Effects of fertilizer regimes on greenhouse gas emissions in a Gray Luvisol from central Alberta, Canada

S X Zhu\textsuperscript{1,2,3} and S X Chang\textsuperscript{2}

\textsuperscript{1}College of Eco-Environmental Engineering, Guizhou Minzu University, Guiyang, Guizhou, 550025, China
\textsuperscript{2}Department of Renewable Resources, University of Alberta, Edmonton, Alberta, T6G2E3, Canada

E-mail: zhusixi2011@163.com

Abstract. This study investigated how different fertilizer regimes with a long-term repeated N application experiment affected on the soil Greenhouse gases (GHGs) emissions in a Gray Luvisolic from central Alberta, Canada. The results showed fertilizer regimes significantly influenced on GHGs emissions. The higher emissions of N$_2$O and CH$_4$ induced by NPKS soils were due to the superior utilization rate of mineral N and organic N. The CO$_2$ emission rates indicated that soil organic carbon (SOC) was upper after Manure application than that after NPKS and Lime applications. The lowest Global Warming Potential (GWP) and highest pH of Lime soils suggested that liming application cause a significant decrease of GHGs by changing soil properties, such as pH. As for CH$_4$ emissions during the incubation period, NPKS soil acted as sources, whereas the Lime and Manure soils acted as CH$_4$ sinks. In addition, the fertilization history with higher SOC stocks in the Manure soils did not affect higher N$_2$O emissions. In conclusion, this research showed liming application could be a better policy for improving soil properties in the acid Gray Luvisol from central Alberta, but liming may result in lower emissions of N$_2$O and CO$_2$ than the treatment of mineral fertilizer or farmyard manure.

1. Introduction

It is known that greenhouse gases (GHGs) includes carbon dioxide (CO$_2$), nitrous oxide (N$_2$O) and methane (CH$_4$), which are the important contributors to the global warming. Although the increasing rates of N$_2$O and CH$_4$ contents in the air are significantly slower than those of CO$_2$, their values of the global warming potential (GWP) over a 100-year time scale are 28 and 265 times higher than that of CO$_2$, respectively [1]. Agricultural soils are regarded as the primary resources of anthropogenic GHGs [2-4]. Soil management practices in agricultural systems, such as fertilization, may influence the release of soil carbon (C) and nitrogen (N) to the atmosphere by changing soil pH and microbial activities that in turn affect C and N cycle [5,6].

Many research indicated fertilizer regimes have significant effects on GHGs emissions in agricultural soils. Numerous studies indicated that N$_2$O emissions from inorganic fertilizers (such as NPK or urea) were significantly higher than those from organic manures in different cultivated soils [7,8]. However, other reports suggested that organic manures improve N$_2$O emissions in comparison with inorganic manure applications [3,9,10]. In addition, there was no remarkable influence on the emissions of N$_2$O between inorganic fertilizer and organic manure [11]. Meanwhile, Barton et al
and Cheng et al [14] showed that lime applications could lower GHGs emissions by decreasing N$_2$O fluxes and increasing CH$_4$ uptake. In spite of many research have analyzed the effects on soil GHGs emissions from different fertilizer regimes between organic and inorganic manures, it is very few reports about the fertilization experiments over decades [6,15]; thus it is important to study soil GHGs emissions in response to long-term fertilizer applications [6,10,16].

The gray-wooded soils occur mainly in the northern interior plains of Manitoba, Saskatchewan and Alberta in Canada, which are now known as Gray Luvisolic soils. The Breton Classical Plots of a Gray Luvisolic soil, which were established in central Alberta in 1930, provide a model of how diverse crop and fertilizer practices affect typical Gray Luvisolic soils. And 8 fertility treatments were founded in the Plots since 1980, including Control, Manure, NPK, Lime, NSK, PKS, NPS and NPKS (NPK in combination S-fertilizer) [17]. In addition, the chronic S-fertilization enhanced carbon fixation and reduces N$_2$O emissions in the Breton Classical Plots [18]. Meanwhile, in agricultural research, laboratory incubation of repacked soils is an important tool for elucidating GHGs emissions from agroecosystems [19]. Therefore, this paper is aimed to estimate the impacts of the standing fertilizer treatments (i.e. Manure, Lime and NPKS as compared with Control) on short-term (30 days) GHGs emission from Gray Luvisolic soils in the Breton classical plots by laboratory incubation experiments.

2. Material and methods

2.1. Soil sampling

Soil samples were collected from the Breton classical plots of the long-term fertilization test. The plots located in central Alberta, which is 53°07′N, 114°28′W and its elevation is 830 m. The soils are classified as a Gray Luvisol, which is typic Cryoboralf named by United States Department of Agriculture taxonomy. The silty loam soil locates in the Breton Plots, and it has a particle size distribution, which is 120 g clay kg$^{-1}$, 620 g silt kg$^{-1}$ and 260 g sand kg$^{-1}$ [20]. And in the plots, there are 8 fertilizer treatments since 1980 [17].

