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Effect of Mechanized Tillage Operations on Soil Physical Properties and Greenhouse Gases Fluxes in Two Agricultural Fields

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Abstract: Soil management practices may affect greenhouse gases emissions and exacerbate global warming. We studied the short-term effect of mechanized tillage operations on soil properties and CO_2, CH_4, NO and N_2O fluxes in a corn and soybean fields. The study was conducted from June to December 2001 at Hokkaido University in Sapporo (Japan). The soil of the experimental site is classified as Eutric Fluvisols (FAO). Two plots of 20 m long by 30 m width each were isolated in fields planted to corn (*Zea mays*) and soybean (*Glucine max*). Plot interrows were compacted by 1, 2, 3 and 4 cycles a tractor. Soil and air samples were collected for measuring CO_2, CH_4, NO and N_2O fluxes and other soil properties. Results showed that soil volumetric water content (θ_v), bulk density (ρ_b), the pore tortuosity factor (τ) and Soil Penetration Resistance (SPR) increased while air-filled porosity (f_a), Total Pore Space (TPS) and the soil gas diffusion coefficient (D_s/D_o) decreased linearly with increasing tractor cycle in both corn ($p<0.0001$) and soybean ($p<0.01$) fields. In corn field, CO_2 ($p<0.0011$), NO ($p<0.0257$) and N_2O ($p<0.0116$) fluxes increased quadratically with increasing tractor cycle. In soybean field, CO_2 and CH_4 fluxes increased while N_2O and NO fluxes decreased linearly with increasing tractor cycle. CO_2 ($r = 0.45$, $p<0.003$) and N_2O ($r = 0.45$, $p<0.003$) fluxes were significantly correlated with soil penetration resistance in corn and soybean field, respectively. Increasing tractor cycle deteriorated soil physical properties and increased greenhouse gas fluxes. More studies are needed to determine if these effects are permanent or only temporary on both soil and gas fluxes.

Key words: Gas fluxes, soil properties, tillage operations

INTRODUCTION

Global atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years. The increase in carbon dioxide concentration is due primarily to fossil fuel use and land-use change, while methane and nitrous oxide increases are primarily caused by agriculture (IPCC, 2007). Agricultural practices such

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as tillage have been shown to change emissions of N_2O and the consumption of patterns of CH_4 in agricultural soils (Teepe *et al*., 2004). Tractor traffic during tillage operations is one of the practices that influence the exchange of CO_2, CH_4, NO and N_2O between the soil and the atmosphere as during such traffic, depending on the moisture level, soil compaction increases (Meek, 1994; Rollerson, 1990). In fact, compaction packs the primary soil particles (sand, silt, clay) and soil aggregates closer together and dramatically alter the balance between solids, air-filled and water-filled pore space (Allbrook, 1986; Bruand and Cousin, 1995). By increasing the portion of water-filled pores, compaction makes the soil prone to denitrification and therefore increases N_2O losses (Ball *et al*., 2000; Douglas and Crawford 1993). There are numerous studies on the effects of soil compaction on soil properties (Greene and Stuart, 1985; Rollerson, 1990; Meek, 1994). However, less work has been reported on the effect of tractor compaction on gases fluxes. Among these few studies, Flessa *et al*. (2002) quantified N_2O and CH_4 fluxes for ridges, uncompacted interrows and tractor-compacted interrows from potato (*Solanum tuberosum*) fields. They found that N_2O emissions were highest for the tractor compacted soil. However, the major fraction of the total CH_4 uptake (+86%) occurred on the ridges. Ruser *et al*. (1998) observed that the gaseous fluxes of N_2O and CH_4 fluxes from potato field were strongly affected by ridge-till practices; this produced areas with increased (ridges) and strongly reduced (tractor-compacted interrows) soil porosity. Hansen *et al*. (1993) compared tractor-compacted and uncompacted soils. They found that N_2O emissions (approximately 35%) increased due to soil compaction. Tractor "trips" during farming operations affect soil properties which lead to greenhouse emissions. Unfortunately the magnitude of these emissions is not still well quantified as many of these studies are conducted either at the beginning, middle or end of the growing season. However, in order to accurately predict the total emissions from agricultural systems, contribution at each stage of farming operations should be known. The objective of this study was therefore to assess the short-term (at early stage of field operations) effect of tractor induced compaction on soil properties and gases fluxes in a corn and a soybean fields of northern Hokkaido.

