THE METHANE UPTAKE CAPACITY OF SOIL GARDEN

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ABSTRACT

Aerobic CH₄ oxidation through methanotrophic bacteria is the only terrestrial sink and the only sink that can be altered directly or indirectly by human so far. However, the capacity of this sink is highly variable in different ecosystems depending on four key factors which are soil diffusivity, soil temperature, soil nitrogen status and soil moisture. While many studies in Australia experience the significant inverse correlation between soil moisture and CH₄ flux magnitude in temperate forests in Victoria and New South Wales, there is a lack of research about the methane uptake capacity of garden soil. Consequently, we hypothesise that there is a similar pattern of CH₄ uptake by garden soil. The aim of this study is to determine the capacity of CH₄ oxidation along the soil garden profile. Our study was conducted at a native garden in Burnley Campus of the University of Melbourne, Victoria, Australia. Our results show three main findings. Firstly, garden soil can become a significant sink of CH₄. Secondly, there was a significant correlation between soil moisture and the soil CH₄ uptake rates. Finally, there was an expansion of the CH₄ oxidation layer to deeper soil layers as the soil dries at the surface.

Keywords: methane, CH₄, greenhouse gases, soil methane uptake

1. INTRODUCTION

Methane (CH₄) is the second most powerful well-mixed greenhouse gas affecting climate change, just after carbon dioxide [1, 2]. The contribution of CH₄ to the total radiative forcing generated by greenhouse gases is about 32 per cent although the concentration of it in the atmosphere (approx. 1.8 ppm) is significant lower than that of CO₂ (approx. 400 ppm) [1]. Therefore, a reduction of CH₄ emission could help to mitigate global warming effectively.

The oxidation by methanotrophic bacteria (MOB) in soils is the only terrestrial sink for CH₄. Although it can consume only approximately 30 Tg CH₄ yr⁻¹, it is the only sink that can be altered directly or indirectly by human so far [1, 3, 4, 5]. However, the capacity of this sink is highly variable in different ecosystems, particularly for upland soils, which were estimated to range from 7 to 120 Tg CH₄ /yr [4, 6]. In recent studies from Australian ecosystems, there are
two contrasting views about the correlation between the CH$_4$ uptake rates and soil moisture. Some studies indicate a strong relationship between soil moisture and soil CH$_4$ uptake rates, for example, studies in wet sclerophyll forest in Tasmania and in temperate forests in Victoria and New South Wales [3, 7, 8, 9]. However, there are also reports that CH$_4$ uptake rates of soils can be very persistent in some ecosystems, such as a eucalypt savanna near Darwin in Northern Territory and eucalypt forest soils in a Mediterranean climate in Western Australia [10, 5]. In these ecosystems CH$_4$ uptake was very stable regardless of the soil moisture content in the soils. Hence, there is still an insufficiently detailed understanding why the correlation between soil moisture and CH$_4$ uptake magnitude is different significantly in different ecosystems.

Despite a growing interest in soil CH$_4$ uptake in the last decade there have been very few studies investigating CH$_4$ oxidation in urban soil with only a relatively small number of published studies on CH$_4$ uptake in urban garden systems [11, 12]. The green vegetated areas within our urban centres can provide important ecosystem services, such as amenity, biodiversity, productivity, climate amelioration, hydrological and biogeochemical cycling; particularly, they can mitigate or offset some of the urban greenhouse gas emissions through directing carbon sequestration in soil and vegetation biomass, and reducing energy demand through shading, insulating and evaporative cooling. However, urban gardens have received little attention with regards to CH$_4$ exchange, even though urban garden spaces occupy a considerable land cover area [13, 14, 15]. The main objectives of this study were to determine the capacity of CH$_4$ oxidation of the soil garden and the correlation between the CH$_4$ uptake rates of soil garden and soil moisture.

