Pedosphere **24**(3): 291–307, 2014
ISSN 1002-0160/CN 32-1315/P

Published by Elsevier B.V. and Science Press

PEDOSPHERE

www.elsevier.com/locate/pedosphere

Methanogenesis and Methanotrophy in Soil: A Review*1

N. SERRANO-SILVA, Y. SARRIA-GUZMÁN, L. DENDOOVEN and M. LUNA-GUIDO*2

Laboratory of Soil Ecology, ABACUS, Cinvestav, Instituto Politecnico Nacional 2508, C.P. 07360 Mexico, D.F. (Mexico)

(Received September 19, 2013; revised March 23, 2014)

ABSTRACT

Global warming, as a result of an increase in the mean temperature of the planet, might lead to catastrophic events for humanity. This temperature increase is mainly the result of an increase in the atmospheric greenhouse gases (GHG) concentration. Water vapor, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the most important GHG, and human activities, such as industry, livestock and agriculture, contribute to the production of these gases. Methane, at an atmospheric concentration of 1.7 μmol mol^{-1} currently, is responsible for 16% of the global warming due to its relatively high global warming potential. Soils play an important role in the CH_4 cycle as methanotrophy (oxidation of CH_4) and methanogenesis (production of CH_4) take place in them. Understanding methanogenesis and methanotrophy is essential to establish new agriculture techniques and industrial processes that contribute to a better balance of GHG. The current knowledge of methanogenesis and methanotrophy in soils, anaerobic CH_4 oxidation and methanotrophy in extreme environments is also discussed.

Key Words: anaerobic CH_4 oxidation, biological production, global warming, methanogenic archaea, methanotrophic bacteria

Citation: Serrano-Silva, N., Sarria-Guzmán, Y., Dendooven L. and Luna-Guido, M. 2014. Methanogenesis and methanotrophy in soil: A review. *Pedosphere*. **24**(3): 291–307.

INTRODUCTION

The rising temperature of earth's atmosphere and oceans, known as global warming (GW), is mainly the result of an increase in the concentration of greenhouse gases (GHG) in the atmosphere since the beginning of the 20th century, and this increase is mostly due to anthropogenic activities (IPCC, 2007; Houghton, 2009). Global warming is one of the major threats to the environment because of the resulting climate change.

Oxygen (O_2) and nitrogen (N_2) are the principal components of the atmosphere at concentrations of 21% and 78%, respectively, but they do not absorb or emit thermal radiation (Seinfeld, 2011). However, water vapor and less abundant components, such as carbon dioxide (CO_2) (390 μmol mol^{-1}), methane (CH_4) (1.7 μmol mol^{-1}) and nitrous oxide (N_2O) (0.3 μmol mol^{-1}) are known as greenhouse gases, because of their long atmospheric lives and their relatively high thermal absorption capacities. The global warming potential (GWP), a quantification of the averaged relative radiative forcing impacts of a particular greenhouse gas, has been set as 1 for CO_2, and, in consequence, the values for CH_4 and N_2O are 25 and 298, respectively, for a 100 year time horizon (IPCC, 2007). Besides water vapor, the most important greenhouse gas is CO_2, but CH_4 and N_2O are also important contributors to GW (Seinfeld, 2011).

Greenhouse gases in the atmosphere play an important role for life on earth. It has been calculated that the average temperature of earth, which is 15 °C nowadays, would be −15 °C or −18 °C if the GHG were not present, which would severely limit life on earth (Seinfeld, 2011).

Biological or non-biological, and natural or anthropogenic processes are involved in GHG cycling. Soils, depending on the conditions, can be a source or a sink of CO_2, CH_4 and N_2O. Unaltered natural soils are principally a sink for CH_4 and N_2O and sequester as much carbon (C) as they emit CO_2, but due to human activities, mainly agriculture, soils are often a source for GHG (Christiansen *et al.*, 2012). In 2005, agriculture accounted for 5 100–6 100 Tg CO_2-equivalents year^{-1}, or 10%–12% of total global GHG: 60% of total global N_2O emissions, 50% of CH_4 emissions and less than 1% of CO_2 emissions (Smith, 2012).

After CO_2, CH_4 is the second most important GHG

*1Supported by the Centro de Investigación y de Estudios Avanzados del IPN, Mexico and the Consejo Nacional de Ciencia y Tecnología, Mexico (Nos. 153216, 232468 and 245119).
*2Corresponding author. E-mail: mluna@cinvestav.mx.

produced as a result of human activity. Methane is responsible for approximately 16% of the greenhouse effect (Aydin *et al.*, 2010). Methane concentration in the atmosphere remained stable for thousands of years (0.715 µmol mol^{-1}), but recently, due to human activities, it has more than doubled (1.774 µmol mol^{-1}) (IPCC, 2007). Nowadays its concentration in the atmosphere increases at a rate of 0.003 µmol mol^{-1} $year^{-1}$ (Butenhoff and Khalil, 2007).

