Global perspective on greenhouse gas emission from agricultural sector
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Life cycle inventory-based assessment of greenhouse gas emissions from arable-land farming systems in the Tokachi region of Hokkaido, northern Japan

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Summary

To assess their impacts on net global warming, total greenhouse gas (mainly CO_2, N_2O, and CH_4) emissions from agricultural production in arable land cropping systems in the Tokachi region of Hokkaido, Japan, were estimated by life cycle inventory (LCI) analysis. The LCI data included CO_2 emissions from on-farm and off-farm fossil fuel consumption, soil CO_2 emissions induced by the decomposition of soil organic matter, direct and indirect N_2O emissions from arable lands, and CH_4 uptake by soils, which were then aggregated in CO_2-equivalents. Under plow-based conventional cropping systems for winter wheat, sugar beet, adzuki bean, potato, and cabbage, on-farm CO_2 emissions from fuel-consuming operations such as tractor-based field operations, truck transportation and mechanical grain drying ranged from 0.424 Mg CO_2 ha^{-1} y^{-1} for adzuki bean to 0.826 Mg CO_2 ha^{-1} y^{-1} for winter wheat. Off-farm CO_2 emissions resulting from the use of agricultural materials such as chemical fertilizers, biocides (pesticides and herbicides), and agricultural machines were estimated by Input-Output Tables to range from 0.800 Mg CO_2 ha^{-1} y^{-1} for winter wheat to 1.724 Mg CO_2 ha^{-1} y^{-1} for sugar beet. Direct N_2O emissions previously measured in an Andosol field of this region showed a positive correlation with N fertilizer application rates. These emissions, expressed in CO_2-equivalents, ranged from 0.041 Mg CO_2 ha^{-1} y^{-1} for potato to 0.382 Mg CO_2 ha^{-1} y^{-1} for cabbage. Indirect N_2O emissions due to N leaching and surface runoff were estimated to range from 0.069 Mg CO_2 ha^{-1} y^{-1} for adzuki bean to 0.381 Mg CO_2 ha^{-1} y^{-1} for cabbage. The rates of CH_4 removal from the atmosphere by soil uptake were equivalent to only 0.020 to 0.042 Mg CO_2 ha^{-1} y^{-1}. From the difference in the total soil C pools (0–20 cm depth) between 1981 and 2001, annual CO_2 emissions from conventionally managed soils were estimated to be 4.91 Mg CO_2 ha^{-1} y^{-1}. In total, CO_2-equivalent greenhouse gas emissions under CT cropping systems in the Tokachi region of Hokkaido amounted to 6.97, 7.62, 6.44, 6.64 and 7.49 Mg CO_2 ha^{-1} y^{-1} for winter wheat, sugar beet, adzuki bean, potato, and cabbage production, respectively. Overall, soil-derived CO_2 emissions accounted for a large proportion (64% to 76 %) of the total greenhouse gas emissions. This illustrates that soil management practices which enhance C sequestration in soil may be an effective means to mitigate large greenhouse gas emissions from arable land cropping systems such as those in the Tokachi region of northern Japan.

Keywords: arable land, fuel consumption, greenhouse gas, life cycle inventory, soil organic carbon

Introduction

Crop production in the Tokachi region of Hokkaido

The Tokachi region of Hokkaido in northern Japan is the primary site of arable land crop production in Japan. Four major crops are cultivated in rotation: winter wheat (*Triticum aestivum* L.), beans (adzuki bean *Vigna angularis* (Willd.) Ohwi & Ohashi; kidney bean *Phaseolus vulgaris* L.; and soybean *Glycine max* Merr.), sugar beet (*Beta vulgaris* L.) and potato (*Solanum tuberosum* L.). In addition, the cultivation of vegetables, including cabbage (*Brassica oleracea* L.), has recently been expanding. Andosol, which is a fine volcanic ash-derived soil, is the main soil type in this region.