2. MATERIALS AND METHODS

2.1. Site description

The study was carried out at the native garden of the Burnley Campus of the University of Melbourne in Victoria in Australia (37° 49’ 47” S, 145° 01’ 15” E) which has been in existence more than 150 years. The soil of the garden has a fine-sand clay loam layer at surface [12]. The annual rainfall of the area is 681 mm and the mean temperature fluctuates from 8.9°C to 19.9°C [12].

2.2. Experimental design

At the native garden section of the Burnley Gardens, we established three study sites (upslope, mid-slope and bottom of slope). Each site contained one control (C) plot (9 m$^2$) and one treatment (T) plot (9 m$^2$). A 9 m$^2$ roof was built at each treatment plot to exclude rainfall. At each plot, three replicate chambers were installed to sample CH$_4$ fluxes. We sampled CH$_4$ fluxes weekly from 26/7/16 to 06/9/16. The roofs at the three treatment plots were installed on 05/8/16. A total of 18 chambers were measured per sampling round. In addition, at each plot, one underground plastic tube with one-meter depth was installed to measure the moisture level of soil under the surface.

2.3. Methane flux measurement

We used a Fast Greenhouse Gas Analyser of the Los Gatos Research Incorporation (LGR INC) to measure CH$_4$ flux. The instrument was connected to each chamber for seven minutes in every measuring circle; the first five minutes were for stabilizing the machine and the last two
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minutes were for measuring the flux. The measurement chambers were PVC rings with fifteen-centimetre diameter and fifteen-centimetre height were slid on top of PVC anchors and fitted with a screw-on-lid during measurements.

2.4. Data analyses

We used linear mixed model (LMM) procedures in Genstat 14.0 (VSN International, UK) to analyse all the data with treatment category (T, C) and measuring campaign as fixed effects. To test the effect of soil moisture and soil temperature on CH₄ flux, we introduced them individually and sequential as covariates to the fixed model term. The p value of each factor was used to interpret their importance. Main effects were considered significant if p ≤ 0.05, and interactions were considered significant at p ≤ 0.01. Additionally, Descriptive Statistics was used for calculating means and standard errors.

3. RESULTS AND DISCUSSION

3.1. The effect of roofs on soil moisture reduction at treatment plots

The results show that after the roofs were installed (after campaign 3 on 05/8/16), moisture content of the surface soil at treatment plots was always lower than that at the control plots (Figure 1). In addition, LMM analysis of soil moisture indicated that the difference between the control and treatment plots was significant at p ≤ 0.001 from campaign 4 onwards (Table 1). The results also show the gradual reduction in soil moisture at surface layer in the treatment plot since the roofs were applied, which did not occur at the control plots (Figure 1). This result means that the treatment effect is consistent on all measurement campaigns. However, LMM shows an interaction between treatment and measurement campaign with p ≤ 0.001 (Table 1) which is probably because before installation of the roofs, at measurement campaign on 5th August, the treatment plots were slightly wetter compared to the control plots (Figure 1). Following the installation of the roofs the soil moisture content in the treatment plot was on average 0.085 ± 0.02 (SE) cm³ cm⁻³ lower as compared to control conditions.

![Figure 1. Soil moisture in the top soil layer (0-5 cm) in control (C) and treatment (T) plots before and after the start of treatment.](image)

Table 1. LMM analysis with treatment and measurement campaign as fixed effects for soil moisture at the top layer (0-5 cm) at C plots and T plots in the last five measurement campaigns.

| Fixed term       | n.d.f. | F statistic | F pr  |
|------------------|--------|-------------|-------|
| Treatment        | 1      | 94.55       | < 0.001 |
| Campaign         | 4      | 8.50        | < 0.001 |
| Treatment.Campaign | 4      | 5.79        | < 0.001 |
3.2. CH$_4$ flux at surface soil