MATERIALS AND METHODS

Experimental Site

This study was conducted at Hokkaido University Experimental Farm in Sapporo, Hokkaido, Japan (43° 11' N, 141° 30' E), from early June to late December 2001. Sapporo, Japan's third largest city enjoys a mild climate with a year-round average temperature of 9.1°C. The average temperature was -3.5°C in January and 20.3°C in July 2001. The soil of the experimental site is classified as Typic Fluvaquents (Soil Taxonomy), Eutric Fluvisols (FAO). The physical and chemical properties of different horizons were reported by Hayashi and Hatano (1999). Soil texture consists of 25.4% sand, 47.0% silt and 27.6% clay. The saturated hydraulic conductivity is 2.99×10^{-5} cm s^{-1}. The carbon and nitrogen contents were 2.1 and 0.16%, respectively. Field preparation began in April and in May, two plots of 30 m long by 20 m width were isolated in fields cropped to corn (*Zea mays*) and soybean (*Glucine max*). These fields were established maintained by the Crop Production Laboratory, Faculty of Agriculture, Hokkaido University. The corn field was fertilized with N, 130; P_2O_5, 180; K_2O, 100 and MgO, 40 kg ha^{-1} while soybean received N, 32; P_2O_5, 100; K_2O, 80 and MgO, 24 kg ha^{-1}. In June 2001, plots interrows in both soybean and corn fields were compacted by 1, 2, 3 and 4 cycles (1 cycle = 2 passes) with a 2.4 tons Fordson Major tractor (as during regular tillage operations) (Fig. 1). The ridges of crop rows were not compacted. Immediately after tractor compaction, Soil Penetration Resistance (SPR) was measured to a depth of 100 cm and soil samples were taken in both interrows and ridges. A second measurement of SPR, sampling for soil properties and greenhouse gas fluxes was conducted three weeks later in August 2001.

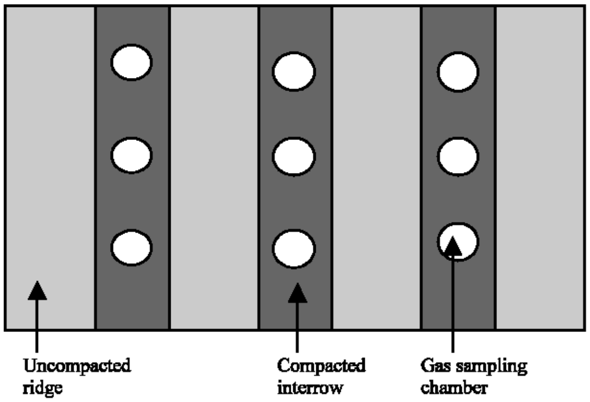

Fig. 1: Experimental site, showing gas sampling chamber, compacted-non compacted interrows and ridges

Measurement of Soil Chemical Properties

Soil samples were taken at each sampling locations immediately after measurements of greenhouse gases emissions, for analyses of chemical properties. Soil samples were collected at 5 cm depth from the soil surface with a 5.1 cm height and 5 cm diameter aluminum cylinder. The properties studied were soil pH (H_2O and KCl), electrical conductivity (EC), nitrite (NO_2^-), nitrate (NO_3^-) and ammonium (NH_4^+). For analyses of NO_2^- and NO_3^-, 10 g of field moist soil sample was extracted by 50 mL of deionized water (1:5 = soil: water) and concentrations of the above anions were determined by ion exchange chromatography. This extract was also used to measure pH (H_2O) and EC. For NH^+_4 determination, 7 g of field moist sample was extracted using 70 mL of 2 M KCl. pH (KCl) was measured using this extract and soil NH_4^+ was determined by colorimetry with indophenol-blue.

