Soil Biology & Biochemistry 80 (2015) 260–272

Contents lists available at ScienceDirect

Soil Biology & Biochemistry

journal homepage: www.elsevier.com/locate/soilbio

Review paper

Soil methane oxidation and land-use change – from process to mitigation

Kevin R. Tate*

Landcare Research, Private Bag 11052, Palmerston North, New Zealand

ARTICLE INFO

Article history:
Received 23 March 2014
Received in revised form
8 October 2014
Accepted 10 October 2014
Available online 24 October 2014

Keywords:
Soil methane fluxes
Afforestation
Processes
Methanotroph communities

ABSTRACT

Global atmospheric methane (CH_4) concentrations are now approaching 1800 ppbv as a result of the growing imbalance between the net CH_4 emissions from natural and anthropogenic sources of this potent greenhouse gas, and its consumption by physical and biological processes. The main focus of this review is on how land-use change and soil management can be used to correct this imbalance. Currently, the main terrestrial source for CH_4 is from natural wetlands and irrigated rice cultivation, although improvements in water management during rice production have resulted in major reductions of CH_4 emissions from this source. Afforestation and reforestation can also enhance soil CH_4 oxidation by influencing the composition and activity of the soil methanotroph (aerobic proteobacteria) community. The effects of these and other land-use changes on soil CH_4 oxidation are not generally well understood, but are known to influence this process through their effects on a range of soil properties such as soil moisture, nitrogen status, and pH that also affects methanotroph community structure and function.

Recent advances in molecular techniques have confirmed the central role of methanotroph communities in regulating soil CH_4 consumption by revealing how they respond to land-use change. Community-level molecular analyses of methanotroph populations under different conditions now provide new insights into the distinct traits of the different subgroups and their ecology.

These advances in understanding the abiotic and biological processes regulating soil CH_4 oxidation now offers the possibility of being able to predict which land-use and management practices, especially for afforestation and reforestation, will achieve high soil CH_4 oxidation rates They also improve the prospects for integrated assessment of the atmospheric impacts on the global greenhouse gas budget from net soil emissions of CH_4, N_2O, and CO_2 with land use and management change.

1. Introduction

Methane (CH_4) is a powerful greenhouse gas produced globally by both biotic and abiotic processes. The rise in CH_4 concentration during the Holocene (~5000 ka ago) has been linked to the emergence of rice cultivation (Ruddiman, 2013), and possibly marks the first indication of a human influence on atmospheric CH_4 concentration. There is also evidence to indicate that natural changes in the Earth's orbit enhanced CH_4 emissions from wetlands in the Southern Hemisphere tropics (Singarayer et al., 2011). While the debate between the anthropogenic and natural hypothesis continues, it is generally accepted that human activity lies behind the rise in atmospheric CH_4 concentration from about 700 ppb at the start of the industrial period in 1750 to the current value of ~1800 ppbv (Heiman, 2011). Much of this increase is due to an increasing imbalance between the production of CH_4 and its consumption (Trotsenko and Murrell, 2008). A major contributor to this imbalance has been the expansion of agriculture, which has reduced the consumption by soil of atmospheric CH_4. Indeed, Ojima et al. (1993) have argued that if no land conversions to crop production had occurred after the mid-19th century, the temperate soil CH_4 sink would have subsequently increased more than three-fold, from 8 to 27 Tg y^{-1}. Currently, about 60% of the global CH_4 emission derives from, or relates to, human activity, such as combustion of fossil fuels (e.g., natural gas, coal), enteric fermentation, rice cultivation, biomass burning, landfills, and animal effluent (Crutzen, 1991). Land-use change and soil management, and land-based feedbacks from global change can shift the balance between soils acting as a CH_4 source or a sink, but are poorly understood aspects of the terrestrial CH_4 budget. Here I examine advances made in the last decade in understanding how land-use change and management, and particularly afforestation and reforestation, can affect the balance between soil CH_4 production and consumption.

* Fax: +64 6 353 4801.
E-mail address: tatek@landcareresearch.co.nz.

http://dx.doi.org/10.1016/j.soilbio.2014.10.010
0038-0717/

2. Soil methane sources and sinks

Numerous reviews have been published on soil sources and sinks of CH_4. Some have been general in nature (Conrad, 1989; Nedwell, 1996; Topp and Pattey, 1997; Le Mer and Roger, 2001), while others have focussed on such ecosystems as rice fields (Wassmann et al., 1993; Neue, 1997; Dubey, 2005), wetlands (Sarmio et al., 2009), forests, grasslands, and cultivated soils (Steudler et al., 1996; Dutaur and Verchot, 2007). In considering the effects of land–use and management on net CH_4 exchange between soils and the atmosphere, a distinction needs to be made here between two different modes of mitigation. In the first, atmospheric CH_4 is consumed by "high-affinity" methanotrophs and takes place primarily in aerobic soils. In the second mode, methanotrophs act as biofilters at oxic–anoxic interfaces in wetlands, lake sediments, and other environments experiencing high CH_4 fluxes.

As discussed later, the application of molecular techniques to study the associated ecology of soil methanogens (strict anaerobes belonging to the *Archaea* phylogenetic domain) and methanotrophs (aerobic proteobacteria) not only enhances our understanding of these two opposing processes, but also creates new opportunities for mitigating CH_4 emissions.

The highest net CH_4 emissions occur in anaerobic soil environments, which include wetlands and rice paddies. There is evidence to suggest that emissions from both these sources in the Northern Hemisphere have been decreasing because of declining soil moisture supplies (Jung et al., 2010). Large-scale changes in water management have also led to major reductions in CH_4 emissions from rice paddies (Li et al., 2002).