Compared to other regions in Japan, crop production in the Tokachi region is practiced on a much larger scale, and most of the production processes are highly mechanized, depending on the crop species. Moreover, farmers in this region largely depend on chemical fertilizers and biocides (pesticides and herbicides) to obtain high and stable yields. For soil management operations, fields were harrowed twice to a depth of roughly 10 cm in early spring for soil preparation and plowed once to a depth of roughly 25 cm after harvesting to incorporate crop residues into soil. As a result of fossil fuel consumption and various soil-disturbing field operations such as tillage, fertilization, and residue management, large quantities of greenhouse gas (mainly CO_2, N_2O, and CH_4) emissions may occur in the Tokachi region of Hokkaido.

Life cycle inventory for greenhouse gases in arable crop production systems

In arable land farming systems, the emission and uptake of greenhouse gases which can affect net global warming occur through fossil fuel consumption and as a result of the activity of relevant microorganisms in soil (Fig. 1). Under mechanized cropping systems, on-farm CO_2 emissions are derived from fuel-consuming operations such as tractor operations, transportation by truck, and grain drying (Koga et al., 2003). Fuels are also consumed in the process of manufacturing and transport of necessary agricultural materials, mainly chemical fertilizers, biocides, and agricultural machines. Given the requirements for large quantities of fossil fuels and other agricultural inputs, large quantities of CO_2 are emitted from a wide variety of agricultural production processes.

Agricultural soils act as a sink or source of CO_2 in the C cycling of agro-ecosystems, which is influenced by soil management practices (Paustian et al., 1997). For example, intensive tillage operations lead to a depletion of soil C pools, resulting in large CO_2 emissions from soil to the atmosphere (Lal, 1997; Paustian et al., 1997). Therefore, conservation tillage including no till and reduced tillage can be an effective means of mitigating CO_2 emissions from cultivated lands (Paustian et al., 1997). Conversely, crop residue incorporation and manure application can exert beneficial effects on soil C sequestration through redistribution of atmospheric CO_2 to soil (Lal, 1997).

In the case of N_2O and CH_4, trace greenhouse gases associated with arable land crop production, the 100-year global warming potentials are 296- and 23-fold greater than that of CO_2, respectively (IPCC, 2001). As shown in Fig. 1, N_2O is directly and indirectly emitted through nitrification and denitrification processes as a result of N fertilizer application in cultivated soils (Bouwman, 1996; IPCC, 1997; Sawamoto et al., 2005). Direct N_2O emissions occur at the surface layers of fertilized soils. The emission rates can vary widely, depending on soil conditions such as soil type, moisture, temperature, and mineral N content and on climatic conditions such as rainfall events and soil freezing. On the other hand, one of the indirect N_2O emissions arises from degassing of supersaturated N_2O when groundwater with a high concentration of NO_3^- due to N leaching is discharged into surface waters (IPCC, 1997; Sawamoto et al., 2005). The other indirect N_2O emissions from dissolved N during nitrification and denitrification processes occur in rivers and estuaries (IPCC, 1997). As atmospheric CH_4 is removed under dry soil conditions through the activity of CH_4-oxidizing bacteria, soils managed for arable land crop production can have a beneficial effect on reducing atmospheric CH_4 (Hütsch, 2001). However, it is generally recognized that CH_4 oxidation is sensitive to soil disturbances such as tillage operations and N fertilization (Hütsch, 2001; Koga et al., 2004).