These field specimens were gathered from four fertilizer treatments (i.e. the Control, Manure, NPKS and Lime) in October, 2015 (table 1). In each treatment, a composite soil sample (about 2000 g) was gathered using soil augers (3.5-cm diameter) in the 0-10 cm depth from 4 random points within each point [21]. With a 2 mm sieve, fresh soil samples were passed through, then removed coarse fragments and roots, and manually homogenized in the laboratory. Then soil samples were stored at 4 °C until needed for the cultivating experiment. The main properties of the four soil samples are given in table 2.

| Treatment | N (kg/ha) | P (kg/ha) | K (kg/ha) | S (kg/ha) |
|-----------|-----------|-----------|-----------|-----------|
| Control   | 0         | 0         | 0         | 0         |
| Manure    | #         |           |           |           |
| NPKS      | *         | 22        | 46        | 5.5       |
| Lime      | 0         | 0         | 0         | 0         |

# N application via manure depends on the rotation (wheat-fallow: 90 kg N ha$^{-1}$ during cropped years).
* N amounts depend on the crop and its place in the rotation (wheat on fallow: 90 kg N ha$^{-1}$).

| Treatment | pH | TC (g kg$^{-1}$) | TN (g kg$^{-1}$) | C/N | WSOC (mg kg$^{-1}$) | WSON (mg kg$^{-1}$) |
|-----------|----|-----------------|-----------------|-----|---------------------|---------------------|
| Control   | 6.28±0.11 | 5.36±0.24 | 0.48±0.08 | 11.17±0.42 | 41.58±2.85 | 16.08±3.03 |
| Manure    | 6.27±0.13 | 10.81±0.46 | 0.82±0.13 | 13.18±0.58 | 93.11±8.85 | 28.25±3.80 |
| NPKS      | 4.70±0.06 | 5.28±0.16 | 0.43±0.09 | 12.28±0.61 | 41.92±4.18 | 47.08±9.43 |
| Lime      | 6.85±0.05 | 6.29±0.15 | 0.45±0.06 | 13.98±0.86 | 45.91±3.63 | 40.97±8.36 |
2.2. Soil incubation and gas sampling

For each fertilizer treatment, 16 soil samples, of which each sample is 25.0 g (dry-weight basis), were placed in conical flasks with 250-mL volume, respectively. Then, with a mini-pipette, each flask was added into deionized water evenly over the soil surface, and makes the soil 60% water-holding capacity (WHC). With rubber stoppers, these flasks were sealed and incubated 30 days at 20°C in the dark. To keep the aerobic condition in the flasks, these flasks were aerated for 5 min each day during the incubation period. And by using a mini-pipette and deionized water was added to compensate for water loss in the flasks every 3 days.

On days 1, 3, 6, 9, 12, 15, 18, 21, 24, 27 and 30, 4 flasks were taken randomly as replicates in each treatment. Using a gas-tight syringe, after the flasks had been sealed with rubber stoppers for 0 and 24 hours, a 20-mL gas sample was gathered from each flask. Then the gas sample was transferred to an evacuated gas-tight vial (12.5 mL) for GHGs analysis by a Varian CP-3800 gas chromatograph (Varian Canada, Mississaugua, Canada) with an electron capture detector. The detailed configuration and working condition of the gas chromatograph was described by Paterson et al. (2004). In addition, for each series and treatment, a set of 15 additional flasks were prepared in triplicate and stored in the same conditions on days 0, 6, 14, 22 and 30 in the incubation period, triplicate flasks from each treatment were randomly selected to test soil NH$_4^+$-N and NO$_3^-$-N, water-soluble organic C (WSOC) and N (WSON).

2.3. Soil properties analysis

Soil samples were shaken for 20 min with deionized water, which was 1:5 (mass: volume ratio). After the mixture stand for 5 min, the pH of the samples was measured using a pH meter (DMP-2 mV, Thermo Orion, USA). The concentrations of total C and N were analyzed by a CN analyzer (NA Series 2, CE Instruments, Italy). By 2 mol L$^{-1}$ KCl solution at a ratio of 1:5 (w:v), soil samples were extracted to analyze soil mineral N, including NH$_4^+$-N and NO$_3^-$-N, by the method of Li et al [22] and Miranda et al [23]. During the incubation (i.e., on days 0, 6, 14, 22 and 30), WSOC and WSON were conducted by extracting 10 g (dry-weight basis) of soil with 50 mL of deionized water, and centrifuged for 20 min at 4000×g. Then each sample was filtered through a 0.45-μm membrane filter. Lastly, SOC and SON concentrations were analyzed by a TOC-V Total Organic Carbon Analyzer (Shimadzu Crop, Kyoto, Japan).