Measurements of Soil Physical Properties

For soil physical properties, soil cores (3 replicates for each of the 5 tractor cycles) were taken in each of corn and soybean fields at 5 cm depth from the soil surface with a 5 cm diameter and a 5.1 cm height cylinder (volume = 100 cm^3). Cores fresh weights were first measured then their bottom covered with a filter paper. The filter paper was strongly held with rubbed elastic. Cores without their top covers were thereafter transferred onto a tension table. The top of the tension table was covered with a plastic paper to prevent evaporation. Cores were saturated for comparison purpose between calculated Total Pore Space (TPS) to that determined as core volumetric water content at saturation. However, in this report only TPS values calculated were used. After 72 h of saturation, cores fresh weights were again measured. They were then transferred into an oven to be dried at 105°C for 72 h. Soil bulk density (ρ_b), Total Pore Space (TPS), volumetric water content (θ_v), air-filled porosity (f_a), relative gas diffusion coefficient (D_s/D_0) and the pore tortuosity factor (τ) were later calculated as follows:

Bulk Density (ρ_b)

$$\rho_b = Ms/Vt \qquad (1)$$

where, ρ_b (kg m^{-3}) is the soil bulk density, Ms (kg) is the mass of dry solids determined after drying the soil sample to constant weight at 105°C and Vt (m^3) is the total volume of soil and thus Vt is the volume of cylinder.

$$Vt = Va + Vw + Vs \qquad (2)$$

where:
V_s (m^3): Volume of soil solids
Vw (m^3): Volume of water
V_a (m^3): Volume of the air fractions successively.

Total Pore Space (TPS)

$$TPS = (Vw+Va)/Vt \qquad (3)$$

where, TPS (m^3 m^{-3}) is the total pore space or the total space of soil filled with fluid (air + water).

Gravimetric Water Content (θ_g)

$$\theta_g = (Mt\text{-}Ms)/Ms \qquad (4)$$

where:
θ_g(kg soil water kg^{-1} soil): Gravimetric water content or mass of water present in each unit mass of the dry soil,
Mt (kg): Weight of the moist soil sample as taken from the field.

Volumetric Water Content (θ_v)

$$\theta v = [(Mt\text{-}Ms).\rho w]/Vt \qquad (5)$$

where:
θ_v (m^3 soil water m^{-3} soil): Volumetric water content or the volume of water present in a unit volume of the sample.
ρ_w: Density of water taken as equals to 1000 kg m^{-3}.

Air-Filled Porosity (*f*$_a$)

$$f_a = TPS\text{-}\theta v \qquad (6)$$

where, f_a (m^3 soil air m^{-3} soil) is a*ir-filled porosity* or the portion of the pore space filled with air (air space).

Relative Gas Diffusivity (D_s/D_o)

Relative gas diffusivity was calculated using Buckinghan (1904) equation:

$$Ds/Do = (f_a)^2 \qquad (7)$$

where:
D_s/D_o(m^2 sec^{-1}. m^{-2} sec): Relative gas diffusion coefficient
Ds: Gas diffusion coefficient in the soil (m^3 soil air m^{-1} soil s^{-1})
D_o: Gas diffusion coefficient in free air (m^2 air s^{-1}).

Pore Tortuosity (τ)

The pore tortuosity factor was calculated by comparing Reible and Shair (1982).

$$\tau = 1/f_a \tag{8}$$

where:

τ ($m\ m^{-1}$): Pore tortuosity factor.

Water Filled Pore Space (WFPS)

$$WFPS = (\theta v/TPS)\times 100 \tag{9}$$

where:

WFPS (%): Percentage of the total pore space filled with water.

Gas Sampling for CO_2, CH_4, NO and N_2O Flux Measurements

CO_2, CH_4, NO and N_2O emissions from tractor-compacted interrows and non-compacted ridges were measured using a closed-chamber technique. This technique has also been used by Tokuda and Hayatshu (2000) and (2004). The chambers were circular with steel frames. The top of each chamber had a gas sampling tube and a bag to control air pressure inside the chamber. The height and diameter of the chamber were 0.35 and 0.30 m, respectively. At each sampling time, 3 chambers (each chamber corresponding to a replicate) spaced 10 m were installed in the soil in the interrow or ridge and kept for 20 min and then samples of the enclosed atmosphere were withdrawn by a 50 mL syringe and transferred into a 1L Tedlar ® Bag with non-sorbant walls. A total of 30 samples (3 replicates × 5 tractor cycles × 2 fields) were taken in both corn and soybean fields. The air temperature inside the chambers was recorded using a digital thermometer. Ambient air between 0 and 2 m from the soil surface was collected and its mean concentration was used as a background concentration for calculation of gas fluxes. Immediately after sampling, a gas chromatography with an electron capture detector and FID used for N_2O and CH_4 analyses, respectively. NO flux was analyzed by chemo-iluminescence with a nitrogen oxide analyzer (Kimoto, Model 265 P) and an infra-red analyzer was used for CO_2. Fluxes were calculated using the equation:

$$F = \rho * \frac{V}{A} * \frac{\Delta C}{\Delta t} * \left(\frac{273}{T}\right) * \alpha \tag{10}$$

were:

