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REVIEW
Greenhouse Gas Sink-Source Functions of Grassland Ecosystems

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Abstract

This review summarizes research on greenhouse gas (GHG) exchange between the atmosphere and grasslands in Japan, identifies research need, and contributes to advances in the research field of GHG mitigation in grassland ecosystems. Applications of farmyard manure (FYM) and synthetic fertilizers do not reduce the ability of intensively managed grassland soils to oxidize methane (CH_4). On the one hand, the use of synthetic fertilizers alone reduces the net ecosystem carbon balance (NECB) of mowed grassland ecosystems. On the other hand, the application of FYM with supplemental synthetic fertilizers at rates determined from the mineralization of FYM increases the NECB at the same yields, due mainly to C brought into the ecosystem as FYM. It also limits further emissions of nitrous oxide (N_2O). Precipitation before and after fertilization in the summer months is the key driver of interannual variation in N_2O emissions. These findings collectively suggest that the application of FYM with the appropriate reduction in supplemental synthetic fertilizers can maintain soil organic C and maximize the net GHG balance of mowed grassland ecosystems in Japan. Studies on organic matter inputs through root growth and turnover, and models to predict large N_2O fluxes are needed to enhance our understanding of the NECB and net GHG balance of grassland ecosystems.

Discipline: Agricultural environment, Grassland
Additional key words: carbon balance, farmyard manure, methane, nitrous oxide, soil

Introduction

In Japan, meadows and pastures (covering ca. 0.62 million ha) account for 13.4% of the total agricultural land area (ca. 4.63 million ha; MAFF 2014). These areas plus natural, semi-natural, and non-agricultural grasslands (ca. 1.87 million ha) cover 5.0% of Japan's total land area (Matsuura et al. 2012). Well-drained Andosols (31%) or brown forest soils (33%) account for about two-thirds of the soil under grasslands in Japan.

Most manure derived from dairy and beef cattle in Japan is composted before being applied to agricultural land (GIO 2014). Bark, sawdust, and rice straw are often added to such mature to promote composting. A substantial proportion of this manure is derived from imported feedstuffs (Hojito et al. 2003). And because the manure thus represents a net import of organic matter (OM) into Japan, it must be properly applied for fertility management and to avoid the increased emission of greenhouse gases (GHGs) from soil. The application of farmyard manure (FYM) to grassland increases the input of OM into soil both directly through the manure itself, and indirectly through the promotion of plant growth. To evaluate the net GHG balance of grassland, the emissions of methane (CH_4) and nitrous oxide (N_2O) from grasslands should be taken into account (Fig. 1). This review summarizes the research on GHG exchange in Japan, identifies research needs, and contributes to advances in the research field of GHG mitigations in grassland ecosystems.

CH_4 oxidation and emissions from grasslands in Japan

CH_4 is a GHG with a lifespan of 12.4 years; its global warming potential is 34 times that of carbon dioxide (CO_2) over a time frame of 100 years (Myhre et al. 2013).

The annual emissions of CH_4 from mowed grassland plots at four sites across the range of climate zones in Japan (from Hokkaido to Kyushu) ranged from −1.9 to 5.5 kg C ha^{-1} year^{-1} (Shimizu et al. 2013). In most cases, however, the soil under grassland functions as a sink for atmospheric CH_4 (i.e., with negative net CH_4 emission values).

The application of ammonium fertilizer reduces the ability of soil under natural grasslands to oxidize CH_4

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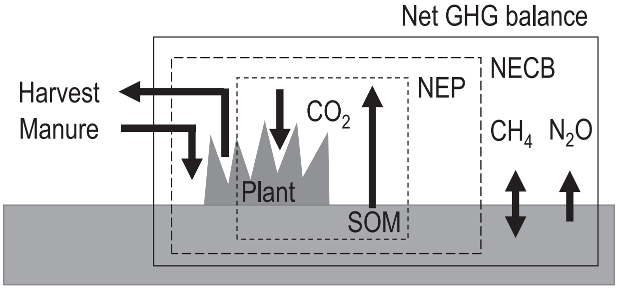