2.4. Calculation and statistical analysis

Emission rates (fluxes) of N$_2$O, CO$_2$, and CH$_4$ were calculated by the following equation (1):

$$ F = \frac{\rho \times \Delta c \times V \times 273}{W \times \Delta t \times (273 + T)} $$

where $F$ is the flux of N$_2$O (ng N$_2$O-N kg$^{-1}$ h$^{-1}$), CO$_2$ (mg CO$_2$-C kg$^{-1}$ h$^{-1}$), and CH$_4$ (ng CH$_4$-C kg$^{-1}$ h$^{-1}$); $\rho$ is the density of N$_2$O, CO$_2$, or CH$_4$ under standard state; $\Delta c$ is the change of gas concentration between incubation time of 0 and 24 h (ppbv h$^{-1}$ or ppmv h$^{-1}$); $V$ is the head space volume of the conical flasks (mL); $W$ is the dry weight of soil (kg); $\Delta t$ is the interval between two measurements; and $T$ is the incubation temperature (°C) [24].

Provided a constant flux rate of each gas sampling from the beginning until the next gas sampling, the cumulative N$_2$O, CH$_4$, and CO$_2$ emissions in each replication were calculated from the integrated daily fluxes. The cumulative emissions of N$_2$O, CH$_4$ and CO$_2$ were calculated as the following equation (2) [25]:

$$ \text{Cumulative N}_2\text{O} \ (\text{or CH}_4, \text{CO}_2) \ \text{emission} = \sum_{i=1}^{n} \frac{(F_i + F_{i+1}) \times 24}{2 \times (t_{i+1} - t_i)} $$

where $F$ is the N$_2$O or CH$_4$, CO$_2$ emission rate (flux), $i$ is the $i$th measurement, the term of $(t_{i+1} - t_i)$ is the days between two adjacent days of the measurements, and $n$ is the total times of the measurements.

The GWPs were expressed by CO$_2$ equivalent flux values. And they were calculated by
multiplying CH₄ emissions rates by 28 and N₂O emission rates by 265, and adding the products to the CO₂ emission rates [1].

By the SPSS 16.0 software package for Windows (SPSS Inc., Chicago, USA), all data were statistically analyzed. The effects of soil properties on each cumulative of the GHGs (N₂O, CO₂ and CH₄) emission was evaluated by one-way ANOVA, followed by the least significant difference test at P<0.05. All figures are made by Origin 9.0 (Origin Lab Inc, Corporation, USA).

Figure 1. Temporal variation of NH₄⁺-N, NO₃⁻-N, available nitrogen (NH₄⁺-N+NO₃⁻-N), pH, SOC and SON contents in different treatments at 60% water holding capacity. AN: Vertical bars indicate standard error of the means (n=4).
3. Results

3.1. Soil properties

During the whole incubation, the means NO$_3^-$-N concentrations of NPKS, Manure, Control and Lime soils were 46.2, 29.7, 22.0 and 13.4 mg kg$^{-1}$, respectively (figure 1(a)). Meanwhile, the means of NH$_4^+$-N concentrations of the four treatments were 18.1, 6.6, 6.4 and 6.2 mg kg$^{-1}$, respectively (figure 1(b)). These indicated that NO$_3^-$-N was the dominant mineral nitrogen (N). In all treatments, NO$_3^-$-N concentrations increased significantly throughout the incubation period (figure 1(a)). Across the incubation period, soil mineral N in Control, Manure and Lime soils were significantly lower than those in NPKS soils (figure 1(a)-1(c), P<0.05). And soil mineral N had significant positive effects on N$_2$O and CH$_4$ cumulative emissions, but not CO$_2$ (P< 0.05; table 3). The pH of Lime, Manure, Control and NPKS soils were 6.3, 5.7, 5.5 and 4.2, respectively (figure 1(d)), indicating that Lime increased significantly pH. And pH had remarkable negative impacts on N2O cumulative emissions (table 3).

During the whole incubation, the means WSOC concentrations in the Manure, NPKS, Lime and Control treatments were 82.0, 45.0, 40.9 and 35.4 mg kg$^{-1}$, respectively (figure 1(e)), indicating that the Manure soils had significantly greater WSOC compared with other treatments. For one thing, the means of SON were 83.6, 46.4, 38.5 and 28.2 mg kg$^{-1}$ in NPKS, Manure, Lime and Control treatments respectively (figure 1(f)), indicating that the NPKS soils had significantly higher SON compared with other soils.