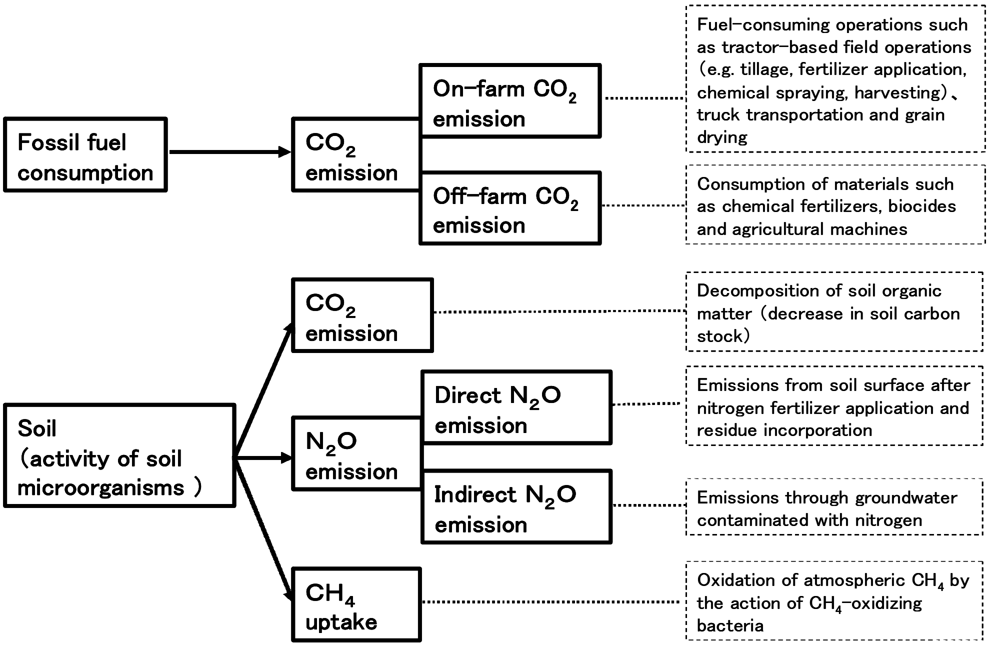

Figure 1. Greenhouse gas (CO_2, N_2O and CH_4) emissions in arable-land farming systems.

Fuel consumption-derived CO_2 emissions

On-farm CO_2 emissions from fuel-consuming operations

On-farm CO_2 emissions were calculated from diesel oil, gasoline, kerosene, and electricity consumption from the following operations: (i) tractor-based field operations (e.g., tillage, fertilization, planting, biocide spraying, and harvesting), (ii) hauling of materials (e.g., seedlings, chemical fertilizers, lime, and water used for biocide spraying) between farmhouse and field, (iii) hauling of farm products between field and their destination, and (iv) other fuel-consuming operations such as wheat grain drying in a drying facility and the application of snow-melting materials by snowmobile. As an example, total diesel oil consumption for tractor-based field operations in sugar beet is presented in Table 1. Fuel consumption for hauling of materials (between farmhouse and field) and farm products (between field and destination) was calculated, based on the assumption that the distances were 1.0 and 10.0 km, respectively. The on-farm CO_2 emissions were calculated from the fuel consumption rates; the combustion of 1.0 L of diesel oil, gasoline, and kerosene resulted in the emission of 2.64, 2.36, and 2.53 kg CO_2, respectively (Ministry of the Environment, Government of Japan, 1999).

As summarized in Table 2, on-farm CO_2 emissions from production of winter wheat, sugar beet, adzuki bean, and potato in this region were 0.826, 0.606, 0.424, and 0.738 Mg CO_2 ha^{-1} y^{-1}, respectively. A large proportion of the on-farm CO_2 emissions was attributed to tillage-related operations (e.g., rotary harrowing for soil preparation and moldboard plowing) and harvesting. The CO_2 emissions from hauling of materials were negligible, while the CO_2 emissions from hauling of farm products were relatively high for such heavy crops as sugar beet, potato, and cabbage (Table 2). In winter wheat, fuel-consuming grain drying was the largest source of CO_2 emissions.

Table 1. Diesel oil consumption for tractor-based field operations under the conventional sugar beet production.

