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Application of Farmyard Manure Rather Than Manure Slurry Mitigates the Net Greenhouse Gas Emissions from Herbage Production System in Nasu, Japan

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Abstract: In Japan, it is important to recycle the nutrients in manure for forage production because most dairy cattle are fed inside, mainly with imported grain and home-grown roughage. To understand the overall effect of manure use on grassland on the net greenhouse gas (GHG) emission and GHG intensity of herbage production systems, the integrated evaluation of emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) is essential. The objective of this study was to compare the net GHG emissions (expressed in CO_2-eq ha^{-1} y^{-1}) and GHG intensity (expressed in CO_2-eq Mg^{-1} dry matter yield) of herbage production based on manure slurry + synthetic fertilizer (slurry system) with that based on farmyard manure + synthetic fertilizer (FYM system). Calculations of net GHG emissions and GHG intensity took into account the net ecosystem carbon balance (NECB) in grassland, the CH_4 and N_2O emissions from grassland, and GHG emissions related to cattle waste management, synthetic fertilizer manufacture, and fuel consumption for grassland management based on literature data from previous studies. The net GHG emissions and GHG intensity were 36% (6.9 Mg CO_2-eq ha^{-1} y^{-1}) and 41% (0.89 Mg CO_2-eq Mg^{-1}), respectively, lower in the FYM system.

Keywords: carbon dioxide; cattle waste management; fuel consumption for grassland management; greenhouse gas intensity; lifecycle assessment; methane; net ecosystem carbon balance; nitrous oxide; synthetic fertilizer manufacture

1. Introduction

Recent greenhouse gas (GHG) profiles of the agriculture sector in Japan show that major GHG sources in terms of carbon dioxide equivalents (CO_2-eq) are rice cultivation (methane (CH_4), 41%), enteric fermentation (CH_4, 22%), manure management (CH_4 and nitrous oxide (N_2O), 19%), and soils (N_2O, 16%) [1]. In Japan, most dairy cattle are fed inside, mainly with imported grain and home-grown roughage. Around 70% of the dairy cattle waste is composted [2] for use in crop and forage production. Therefore, it is important to apply manure to meadows and pastures, which account for 13.4% of the total agricultural land area of Japan [3]. In the year 2015, 570,475 Mg-N y^{-1} was excreted by livestock in Japan, of which 304,285 Mg-N y^{-1} was applied to agricultural soil (4,496,000 ha) [1].

The application of farmyard manure (FYM) to grassland increases the net ecosystem carbon balance (NECB) relative to manure slurry application [4]. This is mainly because the amount of C input to grassland from FYM is greater than that from slurry, but the decomposition of FYM is slower than that of slurry [4]. Consequently, FYM application has a greater potential to improve the C stock in grassland soil than slurry application. However, emissions of CH_4 and N_2O from manured grassland [5] need to be considered in evaluating the overall effect of manure application on the net GHG emissions from grassland [3]. The soil of grassland usually acts as a sink of atmospheric CH_4, and manure application only temporarily increases CH_4 emission from grassland [3]. In contrast, N_2O emission increases with increasing the N surplus in grassland soil [6]. Therefore, judicial application of organic and inorganic N is necessary to mitigate the N_2O emission from grassland [3]. Cattle waste management, including slurry storage [7] and composting [8], is another source of GHG, and in addition to CH_4 and N_2O emissions from cattle waste management, farm machinery used for composting FYM also emits CO_2 [9]. To maintain productive sward, supplemental fertilizers are used to make up for nutrient insufficiencies in manure (e.g., N and P in the case of cattle manure) [5], but their manufacture also emits GHG [10]. Furthermore, GHG emissions from fuel consumption for grassland management also need to be taken into consideration [11].

To assess the net GHG emissions (i.e., integrated evaluation of CO_2, CH_4 and N_2O) and GHG intensity (GHGI) of herbage production systems, an integrated evaluation of the above processes is necessary (Table S1). On that basis, the identification of important processes with significant contributions is necessary in order to determine the priority of countermeasures to mitigate GHG. To date, it is recognized that the quality and quantity of organic materials applied have great influence on soil organic carbon [4,12]; however, insufficient information is available on the effect of manure type (i.e., slurry or FYM) on the net GHG emissions and GHGI of herbage production systems.