| Gas                  | pH  | NO$_3^-$-N (mg kg$^{-1}$) | NH$_4^+$-N (mg kg$^{-1}$) | AN (mg kg$^{-1}$) | WSOC (mg kg$^{-1}$) | WSON (mg kg$^{-1}$) |
|----------------------|-----|--------------------------|---------------------------|------------------|-------------------|-------------------|
| N$_2$O cumulative    | -0.897** | 0.804**                   | 0.974**                   | 0.880**          | -0.131            | 0.718**           |
| emission (µg N kg$^{-1}$) |     |                          |                           |                  |                   |                   |
| CO$_2$ cumulative     | 0.158 | 0.011                    | -0.279                    | -0.068           | 0.839**           | -0.328            |
| emission (mg N kg$^{-1}$) |     |                          |                           |                  |                   |                   |
| CH$_4$ cumulative     | -0.622 | 0.578*                    | 0.840**                   | 0.671**          | -0.307            | 0.709**           |
| emission (µg C kg$^{-1}$) |     |                          |                           |                  |                   |                   |

*Correlation is significant at the 0.05 level; ** Correlation is significant at the 0.01 level.

3.2. N$_2$O emissions

For the NPKS soils, from the first day to the fifteenth day, the temporal pattern of the N$_2$O emission increased gradually and then declined little by little to the end of the 30-day incubation. However, the N$_2$O fluxes in Control, Manure and Lime soils remained relatively constant during the whole incubation except on day 27 (figure 2(a)). During the whole incubation, the N$_2$O emission rates ranged from 201.0 to 343.3 ng N kg$^{-1}$ h$^{-1}$ in the NPKS soil, while Control, Manure and Lime soils were from 21.8 to 98.7, 16.0 to 64.8 and 6.7 to 31.0 ng N kg$^{-1}$, respectively. In addition, the NPKS soils had significantly higher N$_2$O cumulative emissions than Control, Manure and Lime soils (figure 2(b)). N$_2$O cumulative emissions were not significant different (30.3 and 25.0 µg N kg$^{-1}$, respectively) between the control and Manure treatments, while the values was significantly higher than that of Lime treatment (12.6 µg N kg$^{-1}$).
Figure 2. Changes of the N\textsubscript{2}O fluxes and cumulative emissions from Control, NPKS, Manure and Lime soils at 60% water holding capacity. Vertical bars indicate standard error of the means (n=4).

3.3. \textit{CO}_2 emissions
As for the CO\textsubscript{2} fluxes, it is a general trend that the values in the first day arrived highest in the four treatments and those subsequently decreased until the incubation come to an end (figure 3(a)). This indicated the available carbon for mineralization declined step by step with time. Fertilizer treatments affected significantly on the CO\textsubscript{2} fluxes, and CO\textsubscript{2} fluxes from Manure soils exceeded outstandingly to Control, NPKS and Lime soils. The mean values of the CO\textsubscript{2} emissions for the Manure, Control, NPKS and Lime soils were 0.82, 0.54, 0.49 and 0.44 mg C kg\textsuperscript{-1}, respectively (figure 3(a)). In addition, the Manure soils had significantly higher CO\textsubscript{2} cumulative emissions than the other soils, but there were no significant differences among the control, NPKS and Lime treatments (393.3, 355.7 and 316.3 mg C kg\textsuperscript{-1}, respectively, figure 3(b)).

Figure 3. Changes of the CO\textsubscript{2} fluxes and cumulative emissions from Control, NPKS, Manure and Lime soils at 60% water holding capacity. Vertical bars indicate standard error of the means (n=4).

3.4. \textit{CH}_4 emissions
In general, the CH\textsubscript{4} fluxes firstly decreased gradually from the first day to the 21\textsuperscript{st} day and then increased gradually during the remainder of the incubation (figure 4(a)). The mean values of the CH\textsubscript{4}
emissions for the NPKS, Lime, Control and Manure soils were 0.4, -10.5, -19.7 and -20.5 ng C kg\(^{-1}\), respectively (figure 4(a)), indicating the NPKS soil acted as sink for atmospheric CH\(_4\) during the incubation period, while the Lime, Control and Manure soils acted as sinks for atmospheric CH\(_4\). In addition, the NPKS soils had significantly higher CH\(_4\) cumulative emissions than the other soils (figure 4(b)). CH\(_4\) cumulative emissions were not significant different (-14.6 and -15.3 ng C kg\(^{-1}\), respectively) between the control and Manure treatments, but was significantly lower than that from Lime treatment (-7.9 ng C kg\(^{-1}\)).

![Figure 4](image)

**Figure 4.** Changes of the CH\(_4\) fluxes and cumulative emissions from Control, NPKS, Manure and Lime soils at 60% water holding capacity. Vertical bars indicate standard error of the means (n=4).

### 3.5. Global warming potential

The contribution to GWP of the three GHGs decreased in the following order by CO\(_2\), N\(_2\)O and CH\(_4\) from high to low in all treatments (figures 2-4). The highest value of GWP (0.58 g CO\(_2\) equivalent/kg) occurred in the Manure soils, the lowest value in the Lime soils (0.32 g CO\(_2\) equivalent/kg), and the intermediate value in the Control and NPKS soils (0.40 and 0.41 g CO\(_2\) equivalent/kg, respectively. figure 5).