Whalen (2005) estimated a total annual emission of CH_4 from natural and anthropogenic sources of 600 Tg $year^{-1}$. Natural sources account for 40% of global CH_4 emissions, whereas 60% comes from anthropogenic sources (Karakurt *et al.*, 2012). Around 70% of atmospheric CH_4 originates from biogenic sources (Conrad, 2009). Biological processes in anoxic environments are considered the main biogenic source of atmospheric CH_4 (Houghton *et al.*, 2001) and produced by a group of microorganisms (methanogens) belonging to the domain archaea.

Anthropogenic sources of CH_4 are the result of agriculture, energy, waste and industrial production, with agriculture and energy production the most important. Waste, energy, industry and agriculture contribute 20.61%, 28.65%, 0.10%, and 50.63% of the calculated annual CH_4 emission, respectively (Karakurt *et al.*, 2012) (Fig. 1). Landfills are responsible for an annual emission of 3%–10% of the total global emissions (Bogner and Matthews, 2003) and are among the largest anthropogenic sources of CH_4 in the United States (USEPA, 2007).

CH_4 PRODUCTION IN SOILS

Most of CH_4 production in soils has been attributed to anaerobic methanogenesis when anoxic microsites are formed, which serve as a refuge for methanogenic archaea (Watanabe *et al.*, 2007), or in flooded soils where a low redox potential required for CH_4 production is present (Dalal *et al.*, 2008). However, several authors reported CH_4 production from oxic environments (Von Fischer and Hedin, 2007). Methane is used as a C and energy source by methanotrophic microorganisms (Smith *et al.*, 2003) and this process contributes up to 10% of global CH_4 oxidation (Lowe, 2006).

While forests are considered important sinks of CH_4 (Grunwald *et al.*, 2012), wetlands are the major biological source (Conrad, 2009), contributing 145 Tg CH_4 $year^{-1}$ (Norina, 2007). Flooded rice fields, mostly in the humid tropics, are among the largest sources of atmospheric CH_4 with an estimated contribution of approximately 5%–19% of total global emissions (IPCC, 2007). Their contribution is increasing as the production of rice (*Oryza* sp.), a staple food in Asia and becoming more popular in the world, to satisfy an increasing demand of a growing world population (Nguyen and Ferrero, 2006).

Northern-latitude soils are of great importance in the global budget of CH_4 as they contain one-third of the global organic C pool (Post *et al.*, 1982), although recent studies suggest that even more C might be stored in these regions (Jungkunst, 2010). As these soils are water saturated during summer, there is a large CH_4 production due to anaerobic metabolism. Because of this, it is expected that in the Arctic the effects of the observed and predicted climate change will be stronger than the global average (Trenberth *et al.*, 2007) and increase with time (Wuebbles and Hayhoe, 2002).

Kammann *et al.* (2009) reported that significant amounts of CH_4 were produced even after homogenization of soil samples, where the anoxic microsites were destroyed. This has led to some authors to hypothesize that methanogens are not the sole source of CH_4 in

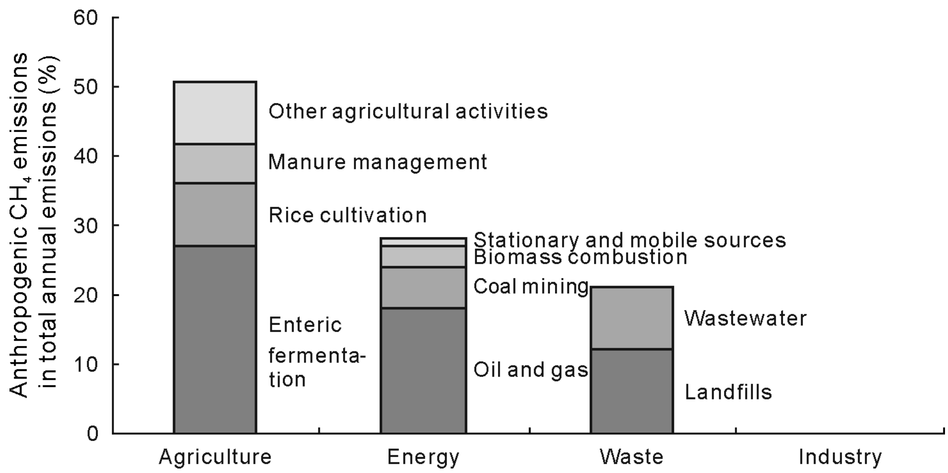

Fig. 1 Anthropogenic methane (CH_4) emissions by sectors and sources in 2010 (Karakurt *et al.*, 2012; Yusuf *et al.*, 2012).