The objectives of this study were: (1) to investigate the net GHG emissions (expressed in CO_2-eq ha^{-1} y^{-1}) and GHGI (expressed in CO_2-eq Mg^{-1} dry matter yield) of herbage production systems based on manure slurry + synthetic fertilizer (slurry system) and on FYM + synthetic fertilizer (FYM system); (2) to show the relative contributions of each process in GHG emission; and (3) to show how farming practices can be adjusted to minimize emissions. My hypotheses were that the FYM system reduces the net GHG emissions in comparison with the slurry system, and that the contributions of grassland soil and cattle waste management to the net GHG emissions of herbage production systems are greater than the other processes.

2. Materials and Methods

2.1. System Boundary and Functional Units

The system boundary comprised the following processes: the NECB in grassland, emissions of CH_4 and N_2O from grassland, and GHG emissions related to cattle waste management (i.e., slurry storage and composting FYM), synthetic fertilizer manufacture, and fuel consumption for grassland management operations. The functional unit was defined as ha^{-1} y^{-1} of grassland or Mg^{-1} of dry matter yield. The study did not take into account the GHG emissions related to the manufacture of farm machinery and buildings, transport of synthetic fertilizers, or indirect N_2O emissions related to leaching of nitrate (NO_3^-) and redeposition of volatilized ammonia (NH_3).

2.2. NECB and Emissions of CH_4 and N_2O from Grassland

The NECB and emissions of CH_4, and N_2O from grassland (1 ha) treated with slurry (65.8 to 66.4 Mg ha^{-1} y^{-1}) or FYM (36.5 to 39.2 Mg ha^{-1} y^{-1}) were based on previous studies [4,5] in which slurry or FYM was applied to the upper limit based on K requirement for herbage production. Annualized values of NECB, emissions of CH_4, and N_2O were calculated by averaging the information of two years.

2.3. GHG Emissions Related to Cattle Waste Management

Emissions of CH_4 and N_2O from stored slurry were calculated from emission factors (EFs, 3.90% and 0.02%, respectively) in Japan [1]. Emissions of CH_4 and N_2O from composting of applied FYM were estimated from a farm study [13] and EFs (3.8% and 2.38% to 2.39%, respectively) in Japan [1]. Biogenic CO_2 losses from manure were excluded (i.e., C neutral), but emissions of CO_2 due to the consumption of electricity or fuel for composting FYM were estimated from a farm study [13] and EFs [14]. Emissions of CH_4, N_2O and CO_2 per unit area of grassland (1 ha) were calculated by multiplying these emissions per unit weight of slurry or FYM and the weight of slurry or FYM annually applied to grassland (Mg ha^{-1} y^{-1}).

2.4. GHG Emissions Related to Synthetic Fertilizer Manufacture

GHG emissions from the manufacture of N and P fertilizers were estimated from the SimaPro 7.1 database (PRé Consultants, Amersfoort, Netherlands). Emissions of CH_4, N_2O and CO_2 per unit area of grassland (1 ha) were calculated by multiplying these emissions per unit weight of synthetic fertilizer and the weight of synthetic fertilizer annually applied to grassland (kg ha^{-1} y^{-1}). No K fertilizer was used, because the applied slurry or FYM covered the K requirement for herbage production [4,5].

2.5. GHG Emissions Related to Grassland Management

GHG emissions due to fuel consumption by farm machinery for loading and spreading of manure and fertilizers and for cutting and harvesting of herbage were estimated from a previous Japanese study in the 1990s [15] and EF [14]. The emission of CO_2 per unit area of grassland (1 ha) was calculated by multiplying the fuel consumption per unit of operation, the operation unit necessary for management of grassland (1 ha), and EF.

2.6. Overall Net GHG Emissions and GHGI of Herbage Production

Emissions of CH_4 and N_2O were converted to CO_2-eq by using values of the 100-year global warming potential, assumed to be 1 for CO_2, 25 for CH_4, and 298 for N_2O [16]. The net GHG emissions (CO_2-eq ha^{-1} y^{-1}) were calculated by considering the NECB and emissions of CH_4 and N_2O from grassland (Section 2.2.) and the GHG emissions related to cattle waste management (Section 2.3.), synthetic fertilizer manufacture (Section 2.4.), and grassland management (Section 2.5.) on an area basis. The GHGI (CO_2-eq Mg^{-1}) was calculated by dividing the net GHG emissions by the dry matter yield of grassland receiving slurry or FYM [4].