![Figure 5](image)

**Figure 5.** Total GWPs of N\(_2\)O, CH\(_4\) and CO\(_2\) during a 30-day incubation. Different letters in the different treatments represent significant difference at P<0.05. Vertical bars indicate standard error of the means (n=4).
4. Discussion

Previous research reported that fertilizer regimes in agricultural system had significant effects on \( \text{N}_2\text{O} \) emissions in soils [26,27]. In this study, fertilizer treatments affected the cumulative \( \text{N}_2\text{O} \) emissions, which decreased in the following order by NPKS, Control, Manure and Lime (figure 2), in line with these studies of Ding et al [7], Zhang et al [6] and Louro et al [28]. Mørkved et al (2007) reported that the highest soil \( \text{N}_2\text{O} \) fluxes from the NPK with straw treatments had a lower pH than those from manure applications. Similarity, this study showed that \( \text{N}_2\text{O} \) emissions had a negative and significant correlation with soil pH. And the NPKS treatment had the highest \( \text{N}_2\text{O} \) emissions with lowest soil pH compared with other three treatments. In contrast, \( \text{N}_2\text{O} \) emissions of NPKS treatments were higher than those from Manure in this study. This result was according with other studies in sandy soils, which indicated that \( \text{N}_2\text{O} \) emissions of inorganic fertilizer treatments were higher than those of Manure [8,29,30].

\( \text{N}_2\text{O} \) emissions in the soils mainly come from nitrification denitrification under anaerobic conditions and under aerobic conditions [31,32]. Meanwhile, under moderately moist conditions, the predominant \( \text{N}_2\text{O} \)-producing process (aerobic, WHC 60%) is generally reduced nitrification [33], which just likes the incubation condition in this study. In addition, the NPKS treatment had the highest \( \text{N}_2\text{O} \) emissions with lowest soil pH compared with other three treatments, which was studied by Kitzler et al [34] and Brumme and Beece [35]. This is likely because that liming application increased pH (figure 1(d)) and might provide an adverse condition for nitrification in the acid Gray Luvisol in central Alberta. Therefore, one of the most important factors to decrease \( \text{N}_2\text{O} \) emissions was likely from the increasing of soil pH by liming in the Gray Luvisolic soils [24].

Many researches showed that there were significant correlations between mineral N and \( \text{N}_2\text{O} \) emissions in soils [3,36-38]. As the mineral N is the primary substrate for \( \text{N}_2\text{O} \) production in soils, an increase in mineral N is generally associated with higher \( \text{N}_2\text{O} \) emissions [39]. In the present study, both \( \text{NH}_4^+ \)-N and \( \text{NO}_3^- \)-N concentrations were significantly and positively correlated with \( \text{N}_2\text{O} \) emissions (table 3), suggesting that the high concentration of available N in the NPKS soils was responsible for the dramatic increase in \( \text{N}_2\text{O} \) fluxes in the soils [24,39,40]. In addition, this study showed that Manure soils had significantly greater SOC but lower \( \text{N}_2\text{O} \) emissions compared with NPKS soils, indicating that the increasing SOC of Manure applications may be an effective way to cut down \( \text{N}_2\text{O} \) emissions in the Gray Luvisolic soils.

\( \text{CO}_2 \) emission in the soils was caused by microbial respiration in the laboratory incubation, which was mainly influenced by the discharge of readily decomposable SOC [33,41,42]. This study showed that \( \text{CO}_2 \) cumulative emissions were significantly, positively affected by SOC (table 3). Moreover, we found that fertilizer treatments had a highly significant effect on the \( \text{CO}_2 \) fluxes emissions, that \( \text{CO}_2 \) fluxes and SOC in the Manure soil significantly greater than those in the Control, NPKS and Lime soils throughout the incubation period. This conclusion was reported by previous studies [3,6,43]. In contrast, the Lime had the lowest \( \text{CO}_2 \) emissions and the lowest GWP indicated that Lime application may be the most effective measure in all treatments to mitigate \( \text{CO}_2 \) emissions from Gray Luvisolic soils in central Alberta. In addition, on the first day, \( \text{CO}_2 \) fluxes in all treatments attained the highest values and then subsequently decreased in the end of the incubation period (figure 3(a)). This was due to higher microbial activity and the rate of soil respiration at the beginning of the incubation [44,45].