F: Gas production rate

ρ: Gas density ($mg\ m^{-3}$) under standard conditions

V (m^3) and A (m^2): Volume and bottom area of the chamber

$\Delta C/\Delta t$: Ratio of change in the gas concentration inside the chamber;

T: Absolute temperature

α: Transfer coefficient (12/44 for CO_2, 12/16 for CH_4, 14/30 for NO and 28/44 for N_2O).

A positive value indicates gas emission from the soil, while a negative value indicates gas uptake. The detectable limits were 0.1 mg C $m^{-2}\ h^{-1}$ for CO_2, 0.01 μg C $m^{-2}\ h^{-1}$ for CH_4 and 0.1 μg N $m^{-2}\ h^{-1}$ for NO and N_2O. Soil temperature was measured at 5 cm and 10 cm from the top soil layer, using a digital thermometer. Statistix 8.0 statistical package was used to calculate summary of simple statistics, analysis of variance, polynomial contrasts, correlation matrix and linear regression.

RESULTS

Effect of Tractor Cycle on Soil Chemical Properties

Soil chemical properties as affected by tractor load and cycle (Table 1 and 2) for corn and soybean, respectively. At 5% probability level, tractor load and cycle did not affect any of the soil chemical properties studied. In magnitude, values of chemical properties observed in ridges were similar to those found in tractor-compacted interrows, except for NO_3^- which tended to increase with tractor cycles.

Effect of Tractor Cycle on Soil Physical Properties

Table 3 and 4 show the effect of tractor load and cycle on soil physical properties. All soil physical properties studied were significantly affected by tractor cycle. Volumetric water content (θ_v), bulk density (ρ_b) and pore tortuosity (τ) increased, whereas air-filled porosity (f_a), Total Pore Space (TPS) and the gas diffusion coefficient (D_s/D_0) decreased linearly with increasing tractor cycle. In comparison to all compacted interrows, average ridge values for θ_v, ρ_b and τ were lower while those for f_a, TPS and D_s/D_0 were higher. In addition, in magnitude, values of θ_v, ρ_b, τ, f_a, TPS and D_s/D_0 were similar in both corn and soybean fields. However, for tractor-compacted interrows, average values of θ_v, ρ_b and τ were higher in corn while those for f_a, TPS and D_s/D_0 were higher in soybean field.

The effect of tractor load and number of cycle on soil resistance (Table 5 and 6) to penetration in July 2001 for corn and soybean, respectively. Tractor cycle linearly increased soil resistance to penetration for both sampling dates and in both fields, but the effect was prevalent only in the top 20 cm of the soil profile. Below this depth, the relationship was no longer prevalent. In addition, in magnitude, values of soil resistance to penetration measured immediately after compaction treatments were as twice as high in comparison to those measured three weeks later. Finally, in comparison to tractor-compacted interrows, SPR values measured on the ridges were lower.

Effect of Tractor Cycle on Greenhouse Gas fluxes

The effect of tractor load and number of cycle on greenhouse gas fluxes (Table 7 and 8) for corn and soybean fields, respectively. Except for CH_4 which failed to respond, all greenhouse gas fluxes

Table 1: Soil chemical properties in a cornfield as affected by mechanized tillage operations

Tractor cycle	pH (H_2O)	pH (KCl)	EC (mS)	NO_2^- (mg N kg^{-1} soil)	NO_3^- (mg N kg^{-1} soil)	NH_4^+ (mg N kg^{-1} soil)
Ridge (non compacted)	6.24	4.71	5.29	0.07	11.13	0.90
1 Cycle compacted interrows	6.15	4.51	4.79	0.09	9.34	0.96
2 Cycles compacted interrows	5.82	4.38	6.11	0.04	10.38	0.96
3 Cycles compacted interrows	6.03	4.59	5.16	0.07	12.67	1.36
4 Cycles compacted interrows	6.12	4.69	5.11	0.10	9.78	1.09
Analysis of variance						
Replications	ns	ns	ns	ns	ns	ns
Cycle (c	ns	ns	ns	ns	ns	ns

ns = non significantly different at LSD = 0.05

Table 2. Soil chemical properties in a soybean field as affected by mechanized tillage operations