3. Results and Discussion

3.1. NECB and Emissions of N_2O and CH_4 from Grassland

The NECB of the slurry system (−12.8 Mg CO_2-eq ha^{-1} y^{-1}) was far lower than that of the FYM system (−1.8 Mg CO_2-eq ha^{-1} y^{-1}); that is, the FYM system contributed more to improving the C stock in grassland than the slurry system (Figure 1). (Please note that negative NECB values represent net CO_2 emission from grassland to the atmosphere.) The NECB of the slurry and FYM systems were similar to previously measured values in Japanese grasslands that respectively received only synthetic fertilizers or FYM + synthetic fertilizers [17], suggesting that slurry C had limited capacity for maintaining soil organic C in comparison with FYM C [12]. The emissions of N_2O from grassland were not significantly different between slurry and FYM systems (2.2 Mg CO_2-eq ha^{-1} y^{-1} in slurry system, 2.3 Mg CO_2-eq ha^{-1} y^{-1} in FYM system), because synthetic N fertilizer was also applied [18,19]. The emissions of CH_4 were much smaller than those of CO_2 and N_2O (+0.034 Mg-CO_2-eq ha^{-1} y^{-1} in slurry system, −0.032 Mg-CO_2-eq ha^{-1} y^{-1} in FYM system).

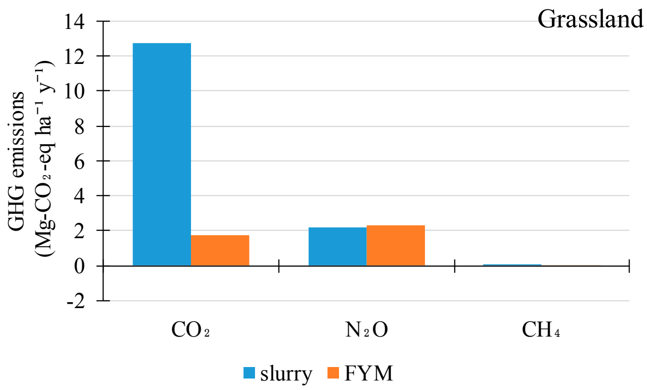

Figure 1. Annualized emissions of CO_2 (NECB), N_2O and CH_4 from grassland receiving manure + fertilizer.

3.2. GHG Emissions Related to Cattle Waste Management

The GHG emissions related to cattle waste management were due mainly to CH_4 (2.9 Mg CO_2-eq ha^{-1} y^{-1}, Table 1) in the slurry system and to both CH_4 (4.2 Mg CO_2-eq ha^{-1} y^{-1}, Table 2) and N_2O (2.0 Mg CO_2-eq ha^{-1} y^{-1}, Table 3) in the FYM system (Figure 2). The emission of CO_2 related to energy consumption (0.15 Mg CO_2-eq ha^{-1} y^{-1}, Table 4) was smaller than the emission of CH_4 and N_2O by composting. This is because the amount of CO_2 emission for composting 1 Mg of FYM was only 4.1 kg. The emission of N_2O by slurry storage (0.028 Mg-CO_2-eq ha^{-1} y^{-1}, Table 5) was much smaller than the emission of N_2O by composting FYM (2.0 Mg CO_2-eq ha^{-1} y^{-1}, Table 3), mainly due to the small EF for slurry storage (0.02%) in comparison with composting FYM (2.4%).

Table 1. Emission of CH_4 related to storage of dairy cattle slurry.

OM in Slurry [1]				CH_4 Emission [2]				CH_4 Emission [3]				
Mg ha^{-1}y^{-1}				kg-CH_4 ha^{-1} y^{-1}				Mg-CO_2-eq ha^{-1} y^{-1}				
1st year		2nd year		1st year		2nd year		1st year		2nd year		Mean
March	May	March	May	March	May	March	May	March	May	March	May	
2.2	2.5	2.6	2.4	52	60	62	57	1.3	1.5	1.5	1.4	2.9
4.7		5.0		113		119		2.8		3.0		

[1] Organic matter content in slurry was determined as 1.764 × C content. [2] Emission factor of CH_4 from slurry storage was 2.38–2.39% (g-CH_4 g-OM^{-1}) [1]. [3] The 100-year global warming potential of CH_4 was assumed to be 25 [16].