Operation	Implemet	Tractor size (kW)	Fuel consumption rate (L ha^{-1})	Operation frequency	Total fuel consumption (L ha^{-1})
Liming	Lime sower	37	6.0	1	6.0
Soil perparation	Rotary harow	59	20.7	2	41.3
Basal fertilization	Fertilizer applicator	44	9.5	1	9.5
Transplanting	Beet transplanter	44	17.0	1	17.0
Herbicide spraying	Boom sprayer	59	1.9	1	1.9
Inter-row cultivation	Cultivator	37	5.7	3	17.2
Pesticide spraying	Boom sprayer	59	1.9	5	9.6
Harvesting	Beet harvester	44	32.5	1	32.5
Loading of harvests	Front loader	59	9.0	1	9.0
Plowing	Moldboard plow	59	29.8	1	29.8
Transportation of materials in the field	Truck		1.0	10	10.0
Total					183.8

Table 2. Summary of the on-farm CO_2 emissions from fuel-consuming operations under conventional cropping systems in the Tokachi region of Hokkaido. (Mg CO_2 ha^{-1} y^{-1})

Operation	Winter wheat	Sugar beet	Adzuki bean	Potato	Cabbage
Tractor-based field operations	0.345	0.485	0.414	0.637	0.567
Hauling of materials	0.007	0.007	0.004	0.005	0.007
Hauling of farm products	0.012	0.091	0.006	0.096	0.096
Other fuel-consuming operations	0.462	0.023			
Total	0.826	0.606	0.424	0.738	0.670

Off-farm CO_2 emissions from material consumption

Off-farm CO_2 emissions derived from the use of agricultural materials (chemical fertilizers, biocides, and agricultural machines) were calculated, based on the input-output tables for 1995 (Nansai et al., 2002). The CO_2 emission factors for chemical fertilizers, biocides, and agricultural machines used in this study were 5.253, 3.119, and 3.743 g CO_2 yen^{-1}, respectively. The data on mean expenditures from 1999 to 2001 for these materials were obtained from the Obihiro Statistics and Information Center (Table 3).

Off-farm CO_2 emissions from material use under the CT systems ranged from 0.800 Mg CO_2 ha^{-1} y^{-1} for winter wheat to 1.724 Mg CO_2 ha^{-1} y^{-1} for sugar beet (Table 3). These off-farm CO_2 emissions were greater than the on-farm CO_2 emissions, except for winter wheat, where fuel-consuming grain drying was the largest source of CO_2 emissions. Higher off-farm CO_2 emission rates for sugar beet and cabbage than in the other three crops were due principally to the higher fertilizer application rates for these crops.

Table 3. Mean expenditures (1999-2001) on chemical fertilizers, biocides and agricultural machines and the resulting off-farm CO_2 emissions.

	Winter wheat	Sugar beet	Adzuki bean	Potato	Cabbage
Mean expenditure[a] (10^3 yen ha^{-1} y^{-1})					
Chemical fertilizers	78.9	185.6	69.2	70.0	153.3
Biocides[b]	50.0	102.4	63.4	60.8	24.8
Agricultural machines	61.4	114.8	115.3	85.9	80.2
Off-farm CO_2 emission (Mg CO_2 ha^{-1} y^{-1})					
Chemical fertilizers	0.414	0.975	0.364	0.368	0.805
Biocides	0.156	0.319	0.198	0.190	0.077
Agricultural machines	0.230	0.430	0.432	0.322	0.300
Total	0.800	1.724	0.994	0.880	1.182

[a] Data cited from Obihiro Statistics and Information Center.

Soil-associated emissions and uptake of CO_2, N_2O, and CH_4

CO_2 emissions through the decomposition of soil organic matter

Assuming that all C losses from soil contributed to CO_2 emissions, annual CO_2 emission from conventionally tilled soils was calculated, on a soil mass basis (Paustian et al., 1997), from the difference in the total soil C to a depth of 20 cm between 1981 and 2001. To eliminate the effect of changes in bulk densities during the long-term tillage experiment, the depths for soils in 2001 were adjusted, so that the dry soil masses considered would be equal between 1981 and 2001. Soil sampling for measuring bulk density and C content in each year was conducted in an experimental long-term tillage field at NARCH.