Tractor cycle	pH (H_2O)	pH (KCl)	EC (mS)	NO_2^- (mg N kg^{-1} soil)	NO_3^- (mg N kg^{-1} soil)	NH_4^+ (mg N kg^{-1} soil)
Ridge (non compacted)	5.91	4.47	5.30	0.23	4.93	1.13
1 Cycle compacted interrows	6.13	4.98	5.84	0.08	10.46	1.27
2 Cycles compacted interrows	5.72	4.64	8.81	0.05	17.87	0.86
3 Cycles compacted interrows	5.84	4.67	5.54	0.05	8.44	1.09
4 Cycles compacted interrows	5.94	4.46	5.25	0.04	6.13	0.82
Analysis of variance						
Replications	ns	ns	ns	ns	ns	ns
Cycle (C)	ns	ns	ns	ns	ns	ns

ns = no significant

Table 3: Soil physical properties in a cornfield as affected by mechanized tillage operations

Tractor cycle	θ_v ($m^3 m^{-3}$)	ρ_b (kg m^{-3})	f_a ($m^3 m^{-3}$)	TPS ($m^3 m^{-3}$)	D_s/D_o ($m^2 sec^{-1} m^{-2}$ sec)	τ (m m^{-1})
Ridge (non compacted)	0.23	0.53	0.57	0.80	0.34	1.77
1 Cycle compacted interrows	0.32	0.74	0.40	0.72	0.16	2.60
2 Cycles compacted interrows	0.38	0.89	0.28	0.66	0.08	3.61
3 Cycles compacted interrows	0.39	0.95	0.25	0.64	0.06	4.08
4 Cycles compacted interrows	0.44	1.06	0.17	0.60	0.03	6.50
Analysis of variance						
Replications	ns	ns	ns	ns	ns	ns
Cycle	****	****	****	****	***	***
Cycle linear	****	****	****	****	****	****
Cycle quadratic	*	ns	*	ns	**	ns

*, **, ***, **** = significantly different at 5, 1, 0.1 and 0.01%, respectively. ns = no significant

Table 4: Soil physical properties in a soybean field as affected by mechanized tillage operations

Tractor cycle	θ_v ($m^3 m^{-3}$)	ρ_b (kg m^{-3})	f_a ($m^3 m^{-3}$)	TPS ($m^3 m^{-3}$)	D_s/D_o ($m^2 sec^{-1} m^{-2}$ sec)	τ (m m^{-1})
Ridge (non compacted)	0.23	0.52	0.57	0.80	0.34	1.79
1 Cycle compacted interrows	0.29	0.73	0.43	0.73	0.19	2.34
2 Cycles compacted interrows	0.32	0.81	0.37	0.69	0.14	2.74
3 Cycles compacted interrows	0.33	0.86	0.35	0.68	0.13	2.90
4 Cycles compacted interrows	0.38	0.98	0.26	0.63	0.07	4.30
Analysis of variance						
Replications	ns	ns	ns	ns	ns	ns
Cycle	*	**	*	**	*	*
Cycle linear	**	***	**	***	**	**
Cycle quadratic	ns	ns	ns	ns	ns	ns

*, **, ***, **** = significantly different at 5, 1, 0.1 and 0.01%, respectively. ns = no significant

Table 5: Soil resistance to penetration (kg cm^{-2}) in a corn field as affected by mechanized tillage operations

	Depth					
Tractor cycle	2.5 cm	5 cm	7.5 cm	10 cm	15 cm	20 cm
Ridge (non compacted)	0.13	0.20	0.23	0.25	0.43	0.97
1 Cycle compacted interrows	0.57	0.65	0.73	0.75	1.10	1.60
2 Cycles compacted interrows	0.61	0.72	0.74	0.76	1.03	1.13
3 Cycles compacted interrows	0.76	0.81	0.80	0.85	0.94	1.08
4 Cycles compacted interrows	0.77	0.84	0.89	0.92	0.88	1.27
Analysis of variance						
Replications	ns	ns	ns	*	**	**
Cycle (C)	****	****	****	****	****	**
Cycle linear	****	****	****	****	***	ns
Cycle quadratic	*	***	***	***	****	ns