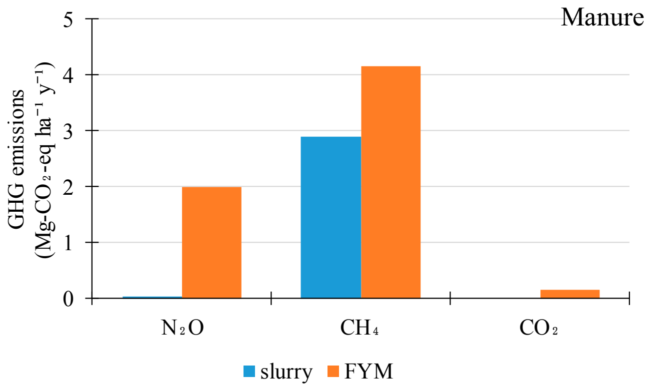

Figure 2. Annualized emissions of N_2O, CH_4, and CO_2 related cattle waste management.

Table 2. Emission of CH_4 related to composting.

Cattle Type	Number [1]	Excreta [2]		OM in Excreta on the Farm [3]	CH_4 Emission on the Farm [4]	CH_4 Emission per Unit Weight of FYM [5,6]		CH_4 Emission per Unit Area of Grassland		
		kg head^{-1} d^{-1}						Mg-CO_2-eq ha^{-1} y^{-1}		
	Head	Feces	Urine	kg (30 d)$^{-1}$	kg-CH_4 (30 d)$^{-1}$	kg-CH_4 Mg^{-1}	kg-CO_2-eq Mg^{-1}	1st year	2nd year	Mean
Lactating	84.1	43	14	17535	666	4.4	110	4.0	4.3	4.2
Non-lactating	19.9	21	6	2024	77					

[1] Based on previous research on the dairy farm from which FYM was collected in this study [13]. [2] Based on the National Greenhouse Gas Inventory Report of Japan [1]. [3] Organic matter content was assumed to be 16% in feces and 0.5% in urine of dairy cattle [1]. [4] Emission factor of CH_4 from composting of dairy cattle excreta was assumed to be 3.8% (g-CH_4 g-OM^{-1}) [1]. [5] FYM production was 168.8 Mg per farm per 30 d [13]. [6] The 100-year global warming potential of CH_4 was assumed to be 25 [16].

Table 3. Emission of N_2O related to composting dairy FYM.

Cattle Type	Number [1]	Excreta [2]		N in Excreta on the Farm [3]	N_2O Emission on the Farm [4]	N_2O Emission per Unit Weight of FYM [5,6]		N_2O Emission per Unit Area of Grassland		
		kg head^{-1} d^{-1}						Mg-CO_2-eq ha^{-1} y^{-1}		
	Head	Feces	Urine	kg (30 d)$^{-1}$	kg-N_2O-N (30 d)$^{-1}$	kg-N_2O Mg^{-1}	kg-CO_2-eq Mg^{-1}	1st year	2nd year	Mean
Lactating	84.1	43	14	717	17.2	0.18	53	1.9	2.1	2.0
Non-lactating	19.9	21	6	79	1.9					

[1] Based on previous research on the dairy farm from which FYM was collected in this study [13]. [2] Based on the National Greenhouse Gas Inventory Report of Japan [1]. [3] N content was assumed to be 0.4% in feces and 0.8% in urine [1]. [4] Emission factor of N_2O from composting of dairy cattle excreta was assumed to be 2.4% (g-N_2O-N g-N^{-1}) [1]. [5] FYM production was 168.8 Mg per farm per 30 d [13]. [6] The 100-year global warming potential of N_2O was assumed to be 298 [16].

Table 4. Emission of CO_2 related to energy consumption for composting dairy FYM.

Energy Consumption		CO_2 Emission on the Farm [2,3]	FYM Production on the Farm [1]	CO_2 Emission per Unit Weight of FYM [1]	CO_2 Emission per Unit Area of Grassland [4]		
Electricity [1]	**Light Diesel Oil [1]**				**Mg-CO_2 ha^{-1} y^{-1}**		
kWh (30 d)$^{-1}$	L (30 d)$^{-1}$	kg-CO_2 (30 d)$^{-1}$	Mg (30 d)$^{-1}$	kg-CO_2 Mg^{-1}	1st year	2nd year	Mean
712.4	160	688	168.8	4.1	0.15	0.16	0.15

[1] Based on previous research on the dairy farm from which FYM was collected in this study [13]. [2] 378 g-CO_2 was assumed to be emitted by 1 kWh of electricity consumption [14]. [3] 2619 g-CO_2 was assumed to be emitted by consumption of 1 L light diesel oil [14]. [4] CO_2 emission per unit area of grassland was calculated by multiplying the CO_2 emission per unit weight of FYM and the weight of FYM applied to 1 ha of grassland.

