Catena 133 (2015) 474–485

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Effect of manure application on seasonal carbon fluxes in a temperate managed grassland in Southern Hokkaido, Japan

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ARTICLE INFO

Article history:
Received 1 December 2014
Received in revised form 12 May 2015
Accepted 13 May 2015
Available online 10 July 2015

Keywords:
Net ecosystem production
Gross primary production
Ecosystem respiration
Heterotrophic respiration
Autotrophic respiration
Manure

ABSTRACT

Manure application in a managed grassland of reed canary grass in Southern Hokkaido, Japan, promotes carbon (C) sequestration. The objective of the present study is to elucidate the effect of manure application on seasonal change in the C balance components in a managed grassland. Net ecosystem production (NEP), ecosystem respiration (RE), and gross primary production (GPP) were measured using the open-path eddy covariance technique, and heterotrophic respiration from soil (RHs) was measured using the closed chamber method over a period of 2 years in the fertilizer and manure plots established in the managed grassland. RE is the sum of autotrophic respiration (RA), RHs, and heterotrophic respiration from manure (RHm). RA in the fertilizer plot was estimated by subtracting RHs from RE. For the manure plot, RA was estimated from GPP multiplied by the RA/GPP ratio, which was assumed to be identical to that in the fertilizer plot. The grass was harvested twice per year, and the aboveground net primary production (ANPP) and aboveground nitrogen (N) uptake were measured at every harvest in the growing season (from the beginning of the growing season until the first crop harvest [G1 season], from the first harvest to the second harvest [G2 season], and from the second harvest to the end of the growing season [G3 season]) and non-growing season (NG). In the manure plot, cattle manure was applied at a rate of 43–44 Mg fresh matter (5.8–7.7 Mg C) ha^{-1} yr^{-1} in the spring, and mineral N was supplemented by adding chemical fertilizer in the amount that equalizes the N supply rate to that of the fertilizer plots.

Period cumulative NEP and GPP were significantly larger in the fertilizer plot than in the manure plot. In contrast, there was no significant difference in the period cumulative RE between the fertilizer and manure plots. The period cumulative RA, RHs, and RHm were significantly positively correlated with the period cumulative RE. The contribution of RA to RE was the largest, and RHm to RE was only 7% in the manure plot. Mineral supply of N through manure mineralization in the G1 and G2 seasons was estimated at 14 ± 3, and 29 ± 22 kg N ha^{-1} yr^{-1}, respectively. The ANPP and aboveground N uptake were significantly positively correlated with the application rate of chemical fertilizer N. The ANPP and aboveground N uptake were greater in the G1 season than in the G2 season except for the manure plot in 2005, in which mineralized N present in the manure was not sufficient for grass growth due to low air temperatures in the G1 season. These results suggest that the supplemental application of chemical fertilizer N is recommended in all periods of a grass growing season to increase grass production. Annual net biome production (NBP) was estimated as NEP − C export by harvest + C import by manure application, and the annual NBP was −0.45 and 4.33 Mg C ha^{-1} yr^{-1} for the fertilizer and manure plot, respectively. This result indicates that manure application is necessary to sequester C in the managed grassland.

1. Introduction

Grasslands are one of the world's most abundant land cover types comprising approximately 40.5% of the Earth's terrestrial ice-free area (Adams et al., 1990; White et al., 2000). Grassland ecosystems have high levels of soil organic carbon (SOC) content and are a potential sink or source of carbon (C) (Arshad et al., 2004; Bronson et al., 2004; Carpenter-Boggs et al., 2003). In addition, grassland ecosystems are important ecosystems through their contribution to biodiversity and their use in food, forage, and livestock production (Peichl et al., 2011; Soussana et al., 2007; White et al., 2000). In a recent review of global grassland ecosystems, Gilmanov et al. (2010) reported a mean annual net ecosystem production (NEP) of 1.9 ± 2.0 Mg C ha^{-1} yr^{-1} for an intensively managed grassland. The C budget in managed grasslands

