博 士（農 学） 金　　　涛

学 位 論 文 題 名

Effect of chemical nitrogen fertilizer and manure application on the greenhouse gases emissions from a managed grassland in southern Hokkaido, Japan

（北海道南部の採草地における温室効果ガス放出に対する窒素化学肥料と堆肥施与の影響）

学位論文内容の要旨

Agricultural lands (lands used for agricultural production, consisting of cropland, managed grassland and permanent crops including agro-forest and bio-energy crops) occupy about 40 – 50 % of the Earth's land surface (IPCC, 2007b). In addition, the managed grasslands cover 3 billion hectares (about 20%) of 14.9 billion of the World's land surface and are a major system of livestock (i.e. sheep, beef and dairy cattle, and deer) production in many countries (Surinder and Saggar, 2007). The agricultural sector plays a significant role in the global mitigation potential for three major greenhouse gases (GHGs); carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). However, as mitigation practices can impact more than one GHG positively and negatively,, it is important to consider the impact of mitigation options on all GHGs. Chemical nitrogen (N) fertilizer and manure application may increase plant growth and in turn mitigate CO_2 emission, but it can increase N_2O emission, and reduce CH_4 uptake. Therefore, the objectives of this study were: to verify the effects of chemical N fertilizer and manure application on the GHGs emissions from a managed grassland in southern Hokkaido, which include all three major greenhouse gases CO_2, CH_4 and N_2O; and to make proper options for mitigation GHGs emissions from managed grassland.

Three experimental plots were set up during November 2004 to October 2009 on a managed grassland of the Shizunai Experimental Livestock Farm, Field Science Center for Northern Biosphere of Hokkaido University, one for treatment with chemical N fertilizer (F plot), another with either both beef cattle manure and chemical N fertilizer or only beef cattle manure (M plot) and the other one with no chemical N fertilizer and no manure (C plot). In M plot, a supplement of chemical N fertilizer was added in 2005, 2006 and 2007, but only manure was applied in 2008 and 2009 (the M plot in 2007 corresponded practically to manure application only, because chemical N fertilization application rate was only 21 kg N ha^{-1} yr^{-1} and contributed only 3.2 % of total soil gross mineral N, which composed of applied chemical N fertilizer and mineral N released from soil organic matter (SOM) and manure decomposition.). Seasonal CO_2, N_2O and CH_4 fluxes were measured by closed-chamber method in each treatment plot at 4 or 6 replications. In order to estimate the mineralization rate of SOM, a bare plot (B plot) was established from November 2004 to October 2009. That B plot received neither chemical N fertilizer nor manure, and the CO_2 fluxes were measured. Soil carbon (C) sequestration is expressed as net biome production (NBP), which dependent on the balance between C input by net plant production (NPP) and manure application and C loss by harvest and CO_2 emissions through organic matter decomposition. Soil denitrifying enzyme activity (DEA) in the root-mat layer (0 – 2.5 cm) and in the mineral soil layer (2.5 – 5 cm) of each treatment plot was measured using an acetylene inhibition method after treatment with NO_3^--N addition only, glucose addition only, both NO_3^--N and glucose addition or neither NO_3^--N nor glucose addition. The global worming potential (GWP) was calculated as sum of N_2O and CH_4 emissions and negative soil C sequestration by converting the each gas unit to CO_2 equivalent by using the factors of GWP at the 100-year time horizon recommended by IPCC 2007a (CO_2:CH_4:N_2O = 1:25:298).

The annual CO_2 emissions from the F, M, C, and B plots were 9.1 – 10.9, 10.9 – 15.2, 8.8 – 12.5 and 4.0 – 4.9 Mg CO_2-C ha^{-1} yr^{-1}, respectively. There were significant differences among years and treatment plots. There were significant differences across different years and treatment plots. Significant interaction between the year and treatment plot was also observed. The annual CO_2 emission from the B plot was always significantly lower than other plots. The annual CO_2 emission from the M plot was significantly higher than that from the F plot in 2007 and significantly higher than that from both the F and C plots in 2008 and 2009. CO_2 emissions did not significantly differ between the F and C plots.

The range of annual NBP in the C plot was -4.6 to -3.9 Mg C ha^{-1} yr^{-1} during 2005 to 2009, which indicated a net C loss from this plot. The NBP in the F plot was slightly higher than that in the C plot, which ranged from -4.5 to -3.7 Mg C ha^{-1} yr^{-1}. The NBP in the M plot ranged from -1.4 to 1.2 Mg C ha^{-1} yr^{-1}, which

was quite larger than that in other plots. Compare with no chemical N fertilizer or manure application, chemical N fertilizer application increased 0 – 0.4 Mg C ha^{-1} yr^{-1} of soil C sequestration and manure application increased 3.8 – 6.0 Mg C ha^{-1} yr^{-1} of soil C sequestration.

