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Emission of N_2O and CO_2 and Uptake of CH_4 in Soil from a Satsuma Mandarin Orchard under Mulching Cultivation in Central Japan

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The flux of nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) from brown lowland soils in a satsuma mandarin (*Citrus unshiu* Marcow, 'Silverhill', 31 years old) orchard located in Okitsu, central Japan facing the North Pacific Ocean, was measured once a week from March 2001 to February 2002 using the closed chamber method. Two categories of treatment, mulching and non-mulching, were used in the experimental field by covering the soil surface with a moisture-permeable and waterproof sheet in the latter half of fruit growing season from mid-September to mid-December in 2001. The annual N_2O emission and the amount of total nitrogen fertilized were 93 mg N/m^2/year and 27.0 g N/m^2/year for the non-mulching treatment and 55 mg N/m^2/year and 18.9 g N/m^2/year for the mulching treatment, respectively. No significant difference was found in the N_2O emission factor between mulching (0.34%) and non-mulching (0.29%) treatment. These emission factors were much lower than the average value (0.62%) for upland fields in Japan and the IPCC default value of 1.25%. On the other hand, a small amount of atmospheric methane was absorbed into the surface soils throughout the year. The annual uptake of CH_4 was 24 and 17 mg CH_4/m^2/year for the non-mulching and mulching treatment, respectively, with no significant difference between the two treatments. Annual CO_2 emission with the non-mulching and mulching treatment was 1.45 and 0.89 kg CO_2/m^2/year, respectively. The difference in the amount of each gas emission between the two treatments was discussed with respect to the soil temperature, water-filled pore space (WFPS), the timing and amount of nitrogen fertilized, and the effect of mulching.

Key Words: emission factor, greenhouse gas emission, water-filled pore space.

Introduction

The major greenhouse gases (GHGs) emitted from agro-ecosystems and contributing to global warming are carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). The main production processes of CO_2 are the respiration of roots and above-ground biomass, and the decomposition of soil organic matter, crop residues, fertilizers and dead leaves (Raich and Schlesinger, 1992). Regarding the production of N_2O, the transformation of nitrogen (N) fertilizers is the major process, through nitrification, the oxidation process of NH_4^+ under aerobic conditions (Goreau et al., 1981), and/or denitirification, the reduction process of NO_3^- under anaerobic conditions (Delwiche, 1981). Methane is produced from the decomposition of organic matter under anaerobic conditions, such as rice straws incorporated in flooded rice paddy fields, and CH_4 is also oxidized under aerobic conditions.

These processes of production, decomposition and oxidation related to GHGs are affected by the activities of microbes (or microorganisms), and are controlled by many factors of the soil environment such as soil type, soil temperature (Koizumi et al., 1993; Leassard et al.,

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1994; Rochette et al., 1992), soil moisture (Leassard et al., 1994; Rochette et al., 1992) and soil physical and chemical properties, and by field managements such as crop species or methods of cultivation.

So far, many crop fields, including irrigated rice paddy fields, have been studied to determine the major factors controlling the emission of GHGs. In contrast, very few studies on GHG emission from orchard ecosystems have been reported in the world. The soil environment in perennial fruit tree orchards is qualitatively different from that in annual crops, because a large amounts of roots exist in soils all the year round, and the frequency of tillage is usually less than in crop fields.

For the flux of CO_2 from soils of deciduous fruit tree orchards, Blanke (1996, 1998) and Proctor et al. (1976) reported on apple orchards. Carbon budget studies on grapevine and peach fields in Japan by Sekikawa et al. (2002, 2003) demonstrated that the soil in grapevine and peach orchards plays an important role in carbon sequestration. In evergreen fruit trees, Keller (1986) reported the flux of CO_2, N_2O, and CH_4 from citrus orchards in tropical regions. There have been, however, no studies on GHG emission from citrus fields in temperate regions. The methods of cultivation and farm management also greatly affect GHG emission (Rochette at al., 1992).

A moisture-permeable and waterproof sheet for mulching has been recently used to produce high quality satsuma mandarin fruit with a higher concentration of sugar in Japan. This mulching can also affect GHG emission from citrus fields. The objective of this study is to measure the annual emission of N_2O and CO_2, and the uptake of CH_4 from soils with and without the application of a mulching sheet in a satsuma mandarin orchard in Japan and to clarify the effects of the mulching sheet on GHG emission.

Materials and Methods

1. *Field site*

The study site is located in an open field of the Department of Citriculture, Okitsu branch, National Institute of Fruit Tree Science, Japan (Lat. 35°03'N, Long. 138°31'E), 1 km from Suruga Bay, facing the North Pacific Ocean. The field is climatologically classified as temperate monsoon, and is appropriate for citriculture.

In the open orchard, satsuma mandarin trees ('Silverhill', 31 years old in 2001) were planted on a ridge (4 m wide) 50 cm higher than furrows at a density of 50 trees per 10 a. An intensive field study was performed from March 2001 to February 2002 using non-mulching and mulching treatment with the first mulching performed in the autumn of 2000. Meteorological data of the air temperature and precipitation measured at the Okitsu branch station were used from the Automated Meteorological Data Acquisition System (AMeDAS, Japan Meteorological Agency, Japan).

