Short communication

N₂O and CH₄ emissions from N-fertilized rice paddy soil can be mitigated by wood vinegar application at an appropriate rate

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ABSTRACT

To understand the impacts of wood vinegar (WV), a by-product of biochar production, on N₂O and CH₄ emissions and their total global warming potential (GWP) from N-fertilized rice paddy soil, a soil column experiment was conducted using three treatments: 240 kg urea-N ha⁻¹ accompanied with 0, 5, and 10 t WV ha⁻¹, respectively. Results showed that N₂O and CH₄ emission flux patterns were dominated by water regime of rice growth cycle, which was independent with WV application. The total N₂O, CH₄ emission loads and GWP, over rice season of three N received treatments were 6.41–8.85 kg ha⁻¹, 127.7–405.0 kg ha⁻¹, and 5.24–12.03 t CO₂-e ha⁻¹, respectively. Rice seasonal N₂O and CH₄ emissions were synchronously mitigated by 22.4% and 36.4%, respectively, when WV was applied at 5 t ha⁻¹. Consequently, 5 t ha⁻¹ WV treatment reduced 31.5% of GWP compared with the urea treatment. In addition, 10 t ha⁻¹ WV treatment exerted a more positive effect on suppressing N₂O with 27.6% reduction. However, it increased GWP, by 57.2% because its CH₄ emission load was increased by 101.8%. In conclusion, WV amendment applied at an appropriate rate (5 t ha⁻¹) or combination with other CH₄ control technologies were suggested to reduce both N₂O and CH₄ emissions and thereby the GWP in N-fertilized rice paddy soil.

1. Introduction

Methane (CH₄) and nitrous oxide (N₂O) are two powerful greenhouse gases (GHGs), being with a global warming potential (GWP) of 25 and 298 times greater than carbon dioxide on a 100-year mass basis (IPCC, 2013). Flooded rice (Oryza sativa L.) systems simultaneously emit CH₄ and N₂O to atmosphere, due to the favorable production, consumption, and transport systems between the rice rhizospheric soil and the atmosphere, especially in the rice paddy soil which received high loads of nitrogen (N) fertilizer (Linquist et al., 2012; Ji et al., 2015; Yao et al., 2017). China, as the world’s leading producer of rice, grows rice on approximately 30 million ha per year, with dramatically increased N consumption (FAO, 2012). It is estimated that 7.7–8.0 Tg CH₄ and 138–154 Gg N₂O are emitted from Chinese rice fields (Liang et al., 2013). Therefore, it is of great importance to mitigate both CH₄ and N₂O emissions from N-fertilized rice paddy soil.

Recently, biochar has been considered as a promising soil amendment, which can improve soil quality, enhance crop productivity and mitigate GHGs emissions (Jeffery et al., 2011; Zhang et al., 2012; Pratiwi and Shinogi, 2016; Feng et al., 2017; Niu et al., 2017; Sun et al., 2017). Based on these positive impacts, biochar will likely have large-scale applications in the future. However, this will lead to the great generation of by-products. Wood vinegar (WV), which is also known as pyroligneous acid, is one of the major by-products during biochar generation of by-products. Wood vinegar production and can be incorporated into farmland soil (Yatagai et al., 2002; Lin and Hwang, 2009; Hanger, 2013a). Therefore, it is interesting to know the impacts of WV on GHGs emissions after incorporation into farmland soils, which will expand the application scope of biochar and its by-products.

The main substances of WV include many organic chemical components (Yatagai et al., 2002; Baimark and Niamsa, 2009). Herein, 2, 6-dimethoxyphenol, 2-methoxyphenol, and 3, 5-dimethoxy-4-hydroxyluene, were found as main three components in WV according to Yang et al. (2016). As reported in previous literature, WV soil addition has showed beneficial effects including crop productivity improvement (Kadota and Niimi, 2004; Lashari et al., 2013, 2015; Polthanee et al., 2013) and the atmosphere, especially in the rice paddy soil which received high loads of nitrogen (N) fertilizer (Yatagai et al., 2002; Baimark and Niamsa, 2009). Herein, 2, 6-dimethoxyphenol, 2-methoxyphenol, and 3, 5-dimethoxy-4-hydroxyluene, were found as main three components in WV according to Yang et al. (2016). As reported in previous literature, WV soil addition has showed beneficial effects including crop productivity improvement (Kadota and Niimi, 2004; Lashari et al., 2013, 2015; Polthanee et al., 2013). China, as the world’s leading producer of rice, grows rice on approximately 30 million ha per year, with dramatically increased N consumption (FAO, 2012). It is estimated that 7.7–8.0 Tg CH₄ and 138–154 Gg N₂O are emitted from Chinese rice fields (Liang et al., 2013). Therefore, it is of great importance to mitigate both CH₄ and N₂O emissions from N-fertilized rice paddy soil.