Annual CH_4 emissions ranged from -0.1 to 4.0, -0.2 to 1.4 and -0.1 to 5.4 kg CH_4-C ha^{-1} yr^{-1} in F, M and C plots, respectively. There was no significant difference in annual CH_4 emission among the treatment plots. Soil temperature and precipitation were important factors for controlling the CH_4 fluxes.

The DEA with both NO_3^--N and glucose addition, which indicates DEA potential, was significantly higher in root-mat soil than in mineral soil in all treatment plots. The DEA potential together with the DEA measured with NO_3^--N addition only had a significantly positive correlation with soil pH ($P < 0.05$). Soil pH was significantly influenced by N source, which was significantly lower in the F plot than in the M and C plots.

The ranges of annual N_2O emissions from the F, M and C plots were 1.2 – 2.9, 0.9 – 4.9, and 0.4 – 0.7 kg N_2O-N ha^{-1} yr^{-1}, respectively. Different linear regression models for the annual N_2O emission and the chemical N application rate were observed in the plots treated with manure ($y = 0.0226x + 1.296$, $R^2 = 0.88$) compared to the plots treated with chemical N fertilizer only ($y = 0.0127x + 0.6088$, $R^2 = 0.92$). And the linear regression model with a higher slope value was found in the plots treated with manure. Across all treatment plots, the annual N_2O emissions were significantly correlated with the total soil gross mineral N ($y = 0.0107x - 3.6999$, $R^2 = 0.62$). When the data were segregated as the N_2O emission from manure application only (including the M plot in 2007) and as the N_2O emission from chemical N fertilizer application, two different regression models between the annual N_2O emissions and the total soil gross mineral N surplus were observed and the regression model with a higher slope value was observed in the plots treated with chemical N fertilizer.

The GWP ranged from 14.6 to 18.0, -3.9 to 6.0 and 14.6 to 17.3 Mg CO_2 equivalents ha^{-1} yr^{-1} in the F, M and C plot, respectively. This indicated chemical N fertilizer application did not decrease the GWP but manure application could decrease the GWP. And in this study, the maximum of CH_4 emission in CO_2 equivalents was only 0.2 Mg CO_2 equivalents ha^{-1} yr^{-1}, which contributed 1.2% of GWP from the managed grassland.

The results obtained in this study summarized as follows: 1) The contribution of CH_4 emission to GHGs emissions for managed grassland can be negligible; 2) To increase the soil C sequestration, manure application is recommend; 3) Chemical N fertilizer application could increase the N_2O emission, especially when apply the chemical N fertilizer with manure together could result in higher N_2O emission compare with chemical N fertilizer only, owing to higher soil DEA with higher soil pH under manure application than under chemical N fertilizer application only; 4) When the total soil gross mineral N surplus increase, chemical N fertilizer application could lead more high N_2O emission than only manure application; and 5) Therefore, application of only manure is highly recommended to mitigate the GWP from managed grasslands.

学位論文審査の要旨

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本論文は英文124頁，図20，表21，9章からなり，参考論文4編が付されている．

管理草地は30億haと，世界の陸地149億haの約20%を占め，多くの国で家畜（例えば羊，肉牛，乳牛および鹿）生産の場となっている。農業部門は，温室効果ガスである二酸化炭素（CO_2），メタン（CH_4），亜酸化窒素（N_2O）の削減において，重要な役割を担う。しかし，ある削減策が 1 種のガスに効果があっても，他のガスの放出を促進する可能性もあるため，削減策を提案するときには，すべてのガスへの影響を考慮することが重要である。窒素化学肥料や堆肥の施与は作物生産を促進し，CO_2 を削減すると考えられるが，N_2O 放出を促進し，CH_4 吸収を抑制する可能性がある。そのため，本研究の目的は窒素化学肥料と堆肥の施与が北海道南部の採草地における温室効果ガス収支（CO_2，CH_4 および N_2O）に与える影響を明らかにし，採草地における適切な温室効果ガス削減策を提案することとした。