2. *Cultivation and field management*

An outline of the conventional cultivation is shown in Figure 1. The soil was cultivated to a depth of about 10 cm by machine on February 13, 2001 after magnesia lime fertilization. Thereafter, ammonium-N fertilizers were applied in both treatments on March 27 (6.75 g N/m^2), May 14 (6.75 g N/m^2) and June 13 (5.4 g N/m^2) and only in the non-mulching treatment on November 16 (8.1 g N/m^2). The total amount of fertilized N was 18.9 and 27.0 g N/m^2 in the mulching and non-mulching treatments, respectively. These N-fertilizers were uniformly spread on the soil surface under the canopy.

Mowing performed three times on May 2, June 5, and July 2 for spring weeds and a herbicide was used to kill summer weeds on August 1. In addition, pruning was done in March and growing fruit were thinned three times from late June to September. The pruned branches

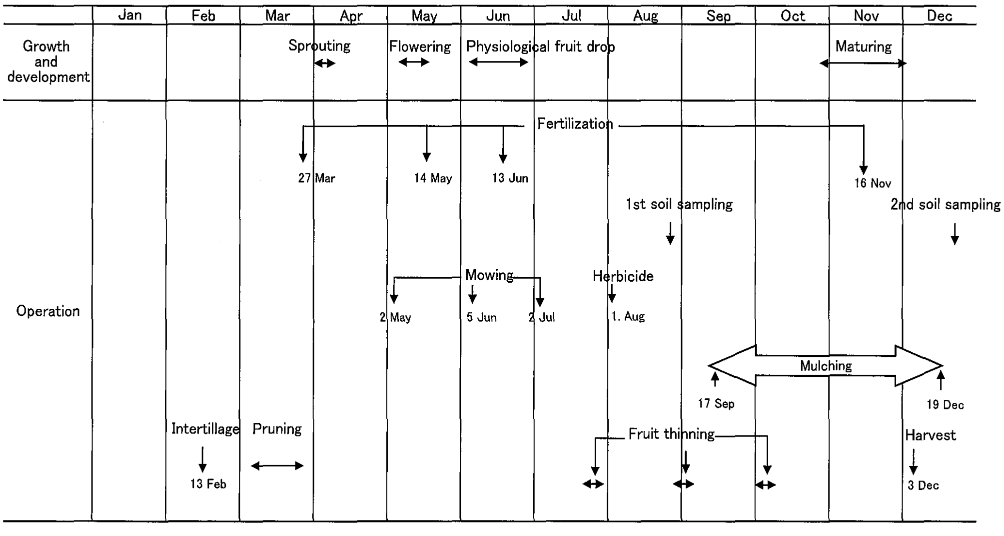

Fig. 1. Summary of growth and development of sastuma mandarin fruit and the management of citrus orchards.

and mown weeds were removed from the orchard because they affect the emission of gases and the thinned fruit and dropped leaves were left in the field. The fruit was harvested on December 3.

In the mulching treatment, a moisture-permeable and waterproof sheet made from fine and high-density polyethylene fibers 0.1 mm thick (Tyvek, Dupont, USA) was used to cover all the soil surface of the ridge for three months from September 17 to December 19, 2001. In the same period of the previous year (2000), the same sheet first covered the same ridge in the mulching treatment. Rain can not penetrate but soil moisture can evaporate through the sheet, which reflects more than 90% of incidental at visible sunlight due to its white color.

3. *Measurement of gas flux*

Three trees were selected from each treatment for the measurement of GHG flux, which was performed from 8 March 2001 to 27 February 2002. Two sampling sites for flux measurement were located 1 m from the trunk of each tree to the west and east. Gas sampling was conducted with six replicates per treatment by a closed chamber technique (Hutchinson and Mosier, 1981), using a cylindrical chamber made of non-transparent PVC without a base (60 cm in diameter and 15 cm in height). The chamber was placed on a frame base which was fixed in the surface soil to a depth of 3 cm throughout the year. During the mulching period when the frame base could not be fixed in the soil in the mulching treatment, a chamber was used with a skirt on the edge with 2 kg weights to avoid air leakage.

Gas samples in the chamber were collected once a week into evacuated glass vial bottles with a butyl rubber stopper by using a portable syringe at 0, 10, and 20 minutes just after placing the chamber on the frame base. The concentration of CH_4 and CO_2 was measured by a gas chromatograph equipped with FID and TCD (GC-9A, Shimadzu Corp., Japan) and N_2O was measured by another gas chromatograph equipped with ECD (GC-14A, Shimadzu Corp.). Each gas flux was calculated from the temporal change in gas concentration with time by using the air temperature in the chamber, also measured during gas sampling. The annual emission rate of each GHG was calculated in the period of March 2001 to February 2002.