Mean CH$_4$ flux rates at plot level varied from -2.13 ppb CH$_4$ s$^{-1}$ m$^{-2}$ to -0.37 ppb CH$_4$ s$^{-1}$ m$^{-2}$. However, the mean CH$_4$ flux was on average $-0.42 \pm 0.12$ (SE) ppb CH$_4$ s$^{-1}$ m$^{-2}$ lower (more negative) in treatment plots than that in control plots during every measuring campaign after the roof installation (Figure 2), which means that the soil CH$_4$ uptake rates were greater in treatment plots. The results of LMM analysis (Table 2) show that there was no significant difference in CH$_4$ flux between measuring campaigns (p = 0.089) and no interaction between treatment and measurement campaigns (p = 0.672). In contrast, there was a significant difference in CH$_4$ flux between C and T plots with p = 0.005.

The mean CH$_4$ uptake rates of soils in the native section of the Burnley Gardens are within the range studied for Australian temperate eucalypt forest [9, 10, 16] and are comparable with similar studies in the world [17, 18]. In addition, the significant higher CH$_4$ uptake rates at treatment plots comparing to control plots (with p = 0.005) (Table 2) demonstrates the significant effect of the rainfall exclusion treatment on CH$_4$ uptake rate. Furthermore, there was no interaction between treatment and measurement campaign (p = 0.672) (Table 2) which means that the treatment effect was consistent on all measuring days.

Table 2. LMM with treatment and measurement campaign as fixed effects for CH$_4$ flux at control plots and treatment plots in the last five measurement campaigns after the roofs were installed.

| Fixed term          | n.d.f. | F statistic | F pr    |
|---------------------|--------|-------------|---------|
| Treatment           | 1      | 8.42        | 0.005   |
| Campaign            | 4      | 2.09        | 0.089   |
| Treatment.Campaign  | 4      | 2.36        | 0.672   |

The installation of rainfall exclusion roofs had a significant impact on increasing soil temperature and decreasing soil moisture which both are influencing factors of CH$_4$ oxidation process [3, 9, 19]. In order to analyse which is the key factor that control the different CH$_4$ flux between control plots and treatment plots, we added soil moisture and soil temperature as covariates to the fixed model term separately.

When we added soil moisture, there was no significant treatment effect on CH$_4$ flux rates between control and treatment plots anymore (p = 0.208) (Table 3) which means that soil moisture is the key driver of the difference in CH$_4$ flux rates between control and treatment plots. However, when we added soil temperature as a covariate, there was still a significant treatment impact on CH$_4$ flux rates with p = 0.005 which means that soil temperature did not influence the CH$_4$ oxidation process much. LMM statistic also indicates that soil moisture has significant impact on soil CH$_4$ uptake (p = 0.003) (Table 3) whereas soil temperature does not (p = 0.174) (Table 4). Therefore, we can conclude that the impact of treatment on CH$_4$ flux is caused by a change in soil moisture.
The significantly greater CH$_4$ uptake in treatment plots compared to control plots in all measurement campaigns after the installation of the roofs shows the inverse correlation between soil moisture and CH$_4$ flux. Moreover, the relationship between soil moisture and CH$_4$ flux also existed clearly at control plots. When soil moisture content at control plots decreased then CH$_4$ flux increased and when soil moisture content increased the CH$_4$ flux deceased (Figure 2). The same pattern also was seen at treatment plots from 26$^{th}$ August onward. This result highly corresponds with many previous reported results [19, 20, 21].

| Fixed term        | n.d.f. | F stat | F pr  |
|-------------------|--------|--------|-------|
| Mean soil moisture| 1      | 9.19   | 0.003 |
| Treatment         | 1      | 1.61   | 0.208 |
| Campaign          | 4      | 1.72   | 0.154 |
| Treat.Campaign    | 4      | 0.72   | 0.578 |

Table 3. LMM analysis with treatment and measurement campaign as fixed effects for CH$_4$ flux at C and T plots in the last five measurement campaigns with soil moisture as a covariate.

| Fixed term        | n.d.f. | F stat | F pr  |
|-------------------|--------|--------|-------|
| Soil temperature  | 1      | 1.88   | 0.174 |
| Treatment         | 1      | 8.16   | 0.005 |
| Campaign          | 4      | 3.76   | 0.007 |
| Treat.Campaign    | 4      | 0.64   | 0.637 |

Table 4. LMM analysis with treatment and measurement campaign as fixed effects for CH$_4$ flux at C and T plots in the last five measurement campaigns with soil temperature as a covariate.