北海道大学北方生物圏フィールド科学センター静内研究牧場の採草地において，2004年11月から2009年10月まで，三つの処理区を設けた。一つ目が窒素化学肥料区（F区），二つ目が肉牛堆肥・窒素化学肥料併用もしくは肉牛堆肥区（M区），三つ目が窒素化学肥料および堆肥無施与区（C 区）である。堆肥区では，2005，2006，2007 年には窒素化学肥料を併用したが，2008，2009年は堆肥のみを施与した。ただし，2007年の堆肥区は，窒素化学肥料が21 kg N ha^{-1} yr^{-1}で，土壌へ施与される無機態窒素の3.2%であったため，実際には堆肥のみの施与に相当した。CO_2，N_2O，CH_4 フラックスは，クローズドチャンバー法で測定した。土壌有機炭素の無機化量は，裸地区（窒素化学肥料および堆肥を施与無し）の CO_2 フラックスから得た。土壌炭素蓄積量は，純生物相生産（NBP）として表され，純一次生産（NPP）と堆肥投入量による炭素インプットと，収穫と有機物分解による炭素アウトプットの差として見積もられた。地球温暖化指数（GWP）は，CO_2，CH_4，N_2O の放射強制力係数をそれぞれ 1，25，298 として，N_2O・CH_4 放出量とNBP(負値)の合計として求めた。

年間CO_2放出量はF，M，C，B区それぞれ9.1～10.9，10.9～15.2，8.8～12.5，4.0～4.9 Mg CO_2-C $ha^{-1}yr^{-1}$であり，年次間および処理区間に有意差が認められた。M区では常に最も大きい年間CO_2放出量が観測され，F区とC区で有意な差は無かった。

年間NBPは，C区では-4.6～-3.9 Mg C ha^{-1} yr^{-1}であり，正味の炭素損失を示した。F区でC区よりわずかに大きく，-4.5～-3.7 Mg C ha^{-1} yr^{-1}であった。M区のNBPは，-1.4～1.2 Mg C ha^{-1} yr^{-1}にあった。窒素化学肥料の施与は無施肥に比べ土壌有機炭素の蓄積を0～0.4 Mg C ha^{-1} yr^{-1}促進し，堆肥の施与は3.8～6.0 Mg C ha^{-1} yr^{-1}促進した。

年間 CH_4 放出量は，F，M，C 区でそれぞれ-0.1～4.0，-0.2～1.4，-0.1～5.4 kg CH_4-C ha^{-1} yr^{-1}であった。年間CH_4放出量は，処理区間に有意な差は認められなかった。地温と降水量は，CH_4フラックスを制御する重要な要因であった。

年間N_2O放出量は，F，M，C区でそれぞれ1.2～2.9，0.9～4.9，0.4～0.7 kg N_2O-N ha^{-1} yr^{-1}であった。年間N_2O放出量と窒素化学肥料施与量の直線回帰モデルは，堆肥を施与した区($y = 0.0226x + 1.296$, $R^2 = 0.88$)と窒素化学肥料のみを施与した区($y = 0.0127x + 0.6088$, $R^2 = 0.92$)で異なり，傾きは堆肥を施与した区で大きかった。年間N_2O放出量は，土壌の総無機態窒素供給量(窒素化学肥料および土壌有機炭素・堆肥由来の無機態窒素供給量の和)と有意な相関を示した($y = 0.0107x - 3.6999$, $R^2 = 0.62$)。N_2O放出量を，堆肥のみを施与した区(2007年のM区を含む)と窒素化学肥料を施与した区に分類すると，N_2O 放出量と土壌の総無機態窒素余剰量の直線回帰モデルは異なり，堆肥施与区で傾きは小さく，堆肥施与のN_2O放出抑制効果が認められた。

GWPは，F，M，C区それぞれ14.6～18.0，-3.9～6.0，14.6～17.3 Mg CO_2 equivalents ha^{-1} yr^{-1}であった。これは，窒素化学肥料の施与はGWPを低下させなかったが，堆肥の施与はGWPを低下させたことを示す。

本研究で得られた結果は次の通りである。1)土壌有機炭素の蓄積を促進させるには，堆肥施与が勧められる。2)窒素化学肥料の施与も堆肥の施与も，CH_4 放出に影響を与えない。3)窒素化学肥料の施与はN_2O 放出を促進させ，特に堆肥と一緒に窒素化学肥料が施与された場合，化学肥料のみの施与より N_2O 放出が大きい。4)土壌の総無機態窒素余剰量が増大すると，堆肥のみの施与より窒素化学肥料の施与の方がN_2O 放出を促進する。5)以上のことから，堆肥のみを施与することが，採草地のGWPを削減策として最も推奨される。

以上のように，本研究は農業分野の温暖化抑制技術として堆肥施与が効果的であることを示したもので，学会からも高く評価されている。よって審査員一同は，Tao Jinが博士（農学）の学位を受けるのに十分な資格を有するものと認めた.