4. *Soil properties*

The soil type in the orchard was brown lowland soil. Soil properties such as total carbon (TC), total nitrogen (TN), bulk density, water-filled pore space (WFPS), and pH were analyzed by standard methods, after soils in both treatments were collected from the topsoil (T: 0–5 cm depth) and subsoil (S: 20–30 cm depth) layers near the tree bottoms on August 30, 2001 before mulching.

In addition, to investigate changes in the soil pH before and after mulching, soils in the mulching plot were also collected from these layers on December 25 after the mulching sheet was removed.

The volume water content (VWC; %) in soil from the soil surface down to a depth of 10 cm was measured with a TDR soil moisture meter (Hydrosense CD620 and CS620, Campbell Scientific, USA) by inserting a probe to a depth of 20 cm at an angle of 30° with three replications in each treatment, and WFPS was calculated from the VWC and soil porosity.

The ammonium and nitrate contents of soils were also measured at the same site as for the VWC. Soil samples collected from the topsoil down to a depth of 5–10 cm were diluted with distilled water (water : sample = 5 : 1), and NH_4^+ and NO_3^- in the extract were analyzed with RQ-flex (Kanto Chemical Co. Japan). Soil temperature was also measured at a depth of 5 cm in both treatments at every flux measurement.

5. *Statistical analysis*

The annual emission and pH in soil were analyzed by ANOVA using SigmaStat 2.0 (SPSS Inc., USA). Single correlation analysis was applied for the flux of CO_2 and CH_4, or N_2O with the soil temperature and WFPS as explanatory variables. Single correlation analysis were performed using Excel 2003 software (Microsoft, USA).

Results

1. *Seasonal variation in air temperature, soil temperature, and precipitation*

Time series of air and soil temperature and precipitation are shown in Figure 2. The average air temperature from March 2001 to February 2002 was 16.7°C, 0.7°C higher than in the last 20 years, and annual precipitation during the same period was 1954 mm, 386 mm less than in the last 20 years. No significant differences in the soil temperature between mulching and non-mulching treatments were observed through the year, except for January and February 2002 with higher temperatures in the mulching treatment.

2. *Soil properties*

In the soil samples collected on 30 August, the averaged total carbon and nitrogen content and C/N ratio showed no significant difference among the topsoil and subsoil of both treatments (Table 1). The bulk density and WFPS showed no significant difference between both treatments, but showed significantly higher values in the subsoil than in the topsoil. The soil pH of the topsoil showed a significant increase in December for both treatments, but in the subsoil it increased only in the non-mulching treatment.

3. *Time series of WFPS*

The seasonal change in WFPS was in accordance with that in precipitation throughout the year (Fig. 3). The WFPS of the mulching treatment showed a 5–27% lower value than in the non-mulching treatment during the

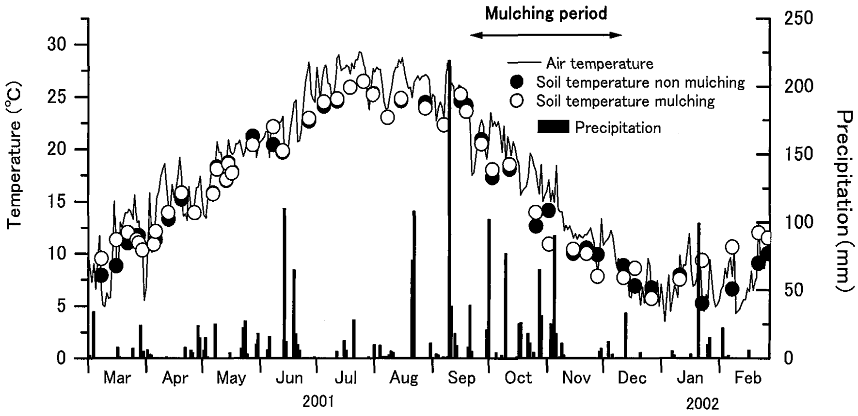

Fig. 2. Seasonal variation in daily mean air temperature, daily precipitation, and soil temperature at 5 cm depth in mulching and non-mulching treatments.

Table 1. Soil properties in topsoil and subsoil for mulching and non-mulching treatments in August (before mulching) and December (after removal of mulching sheet).

Treatment	Depth (cm)	TC[z] (g C/kg)	TN[y] (g N/kg)	C/N	pH (H_2O)		Bulk density (g/cm^3)	WFPS (%)
					30 Aug.	25 Dec.		
Non-mulching	0–5	15.9±1.1[x]	1.56±0.18	10.2±0.7	5.82±0.30	6.32±0.68	1.01±0.06	29±4
	20–30	14.4±2.1	1.42±0.17	10.1±0.7	5.50±0.55	6.50±0.51	1.30±0.09	61±8
Mulching	0–5	17.6±1.7	1.75±0.21	10.1±0.7	5.15±0.36	6.40±0.58	0.96±0.04	26±3
	20–30	16.5±2.1	1.58±0.21	10.5±0.1	6.09±0.21	5.96±0.46	1.26±0.01	56±5

[z] Total carbon.

[y] Total nitrogen.