Table 5. Emission of N_2O related to storage of cattle slurry.

N in Slurry				**N_2O Emission [1]**				**N_2O Emission [2]**				
kg-N ha^{-1} y^{-1}				**kg-N_2O-N ha^{-1} y^{-1}**				**Mg-CO_2-eq ha^{-1} y^{-1}**				
1st year		2nd year		1st year		2nd year		1st year		2nd year		Mean
March	May	March	May	March	May	March	May	March	May	March	May	
150	150	150	150	0.030	0.030	0.030	0.030	0.014	0.014	0.014	0.014	0.028
300		300		0.060		0.060		0.028		0.028		

[1] Emission factor of N_2O from slurry storage was 0.02% (g-N_2O-N g-N^{-1}) [1]. [2] The 100-year global warming potential of N_2O was assumed to be 298 [16].

3.3. GHG Emissions Related to Fertilizer Manufacture

The GHG emission related to fertilizer manufacture in the FYM system (1.5 Mg CO_2-eq ha^{-1} y^{-1}, Table 6) was almost double that for the slurry system (0.82 Mg CO_2-eq ha^{-1} y^{-1}, Table 6), mainly owing to the difference in N application rate. Slurry contains substantial amount of readily available N, however, most of N in FYM is in organic form. Therefore, the amount of N fertilizer supplemented to grassland in FYM system (159 to 177 kg-N y^{-1}) was greater than that in slurry system (90 kg-N y^{-1}).

3.4. GHG Emissions Related to Grassland Management

The GHG emissions related to grassland management were similar between the FYM and slurry systems (0.49 vs. 0.47 Mg CO_2-eq ha^{-1} y^{-1}, Table 7), because the herbage yields were not significantly different between the slurry (8.8 Mg y^{-1}) and FYM (9.5 Mg y^{-1}) systems. The GHG emissions related to grass cutting, turning and harvesting, bailing and wrapping were greater than those related to loading and spreading of slurry or FYM. This is mainly because slurry and FYM were spread twice and once a year, respectively; however, grass cutting, turning and harvesting, bailing and wrapping was performed four times a year in both the slurry and FYM systems.

Table 6. Emissions of GHG related to synthetic fertilizer manufacture.

	Emission from Synthetic N Fertilizer Manufacture per Unit Weight [1,2]		N application Rate kg-N ha^{-1} y^{-1}				GHG Emissions Mg-CO_2-eq ha^{-1} y^{-1}					
			1st year		2nd year		1st year		2nd year		Mean	
	kg Mg-N^{-1}	kg-CO_2-eq Mg-N^{-1}	Slurry	FYM	Slurry	FYM	Slurry	FYM	Slurry	FYM	Slurry	FYM
CO_2	2769	2769										
CH_4	0.13	3	90	177	90	159	0.77	1.51	0.77	1.36	0.77	1.43
N_2O	19.3	5751										
	Emission from Synthetic P Fertilizer Manufacture per Unit Weight [1,2]		**P_2O_5 Application Rate kg-P_2O_5 ha^{-1} y^{-1}**				**GHG Emissions kg-CO_2-eq ha^{-1} y^{-1}**					
			1st year		**2nd year**		**1st year**		**2nd year**		**Mean**	
	kg Mg-$P_2O_5{}^{-1}$	**kg-CO_2-eq Mg-$P_2O_5{}^{-1}$**	**Slurry**	**FYM**	**Slurry**	**FYM**	**Slurry**	**FYM**	**Slurry**	**FYM**	**Slurry**	**FYM**
CO_2	1117	1117										
CH_4	2.07	52	49	67	46	45	0.06	0.08	0.05	0.05	0.06	0.07
N_2O	0.038	11										
	Emission from Synthetic K Fertilizer Manufacture per Unit Weight [1,2]		**K_2O Application Rate kg-K_2O ha^{-1} y^{-1}**				**GHG Emissions kg-CO_2-eq ha^{-1} y^{-1}**					
			1st year		**2nd year**		**1st year**		**2nd year**		**Mean**	
	kg Mg-K_2O^{-1}	**kg-CO_2-eq Mg-K_2O^{-1}**	**Slurry**	**FYM**	**Slurry**	**FYM**	**Slurry**	**FYM**	**Slurry**	**FYM**	**Slurry**	**FYM**
CO_2	617	617										
CH_4	1.38	35	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
N_2O	0.049	15										
Total							0.82	1.6	0.82	1.4	0.82	1.5

[1] Based on the SimaPro 7.1 database. [2] The 100-year global warming potential was assumed to be 1 for CO_2, 25 for CH_4, and 298 for N_2O [16].