In 1981, the total soil C at the 0–20 cm depth was 81.5 Mg C ha^{-1} (Table 4). In contrast, the total C contents of the conventionally tilled soils in 2001 were 54.8 Mg C ha^{-1} for the 0–20.59 cm depth, equivalent to the 0–20 cm depth in 1981. Consequently, the annual CO_2 emission from the soil was 4.91 Mg CO_2 ha^{-1} y^{-1} (Table 4). This indicates that use of arable lands for crop production in the Andosol region of Hokkaido resulted in the rapid decomposition of soil organic matter and considerable emissions of CO_2 from the soil. The rapid decomposition of soil organic matter resulting in CO_2 emissions from soil was also reported to occur in long-term field experiments in four Andosol regions of Japan (Shirato et al., 2004). These large reductions in soil C pools imply that arable soils used for crop production are a significant source of CO_2 emissions to the atmosphere in Japanese agro-ecosystems.

Table 4. Annual CO_2 emissions from soils at NARCH.

Total C		Total C loss in a year	Annual soil CO_2 emission
1981[a]	2001		
Mg C ha^{-1}		Mg C ha^{-1} y^{-1}	Mg CO_2 ha^{-1} y^{-1}
81.5	54.8	1.34	4.91

[a] Total C in soil sampled from shallow tillage plot in 1981 was used as a basis for the calculation of soil CO_2 emissions.

Direct and indirect N_2O emissions

The annual rates of direct N_2O emissions were measured in the experimental long-term tillage field at NARCH (Koga et al., 2004) and used in this study. The new indirect N_2O emission factor for degassing after discharge to surface waters ($EF_{5\text{-}g}$) of 0.0024 was used; this factor was re-evaluated by reviewing all available data on NO_3^- and dissolved N_2O concentrations in leached water (Sawamoto et al., 2005). According to the default values reported by IPCC (1997), the indirect N_2O emission factors for rivers ($EF_{5\text{-}r}$) and estuaries ($EF_{5\text{-}e}$) were 0.0075 and 0.0025, respectively. Indirect N_2O emission rates were calculated by multiplying the amount of N leaching or runoff by 0.0124, the combined indirect emission factor for N_2O due to N leaching (EF_5). The quantity of N lost through leaching or runoff was calculated by multiplying the amount of N applied by the IPCC default value of 0.3 as a fraction for N leaching (IPCC, 1997).

In the field investigated in this study, direct N_2O emission rates under conventional cropping systems were 0.88, 0.53, 0.30, 0.14, and 1.29 kg N_2O ha^{-1} y^{-1} for winter wheat, sugar beet, adzuki bean, potato, and cabbage, respectively (Table 5). These emission rates were equivalent to 0.041 Mg CO_2 ha^{-1} y^{-1} for potato to 0.382 Mg CO_2 ha^{-1} y^{-1} for cabbage. The direct N_2O emission factor (the percent ratio of N_2O-N emitted out of N applied as fertilizer) averaged 0.36 % across the five crops (Koga et al., 2004), which was much lower than the IPCC default value of 1.25 % (IPCC, 1997) or the 2.8 % from an onion (*Allium cepa* L.) field on a gray lowland soil at Mikasa, central Hokkaido (Kusa et al., 2002). Similar lower N_2O emission factors have been recorded in Japanese Andosol fields (Akiyama and Tsuruta, 2002; Cheng et al., 2002). Andosols, typically used for arable land crop production in Japan, may display lower N_2O emission factors than other soil types in Japan.

Table 5. Annual rates of direct N_2O emissions and CH_4 uptake in soils at NARCH.

