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Modeling the effects of vegetation on methane oxidation and emissions through soil landfill final covers across different climates

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ABSTRACT

Plant roots are reported to enhance the aeration of soil by creating secondary macropores which improve the diffusion of oxygen into soil as well as the supply of methane to bacteria. Therefore, methane oxidation can be improved considerably by the soil structuring processes of vegetation, along with the increase of organic biomass in the soil associated with plant roots. This study consisted of using a numerical model that combines flow of water and heat with gas transport and oxidation in soils, to simulate methane emission and oxidation through simulated vegetated and non-vegetated landfill covers under different climatic conditions. Different simulations were performed using different methane loading flux (5–200 g m^{-2} d^{-1}) as the bottom boundary. The lowest modeled surface emissions were always obtained with vegetated soil covers for all simulated climates. The largest differences in simulated surface emissions between the vegetated and non-vegetated scenarios occur during the growing season. Higher average yearly percent oxidation was obtained in simulations with vegetated soil covers as compared to non-vegetated scenario. The modeled effects of vegetation on methane surface emissions and percent oxidation were attributed to two separate mechanisms: (1) increase in methane oxidation associated with the change of the physical properties of the upper vegetative layer and (2) increase in organic matter associated with vegetated soil layers. Finally, correlations between percent oxidation and methane loading into simulated vegetated and non-vegetated covers were proposed to allow decision makers to compare vegetated versus non-vegetated soil landfill covers. These results were obtained using a modeling study with several simplifying assumptions that do not capture the complexities of vegetated soils under field conditions.

1. Introduction and background

The microbiological process of oxidizing CH_4 to CO_2 by methanotrophs is called microbial CH_4 oxidation. Several previous studies on landfill CH_4 oxidation in the cover layer have demonstrated the ability of methane oxidation as a mechanism to reduce CH_4 emissions from landfill surfaces (Bogner et al., 1995; Börjesson and Svensson, 1997; Kjeldsen et al., 1997; Scheutz et al., 2003; Huber-Humer, 2004; Bogner and Spokas, 1993, to name few). However, the capacity of landfill cover soil to oxidize CH_4 depends on both the physical and the chemical properties of landfill cover materials such as soil type, moisture content, density, organic and nutrient content. Additionally, environmental conditions such as temperature and precipitation can also impact the performance of landfill cover soils to oxidize CH_4. Plant roots are also reported to enhance the aeration of soil by creating secondary macropores which improve the diffusion of oxygen into soil as well as the supply of methane to bacteria. Therefore, methane oxidation can be affected by the soil structuring processes of vegetation, along with the increase of organic biomass in the soil associated with plant roots.

In addition to agglomeration, isolation against high temperature variability, mechanical stabilization, and protection from erosion, vegetation has positive effects on methane oxidation in landfill covers. Vegetation growing on final landfill covers can improve the air capacity of less permeable soil materials through soil aggregation, formation of secondary macropores via spreading roots and transpiration of pore water within the limit of the available field capacity. The main objective of this study was to use a

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modeling approach similar to the one employed by Abichou et al. (2010, 2013) to compare methane oxidation in simulated vegetated and non-vegetated landfill final covers across climatic zones of the United States. The second objective of the study was to separate the increase in methane oxidation associated with the change of the physical properties of the vegetative soil layer from that caused by the increase of organic matter associated with vegetated soil layers.

1.1. Main factors affecting methane oxidation in landfill covers

1.1.1. Soil water content and temperature profile

Water content is a very important factor affecting CH_4 oxidation in landfill cover soils. Abichou et al. (2010) reported that little to no bacterial activity (very low oxidation rate) was occurring when the gravimetric water content was lower than 10%. Czepiel et al. (1996) and Boeckx et al. (1996) reported a significant drop in oxidation capacity at water contents lower than 5% and credited that to water stress. Abichou et al. (2010) showed that microbial activity seems to increase with increasing water content and reaches an upper limit or when the soil reaches a water content higher than 18–20%. These results are consistent with other literature data indicating a maximum oxidation rate when the water content is in the range of 10–20% (gravimetric) (Boeckx et al., 1996; Park et al. 2002; Schnell and King, 1996; Albanna and Fernandes, 2009). Bender and Conrad, (1995) reported optimal water content in the range of 20–35%.

Generally, CH_4 oxidation rates increase with rising temperature (De Visscher et al., 2001; Whalen et al., 1990; Nozhevnikova et al., 1993; Börjesson and Svensson, 1997; Visvanathan et al., 1999; Czepiel et al., 1996; Humer and Lechner, 2001; Boeckx et al., 1996; Nesbit, 1992; Spokas and Bogner, 2011; Albanna and Fernandes, 2009; Schnell and King, 1996; Borjesson et al., 2004; De Visscher and Van Cleemput, 2003; Dunfield et al., 1993; Christophersen et al., 2000; Abichou et al., 2010; Powelson et al., 2006). Czepiel et al. (1996) and Abichou et al. (2010) reported that oxidation rate increased as temperature increased to 36 °C and that CH_4 oxidation essentially stopped when temperature reached 45 °C. Börjesson and Svensson (1997) reported that the optimum temperatures for CH_4 oxidation were ~25–35 °C. Boeckx et al. (1996) reported that the optimal incubation temperatures for CH_4 oxidation were ~20–30 °C and decreased with increasing water content. Dunfield et al. (1993) measured optimum methane oxidation temperatures of ~20–25 °C.