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http://dx.doi.org/10.1016/j.catena.2015.05.011
0341-8162/

includes C output through crop harvest and grazing and C input through manure application and NEP. This budget, taking abiotic processes such as harvest, manure application, fire, and erosion into account, is defined as the net biome production (NBP) (Schulze et al., 2000). In non-grazing grasslands, the NBP is estimated using the following equation (Ammann et al., 2007; Shimizu et al., 2009):

$$\mathrm{NBP} = \mathrm{NEP} + (\mathrm{C\ applied\ in\ manure}) - (\mathrm{harvested\ C}). \quad (1)$$

Skinner (2008) has reported an NBP of -0.81 Mg C ha^{-1} yr^{-1} for two mature pastures in the northeast USA and that the pastures acted as net C source because of high biomass removal.

In Japan, livestock husbandry depends on massive amounts of imported feed, and produces excess livestock excreta (Mishima, 2001; Mishima et al., 2006). Therefore, for an environment friendly agro-ecosystem, manure should be returned efficiently and appropriately to crop fields. It is expected to sequester the applied manure C in soils (Janzen et al., 1998). In addition, applied manure releases nutrient elements essential to crop growth through mineralization, which reduces dependence on chemical fertilizers.

In the grasslands of Southern Hokkaido, Japan, which were used for this study, C budgets have been measured using an ecological technique, in which net primary production (NPP) was estimated by the harvest method and heterotrophic respiration (RH) was estimated as soil surface CO_2 flux in a bare-soil plot measured by the closed chamber method (Shimizu et al., 2009). Two experimental plots were set up in the grassland, one plot for treatment with chemical fertilizer and the other for treatment with beef cattle manure compost. We found that organic C input through manure application was greater than C output through harvest, and the annual NBP was higher in the manure plot than in the fertilizer plot. This indicates that manure application promoted C sequestration in the managed grassland. In the previous report, we evaluated annual C balance but not seasonal changes in NEP. However, seasonal changes in NEP are reflected by the phenological development of the vegetation and seasonal changes in environmental driving forces (Falge et al., 2002a,b). In addition, C mineralization of manure regulates CO_2 emissions into the atmosphere, and it affects the RH, ecosystem respiration (RE), and NEP. Understanding the seasonal change in C mineralization from manure will facilitate selecting the amount of chemical fertilizer that needs to be supplemented to the soil treated with manure. For successful management of grasslands as well as croplands, frequency, timing, and duration of management practices are important factors of seasonal and inter-annual variations in NEP and each C balance component (Ammann et al., 2007; Barcza et al., 2003; Jaksic et al., 2006; Lawton et al., 2006; Marcolla and Cescatti, 2005; Novick et al., 2004; Rogiers et al., 2005; Wohlfahrt et al., 2008).

In the present study, NEP was measured at the fertilizer and manure plots in the managed grassland using the eddy covariance technique, which permits continuous measurements of the net exchange of CO_2 between the atmosphere and the grassland. The objective of the present study was to elucidate the effect of management practices, such as chemical fertilizer and manure application and harvesting, on the seasonal change in C balance components in an intensively-managed grassland.

2. Materials and methods

2.1. Site description

This study was conducted from October 2004 to August 2007 in a managed grassland located at the Shizunai Experimental Livestock Farm, Field Science Center for Northern Biosphere of Hokkaido University in Southern Hokkaido, Japan (42°26′N, 142°29′E, 120 m asl). The region belongs to the cool-temperate climate zone and is characterized by cold winters and warm summers, without apparent wet or dry seasons. The mean annual precipitation for 22 years (1989–2010) is approximately 1290 mm at the Sasayama station (110 m asl) of the nearest Automated Meteorological Data Acquisition System (AMeDAS) of the Japan Meteorological Agency, which was located within 1 km from the study site. The mean annual temperature for 30 years (1981–2010) is 8.0 °C, with the mean monthly temperatures ranging from 20.7 °C in August to -3.9 °C in January at the Shizunai station (10 m asl) of AMeDAS, which was located within 15 km from the study site. The site is covered with snow from end of December to the beginning of March, and normally soil is frozen from December to March.