Recently, biochar has been considered as a promising soil amendment, which can improve soil quality, enhance crop productivity and
2.3. N$_2$O and CH$_4$ measurement

GHGs samples were collected using static chambers (29 cm in diameter and 100 cm in height) according to the modified method in Sun et al. (2013). Gas samples were taken on the 1st, 3rd, 5th, and 7th day after each split urea N fertilization applied and after surface floodwater drained. During other monitoring periods, gas samples were collected two or three times per month. Before gas samples were collected, the chambers were placed on the basal fixed frame in each soil column and sealed with water. For each observation, four gas samples were extracted from the chamber with a 50 mL syringe at the 1st, 16th, 31st, and 46th min after chamber sealed and were immediately transferred into evacuated vials. The N$_2$O and CH$_4$ concentrations analysis, GHGs emission rates calculation and the rice seasonal cumulative N$_2$O and CH$_4$ emission loads evaluation were performed according to Sun et al. (2013).

2.4. Total global warming potential (GWP$_t$) of N$_2$O and CH$_4$

GWP$_t$ (kg CO$_2$-e ha$^{-1}$) was used to compare the total GHGs emission in CO$_2$-equivalents per hectare under different treatments. Based on this method, CH$_4$ and N$_2$O emission can be evaluated and help assessing the potential trade-off effects between soil N$_2$O and CH$_4$ emissions as affected by WV amendment in rice paddy soil. In the current study, GWP$_t$ was calculated using the following equation (Zhang et al., 2012):

$$GWP_t = 298 \times EM(N_{2}O) + 25 \times EM(CH_{4})$$

where EM(N$_2$O) and EM(CH$_4$) represent rice seasonal emissions of N$_2$O and CH$_4$, respectively; 298 and 25 are coefficients for transforming N$_2$O and CH$_4$, respectively, into equivalent CO$_2$ emissions within a 100-year time horizon.

2.5. Data statistical analysis

One-way analysis of variance (ANOVA) was performed to assess the effects of WV application with different rates on the N$_2$O and CH$_4$ emissions from N-fertilized rice paddy soil. Statistical differences ($P < 0.05$) among tested individual treatments were determined using Duncan multiple comparison tests (SPSS Ver. 16.0 for Windows, SPSS Inc., Chicago, IL, USA).

3. Results and discussion

3.1. N$_2$O emission flux pattern and cumulative emission load during rice season

In rice season, similar N$_2$O emission flux pattern was observed in three treatments, which was mainly determined by water regime (Fig. 1). This was consistent with previous results evidenced from rice paddy soil (Zou et al., 2005; Liang et al., 2013; Sun et al., 2015). In the continuous flooded period until August 5, almost no N$_2$O emission was observed, even after BF and SF1 were applied. During the mid-season drainage period, a large proportion of N$_2$O emissions was detected immediately after disappearance of the floodwater. The N$_2$O emission rates of N-fertilized treatments came to peaks with 3205–4858 µg m$^{-2}$ h$^{-1}$ (Fig. 1). Then the soils were re-flooded, and N$_2$O emission rates dropped off immediately and kept at a very low level. This could be mainly attributed to the anaerobic conditions in continuous flooded paddy soil (Sun et al., 2015).

Considerable amount of N$_2$O emissions with 6.41–8.85 kg ha$^{-1}$ was recorded in three treatments. In comparison with the urea treatment, WV incorporation significantly ($P < 0.05$) reduced the cumulative N$_2$O emissions by 22.4–27.6% (Fig. 2), though no obvious difference was found between Urea + WV5 and Urea + WV10 treatment groups. Mitigation of N$_2$O emission from rice paddy soils received WV is of great significance since N$_2$O is a powerfully potent GHG. As result of the
organic C input and soil pH change, WV amendment could potentially favor the activity of N$_2$O reductase from denitrifying microorganisms, while inhibited the activity of reductases involved in the conversion of NO$_3^-$ to N$_2$O (Yanai et al., 2007; Ranatunga et al., 2018). Indeed, changes in soil microbial community structure and enzyme activity after WV addition have been reported (Lu et al., 2015; Yang et al., 2016). As a consequence, what is the main emission factor contributing to the reduction of N$_2$O from N fertilizer plus WV needs further investigations.

3.2. Methane (CH$_4$) emission flux pattern and cumulative emission load during rice season

Fig. 3 shows the CH$_4$ flux pattern from paddy soil throughout the rice growth period. There was no difference in the pattern of seasonal variations of CH$_4$ flux among the treatments whether WV was added or not. Seasonal pattern of CH$_4$ emissions varied with water regime (Zou et al., 2005; Zhang et al., 2012), which was also confirmed in our present study (Fig. 3). The CH$_4$ flux generally increased and reached peaks at about 30 days after rice seedlings were transplanted and then dropped off. After soil re-flooded, the CH$_4$ flux increased to another peaks and remained at low level afterwards, until the rice was harvested. The patterns of seasonal variations in CH$_4$ flux from rice paddy plots were quite different from those of N$_2$O flux (Figs. 2 and 3): CH$_4$ mainly emitted during water flooding stage, whereas N$_2$O emitted mainly during mid-season drainage period. Similarly, a trade-off emission pattern between CH$_4$ and N$_2$O resulting from mid-season drainage has been well documented in rice paddy soils (Zou et al., 2005; Yao et al., 2017). Based on the observed data in the present work, WV amendment did not change either the CH$_4$ or N$_2$O emission flux pattern of rice growth cycle.