Soils \( \text{CH}_4 \) emissions originate from the process of microbial decomposition under strictly anaerobic conditions [46,47]. During the incubation period, NPKS soils acted as sources for atmospheric \( \text{CH}_4 \), while the Lime, Control and Manure soils might be sinks in this study (figure 4). However, anaerobic microsites in NPKS soils could induce weak fluxes of \( \text{CH}_4 \) at 60% WHC. Meanwhile, \( \text{CH}_4 \) emissions are influenced by soil properties, such as soil pH, \( \text{NH}_4^+ \)-N and SOC [48-50]. In addition, \( \text{CH}_4 \) emissions have a direct relationship with soil mineral N by preventing the oxidation of \( \text{CH}_4 \) to the atmosphere [51]. In this study, soil mineral N had significant positive effects on \( \text{N}_2\text{O} \) and \( \text{CH}_4 \) cumulative emissions (table 3). This result was not in agreement with other reports, which were negative relationships of \( \text{CH}_4 \) uptake and soil \( \text{NH}_4^+ \)-N concentration [52,53]. This phenomenon may
due to the higher amount of mineral N, which induced the positive emissions from the Gray Luvisolic soils in central Alberta.

In this study, the contribution of the three GHGs to GWPs increased in the following order by CH$_4$, N$_2$O and CO$_2$ (figures 2-4), which indicated that the greenhouse effect for the releases of CO$_2$, N$_2$O and CH$_4$ mainly depended on CO$_2$ emissions from the Gray Luvisolic soils to atmosphere [54-56]. Meanwhile, the GWPs of the three GHGs were significantly influenced by fertilizer treatments, and the highest GWPs were observed for the Manure soils (figure 5).

5. Conclusion
In this study, fertilizer regimes had significant effects on soil GHGs emissions, which higher N$_2$O and CH$_4$ emissions were induced by NPKS application and higher CO$_2$ emissions by the Manure applications. Meanwhile, the lowest GWP and GHGs emissions of Lime soils suggested that it may be a preferred fertilizer strategy for mitigating soil greenhouse effect from the application of liming in the acid Gray Luvisolic soils in central Alberta. In addition, higher N$_2$O and CH$_4$ emissions from NPKS soils were due to a high availability of mineral N and organic N. However, further studies in the field environments should be carried out to confirm the result from the laboratory incubation experiments.

Acknowledgments
This work was supported by National Natural Science Foundation of China (31560107) and Guizhou Provincial Science-technology Support Plan Projects in 2018 (Guizhou Science Support [2018]2807).

References
[1] IPCC Climate Change 2013 The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press)
[2] Sass R L and Fisher F M 1997 Methane emission from rice paddies: a process study summary Nutr. Cycl. Agroecosyst. 49 119-27
[3] Ding W, Meng L, Yin Y, Cai Z and Zheng X 2007 CO$_2$ emission in an intensively cultivated loam as affected by long-term application of organic manure and nitrogen fertilizer Soil Biol. Biochem. 39 669-79
[4] Rock L, Ellert B H, Mayer B and Norman A L 2007 Isotopic composition of tropospheric and soil N$_2$O from successive depths of agricultural plots with contrasting crops and nitrogen amendments J. Geophys. Res. 112 D18303
[5] Johnson J M, Archer D W, Weyers S L and Barbour N W 2011 Do mitigation strategies reduce global warming potential in the northern US corn belt? J. Environ. Qual. 40 1551-9
[6] Zhang X B, Wu L H, Sun N, et al 2014 Soil CO$_2$ and N$_2$O emissions in maize growing season under different fertilizer regimes in an upland red soil region of South China J. Integrat. Agr. 13 604-14
[7] Ding W X, Luo J F, Li J, et al 2013 Effect of long-term compost and inorganic fertilizer application on background N$_2$O and fertilizer-induced N$_2$O emissions from an intensively cultivated soil Sci. Total Environ. 465 115-24
[8] Lopez-Fernandez S, Diez J A, Hernaiz P, Arce A, Garcia-Torres L and Vallejo A 2007 Effects of fertiliser type and the presence or absence of plants on nitrous oxide emissions from irrigated soils Nutr. Cycl. Agroecosyst. 78 279-89
[9] Hayakawa A, Akiyama H, Sudo S, et al 2009 N$_2$O and NO emissions from an andisol field as influenced by pelleted poultry manure Soil Biol. Biochem. 41 521-9
[10] Zhai L M, Liu H B, Zhang J Z, et al 2011 Long-term application of organic manure and mineral fertilizer on N$_2$O and CO$_2$ emissions in a red soil from cultivated maize-wheat rotation in China Agr. Sci. Chin. 10 1748-57
[11] Meng L, Ding W X and Cai Z C 2005 Long-term application of organic manure and nitrogen fertilizer on N$_2$O emissions, soil quality and crop production in a sandy loam soil Soil Biol.
[12] Bartona L, Murphya D V and Butterbach-Bahlb K 2013a Influence of crop rotation and liming on greenhouse gas emissions from a semi-arid soil Agr. Ecosyst. Environ. 167 23-32

[13] Barton L, Gleeson D B, Maccarone L D, et al 2013b Is liming soil a strategy for mitigating nitrous oxide emissions from semi-arid soils? Soil Biol. Biochem. 62 28-35