Fig. 1. Component fluxes of the net GHG balance of mowed grassland. GHG, greenhouse gas; NECB, net ecosystem carbon balance; NEP, net ecosystem production; CH_4, methane; N_2O, nitrous oxide; SOM, soil organic matter

(Mosier et al. 1991). However, ammonium fertilizer applied periodically does not decrease the CH_4 oxidizing ability of soil under intensively managed grasslands (Shimizu et al. 2013), partly due to an increase in ammonium-oxidizing microbial species capable of oxidizing CH_4 in the soil (Bodelier & Laanbroek 2004). By regulating the diffusion of oxygen and CH_4, soil moisture content also controls the rate of CH_4 oxidation on the surface (Mori et al. 2005, Sawamoto et al. 2010). CH_4 was emitted from poorly drained grassland because soil moisture promotes microbial methanogenesis (Shimizu et al. 2013).

The surface application of manure slurry moderately increases the annual emissions of CH_4 from grassland (1.4-3.0 kg C ha^{-1} year^{-1}), while the surface application of composted FYM results in a smaller increase (less than 1.0 kg C ha^{-1} year^{-1}, Mori and Hojito 2011, 2015a). Anaerobic decomposition of the dung of grazing cattle just after deposition on grazing land is another source of CH_4, but urine deposition does not increase CH_4 emissions, owing to an increase in ammonium-oxidizing microbial species as mentioned above, because the grassland has received urine-N of grazing cattle for decades (Mori and Hojito 2015b).

Carbon balance of grasslands in Japan

CO_2 in grassland ecosystems is exchanged between the soil, plants, and atmosphere. Therefore, plant growth and the decomposition of soil organic matter (SOM) are components of net ecosystem production (NEP, Fig. 1). In managed grasslands, the application of manure (i.e., input of C into the ecosystem) and the harvesting of plants (i.e., output of C from the ecosystem) contribute significantly to the net ecosystem C balance (NECB, Fig. 1).

In mowed grassland plots at four sites across the range of climate zones in Japan (from Hokkaido to Kyushu), the NEP of C (NEP-C: 0.5-3.5 Mg C ha^{-1} year^{-1}) of plots that received only synthetic fertilizers was smaller than the amount harvested (2.9-5.5 Mg C ha^{-1} year^{-1}), indicating that these plots lost C (Hirata et al. 2013). However, in the adjacent mowed grassland plots that received FYM plus supplemental synthetic fertilizers, the sum of NEP-C (0.12-2.63 Mg C ha^{-1} year^{-1}) and FYM-C (1.9-7.7 Mg C ha^{-1} year^{-1}) was greater than the amount harvested (3.2-5.2 Mg C ha^{-1} year^{-1}), thus indicating that these plots gained C. There was no significant difference between treatments in the amount harvested. Therefore, the difference in the NECB between the treatments was due mainly to FYM-C that remained undecomposed on the surface (Hirata et al. 2013). During the three-year observation period, the cumulative rate of decomposition was estimated to be 25% ± 37% of the amount of FYM-C applied during the same period (Shimizu et al. 2014a, b). These results suggest that the application of FYM is necessary to maintain the soil organic C of mowed grasslands in Japan (Shimizu et al. 2009), and the effect of FYM application on the NECB is substantial due to the slower rate of decomposition than that of manure slurry (Mori and Hojito 2015c).

NEP during the first crop (i.e., grass growth during the spring period) in mowed grassland makes a significant contribution to annual NEP (Matsuura et al. 2014). It also occupies an important position in the annual NECB in C stocks belowground. Belowground C generally has a slower turnover rate than aboveground C, as most organic C in soils (humic substances) is produced by the transformation of plant litter into more persistent organic compounds (Soussana et al. 2010). Future research should focus on the input of OM into grassland ecosystems through root growth and turnover, in order to enhance our understanding of the NECB of grassland ecosystems (Mori and Hojito 2015c).

Extensive management (including burning, grazing, and harvesting) is practiced to maintain semi-natural grassland, unlike intensive grassland. Semi-natural grassland, with traditional pasture species, usually receives no fertilizer. In the mountains of Aso, Japan, burning has been used for several thousand years to maintain *Miscanthus sinensis* grasslands (Toma et al. 2010). The rate of C accumulation in the soil of *M. sinensis* grasslands (0.503 Mg C ha^{-1} year^{-1}) was greater than that in *Cryptomeria japonica* forest plantations (0.284 Mg C ha^{-1} year^{-1}; Toma et al. 2012). The mean soil organic C sequestration rates of semi-natural grassland in Aso over 34, 50, and 100 years were estimated to be 0.618, 0.483, and 0.332 Mg C ha^{-1} year^{-1}, respectively (Toma et al. 2013).