Total of CH$_4$ emission loads of N-fertilized treatments were from 127.7 kg ha$^{-1}$ to 405.0 kg ha$^{-1}$ in the present study. Results in Fig. 4 shows that CH$_4$ emission was reduced by 36.4% when WV applied at 5 t ha$^{-1}$; however, it was increased dramatically by 101.8% when the WV application rate increased to 10 t ha$^{-1}$.
It is well known that multiple factors contribute to the intensity of CH4 emissions from rice paddy soil (Schimel, 2000; Bridgham et al., 2013). The CH4 emitted from rice paddy soil is primarily determined by three processes: CH4 production, oxidation, and transport from soil to atmosphere (Cai et al., 2007; Linquist et al., 2012). WV contains many organic components and the composition is very complicated (Mum and Ku, 2010; Yang et al., 2016), also reflected from our WV. It is possible, WV enhanced CH4 oxidation in the root rhizosphere which leads to a reduction in CH4 emissions under Urea + WV5 treatment. However, WV applied at higher load (10 t ha\(^{-1}\) in present study) stimulated CH4 emission from N-fertilized rice paddy soil. The largest fraction of the organic components in the WV is acids in present work and Choi et al. (2012), which might increase soil soluble C source for CH4 generation and emission (Cai et al., 2007). According to Win et al. (2009), WV addition suppressed NH3 volatilization from a paddy soil by preventing the transition of NH4\(^+\) into liquid NH3 concentration (Sommer et al., 2003). In addition, in our study, Urea + WV10 treatment effectively suppressed N2O emission indicating the probably lower nitrification-denitrification rate and thereby higher NH4\(^+\) existed in soil. Perhaps, competition of NH4\(^+\) for the oxidation with CH4 by methanotrophs (Mosier et al., 1991), adversely stimulate CH4 emission from N-fertilized rice paddy fields receiving higher load of WV. Therefore, in flooded rice systems, the interactions between WV application and the CH4 cycle are complex with different processes when WV was applied at different levels, which needs further research in the future.

3.3. Total global warming potential (GWP\(_t\)) of N\(_2\)O and CH4

Data of GWP\(_t\) of N\(_2\)O and CH4 from rice paddy soil were organized in Fig. 5. GWP\(_t\) of N-fertilized paddy soil under a single rice cycle ranged from 5.24 ± 0.53 t CO\(_2\)-e ha\(^{-1}\) to 12.0 ± 0.71 t CO\(_2\)-e ha\(^{-1}\) and CH4 contributed 61.1–84.1% of GWP\(_t\). Interestingly, application of WV at a lower rate (5 t ha\(^{-1}\)) mitigated GWP\(_t\) by 31.5%, as result of its positive effect on reducing both N\(_2\)O and CH4 emissions (Figs. 2 and 4). However, if applied with larger amount (10 t ha\(^{-1}\)), WV reduced N\(_2\)O...
but increased CH₄ emission at a much larger scale (Figs. 2 and 4). Simultaneously considering the fact that CH₄ contributed 61.1–84.1% of GWP, in N-fertilized rice paddy soil, WV adversely increased GWP by 57.2% (Fig. 5). Therefore, 5 t ha⁻¹ WV is suggested for incorporating into rice paddy soil because it can suppress both N₂O and CH₄ emissions and thereby the GWPᵢ.

Present work evidenced that WV applications with different rates have contrast impacts on GWP, from rice paddy soil received N fertilizer, which was mainly as results of its contrary impact on CH₄ emission. In rice paddy soil, WV could change the C and N fates by influencing soil pH (Win et al., 2009), soil microbial community structure and enzyme activity (Lu et al., 2015) and the crop growth (Lashari et al., 2013; Polthanee et al., 2015). It is easily understood that WV application at varied rates has diverse impacts on these aspects related to the eventual CH₄ and N₂O emissions. Therefore, the optimal rate of soil amendment (such as MV in the present study) should be firstly investigated before its large-scale application.

4. Conclusion

Soil column experiment was conducted to evaluate the impact of WV application on N₂O, CH₄ emissions and the GWP, from N-fertilized rice paddy soil. Both N₂O and CH₄ emission flux patterns were not changed after WV incorporation. However, WV application indeed influenced GHGs emission rates, as well as the cumulative emission loads. When applied at lower rate (5 t ha⁻¹), WV simultaneously suppressed N₂O and CH₄ emission, and the corresponding GWPᵢ. Reduced N₂O, but dramatically increased CH₄ emissions were observed in rice paddy soil receiving 10 t ha⁻¹ WV, leading to a higher GWPᵢ. Therefore, application of WV at an optimal rate was recommended for its function of both reducing N₂O and CH₄ emissions from N-fertilized rice paddy soil. However, its impact mechanisms and long-term effects need further investigations.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2018.05.015.

References