[x] Mean±SD (n=3).

mulching period of mid-September to December, and was followed by a further 10% decrease from January to February 2002 after removal of the mulching sheet. Even in the other non-mulching period except for summer, the WFPS in the mulching treatment was a little bit lower than in the non-mulching treatment.

4. *Change in inorganic nitrogen in soil*

The concentration of NH_4^+ and NO_3^- in the topsoil in both treatments increased after the second application of N fertilizers and also after the third fertilization in the non-mulching treatment; however, no such increase in non-mulching treatment was observed after the fourth fertilization on November 16 (Fig. 4a). In contrast, a broad peak with the highest concentration in NO_3^- was only found in the mulching treatment in November, the latter period of mulching, without any increase in NH_4^+ (Fig. 4b).

5. *Gas flux*

1) N_2O: N_2O flux was almost always higher in non-mulching treatment than in mulching treatment from April to November, while it showed no difference between the two treatments in the other months due to very low flux. High peaks of N_2O flux in both treatments from April to June (Fig. 5) followed the application of N fertilization. In both treatments, another sharp increase in N_2O flux was observed in late August and mid-September, just after heavy rain of 100–200 mm per day.

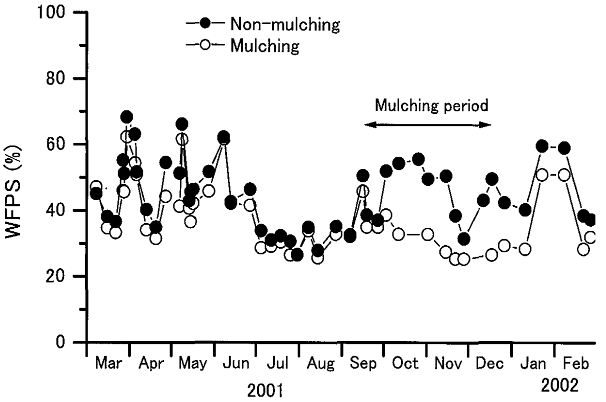

Fig. 3. Seasonal changes in water-filled pore space (WFPS) in the soils of citrus orchards with mulching and non-mulching treatments.

2) CH_4: From March to July, CH_4 flux showed a large fluctuation with no systematic change. After August, however, CH_4 flux almost always had a small negative value, ranging from 0 to −10 µg CH_4/m/h (Fig. 6). As a result, CH_4 flux showed no clear seasonal change in both treatments.

3) CO_2: CO_2 flux in non-mulching treatment was almost always higher than in mulching treatment throughout the year except for November when it was equal in both treatments (Fig. 7). In non-mulching treatment, CO_2 flux was in the range of 30–100

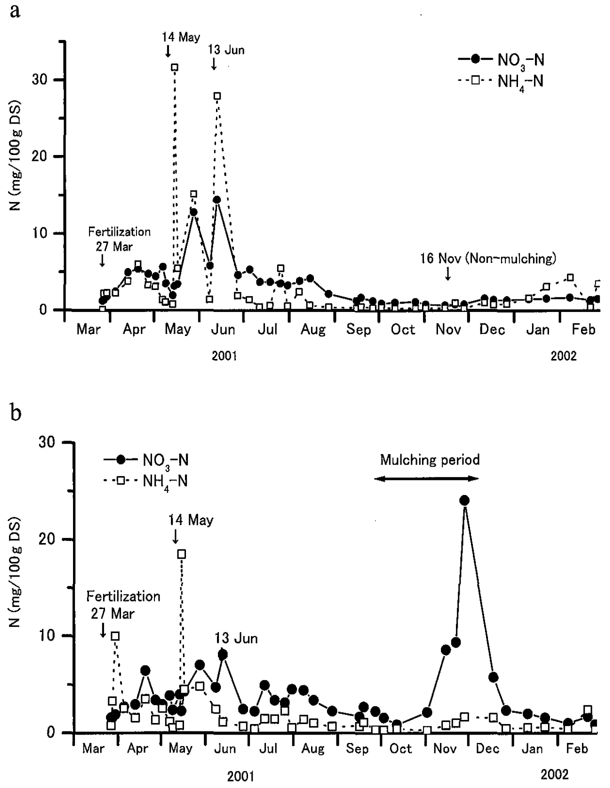

Fig. 4. Seasonal changes in NH_4^+-N (dotted line) and NO_3^--N (solid line) in topsoil in non-mulching (a) and mulching treatments (b). Time of fertilizer application is indicated by a vertical arrow.

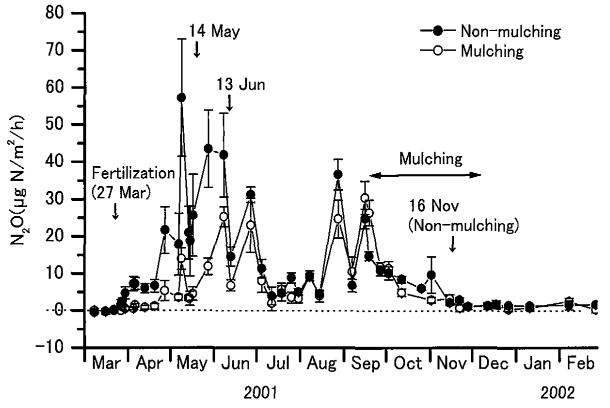

Fig. 5. Seasonal changes in N_2O flux in mulching (○) and non-mulching (●) treatments. Time of fertilizer application is indicated by a vertical arrow.