*, **, ***, **** = significantly different at 5, 1, 0.1 and 0.01%, respectively. ns = no significant

Table 6: Soil resistance to penetration (kg cm^{-2}) in a soybean field as affected by mechanized tillage operations

	Depth					
Tractor cycle	2.5 cm	5 cm	7.5 cm	10 cm	15 cm	20 cm
Ridge (non compacted)	0.11	0.11	0.16	0.22	0.68	1.25
1 Cycle compacted interrows	0.58	0.66	0.70	0.64	0.60	1.27
2 Cycles compacted interrows	0.98	1.03	0.94	0.93	1.02	0.94
3 Cycles compacted interrows	0.90	1.01	1.02	0.98	1.27	1.52
4 Cycles compacted interrows	0.99	1.03	1.02	0.93	1.19	1.38
Analysis of variance						
Replications	ns	**	*	**	*	**
Cycle (C)	****	****	****	****	****	*
Cycle linear	****	****	****	****	****	ns
Cycle quadratic	***	****	****	****	ns	ns

*, **, ***, **** = Significantly different at 5, 1, 0.1 and 0.01%, respectively. ns = no significant

Table 7: Greenhouse gas fluxes in a cornfield as affected by mechanized tillage operations

Tractor cycle	CO_2 (mg CO_2-C m^{-2} h^{-1})	CH_4 (μg CH_4-C m^{-2} h^{-1})	NO (μg NO-N m^{-2} h^{-1})	N_2O (μg N_2O -N m^{-2} h^{-1})
Ridge (non compacted)	66.55	-15.18	3.79	77.43
1 Cycle compacted interrows	65.54	-27.05	2.17	68.85
2 Cycles compacted interrows	85.47	-13.32	9.09	47.96
3 Cycles compacted interrows	71.25	-27.27	1.05	77.61
4 Cycles compacted interrows	69.28	-15.47	1.94	92.48
Analysis of variance				
Replications	ns	ns	ns	ns
Cycle (C)	***	ns	**	*
Cycle linear	ns	-	ns	ns
Cycle quadratic	***	-	*	**

*, **, ***, **** = significantly different at 5, 1, 0.1 and 0.01%, respectively. ns = no significant

Table 8: Greenhouse gas fluxes in a soybean field as affected by mechanized tillage operations

Tractor cycle	CO_2 (mg CO_2-C m^{-2} h^{-1})	CH_4 (μg CH_4-C m^{-2} h^{-1})	NO (μg NO-N m^{-2} h^{-1})	N_2O (μg N_2O -N m^{-2} h^{-1})
Ridge (non compacted)	45.28	7.31	8.02	-16.35
1 Cycle compacted interrows	62.98	-12.14	0.10	18.55
2 Cycles compacted interrows	83.97	-5.62	1.06	60.75
3 Cycles compacted interrows	73.97	-17.89	3.55	39.01
4 Cycles compacted interrows	57.92	-8.36	2.52	73.25
Analysis of variance				
Replications	ns	ns	ns	ns
Cycle	*	ns	*	**
Cycle linear	ns	-	ns	**
Cycle quadratic	**	-	**	ns

*, **, ***, **** = significantly different at 5, 1, 0.1 and 0.01%, respectively. ns = no significant

were significantly affected by tractor load and cycle. In addition, except for NO fluxes which increased linearly in the soybean field, all gas fluxes increased quadratically with increasing tractor cycle. In soybean field, CO_2 and N_2O fluxes measured in the ridges were lower than those obtained in tractor-compacted interrows. However, NO and CH_4 fluxes were higher in the ridges than tractor-compacted interrows. There was no specific trend for the relationship between ridges and compacted interrows fluxes in the corn field, but after computing the average values for all tractor-compacted interrows and comparing them with ridge values, the same trend as in the soybean field was found. Among ridges, CO_2 and N_2O fluxes were higher in the corn as compared to soybean while NO fluxes dominated in soybean. A close examination of the means also reveal that in both fields, the highest CO_2 and N_2O fluxes were obtained after 2 and 4 cycles of interrows compaction, respectively. The highest fluxes for NO were obtained after 2 cycles in corn, but in the ridge for soybean. In cornfield, CH_4 was consumed in both ridges and tractor-compacted interrows. However, in soybean field, CH_4 was emitted in non-compacted ridges and consumed in tractor-compacted interrows. Finally, uptake of N_2O (negative fluxes) was observed in non-compacted ridge of soybean field, indicating that denitrification was enhanced as a result of soil compaction.