N_2O emissions from grasslands in Japan

N_2O is a GHG with a lifespan of 121 years; its global warming potential is 298 times that of CO_2 (Myhre et al. 2013). N_2O also contributes to stratospheric ozone depletion (Ravishankara et al. 2009). Nitrogen (N) fertilizer is essential to maintaining production. Although it can increase the input of OM into the soil through enhanced plant growth, it can also increase the emissions of N_2O into the atmosphere.

Microbial nitrification and denitrification of mineralizable N in the soil are the main causes of N_2O emissions from unfertilized grassland (Mu et al. 2009). N_2O emissions increase with increasing N surplus, calculated as N inputs minus N uptake by forage (Shimizu et al. 2010). Therefore, the judicial application of organic plus inorganic N at rates determined from the mineralization of manure is crucial to mitigate N_2O emissions. Manure storage conditions (i.e., composting vs. storage of manure slurry) have little impact on annual N_2O emissions from soils under optimized fertility management (Mori and Hojito 2015a). In addition, the annual emissions of N_2O from soils do not differ significantly between grassland plots that receive ammonium-N as anaerobically digested cattle slurry and plots that receive the same rate of ammonium-N as ammonium sulfate (Sawamoto et al. 2010).

The measurement of N_2O emissions from mowed grassland plots at four sites across the range of climate zones in Japan has revealed that the mean N_2O emission factor (*EF*) of synthetic N fertilizer (1.8% ± 1.5%) is greater than that of FYM (0.36% ± 0.61%; Shimizu et al. 2013, Jin et al. 2010). The N_2O *EF* of synthetic fertilizer (0.1%-5.7%) increases with increasing annual mean air temperature (5.2-15.8°C) and precipitation (1160-2595 mm year^{-1}), but the N_2O *EF* of FYM (−3.2% to +1.3%) has shown no clear relationships (Shimizu et al. 2013). The smaller N_2O *EF* for FYM is due mainly to less inorganic N in FYM as compared with synthetic fertilizer (Mori and Hojito 2011). The background N_2O emissions (0.2-4.2 kg N ha^{-1} year^{-1}) also increase with increasing temperature and precipitation.

Annual N_2O emissions show substantial variation between years. Variations in precipitation before and after the application of fertilizer, especially at ambient temperature higher than 15°C, account for differences in N_2O emissions between years, thereby suggesting that denitrification contributes significantly to N_2O emissions because greater precipitation creates anoxic conditions that favor denitrifiers (Mori et al. 2008, Mori and Hojito 2012). A previous study in Hokkaido also suggests that high N_2O fluxes in grassland plots result from increased denitrification activity (Katayanagi et al. 2008). Future research should focus on predicting high N_2O fluxes, which contribute significantly to interannual differences in N_2O emissions.

Excreta from grazing cattle are another source of N_2O. The N_2O *EF* of dung (0.024%) is much smaller than that of urine (0.684%), possibly because dung-N is more refractory than urine-N (Mori and Hojito 2015b). The renovation of grassland (i.e., plowing, resowing) also increases N_2O emissions (2.1-5.3 kg N ha^{-1} over 65-67 days), as does precipitation during and after renovation (Mori and Hojito 2007). In Hokkaido, less N_2O trapped in frozen soil was released during a thaw from grassland plots than from cornfield plots, because more N_2O that accumulated during the freezing and transition periods was reduced to N_2 during the thaw in the grassland plots (Katayanagi and Hatano 2012).

Conclusions

The application of FYM with the appropriate reduction in supplemental synthetic fertilizers can maintain soil organic C and maximize the net GHG balance of mowed grassland ecosystems in Japan. Future research focusing on root growth and turnover, and models to predict large N_2O fluxes are necessary to enhance our understanding of the NECB and net GHG balance of grassland ecosystems.

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