and IA), the cumulative precipitation for the entire period was 1717.9cm and 977.1cm, respectively. The runoff of FL site was much higher than IA site since the rainfall was basically very dense in several events in FL. Transpiration and evaporation in FL was also higher than IA site, therefore the percentage of percolation over total precipitation for FL was 8.67%, which was lower than the IA site for 16.13%.

Table 1. HYDRUS1D modeling results.

Water balance (cm)	CA	FL	IA	MT
Precipitation	503	1717.9	977.1	357.9
Runoff	0	445.9	62.4	0
Evaporation	255.9	462.9	226.3	211.6
Transpiration	217.9	659.8	509.6	140.5
Percolation	29.1	149.3	157.7	15.6
Percentage of Percolation	5.78%	8.67%	16.13%	4.36%

Methane Emission and Oxidation Modeling

Fig. 2 shows 32 simulations with different pressure boundary condition and different Vmaxmax. Complete values are listed in Table 2. For semiarid sites (CA and MT), the overall emissions are higher than the wet sites (FL and IA), since there was more air filled void space for gas to migrate through the cover. Methane emission in MT site ranged from 2877.1~44904.1 g m-2 yr-1 and from 466~24152.6 g m-2 yr-1 in CA. However for the wet sites, the emission in FL was only 160.6~857.4 g m-2 yr-1 and 48.2~118 g m-2 yr-1 in IA. Lowest emissions were obtained when the bottom boundary is vacuum and with higher Vmaxmax for all sites. Highest emissions were obtained when the bottom boundary is high pressure (1.1 atm) and with low Vmaxmax.For each site, high Vmaxmax leads to low emission and low Vmaxmax leads to high emission. The differences of methane emission due to Vmaxmax of Dry sites are larger than wet sites due to the higher influx of dry site. At medium pressure, the differences of emissions between high Vmaxmax and low Vmaxmax were 4.3, 163.5, 3520.1, and 5617.6 corresponding to influx values of 199.9, 3806.3, 21209, and 32744 for IA, FL, CA, and MT, respectively. The reason for phenomena is that low influx in wet sites had no enough methane for the methanotrophic bacterial to reach its oxidation capacity. So choosing a high oxidation capacity soil can be an efficient way to mitigate methane emissions. however for low emission site such IA, high oxidation capacity soil didn't significant reduced the emission.

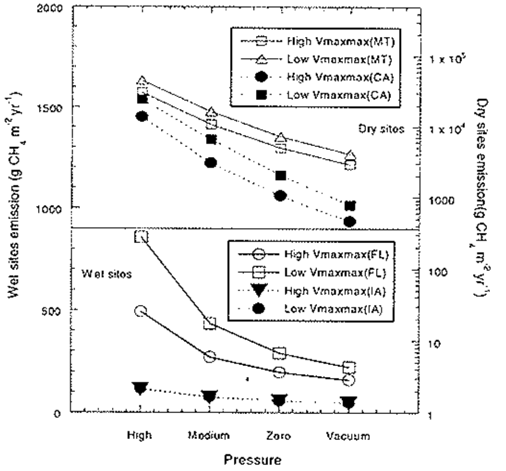

Fig. 2 Yearly cumulative emission simulations summary for all sites.

For each site, methane mass removed by oxidation increase with increasing of pressure. In FL site at low Vmaxmax, the mass removed is 2683.6, 2935.3, 3365.1, and 4098.1 g CH_4 m^{-2} yr^{-1} for vacuum, zero, medium, and high pressure, respectively.

Emissions from all sites increase with pressure increases. For FL site, the emissions of high pressure, medium pressure, zero pressure, and vacuum pressure were 857, 434.4, 290.9, and 221.9 g m^{-2} yr^{-1}, respectively (low Vmaxmax). This show even with active landfill gas collection system, there was still emission of methane into the atmosphere due to the diffusion of methane. In dry sites, this emissions can be as high as 785.5 and 4039 g m^{-2} yr^{-1} for CA and MT site, respectively (low Vmaxmax).

Table 2 summary of the yearly cumulative emission of all ET sites (g m^{-2})

	Pressure		IA	FL	CA	MT
High Vmaxmax	High	Influx	264.5	5173.4	42795.6	62726.3
		outflux	114.6	493.2	13724	30339
		mass removed	149.9	4680.2	29071.6	32387.3
		oxidation	56.67%	90.47%	67.93%	51.63%
	Medium	Influx	199.9	3806.3	21208.6	32744.4
		outflux	73.6	270.9	3014.5	10657
		mass removed	126.3	3535.4	18194.1	22087.4
		oxidation	63.18%	92.88%	85.79%	67.45%
	Zero	Influx	168.2	3230.6	15254.6	20954
		outflux	58.1	198	1056.8	4943.4
		mass removed	110.1	3032.6	14197.8	16010.6
		oxidation	65.46%	93.87%	93.07%	76.41%
	Vacuum	Influx	151.2	2909.4	10307.3	16412.2
		outflux	48.2	160.6	466	2877.1
		mass removed	103	2748.8	9841.3	13535.1
		oxidation	68.12%	94.48%	95.48%	82.47%
Low Vmaxmax	High	Influx	264	4955.5	42359	63566.5
		outflux	118	857.4	24152.6	44904.1
		mass removed	146	4098.1	18206.4	18662.4
		oxidation	55.30%	82.70%	42.98%	29.36%
	Medium	Influx	199.6	3799.5	21049	32277.8
		outflux	77.9	434.4	6534.6	16274.6
		mass removed	121.7	3365.1	14514.4	16003.2
		oxidation	60.97%	88.57%	68.96%	49.58%
	Zero	Influx	168	3226.2	15199.2	20759.5
		outflux	59.1	290.9	2030.8	7195
		mass removed	108.9	2935.3	13168.4	13564.5
		oxidation	64.82%	90.98%	86.64%	65.34%
	Vacuum	Influx	151	2905.5	10286	16300.4
		outflux	48.9	221.9	785.5	4039
		mass removed	102.1	2683.6	9500.5	12261.4
		oxidation	67.62%	92.36%	92.36%	75.22%

CONCLUSIONS

A model was developed to study how landfill final earthen cover's construction and climate conditions affect methane emission and oxidation from landfills. This numerical model combines the water and heat flow model (HYDRUS1D) and a gas transport and oxidation scheme. The gas transport and oxidation model is able to incorporate dynamic parameters associated with water content and temperature, such as, air filled porosity, diffusion coefficient, and gas permeability. A dynamic oxidation capacity parameter (Vmax) is also embedded in the gas transport scheme. Four sites were selected to showcase how emissions and oxidation can be estimated knowing cover design, management practices, and climatic conditions. Simulations were performed for scenarios with and without an active gas collection system. Different simulations was performed with and without organic amendments to the soil cover

Simulations showed that soil covers in subhumid areas can prevent high methane emission with blockage and decent oxidation capacity. In semiarid sites, higher emission was obtained due to the higher air filled void space of the soil. Oxidation capacities in semiarid sites are higher than those in subhumid sites since influxes of methane are higher in semiarid sites. High pressure underneath the cover caused higher emission in all sites. Even with active gas collection system (vacuum pressure), emissions were significant in semiarid climates. Soil oxidation is not only dependent on the potential methane oxidation capacity (Vmaxmax), but depends on methane availability. The simulations are however the results of a numerical analysis. A verification of the results of the predictions of the developed model should be performed.

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