Correlation between Soil Physical Properties and Greenhouse Gas Fluxes

The relationship between CO_2 fluxes and soil penetration resistance (SPR) measured at 2.5 cm depth in the cornfield (Fig. 2). CO_2 fluxes were also significantly correlated with SPR measured at 5 cm ($r = 0.58$, $p = 0.029$) and 10 cm ($r = 0.58$, $p = 0.044$) depth. CH_4 fluxes were only correlated with SPR measured at 15 cm depth ($r = 0.62$, $p = 0.014$). The relationship between N_2O fluxes and SPR measured at 2.5 cm depth for the soybean field (Fig. 3). N_2O fluxes were also significantly correlated with SPR measured at 15 cm ($r = 0.64$, $p = 0.011$) and 30 cm ($r = 0.52$, $p = 0.045$) depth. CO_2 was

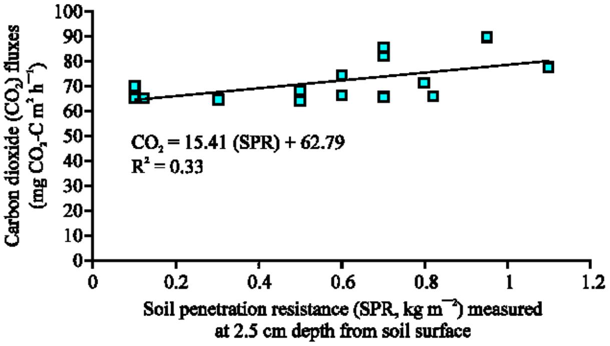

Fig. 2: Relationship between Carbon dioxide (CO_2) fluxes and soil penetration resistance in a cornfield

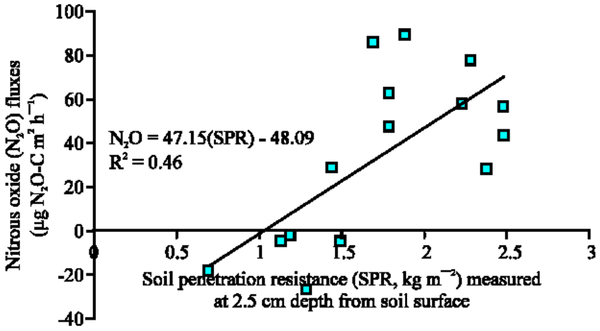

Fig. 3: Relationship between Nitrous oxide (N_2O) fluxes and soil penetration resistance in soybean field

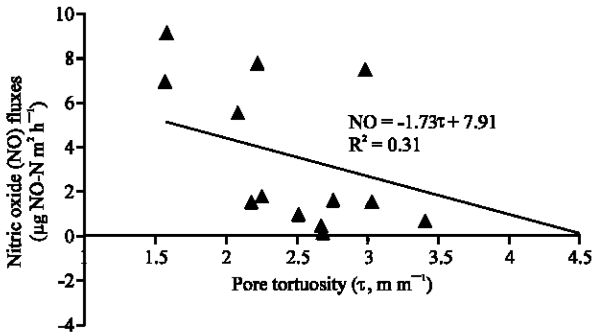

Fig. 4: Relationship between Nitrous oxide (NO) fluxes and the pore tortuosity factor in soybean field

only correlated with SPR measured at 20 cm (r = 0.59, p = 0.021). In addition, NO was either positively correlated with f_a (r = 0.68, p = 0.005), D_s/D_0 (r = 0.71, p = 0.003) and TPS (r = 0.70, p = 0.004), or negatively correlated with ρ_b (r = -0.69, p = 0.0044), θ_v (r = 0.67, p = 0.006), WFPS (r = -0.67, p = 0.0067) and with pore tortuosity in Fig. 4.