	Direct N_2O emission		CH_4 uptake	
	(kg N_2O ha^{-1} y^{-1})	(Mg CO_2 ha^{-1} y^{-1})	(kg CH_4 ha^{-1} y^{-1})	(Mg CO_2 ha^{-1} y^{-1})
Winter wheat	0.88	0.261	0.85	0.020
Sugar beet	0.53	0.157	1.49	0.034
Adzuki bean	0.30	0.089	1.81	0.042
Potato	0.14	0.041	1.44	0.033
Cabbage	1.29	0.382	1.61	0.037

Data cited from Koga et al. (2004).

Indirect N_2O emissions due to N leaching were estimated to range from 0.234 kg N_2O ha^{-1} y^{-1} (0.069 Mg CO_2 ha^{-1} y^{-1}) for adzuki bean to 1.286 kg N_2O ha^{-1} y^{-1} (0.381 Mg CO_2 ha^{-1} y^{-1}) for cabbage (Table 6). This indicates that the contribution of indirect N_2O emissions to the total greenhouse gas emissions (1 to 5 %) is similar to that of direct N_2O emissions.

CH_4 uptake by arable soil

The annual rates of soil CH_4 uptake were also measured in the experimental long-term tillage field at NARCH (Koga et al., 2004) and used in this study.

Although CH_4 uptake rates varied considerably among different tillage and crop treatments, the quantity of CH_4 taken up, expressed on a CO_2 basis, was negligible compared to the emissions of CO_2 and N_2O (Table 5).

Table 6. Estimated indirect N_2O emissions from crop production.

Crop	N application rate	Indirect N_2O emission[a]	
	kg N ha^{-1} y^{-1}	kg N_2O ha^{-1} y^{-1}	Mg CO_2 ha^{-1} y^{-1}
Winter wheat	110	0.643	0.190
Sugar beet	150	0.877	0.260
Adzuki bean	40	0.234	0.069
Potato	60	0.351	0.104
Cabbage	220	1.286	0.381

Aggregation of the sink/source categories of greenhouse gases

Taking into account the six sink/source categories for CO_2, N_2O, and CH_4, large quantities of greenhouse gases were emitted under arable land crop production in the Tokachi region of Hokkaido (Fig. 2). Under the CT cropping systems, total CO_2-equivalent greenhouse gas emissions in a single year amounted to 6.97, 7.62, 6.44, 6.64, and 7.49 Mg CO_2 ha^{-1} y^{-1} for production of winter wheat, sugar beet, adzuki bean, potato, and cabbage, respectively. A large proportion (64 % for sugar beet to 76 % for adzuki bean) of the greenhouse gases was emitted as CO_2 from soil due to the decomposition of soil organic matter (Fig. 2). As mentioned previously, large soil C losses, resulting in CO_2 emissions, have also been observed in other Japanese arable land soils (Shirato et al., 2004). This illustrates the importance of soil management operations to decelerate soil organic matter decomposition or to increase the amount of organic matter in soil in order to reduce net greenhouse gas emissions from arable land cropping systems. One way to enhance C sequestration in soil is conservation tillage, particularly no till (Paustian et al., 1997). In a number of long-term field experiments in temperate zones, total soil C was 8% higher under no till than under conventional tillage on the average (Paustian et al., 1997). The supply of organic matter to soil through residue incorporation and manure application is also a beneficial practice for sequestering more C in soil (Lal, 1997).

The off-farm CO_2 emissions from material use contributed to 12% and 23% of the total greenhouse gas emissions for winter wheat and sugar beet, respectively (Fig. 2). This suggests that limiting agricultural material inputs may reduce greenhouse gas emissions from arable land farming systems in this region. Compared to off-farm CO_2 emissions, on-farm CO_2 emissions from fossil fuel consumption (except for CT winter wheat production) were smaller even under such highly mechanized cropping systems as those in the Tokachi region of Hokkaido.