The grassland was established more than 30 years ago, and has been continuously managed since then. Chemical fertilizers have been predominantly applied to the grassland, with an average nitrogen application rate of 133 ± 36 kg N ha^{-1} yr^{-1} from 1984 to 2004. The dominant species of the grassland are reed canary grass (*Phalaris arundinacea* L.) and meadow foxtail (*Alopecurus pratensis* L.). The soil is derived from Tarumae-b volcanic ash, and is classified as Thaptic Melanudands (Soil Survey Staff, 2006; Mollic Andosol according to IUSS Working Group WRB, 2006). A layer of 3-cm thick root-mat was found on the top, and a 21-cm thick Ap-layer was found under the root-mat in a survey conducted in August 2004. C content of the Ap-layer was 3.7% with a dry bulk density of 0.71 g cm^{-3} (Shimizu et al., 2009). SOC stocked in the topsoil (0–30 cm depth) was 76.6 Mg C ha^{-1}.

2.2. Management practices

Two adjacent experimental plots (100 m × 100 m) were set up in the study site, one for treatment with fertilizer (fertilizer plot) and the other for treatment with beef cattle manure (manure plot). The treatments were initiated in the spring of 2005. Grass was harvested twice a year (June 20 and August 10 in 2005, June 26 and August 22 in 2006, and June 18 and August 18 in 2007). The application rates of fertilizer and manure and the application dates are given in Table 1. The fertilizer application rates in 2005, 2006, and 2007 were 164, 184, and 74 kg N ha^{-1} yr^{-1}, respectively. The manure application rates were the optimum levels used by farmers in the region, and were based on the application of adequate amounts of potassium to the fields. Beef cattle manure with bedding litter (bark) was applied to the manure plot at rates of 44 Mg fresh matter (FM) ha^{-1} (236 kg T-N ha^{-1} and 5.8 Mg T-C ha^{-1}) in May 2005, 43 Mg FM ha^{-1} (310 kg T-N ha^{-1} and 6.0 Mg T-C ha^{-1}) in May 2006, and 44 Mg FM ha^{-1} (331 kg T-N ha^{-1} and 7.7 Mg T-C ha^{-1}) in May 2007. The C:N ratios of manure were 24.7, 19.2, and 23.3 in 2005, 2006 and 2007, respectively. The nutrient supply rates in the manure plot were estimated from manure by multiplying the application rate by the mineralization rate; the difference between the supply rates from manure and the application rates in the fertilizer plot was supplemented with chemical fertilizer. The supplemental application of chemical fertilizer was conducted after the first

Table 1
Application date and application rates of chemical fertilizer and manure. Chemical fertilizer is composed of ammonium sulfate, ammonium phosphate, potassium sulfate, and potassium magnesium sulfate. Beef cattle manure with bedding litter (bark) was applied in the manure plot.

Treatment	Date	Fertilizer type	Application rates (kg ha^{-1})			
			T-C	T-N	P_2O_5	K_2O
Fertilizer	May 2005	Chemical fertilizer	0	103	23	168
	July 2005	Chemical fertilizer	0	61	23	97
	May 2006	Chemical fertilizer	0	124	50	177
	July 2006	Chemical fertilizer	0	59	18	97
	May 2007	Chemical fertilizer	0	49	14	73
	July 2007	Chemical fertilizer	0	25	7	37
Manure	May 2005	Manure	5833	236	191	266
	July 2005	Chemical fertilizer	0	133	7	70
	May 2006	Manure	5958	310	212	167
	May 2006	Chemical fertilizer	0	71	0	33
	July 2006	Chemical fertilizer	0	59	6	97
	May 2007	Manure	7714	331	342	336
	July 2007	Chemical fertilizer	0	21	0	0