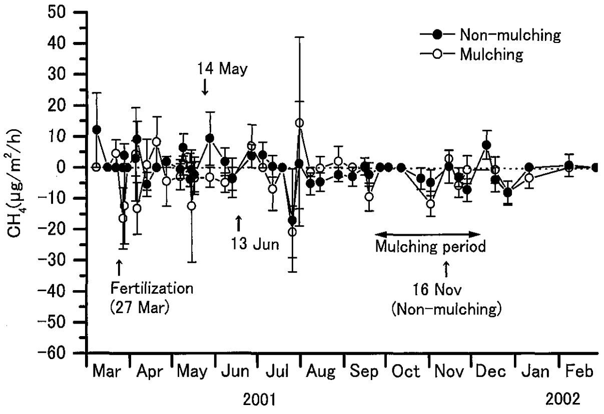

Fig. 6. Seasonal changes in CH_4 flux in mulching (○) and non-mulching (●) treatments. Time of fertilizer application is indicated by a vertical arrow.

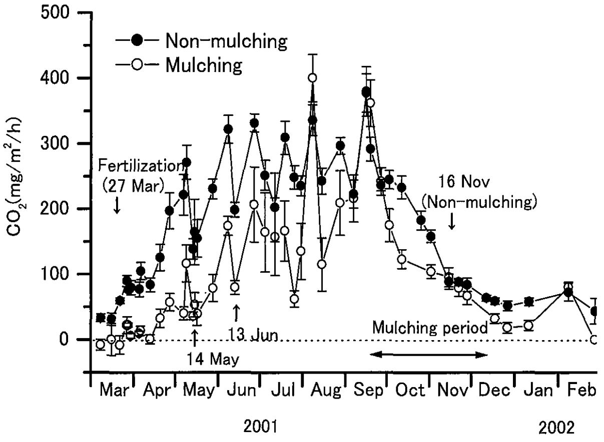

Fig. 7. Seasonal changes in CO_2 flux in mulching (○) and non-mulching (●) treatments. Time of fertilizer application is indicated by a vertical arrow.

mg CO_2/m^2/h from March to mid-April, and then increased rapidly until mid-May, reaching 280 mg CO_2/m^2/h and was in the range of 200–380 mg CO_2/m^2/h between June and September. In the mulching treatment, however, very low CO_2 flux less than 60 mg CO_2/m^2/h was observed from March to early April. Then, it gradually increased until May and was in the range of 70–400 mg CO_2/m^2/h from June to September. Thereafter, flux in both treatments continuously decreased as air and soil temperatures decreased.

6. Annual emission of GHGs and emission factor of N_2O

The annual emission of N_2O, CH_4 and CO_2 and their CO_2-equivalent value by using the global warming potential ($CO_2 : CH_4 : N_2O = 1 : 23 : 296$) (Intergovernmental Panel on Climate Change, 2001) are shown in Table 2. The annual emission of CO_2 was 0.886 kg CO_2/m^2/year in mulching treatment, significantly lower by 39% than that in non-mulching treatment (1.45 kg CO_2/m^2/year). As well as CO_2, the annual emission of N_2O in mulching treatment (55 mg N/m^2/year) is significantly lower by 41% than that in non-mulching treatment (93 mg N/m^2/year). The N_2O emission factor, the ratio of annual N_2O-N emission to the annual input of nitrogen fertilized, was 0.34 and 0.29% for mulching and no-mulching treatments, respectively, with no significant difference between these two treatments. The annual uptake of CH_4 was not significantly different between mulching treatment (−0.017 g CH_4/m^2/year) and non-mulching treatment (−0.024 g CH_4/m^2/year). As a result, total CO_2 equivalent GHG emissions amounted to 1.49 and 0.92 kg CO_2/m^2/year for non-mulching and mulching treatments, respectively. Furthermore, 97% of the total GHG emission as the CO_2 equivalent value from soil in satsuma mandarin fields was CO_2 and the emission ratio of N_2O was only 3% of the total emission.

Table 2. Annual emission of CO_2, CH_4, and N_2O, their percentage of total emission, and emission factor of N_2O in mulching and non-mulching treatments.

	N_2O			CH_4		CO_2	
Treatment	Emission (g N/m^2/year)	% of total emission by CO_2 equivalent	Emission factor (%)^z (N_2O-N/T N × 100)	Emission (g CH_4/m^2/year)	% of total emission by CO_2 equivalent	Emission (kg CO_2/m^2/year)	% of total emission by CO_2 equivalent
Non-mulching	0.093	2.9	0.34	−0.017	0.0	1.45	97.1
Mulching (permeable sheet)	0.055	2.8	0.29	−0.024	−0.1	0.89	97.3
Significance^y	**	NS	NS	NS	NS	**	NS

[z] Nitrogen emitted as N_2O per total nitrogen applied.