[14] Cheng Y, Zhang J B, Wang J, et al 2015 Soil pH is a good predictor of the dominating N2O production processes under aerobic conditions J. Plant Nutri. Soil Sci. 178 370-3

[15] Jäger N, Duffner A, Ludwig B and Flessa H 2013 Effect of fertilization history on short-term emissionof CO2 and N2O after the application of different N fertilizers - a laboratory study Arch. Agron. Soil Sci. 59 161-71

[16] Johnston A E 1997 The value of long-term field experiments in agricultural, ecological and environmental research Adv. Agron. 59 291-333

[17] Dyck M F, Roberston J A and Puurveen D 2012 The university of Alberta Breton plots Prairie Soil Crops J. 5 96-115

[18] Giweta M, Dyck M F, Malhi S S, et al 2014 Long-term S-fertilization increases carbon sequestration in a sulfur-deficient soil Can. J. Soil Sci. 94 295-301

[19] Guo X B, Drury G F, Eynolds W D, et al 2013 Nitrous oxide and carbon dioxide emissions from aerobic and anaerobic incubations: effect of core length Soil Sci. Soc. Am. J. 77 817-29

[20] Goglio P, Grant B B, Smith W N, et al 2014 Impact of management strategies on the global warming potential at the cropping system level Sci. Total Environ. 490 921-33

[21] Duan M, House J and Chang S X 2015 Limiting factors for lodgepole pine (Pinus contorta) and white spruce (Picea glauca) growth differ in some reconstructed sites in the Athabasca oil sands region Ecol. Eng. 75 323-31

[22] Li Y F, Zhang J J and Chang S X 2014 Converting native shrub forests to Chinese chestnut plantations and subsequent intensive management affected soil C and N pools Forest Ecol. Manag. 312 161-9

[23] Miranda K M, Espey M G and Wink D A 2001 A rapid, Simple spectrophotometric method for simultaneous detection of nitrate and nitrite Biol. Chem. 5 62-71

[24] Cheng Y, Cai Z C, Chang S X, Wang J and Zhang J B 2013 Effects of soil pH and salt on N2O production in adjacent forest and grassland soils in central Alberta, Canada J. Soil Sediment. 13 863-8

[25] Cai Y J, Wang X D, Ding W X, Tian L L, Zhao H and Lu X Y 2013 Potential short-term effects of yak and Tibetan sheep dung on greenhouse gas emissions in two alpine grassland soils under laboratory conditions Biol. Fertil. Soil. 49 1215-26

[26] Bouwman A F, Boumans L J M and Batjes N H 2002 Emissions of N2O and NO from fertilized fields: summary of available measurement data Global Biogeochem. Cy. 16 1058

[27] Stehfest E and Bouwman L 2006 N2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions Nutr. Cycl. Agroecosyst. 74 207-28

[28] Bouwman A F, Boumans L J M and Batjes N H 2002 Emissions of N2O and NO from fertilized fields: summary of available measurement data Global Biogeochem. Cy. 16 1058

[29] Louro A, Báez D, García M I, et al 2015 Nitrous oxide emissions from forage maize production on a Humic Cambisol fertilized with mineral fertilizer or slurries in Galicia, Spain Geoderma. Regional 5 54-63

[30] Dick J, Kaya B, Soutoura M, Skiba U, Smith R, Niang A and Tabo R 2008 The contribution of agricultural practices to nitrous oxide emissions in semi-arid Mali Soil Use Manage. 24 292-301

[31] Stevens R J, Laughlin R J, Burns L C, Arah J R M and Hood R C 1997 Measuring the contributions of nitrification and denitrification to the flux of nitrous oxide from soil Soil Biol. Biochem. 29 139-51

[32] Wolf I and Russow R 2000 Different pathways of formation of N2O, N2 and NO in black earth
soil **Soil Biol. Biochem.** **32** 229-39

[33] Yang G R, Hao X Y, Li C L and Li Y M 2015 Effects of greenhouse intensive cultivation and organic amendments on greenhouse gas emission according to a soil incubation study *Arch. Agron. Soil Sci.* **61** 89-103

[34] Brumme R and Beese F 1992 Effects on liming and nitrogen fertilization on emissions of CO$_2$ and N$_2$O from a temperate forest *J. Geophys. Res.* **97** 12851-8

[35] Kitzler B, Zechmeister-Boltenstern S, Holtermann C, Skiba U and Butterbach-Bahl K 2006 Nitrogen oxides emission from two beech forests subjected to different nitrogen loads *Biogeosciences* **3** 293-310

[36] Martin L S, Vallejo A, Dick J and Skiba U M 2008 The influence of soluble carbon and fertilizer nitrogen on nitric oxide and nitrous oxide emissions from two contrasting agricultural soils *Soil Biol. Biochem.* **40** 142-51

