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Carbon dioxide exchange at four intensively managed grassland sites across different climate zones of Japan and the influence of manure application on ecosystem carbon and greenhouse gas budgets

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ABSTRACT

To investigate the influence of different fertilization regimes on carbon dioxide (CO_2) exchange and the effect of manure application on the carbon balance, we established two experimental plots, one with chemical fertilizers only and one with manure and supplementary chemical fertilizers, at each of four intensively managed grassland sites across the range of climate zones in Japan. By using eddy covariance CO_2 flux and biometric measurements, we evaluated gross primary production (GPP), ecosystem respiration (RE), net ecosystem production (NEP), and the net ecosystem carbon balance (NECB), which accounts for carbon input through manure application and carbon loss through harvest. The sites in warmer zones showed larger annual GPP and RE, but annual NEP did not display any clear temperature dependence. The annual NEP was positive at all study sites and plots. The annual GPP and autotrophic respiration differed only slightly between the two plots despite the different fertilization regimes, but the decomposition of applied manure increased the annual heterotrophic respiration, thus causing a reduction in the annual NEP. At all the study sites, NECB of the plots with application of chemical fertilizers only was negative, indicating the loss of carbon. Manure application increased NECB, and its effect was larger at the cool temperate sites than at the temperate and warm temperate sites because of the greater amount of applied manure and larger sequestration rate at the cool temperate sites. Thus, manure application increased the accumulation of carbon in grassland, which is favorable from the viewpoint of ecosystem carbon management. Even when the enhanced nitrous oxide emission from the plots with manure application was taken into account, our findings suggest that manure application is a favorable option for mitigating greenhouse gas emission from Japanese grasslands and effectively managing livestock waste.

1. Introduction

The area of grassland on Earth is approximately 49 million km^2, representing about 30% of terrestrial ecosystems, and about half of the grassland area in Asia is managed to produce fodder rather than used directly for grazing (Loveland et al., 2000). Grassland ecosystems contain large amounts of organic carbon in the soil (Bronson

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et al., 2004; Scurlock and Hall, 1998). The accumulation and loss of this carbon store influences the carbon dioxide (CO_2) concentration in the atmosphere, and is thus important for climate change processes (Gregory et al., 2009; Piao et al., 2012). As in agricultural ecosystems in general, the uptake and release of CO_2 from grassland ecosystems are affected not only by climate, vegetation, and soil, but also by management practices such as grazing, the application of organic matter, and the harvesting of vegetation (Smith et al., 2010). As reported by Lal (2009), the carbon stock of croplands can be increased by management practices such as no-till farming, water management in paddy fields, and returning harvest residues to the soil. For grassland ecosystems, one management practice expected to increase carbon sequestration is manure application, the primary purpose of which is to restore degraded soil or improve productivity by securing soil organic matter (SOM; Lal, 2009).

Manure application to grassland is also regarded as an effective method of minimizing environmental pollution, especially in Japan, where the livestock industry is highly intensive and dependent on imported fodder. A major portion of Japanese grassland is managed as cultivated pastureland, in which the grasses are harvested for fodder rather than grazed by livestock. The area of planted grassland in Japan is 8475 km^2, about 18% of the total farmland area and the second largest category of farmland following paddy fields (Matsuura et al., 2012). The annual yield of grass was estimated at 27.7 Mt in 2009, amounting to 83% of the total yield of forage crops in Japan (Ministry of Agriculture, Forestry and Fisheries Japan, Statistics Department, 2011a). However, Japan's self-sufficiency rate in forage crops is low, at only 26% in FY2008 (Ministry of Agriculture, Forestry and Fisheries Japan, Statistics Department, 2011b), and the shortfall must be satisfied by imported fodder. The management of waste is one of the most serious environmental issues for the Japanese livestock industry because of the potential for nutrients from livestock waste to contaminate ground and surface water (Kato et al., 2009). Manure application to farmland is a recommended countermeasure for this problem.

Applying chemical fertilizer stimulates plant growth and affects the ecosystem carbon balance by increasing net primary production (NPP; Shimizu et al., 2009). On the other hand, applying manure affects the ecosystem carbon balance not only through NPP but also by increasing SOM (Gong et al., 2009; Shimizu et al., 2009; Triberti et al., 2008), because refractory organic matter in applied manure remains in the soil. Most studies of the effects of manure application on the carbon balance of farmlands have adopted carbon inventory or simulation modeling approaches (Gong et al., 2009; Mandal et al., 2007; Shen et al., 2007; Triberti et al., 2008). Although these studies provided insights into the long-term effects of manure application to farmland on SOM, they did not fully reveal the influence of manure application on the ecosystem carbon balance, which is what eventually leads to changes in SOM. To gain such an understanding, it is necessary to study not only carbon assimilation but also the ecosystem carbon balance under various climatic conditions and management practices.