There was an uncertain trend at treatment plots from measurement campaign on 9$^{th}$ August to 26$^{th}$ August. In this period, there was an increase in CH$_4$ flux at treatment plots right after the installation of the roofs and then CH$_4$ flux declined whereas the soil moisture decreased. Nevertheless, the inverse correlation between CH$_4$ flux and soil moisture happened again after about 17 days (Figure 2).

### 3.3. CH$_4$ flux in soil profile

![Figure 3. CH$_4$ flux in soil profile at control and treatment plot (a), water content in soil profile (b)](image)

The result showed that CH$_4$ uptake rates in treatment plots in the top 15 cm of the soil profile was greater than that of control plots (Figure 3a). The soil moisture at the respective soil levels was comparatively lower in treatments plot than control plots (Figure 3b). This result again confirms the inverse correlation of CH$_4$ uptake with soil moisture; and importantly, it also confirms that CH$_4$ oxidation can increase further down in the soil profile due to soil moisture reduction. Therefore, the significant increase in soil CH$_4$ uptake rates at the soil surface at treatment plots (Figure 2) could be the result of the significant increase of soil CH$_4$ uptake rates at deeper soil levels within the top 15 cm of the soil profile (Figure 3a). This finding is similar with the result that reported by Fest [7]. He argues that there is a strong correlation between CH$_4$.
The methane uptake capacity of soil garden uptake and the soil moisture content in the top 10 cm in temperate eucalypt forest in Victoria, Australia.

4. CONCLUSION

The installation of rainfall exclusion roofs in the native garden led to a significant decrease of soil moisture at the surface and the top layers of the soil profile (top 15 cm). The decrease in soil moisture resulted in a corresponding increase in CH$_4$ uptake in the soil which is comparable to other temperate eucalypt forest studies in Australia. It is likely that the reduction in soil moisture increased the diffusion of CH$_4$ into the soil profile and the study indicated an expansion of the CH$_4$ oxidation layer to deeper soil layers as the soil dries at the surface. Therefore, open space in urban area can become a significant CH$_4$ sink with an appropriate irrigation and fertilization.

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REFERENCES

1. Stocker T., Qin D., Plattner G., Tignor M., Allen S., Boschung J., Nauels A., Xia Y., Bex B., and Midgley B. - IPCC, 2013: climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change, 2013.

2. Lelieveld J., Crutzen P. J., and Dentener F. J. - Changing concentration, lifetime and climate forcing of atmospheric methane, Tellus B 50 (2) (1998) 128-50.

3. Del Grosso S., Parton W., Mosier A., Ojima D., Potter C., Borken W., Brumme R., ButterbachBahl K., Crill P., and Dobbie K. - General CH$_4$ oxidation model and comparisons of CH$_4$ oxidation in natural and managed systems, Global Biogeochemical Cycles 14 (4) (2000) 999-1019.

4. Kirschke S., Bousquet P., Ciais P., Saunois M., Canadell J. G., Dlugokencky E. J., Bergamaschi P., Bergmann D., Blake D. R., and Bruhwiler L. - Three decades of global methane sources and sinks, Nature Geoscience 6 (10) (2013) 813-23.

5. Ojima D., Valentine D., Mosier A., Parton W., and Schimel D. - Effect of land use change on methane oxidation in temperate forest and grassland soils, Chemosphere 26 (1) (1993) 675-85.