Table 7. Emission of CO_2 related to fuel consumption for grassland management and transport.

Machine Operation		Consumption of Light Diesel Oil per Operating Unit	Operating Unit				CO_2 Emission [8] $Mg\text{-}CO_2\ ha^{-1}\ y^{-1}$					
			1st year		2nd year		1st year		2nd year		Mean	
		$L\ ha^{-1}\ unit^{-1}$	Slurry	FYM	Slurry	FYM	Slurry	FYM	Slurry	FYM	Slurry	FYM
Loading FYM [1]	30 Mg $unit^{-1}$	10.0	0	1.22	0	1.31	0.00	0.03	0.00	0.03	0.00	0.03
FYM transport [1,2]	30 Mg $unit^{-1}$	2.15	0	1.22	0	1.31	0.00	0.01	0.00	0.01	0.00	0.01
FYM spreading [1]	30 Mg $unit^{-1}$	3.3	0	1.22	0	1.31	0.00	0.01	0.00	0.01	0.00	0.01
Slurry transport [2,3]	80 Mg $unit^{-1}$	18.4	0.83	0	0.82	0	0.04	0.00	0.04	0.00	0.04	0.00
Slurry spreading [3]	80 Mg $unit^{-1}$	3.8	0.83	0	0.82	0	0.01	0.00	0.01	0.00	0.01	0.00
Fertilizer distribution [2,4]	500 kg $unit^{-1}$	2.4	1.42	2.45	1.38	2.03	0.01	0.02	0.01	0.01	0.01	0.01
Grass cutting [2]	ha $unit^{-1}$	8.1	4	4	4	4	0.08	0.08	0.08	0.08	0.08	0.08
Turning and harvesting [2]	ha $unit^{-1}$	15.35	4	4	4	4	0.16	0.16	0.16	0.16	0.16	0.16
Bailing haylage [2,5]	7 Mg-DM $unit^{-1}$	19.6	1.10	1.21	1.41	1.50	0.06	0.06	0.07	0.08	0.06	0.07
Wrapping haylage [2,6]	3 Mg-DM $unit^{-1}$	11.1	2.57	2.83	3.30	3.50	0.07	0.08	0.10	0.10	0.09	0.09
Haylage transport [2,7]	7 Mg-DM $unit^{-1}$	5.6	1.10	1.21	1.41	1.50	0.02	0.02	0.02	0.02	0.02	0.02
Total											0.47	0.49

[1] Loading, transport, and spreading of 30 Mg-FYM was assumed to be 1 operating unit [15]. [2] Grassland was assumed to be 500 m from cowshed [15]. [3] Loading, transport, and spreading of 80 Mg-slurry was assumed to be 1 operating unit [15]. [4] Distribution of 500 kg fertilizer was assumed to be 1 operating unit [15]. [5] Bailing of 7 Mg-DM haylage was assumed to be 1 operating unit [15]. [6] Wrapping of 3 Mg-DM haylage was assumed to be 1 operating unit [15]. [7] Transport of 7 Mg-DM haylage was assumed to be 1 operating unit [15]. [8] 2619 g-CO_2 was assumed to be emitted by consumption of 1 L light diesel oil [14].

3.5. Overall Net GHG Emissions and GHGI

The net GHG emissions was 19 Mg CO_2-eq ha^{-1} y^{-1} in the slurry system and 12 Mg CO_2-eq ha^{-1} y^{-1} in the FYM system (Figure 3). The GHGI was 2.2 Mg CO_2-eq Mg^{-1} in the slurry system and 1.3 Mg CO_2-eq Mg^{-1} in the FYM system. Thus, the net GHG emissions of the FYM system was 36% (6.9 Mg CO_2-eq ha^{-1} y^{-1}) less and the GHGI of the FYM system was 41% (0.89 CO_2-eq Mg^{-1}) less than that of the slurry system.