[37] Tapia N T, Mondragon C C, Murrieta M S V, Cleemput O V and Dendooven L 2008 Inorganic N dynamics and N$_2$O production from tannery effluents irrigated soil under different water regimes and fertilizer application rates: A laboratory study *Appl. Soil Ecol.* **38** 279-88

[38] Lin X, Wang S, Ma X, Xu G, Luo C, Li Y, Jiang G and Xie Z 2009 Fluxes of CO$_2$, CH$_4$, and N$_2$O in an alpine meadow affected by yak excreta on the Qinghai-Tibetan plateau during summer grazing periods *Soil Biol. Biochem.* **41** 718-25

[39] Vaughan S M, Dalal R C, Harper S M and Menzies N W 2011 Effect of fresh green waste and green waste compost on mineral nitrogen, nitrous oxide and carbon dioxide from a Vertisol *Waste Manage.* **31** 1720-8

[40] Huang J X, Chen Y Q, Sui P, Nie S W and Gao W S 2014 Soil nitrous oxide emissions under maize-legume intercropping system in the North China Plain *J. Integr. Agr.* **13** 1363-72

[41] Rustad L E, Huntington T G and Boone R D 2000 Controls on soil respiration: Implications for climate change *Biogeochemistry* **48** 1-6

[42] Janssens I A, Lankreijer H, Matteucci G, Kowalski A S, Buchmann N, Epron N, Pilegaard K, Kutsh W, Longdoz B, Grünwald T, et al 2001 Productivity overshadows temperature in determining soil and ecosystem respiration across European forests *Glob. Chang. Biol.* **7** 269-78

[43] Mancinelli R, Campiglia E, di Tizio A and Marinari S 2010 Soil carbon dioxide emission and carbon content as affected by conventional and organic cropping systems in Mediterranean environment *Appl. Soil Ecol.* **46** 64-72

[44] Scott A, Ball B C, Crichton I J and Aitken M N 2000 Nitrous oxide and carbon dioxide emissions from grassland amended with sewage sludge *Soil Use Manage.* **16** 36-41

[45] Urzedo D I, Franco M P, Pitombo L M and Carmo J B 2013 Effects of organic and inorganic fertilizers on greenhouse gas (GHG) emissions in tropical forestry *Forest Ecol. Manage.* **310** 37-44

[46] Smith K A, Ball T, Conen F, Dobbie K E, Massheder J and Rey A 2003 Exchange of greenhouse gases between soil and atmosphere: interactions of soil physical factors and biological processes *Eur. J. Soil Sci.* **54** 779-91

[47] Lang M, Cai Z C and Changeet S X 2011 Effects of land use type and incubation temperature on greenhouse gas emissions from Chinese and Canadian soils *J Soil. Sediment.* **11** 15-24

[48] Verchot L V, Davidson E A, Cattânio J H, et al 2000 Land-use change and biogeochemical controls of methane fluxes in soils of eastern Amazonia *Ecosystems* **3** 41-56

[49] Bodelier P L E and Laanbroek H J 2004 Nitrogen as regulatory factor of methane oxidation in soils and sediments *FEMS Microbiol. Ecol.* **47** 265-77

[50] Merino A, Pérez-Batallón P and Macías F 2004 Responses of soil organic matter and greenhouse gas fluxes to soil management and land use changes in a humid temperate region of southern Europe *Soil Biol. Biochem.* **36** 917-25

[51] Bodelier P L E 2011 Interactions between nitrogenous fertilizers and methane cycling in wetland and upland soils *Curr. Opin. Environ. Sustain.* **3** 379-88
[52] Dobbie K E and Smith K A 1996 Comparison of CH$_4$ oxidation rates in woodland, arable and set aside soils *Soil Biol. Biochem.* 28 1357-65

[53] Ruser R, Flessa H, Schilling R, Steindl H and Beese F 1998 Soil compaction and fertilization effects on nitrous oxide and methane fluxes in potato fields *Soil Sci. Soc. Am. J.* 62 1587-95

[54] Pei Z, Ouyang H, Zhou C and Xu X 2003 Fluxes of CO$_2$, CH$_4$ and N$_2$O from alpine grassland in the Tibetan Plateau *J. Geogr. Sci.* 13 27-34

[55] Lin X, Wang S, Ma X, Xu G, Luo C, Li Y, Jiang G and Xie Z 2009. Fluxes of CO$_2$, CH$_4$, and N$_2$O in an alpine meadow affected by yak excreta on the Qinghai-Tibetan plateau during summer grazing periods. *Soil Biol. Biochem.* 41 718-25.

[56] Jiang C, Yu G, Fang H, Cao G and Li Y 2010 Short-term effect of increasing nitrogen deposition on CO$_2$, CH$_4$ and N$_2$O fluxes in an alpine meadow on the Qinghai-Tibetan Plateau, China *Atmos. Environ.* 44 2920-6