[y] NS and ** represent non-significance and significance at 1% level by T-test, respectively.

Table 3. Single correlation coefficient of each flux for soil temperature and water-filled pore space (WFPS) in mulching and non-mulching treatments.

	Mulching			Non-mulching		
	N_2O	CH_4	CO_2	N_2O	CH_4	CO_2
Soil Temp.	0.517**^{z}	0.092	0.602**	0.310**	−0.157	0.806**
WFPS	0.238**	−0.063	0.602**	0.295**	0.377**	−0.028

[z] Significant at 1% level by T-test.

7. *Single correlation analysis between each gas flux and soil temperature or WFPS*

1) N_2O: Single correlation analysis of N_2O with soil temperature and WFPS as explanatory variables showed a significantly positive correlation ($P < 0.01$) for both variables in both treatments (Table 3).

2) CH_4: Methane showed a significantly positive correlation ($P < 0.01$) only for WFPS in non-mulching treatment ($r = 0.377$).

3) CO_2: The single correlation coefficient of CO_2 flux with soil temperature in mulching treatment and non-mulching treatment was 0.602 and 0.806 with significance ($P < 0.01$), respectively. In non-mulching treatment, the flux did not depend on WFPS ($r = -0.028$), but in mulching treatment, it depended on WFPS ($r = 0.602$).

Discussion

1. *Relationship between each gas flux and soil temperature or WFPS*

1) N_2O: The positive correlation of N_2O flux with soil temperature and WFPS in both treatments suggests that the increase in soil temperature and WFPS with a range of 30–70% also increased the activity of microorganisms in soil to produce N_2O (Granli and Bøckman, 1994). As N_2O flux increased a few days after the increase in the soil inorganic nitrogen content, especially NH_4^+, due to the application of N-fertilizers, this indicates that N_2O was mainly produced by nitrification. On the other hand, in both treatments, the sharp increases in N_2O flux in late August and mid-September just after heavy rain with no increase in inorganic nitrogen in the topsoil might be attributed to denitrification in soils in the deeper layer below the topsoil as shown in onion fields in central Hokkaido (Sawamoto and Hatano, 2000).

2) CH_4: Positive correlation of CH_4 with the WFPS (Table 3) in non-mulching treatment ($r = 0.377$) was also shown in arable cropping fields with Andosol in northern Hokkaido (Koga et al., 2004). Atmospheric CH_4 was usually absorbed by the soil in this experiment, consistent with the fact already reported from forest soils or arable cropping fields under aerobic conditions (Keller et al., 1983; Koga et al., 2004; Steudler et al., 1989). Kagotani et al. (1999) reported that CH_4 flux from forest soils showed a seasonal change in accordance with soil temperature, but no significant correlation between CH_4 flux and soil temperature was observed in this study or in northern Hokkaido (Koga et al., 2004).

3) CO_2: The dependence on WFPS was different between treatments. In non-mulching treatment, the flux did not depend on WFPS ($r = -0.028$), because WFPS showed a minimum of around 30% in July and August when the CO_2 flux was highest and no correlation with CO_2 flux in autumn and winter (Figs. 3 and 7). On the other hand, in mulching treatment, it depended on WFPS ($r = 0.602$) as well as soil temperature ($r = 0.602$). There was almost no difference in the soil temperature between the two treatments except for the winter period, but the soil in the mulching treatment tended to be dry even in the non-mulching period, possibly due to the previous year's mulching effect (Fig. 4).

The rapid increase in CO_2 flux began in mid-April (Fig. 7). A similar increase in soil from a peach and grapevine orchard began about one month earlier than in the present study (Sekikawa et al., 2002, 2003). Sekikawa et al. (2002, 2003) concluded that the major factor in the rapid increase of CO_2 flux from the peach and grapevine fields in spring was the development of new roots in these trees increasing the amount of exudation from roots. This mechanism could also occur with citrus roots because they begin to grow from late-April (Kadoya, 2001).

In our experiment, flux was measured by removing floor vegetation three times and by one application of herbicide in the weed-growing season of May to August as previously mentioned. As a result, the amount of litter from floor vegetation was usually small. Moreover, the influence of their respiration and/or decomposition on CO_2 flux was assumed to be negligible, because the difference in CO_2 flux between non-mulching and mulching treatment showed no remarkable change before and after weeding (May 2, June 5, July 2, and August 1). Note that the amount of above-ground biomass for ground vegetation (dry matter $g \cdot m^{-2}$) measured on July 18 before herbicide application in mulching treatment was 132.2 ± 43.8 (Mean ± SD, n = 3), less than that in non-mulching treatment (227.6 ± 30.5, n = 3).

2. *Effect of mulching on the flux of GHGs*

A possible effect of mulching on soil environment is the modification of soil temperature and/or soil moisture, compared to soils without mulching.