The contribution of grassland soil, cattle waste management, fertilizer manufacture and grassland management to the net GHG emissions were 78% (CO_2: 66%, N_2O: 11% and CH_4: 0.2%), 15% (CO_2: 0.0%, CH_4: 15%, N_2O: 0.1%), 4% and 2% in the slurry system, and 33% (CO_2: 14%, N_2O: 19% and CH_4: −0.3%), 51% (CO_2: 1%, N_2O: 16%, CH_4: 34%), 12% and 4% in the FYM system, respectively. These results collectively suggest that NECB and the N_2O emissions from grassland and the CH_4 and N_2O emissions related cattle waste management are crucial to the control of net GHG emission and GHGI.

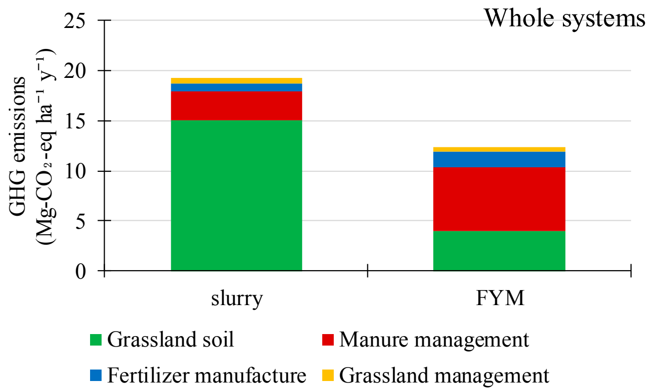

Figure 3. Annualized overall net GHG (greenhouse gas) emissions from herbage production.

The FYM system reduced the net GHG emissions and GHGI relative to the slurry system (Figure 3). The net reduction was due largely to the improvement of C stock in grassland (Figure 1). Although the emissions of GHG related to cattle waste management and fertilizer manufacture were greater in the FYM system than in the slurry system (Figure 3), the FYM system maintained an advantage in net GHG emissions and GHGI, due mainly to the difference in NECB in grassland (Figure 1)—that is, the persistent organic matter in FYM decomposed slowly in the soil and contributed to the improvement of C stock, but the labile organic matter in slurry decomposed quickly in the soil and was released to the atmosphere as CO_2 [4]. Our results support the validity of FYM application for the mitigation of GHG emissions [20,21], not only from grassland, but also during herbage production. In the slurry and FYM systems, N and P were supplemented based on the fertilizer recommendation. Therefore, the yields in the slurry (8.8 Mg y^{-1}) and FYM (9.5 Mg y^{-1}) systems were comparable to the standard yield (8–10 Mg y^{-1}) in Nasu, Japan [4].

3.6. Adjustment of Farming Practices

These results show that the FYM system improved the net GHG emissions and GHGI relative to the slurry system (Figure 3). In Japan, a substantial amount of manure is derived from imported feed, and thus represents the net import of organic matter, which must be used with care for fertility management [3]. Making maximum use of manure in consideration of N, P, and K requirements for herbage production to reduce synthetic fertilizer rates to the absolute minimum is crucial to mitigating overall GHG emissions [18,22]. Applying manure and synthetic N fertilizer in excess of demand increases N_2O emissions from grassland [23,24]. Therefore, the tightening of N application rates can limit overall GHG emissions. Mixing low-quality dried grass as a bulking agent into FYM reduced CH_4 and N_2O emissions [2] and could further improve the C stock in grassland. For this goal, both the selection of appropriate methods for cattle waste management and the decision to base fertilizer application rates on the N supply from manure are crucial to reducing the net GHG emissions and GHGI.

4. Conclusions

The FYM system reduced the overall net GHG emissions and GHGI by 36% (6.9 Mg CO_2-eq ha^{-1} y^{-1}) and 41% (0.89 Mg CO_2-eq Mg^{-1}), respectively, relative to the slurry system. The net reduction was due largely to the improvement of C stock in grassland. Although the emission of GHG related to cattle waste management and supplemental fertilizer manufacture was greater in the FYM system than in the slurry system, the FYM system maintained an advantage. NECB and the N_2O emissions from grassland and the CH_4 and N_2O emissions related to cattle waste management are crucial to the control of net GHG emissions and GHGI.

Supplementary Materials: The following is available online at http://www.mdpi.com/2073-4433/9/7/261/s1, Table S1: Calculation bases of greenhouse gas emissions.

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