Nevertheless, wetlands and rice cultivation remain the major soil source of CH_4 production globally, as a result of a complex interaction between three processes. First, CH_4 is produced in the anoxic zones of flooded soils by methanogens through the anaerobic decomposition of plant material and soil organic matter, including manures. Second, CH_4 is transported to the atmosphere either via the rice plant (in temperate paddy fields), or directly in gas bubbles (ebullition), as in wetlands (Sarmio et al., 2009) and tropical rice fields (Dubey, 2005). The third process is one of CH_4 oxidation by methanotrophs in the oxic zone of soils, either in the rhizosphere (Gilbert and Frenzel, 1998; Dubey et al., 2003), or in the surface layer of rice paddy soils. About 80% of the CH_4 diffusing through the oxic zone at the soil-water interface in rice fields is oxidized by methanotrophs, in the absence of which CH_4 emissions would be 5–10 times higher than they are at present (Banker et al., 1995). Indeed, compared with bulk or bare soil, most of the CH_4 produced in the rhizosphere is microbially oxidized (64–86% in dryland; 46–64% in flooded rice soil) (Dubey, 2005). As methanogenic Archaea are globally ubiquitous (Angel et al., 2012), this interplay between CH_4 production and consumption is observable in all soils where either permanent or incipient anaerobic sites are present.

Biological oxidation at, or near, the sites of CH_4 production (700 Tg y^{-1}), and photochemical oxidation of CH_4 in the atmosphere (~450 Tg y^{-1}), are the major global sinks, while the oxidation of atmospheric CH_4 by aerobic soils serves as a small but significant additional sink (20–45 Tg y^{-1}) (Dutaur and Verchot, 2007). The CH_4 flux between aerobic soils and the atmosphere also results from the balance between methanogenesis (production of CH_4) and methanotrophy (consumption of CH_4), the latter process being dominant in well-aerated mineral soils (Conrad, 2009). Nitrite-driven anaerobic CH_4 oxidation is also mediated by methanotrophs (Ettwig et al., 2010), but the influence of this process as a soil sink for CH_4 has yet to be determined.

Between 30 and 50% of the global soil CH_4 sink is apparently located in temperate latitudes (Ojima et al., 1993). Generally, the largest CH_4 uptake rates are measured in soils under forests, especially those of coarse texture, where aerobic processes are favoured (Dutaur and Verchot, 2007). Thus, natural forests that have remained undisturbed for long periods can provide valuable insights into the key processes regulating soil CH_4 oxidation. For example, in a New Zealand old-growth mountain beech (*Nothofagus solandri* var. *cliffortioidies* [Hook]) forest where deposition of atmospheric pollutants, including nitrogen, was practically undetectable, soil CH_4 oxidation rates were 6.5 times higher than global average values (Price et al., 2003).

Among the abiotic factors that influence oxidation rates (temperature, moisture, nitrogen, inorganic salts), changes in soil moisture account for about 88% of the variability. The highest oxidation rates (17 kg CH_4 ha^{-1} y^{-1}) reported by Price et al. (2004), were for soils that had dried out to about 19% of water-filled pore space during a drought. This finding was attributed partly to the ready diffusion of atmospheric CH_4 into the freely draining soil, and partly to a limited supply of CH_4 from a small population of methanogens located in the organic horizon of the forest floor. It also appeared that CH_4 diffusion was not limited by water in the pore space of the soil, enabling CH_4 to reach the zone of maximum methanotrophy, located 50–100 mm beneath the soil-forest floor interface.

In most ecosystems, a number of natural factors regulate soil CH_4 oxidation rates. These assume greater importance where human disturbances occur, including atmospheric N deposition and agricultural activity. In their global assessment, Dutaur and Verchot (2007) identified soil texture as having the most pronounced effect in temperate forest soils, where high oxidation rates were associated with high but poorly understood variances. For example, physical disturbance of soil by cultivation can greatly reduce soil CH_4 oxidation (Smith et al., 2000). Overall, oxidation rates vary markedly between different ecosystems, although some systems, such as temperate and tropical grasslands, and chaparral, were under-represented (Dutaur and Verchot, 2007).

In examining this inter-ecosystem variability across the main temperate to sub-tropical ecosystems of New Zealand, Saggar et al. (2008) found that soils under native forests gave the highest CH_4 oxidation rates (up to 11 kg CH_4 ha^{-1} y^{-1}), followed by those under planted pine forests (4–6 kg CH_4 ha^{-1} y^{-1}), while the lowest rates (<1 kg CH_4 ha^{-1} y^{-1}) were measured in most managed grassland and cropland soils where fertilizer applications and soil disturbances were commonplace. Other investigators have also found that undisturbed soils oxidize CH_4 more strongly than disturbed soils (Bender and Conrad, 1994; Smith et al., 2000; Kim and Kirschbaum, 2014). Similarly, in soils where inorganic fertilizers have been applied depressed rates of soil CH_4 oxidation are generally observed (Mosier et al., 1991; Ojima et al., 2003).

3. Soils and land-use change

On a global scale, the role of soil as both a source and sink for CH_4, and the shifting balance between these two entities with changing land use or management, are not well understood.

Wide variations in CH_4 oxidation, arising from direct human disturbance of soils, have been reported for a variety of land uses, encompassing different soil types and climates (Priemé et al., 1997; Smith et al., 2000; Borken and Beese, 2006; Kim and Kirschbaum, 2014). Some recent examples are also included in Table 1 where land-use changes have been primarily responsible for the observed shifts in soil CH_4 oxidation.

In the first example shown in Table 1 (Saggar et al., 2008), soil CH_4 oxidation was substantially increased when established pastures were planted in pine (*Pinus radiata*), and this was initially