No significant difference, however, was observed in soil temperature between the two treatments during the mulching period as well as other periods, possibly due to its white color, and vapor-permeable material. In contrast, soil moisture shown as WFPS in this study was higher in non-mulching treatment than in mulching treatment throughout the year (Fig. 3). The following two facts demonstrate a clear effect of mulching on soil moisture. The difference in WFPS between the two treatments was greater than 10% in the mulching period than in the non-mulching period; and the difference in WFPS continued to be 10% for at least two months, even after the sheet was removed in mid-December. Therefore, the major reason why WFPS in the period of March to August 2001 was a little bit lower in mulching treatment than in non-mulching treatment is possibly attributed to the effect of previous mulching in the period of September to December 2000.

CO_2: It is well known that the soil respiration rate measured as CO_2 flux in this experiment is the sum of CO_2 emission derived from root respiration and decomposition of soil organic matter by microorganisms, both of which are affected by soil temperature and soil moisture (Raich and Schlesinger, 1992). A decrease in WFPS usually causes a decrease in the activity of roots and microorganisms in soils (Raich and Schlesinger, 1992). Considering the result that there was no difference in soil temperature between the two treatments, the large decrease in CO_2 flux in the mulching treatment could be due to the decrease in root activity and/or the decomposition rate of soil organic matter via influencing the decrease in soil moisture.

N_2O: As described previously, the emission factor of N_2O for one year showed no significant difference between the two treatments, because almost no enhancement of N_2O flux after the fourth fertilization was observed in non-mulching treatment (Fig. 5). Another emission factor in the period from March to September, during which the total amount of N input was equal in both treatments, was much higher in non-mulching treatment than in mulching treatment. This could be attributed to the higher soil moisture in non-mulching treatment (Fig. 3), because N_2O flux is usually controlled by soil moisture and soil temperature (Granli and Bøckman, 1994).

NO_3^- concentration in mulching treatment showed a remarkable increase during the mulching period from November to December with no increase in N_2O flux (Figs. 4b and 5). This could be attributed to capillary phenomena that ground water or a wet soil layer with high NO_3^- concentration was temporarily raised up to the dry surface soil layer through small pore spaces in soils and not to salt accumulation in topsoil. In our experiment, the increase of NO_3^- concentration was much lower than in soil suffering salt accumulation in the greenhouse (Nakano et al., 2001) and temporarily occurred only during the short mulching period.

3. *Comparison of GHG emission from citrus orchard in the temperate zone with that from other fields in agro-ecosystems*

In Table 4, GHG emissions from orchards and other fields are listed.

1) N_2O: According to an intensive three-year (1992–1994) field program on CH_4 and N_2O emission from agro-ecosystems all over Japan, the emission factor of N_2O in a persimmon and pineapple orchard with only inorganic nitrogen fertilization was 0.59–0.79 and 0.26%, respectively (Tsuruta, 1998). Together with these previous results, the present results of non-mulching treatment (0.34%) can lead to the conclusion that annual N_2O emission in the Japanese orchard is around 0.5% of the total amount of synthesized N fertilizers and that the N_2O emission factor is slightly lower than the average value from soils in agro-ecosystems (0.62%) for upland crop fields in Japan (Ministry of the Environment, Japan, 2006) and lower than the IPCC default value of 1.25% (Intergovernmental Panel on Climate Change, 1997). The major reason for the lower N_2O emission in the present study is that N fertilizers are applied only on the soil surface with no incorporation into topsoil and that soil moisture in the present field had a lower level than arable cropping fields with Andosol in northern Hokkaido (Koga et al., 2004) and in Tsukuba (Cheng et al., 2002).

The emission factors from Andosol in northern Hokkaido (Koga et al., 2004) and Tsukuba (Akiyama and Tsuruta, 2003; Cheng et al., 2002) in Japan are almost the same as those in the present study, which

Table 4. Annual emission of CO_2 and N_2O, and uptake of CH_4 from orchards, some agro-ecosystems and forests.