6. Smith K., Ball T., Conen F., Dobbie K., Massheder J., and Rey A. - Exchange of greenhouse gases between soil and atmosphere: interactions of soil physical factors and biological processes, European Journal of Soil Science 54 (4) (2003) 779-91.

7. Fest B. - The Impact of Fire Disturbance and Simulated Climate Change Conditions on Soil Methane Exchange in Eucalypt Forests of South-Eastern Australia, 2013.

8. Fest B. J., Livesley S. J., von Fischer J. C., and Arndt S. K. - Repeated fuel reduction burns have little long-term impact on soil greenhouse gas exchange in a dry sclerophyll eucalypt forest, Agricultural and Forest Meteorology 201 (2015) 17-25.

9. Reeburgh W. - Global methane biogeochemistry, Treatise on geochemistry 4 (2003) 347.
10. Livesley S., Kiese R., Miehle P., Weston C., Butterbach-Bahl K., and Arndt S. - Soil–atmosphere exchange of greenhouse gases in a Eucalyptus marginata woodland, a clovergrass pasture, and Pinus radiata and Eucalyptus globulus plantations, Global change biology 15 (2) (2009) 425-40.

11. Goldman M. B., Groffman P. M., Pouyat R. V., McDonnell M. J., and Pickett S. T. - CH₄ uptake and N availability in forest soils along an urban to rural gradient, Soil Biology and Biochemistry 27 (3) (1995) 281-286.

12. Livesley S. J., Dougherty B. J., Smith A. J., Navaud D., Wylie L. J., and Arndt S. K. - Soil-atmosphere exchange of carbon dioxide, methane and nitrous oxide in urban garden systems: impact of irrigation, fertiliser and mulch, Urban ecosystems 13 (3) (2010) 273-293.

13. Barnett G., Doherty M., and Beaty M. - Urban greenspace: connecting people and nature, Environment 13 (1) (2005) 1-10.

14. Groffman P. M. and Pouyat R. V. - Methane uptake in urban forests and lawns, Environmental Science and Technology 43 (14) (2009) 5229-5235.

15. Milesi C., Running S. W., Elvidge C. D., Dietz J. B., Tuttle B. T., and Nemani R. R. - Mapping and modeling the biogeochemical cycling of turf grasses in the United States, Environmental management 36 (3) (2005) 426-438.

16. Dalal R., Allen D., Livesley S., and Richards G. - Magnitude and biophysical regulators of methane emission and consumption in the Australian agricultural, forest, and submerged landscapes: a review, Plant and Soil 309 (1) (2008) 43-76.

17. Butterbach-Bahl K., Breuer L., Gasche R., Willibald G., and Papen H. - Exchange of trace gases between soils and the atmosphere in Scots pine forest ecosystems of the northeastern German lowlands: Fluxes of N₂O, NO/NO₂ and CH₄ at forest sites with different N-deposition, Forest Ecology and Management 167 (1) (2002) 123-34.

18. Price S. J., Sherlock R. R., Kelliher F. M., McSeveny T. M., Tate K. R., and Condron L. M. - Pristine New Zealand forest soil is a strong methane sink, Global change biology 10 (1) (2004) pp. 16-26.

19. Ball B., Dobbie K., Parker J., and Smith K. - The influence of gas transport and porosity on methane oxidation in soils, Journal of Geophysical Research: Atmospheres 102 (D19) (1997) 23301-8.

20. Castro M. S., Steudler P. A., Melillo J. M., Aber J. D., and Bowden R. D. - Factors controlling atmospheric methane consumption by temperate forest soils, Global Biogeochemical Cycles 9 (1) (1995) 1-10.

21. Khalil M. and Baggs E. - CH₄ oxidation and N₂O emissions at varied soil water-filled pore spaces and headspace CH₄ concentrations, Soil Biology and Biochemistry 37 (10) (2005) 1785-94.