Another factor to consider is that manure application to farmland increases nitrous oxide (N_2O) releases from the soil (Bouwman et al., 2002), may influence the methane (CH_4) flux, and leads to the release of nitrogenous compounds into connected ground and surface water (Kato et al., 2009). The application of manure, as well as that of nitrogen fertilizers, causes an increase of N_2O emission from grasslands (Mori and Hojito, 2012; Shimizu et al., 2013).

To evaluate the effects of manure application on the greenhouse gas balance in grassland, the Greenhouse Gases of Grassland in Japan project has established a network of four flux tower sites at intensively managed grasslands across Japan (Hatano, 2006). Each site has two experimental plots with different fertilization regimes: one with chemical fertilizers only and one with manure and supplementary chemical fertilizers. The carbon balance of each plot is estimated from eddy covariance CO_2 flux and biometric measurements. Eddy covariance measurements provide the net ecosystem production (NEP), and the biometric measurements provide NPP. Gross primary production (GPP) and ecosystem respiration (RE) are estimated by semi-empirical models using NEP and meteorological components. The net ecosystem carbon balance (NECB) is estimated by taking carbon input through manure application and carbon loss through harvest into account. NECB equals the change in soil organic carbon in annual crop fields (Smith et al., 2010). The experimental design, with additional chamber-based measurement of N_2O and CH_4 fluxes (Shimizu et al., 2010), allows us to investigate the greenhouse gas budget of the grassland, as well as the influence of climate and management practices on this budget.

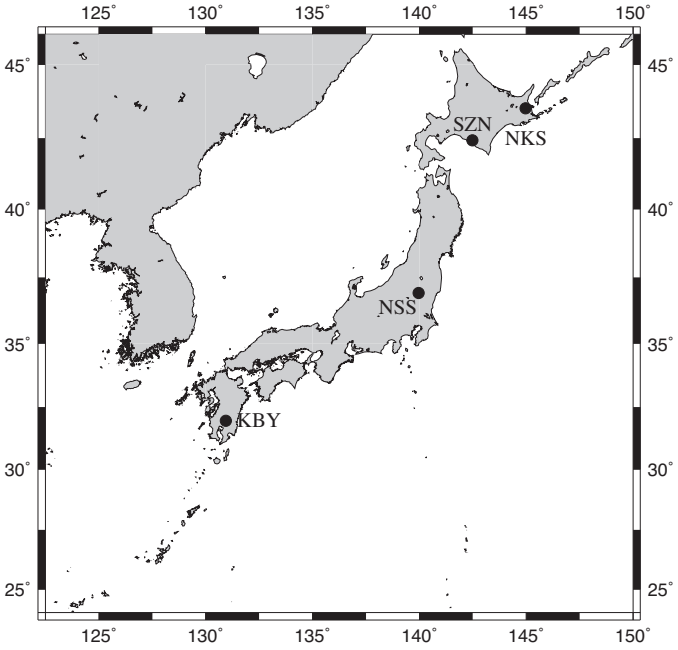

Fig. 1. Map of Japan showing the locations of the four grassland sites.

In this paper, we present the seasonal patterns of CO_2 exchange and annual carbon balance of these intensively managed grassland sites, with a particular focus on the effect of manure application. We also discuss the influence of manure application on the net greenhouse gas balance (NGB) of the grassland sites by considering the chamber-based N_2O and CH_4 fluxes as well.

2. Materials and methods

2.1. Study sites

We studied the carbon balance of grassland at the four flux tower sites in Japan (Fig. 1): the Nakashibetsu (NKS) site at the Konsen Agricultural Experiment Station; the Shizunai (SZN) site at the Hokkaido University Shizunai Livestock Farm; the Nasushiobara (NSS) site at the NARO Institute of Livestock and Grassland Science; and the Kobayashi (KBY) site at the National Livestock Breeding Center's Miyazaki Station. These four sites cover a geographic range from 31° N to 43° N in latitude and from 130° E to 144° E in longitude, and they have vegetation types with major grass species that are typical of climates ranging from cool temperate to warm temperate. Annual mean air temperature ranged from 5.6 to 16.1 °C and mean annual precipitation ranged from 1160 to 2454 mm y^{-1} (Table 1). The NKS and SZN sites are located on Hokkaido, which contributed 66% of total Japanese grass yield in 2009 (Ministry of Agriculture, Forestry and Fisheries Japan, Statistics Department,