The impact of direct N_2O emissions on the total greenhouse gas emissions was relatively small (Fig. 2), given the lower direct N_2O emission factor (0.36%) measured in an Andosol field in this region (Koga et al., 2004). In gray lowland soils cultivated with onions in central Hokkaido, the N_2O emission factor (2.8%) was much higher (Kusa et al., 2002) than that in the Andosol of the study region. Were such a high N_2O emission factor employed in this study, the contribution of the direct N_2O emissions to total greenhouse gas emissions would be much larger. Soil physical properties, different from soil to soil, are crucial in determining the N_2O emission factor (McTaggart et al., 2002). Therefore, the importance of direct N_2O emissions in the total greenhouse gas emissions from agro-ecosystems varies substantially with the soil type. In this study, the quantities of indirect N_2O emissions were comparable to those of direct N_2O emissions. The CH_4 uptake rates were negligible on a CO_2 basis.

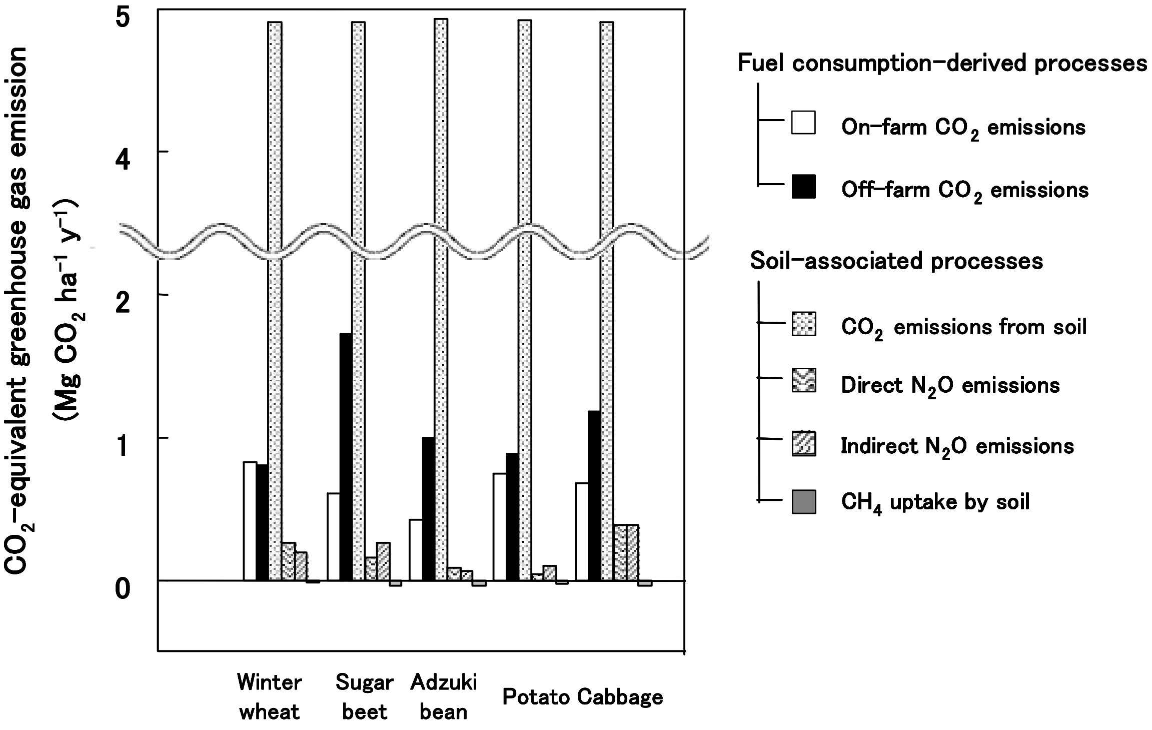

Figure 2. Total CO_2-equivalent greenhouse gas emissions under each cropping system in the Tokachi region of Hokkaido.

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