Environment and location	Total carbon	Estimated annual emission (uptake for CH_4)			Emission factor (%)[z] (N_2O-N/T N × 100)	Sampling duration	Reference
	g C/kg	CO_2 (kg/m^2/year)	CH_4 (g/m^2/year)	N_2O (g/m^2/year)			
Agro-ecosystems							
Citrus orchard (non-mulching)	15.9 (0–5 cm)	1.45	0.017	0.093	0.34	Mar. 2001–Feb. 2002	This study
Citrus orchard (mulching)	17.6 (0–5 cm)	0.89	0.024	0.055	0.29	Mar. 2001–Feb. 2002	This study
Persimmon orchard				0.118 (N) 0.238 (N)	0.59, 0.79	Mar. 1994–Feb. 1995 Aug. 1993–Jul. 1994	Tsuruta, 1998
Pineapple orchard				0.088 (N)	0.26	10 months (1993–1994)	Tsuruta, 1998
Peach (Japan)	35 (0–5 cm)	3.91				Sep. 1999–Aug. 2000	Sekikawa et al., 2002
Grapevine (Japan)	22 (0–5 cm)	1.55				Sep. 1998–Aug. 1999	Sekikawa et al., 2003
Apple (Germany)		1.9~2.5				Jan. 1994–Dec. 1997	Blanke, 1998
Onion field (central Hokkaido)	32.1 (0–10 cm)	0.69, 1.82				May–Nov. (1999, 2000)	Hu et al., 2004
Five crop fields (coventional tillage)	29.8 (0–5 cm)		0.085–0.181	0.019–0.056 (N)	0.36	May (Sep) 2001–Apr. (Aug) 2002	Koga et al., 2004
Three crop fields (reduced tillage)	36.1 (0–5 cm)		0.221–0.252	0.031–0.236 (N)		May (Sep) 2001–Apr. (Aug) 2002	Koga et al., 2004
Double-cropping systems							
Peanut and wheat (Japan)		2.92				Jun. 1985–May 1988	Koizumi et al., 1993
Upland rice and barly		2.63				Jun. 1985–May 1988	Koizumi et al., 1993
Dentcorn and Italian ryegrass		3.85				Jun. 1985–May 1988	Koizumi et al., 1993
Natural forest (central Japan)			0.692			Apr. 1991–Mar. 1993	Kagotani, et al., 1999
Two secondary forests (central Japan)			0.329			Apr. 1991–Mar. 1993	Kagotani, et al., 1999
Forests (25 sites in Japan)			0.326–2.478 (average 1.04)			for 1–7 years	Ishizuka et al. (unpublished data)

[z] Nitrogen emitted as N_2O per total nitrogen applied.

indicates that another major factor controlling N_2O emission is soil type. In order to clarify the major factors controlling N_2O emission from orchard fields, more field study is expected in future.

2) CH_4: So far, no other measurement of CH_4 flux from soils in orchards has been reported. In arable cropping fields with Andosol in northern Hokkaido, the averaged annual CH_4 uptake from three crops in conventional and reduced tillage fields was 0.138 and 0.241 g CH_4/m^2/year, respectively (Koga et al., 2004). According to an intensive field study on CH_4 uptake in forest soils all over Japan, the averaged annual CH_4 uptake was 1.04 (0.326–2.478) g CH_4/m^2/year (Ishizuka et al., unpublished data). In temperate forest soils in Shiga, western Japan, annual CH_4 uptake was 0.701 and 0.354 g CH_4/m^2/year in a natural forest and two secondary forests, respectively (Kagotani et al., 1999). These data clearly showed that the annual uptake of CH_4 in the present study was much lower than in arable cropping fields of Andosol and forest soils in Japan. Generally, the uptake of CH_4 is higher in forest soils than agricultural soils and is higher in no/reduced tillage soils than in conventional tillage soils in agro-ecosystems (Koga et al., 2004). These studies indicate that soil disturbance such as tillage affects the potential of CH_4 uptake, while porosity or gas diffusion in soils is well known to be one of the major factors controlling CH_4 uptake (Dörr et al., 1993). It is unclear at this stage why CH_4 uptake in the citrus orchard was very low even in a reduced tillage field.

3) CO_2: Compared with other agro-ecosystems, the annual CO_2 emission of 1.45 kg CO_2/m^2/year from soils observed in the present study belonged in the low CO_2 emission group in Table 4. It was also lower than other fruit tree orchards, peach (3.91 kg CO_2/m^2/year), grapevine (1.55 kg CO_2/m^2/year) and apple (1.9–2.5 kg CO_2/m^2/year). These differences could be attributed to the difference in soil environment such as soil types, soil physical/chemical properties, organic/fertilizer management and cultivation practice. Soil carbon content is also one of the critical factors affecting CO_2 emission from soil. Understanding carbon budgets in agro-ecosystems is important, because carbon sequestration in soils contributes to reduce CO_2 emission from anthropogenic sources and can be a mitigation option (Intergovernmental Panel on Climate Change, 2001). According to long-term monitoring of soil characteristics of arable lands all over Japan, which has been made every 5 years since 1979 (Nakai and Obara, 2003), the averaged soil carbon contents in Japanese orchards were around 3.5% (Obara, 2000). Sekikawa et al. (2002, 2003) reported that total carbon content was 3.5% and 2.2% in peach and grapevine, respectively. In contrast, the orchard soil in our experiment had a total carbon of about 1.6%. These data strongly suggest that a study on carbon and nitrogen budgets including GHG emission in orchards is also needed in future.

The flux of N_2O, CH_4, and CO_2 from soils in an open orchard of satsuma mandarin was measured from March 2001 to February 2002 under two treatments with and without mulching by covering the soil surface with a moisture-permeable and waterproof sheet during September to December 2001. No significant difference was found in total carbon and C/N in soil and soil temperature between the two treatments. WFPS was, however, significantly lower in mulching treatment than in non-mulching treatment throughout the year, especially in the period of mulching. This mulching effect on WFPS contributed to significant reduction of CO_2 emission from mulching treatment compared to that in non-mulching treatment, while there was no difference in apparent N_2O emission and CH_4 absorption. The above results focused on GHG emission from soil and did not consider the absorption and/or emission of GHGs from the tree. To consider emission from the agro-ecosystem, more study at the tree or orchard level is needed.

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