1.1.2. Organic matter content and porosity

Generally, oxidation rates accelerate with increasing organic matter content in soils. The use of cover soils with higher organic matter contents has been reported to be an efficient way to mitigate CH_4 emissions (Börjesson and Svensson, 1997; Christophersen et al., 2000; Nozhevnikova et al., 1993; Visvanathan et al., 1999). Highly organic material such as compost has been known to be very efficient in regards to CH_4 oxidization. Humer and Lechner (2001) reported that compost covers enriched with organic matter were able to entirely oxidize all CH_4 emitted from their respective landfills. Additionally, organic matter provides nutrients for methanotrophic bacteria and has a high porosity which allows for more O_2 penetration. The porosity of soil directly influences the penetration of O_2 into soil and provides channels for O_2 penetration and contacting surface areas for methanotrophic bacteria. Soils with high porosity retain CH_4 and O_2 longer, leading to higher oxidation rates (Humer and Lechner, 1999).

1.1.3. Vegetation and methane oxidation

Vegetation type influences soil properties such as pH, water content, and gas transport. They also provide channels for O_2 penetration into soil, therefore enhancing CH_4 oxidation. Plants may indirectly affect O_2 penetration through mechanical soil alterations such as soil density reductions. The root systems of vegetation also induce a more suitable microbiological environment for CH_4 oxidation. Vegetation on landfills covers could help encourage the penetration of oxygen downward into the rhizosphere via plant lacunae or aerenchyma as well.

Vegetation also has positive effects on final soil landfill covers since it improves agglomeration, thermal isolation against high temperature variability along with mechanical stabilization. Soils such as clay and silt are rich in fine-grained particles that can seal the surface layer of the soil surface when wet. This process can lead to blocked pores that restrain soil air diffusivity, and diminish methane oxidation due to limited oxygen concentration (King, 1994). A well-developed vegetation zone should counteract this kind of vertical erosion and stabilize the particles. Additionally, plant roots can enhance the aeration of soil by creating larger macropores, which improve the diffusion of oxygen into soil as well as the supply of methane to bacteria. As a result, the methane oxidation potential of vegetated soils is expected to increase. The following is a limited literature review of the effects of vegetation on methane oxidation.

Hilger et al. (2000) conducted a study to evaluate the effects of vegetation, N fertilizers, and lime on landfill CH_4 oxidation. Columns filled with compacted sandy loam and sparged with synthetic landfill gas were used to simulate a landfill cover. Bare-soil and grass-topped columns reduced CH_4 emissions by 37% and 47%, respectively, at peak uptake. The oxidation rate for both columns was about 18% at steady state. Tantachoon et al. (2008) used lab-scale column studies with different types of soil and vegetation to investigate the influence of vegetation on physical soil properties and thus the methane oxidation process. The results showed that without vegetation, air influx into cover soil was limited by a decreased share in pores available for gas transport. All of their vegetated columns contained high amounts of methanotrophs (10–30% of the DAPI counts) at almost entire column depth, especially at the rhizosphere, whereas columns without vegetation revealed an abundance of methanotrophs only at the top soil (5–15 cm). Amaral et al. (1995) reported that type I methanotrophs were abundant in the top layer and rhizosphere where high oxygen and nitrogen were available. Furthermore, root systems responded significantly to the abundance of methanotrophs in the lower part when compared to non-vegetated columns. The oxygen supplied in deeper zones by root systems seems to be an important factor in regulating methanotrophic growth. Gebert (2008) reported that vegetation growing on the top layer alters soil physical properties, stabilizes and protects the top cover soil from erosion by spreading roots, and improves the natural aeration and thus the diffusion of oxygen into the soil as well as the supply of methane to localized methane-oxidizing bacteria. Due to these effects, methane oxidation can be enhanced by at least 50%.

2. Methods

A numerical model (FSU model) that combines flow of water and heat with gas transport and oxidation in soils, was used to estimate methane emission and oxidation from simulated vegetated and non-vegetated landfills with different climates. Compacted clay final covers (60 cm clay barrier and 45 cm of vegetative or topsoil layer) were simulated in climate zones: Mediterranean, Semiarid (Cold), and Humid Subtropical. Average climatic conditions were obtained from available data sets (Table 1). Climatic input data for Semiarid (Cold) was obtained from a weather station built in Montana as part of the U.S. EPA Alternative Cover Assessment Program (ACAP). Other sites' historical data were obtained from