DISCUSSION

The average values for bulk density, volumetric water content and pore tortuosity were higher in tractor-compacted interrows as compared to rigdes. These results agree with those reported by

Canqui *et al*. (2004) who found that wheel traffic reduced K_{sat} by three times and increased bulk density by 6%. Our results are however opposed to those reported by Ginting and Eghball (2005) who found that wheel traffic had no significant effect on a specific soil physical property [(bulk density, soil moisture and water filled porosity (WFP)] and N_2O fluxes. The lack of difference in bulk density for example in Ginting and Eghball (2005) study could be due to their depth of soil bulk density measurements (20 cm) as compared to our depth of sampling (5 cm). In fact, it has been suggested that small depth increments might detect bulk density differences that would be obscured in a large depth increment samples (Unger, 1991). Logsdon and Cambardella (2000) indicated that changes in no-till bulk density at the 0- to 12-cm depth was partially due to biopores from surface-feeding earthworms (*Lumbricus terrestris* L.) that were observed in the no-till field but not in the disk field. The air-filled porosity, total pore space and the gas diffusion coefficient were higher in ridges as compared to tractor-compacted interrows. These results agree with those of Ruser *et al*. (1998) who reported that ridge-till practice produced areas with increased (ridges) and strongly reduced (interrow soil compacted by tractor traffic) soil porosity. The air-filled porosity and soil gas diffusion coefficient were lowest and soil penetration resistance of 0-10 cm depth highest in the 4 cycles tractor-compacted interrows. This treatment also corresponded to the highest N_2O fluxes in both corn and soybean fields. These results agree with those of Klemedtsson *et al*. (1988) who suggested that the highest N_2O production should occur in the presence of low concentrations of O_2, at the transition between aerobic and anaerobic conditions. Flessa *et al*. (2002) and Ruser *et al*. (1998) also found that soil compaction was an important factor for increased N_2O emissions from ridge-tilled potato fields. Teepe *et al*. (2004) reported that high N_2O emissions which occurred after compaction were restricted to short periods at the sandy loam and silty clay loam sites whereas emissions at the silt site remained high throughout the entire growing season. Hansen *et al*. (1993) compared tractor-compacted and uncompacted soils and found increased N_2O emissions (approximately 35%) due to soil compaction. However, emission rates reported by these authors are considerably higher as compared to flux rates measured in the present study. The higher N_2O fluxes in these studies can be explained by the much stronger soil compaction (e.g., a bulk density of 1.56 g cm^{-3} for tractor-compacted soil) and greater WFPS (mean of 85% for tractor-compacted soil) in Ruser *et al*. (1998) for example. In our study, the highest bulk density observed for the 4 cycles tractor-compacted interrows was less than unity and the corresponding WFPS below 65%. In non-compacted ridges, even though the averages air-filled porosity and gas diffusion coefficient were highest, denitrification could still happen, perhaps at a lower level in comparison to compacted soil. In fact, Rolston (1981) reported that in aerobic soils, anaerobiosis can still occur at microsites where consumption of oxygen exceeds the oxygen-supply via diffusion. In addition, uptake of N_2O (negative fluxes) was observed in the ridges of soybean This behavior is unusual as in most studies, soils have been reported a source of N_2O (Ball *et al*., 2000; Matson *et al*., 1990). However, several studies where soils have acted occasionally as sinks have also been reported. Donoso *et al*. (1993) found that in contrast with a significant emission in the rainy season, the soil of a scrub-grass savannah of Venezuela acted as a sink for N_2O in the dry season. Cicerone *et al*. (1978) found a significant sink activity in wet grass-covered soil of Michigan. Blackmer and Bremner (1976) found that cultivated soils of Iowa acted as sinks for atmospheric N_2O at certain times during spring. Ryder (1981) reported that the soil acts as both a source and sink for atmospheric N_2O depending on soil condition and the amount of nitrogenous fertilizer applied, the sink activity was observed in conditions conducive to microbial reduction of N_2O (i.e. very low nitrate in the soil). Matson and Vitousek (1987) suggested that even though the overall average fluxes measured in La Selva, Costa Rica were positive, under certain conditions uptake of N_2O occurred in this tropical soils. The mechanism by which soil acts as a sink for N_2O is not known. It has been suggested that the net flux of N_2O to the atmosphere results from its production by nitrifying and or denitrifying bacteria. N_2O consumption is therefore likely due to the reduction of N_2O to N_2 (Donoso *et al*., 1993). It has also been reported that N_2O production was somewhat higher and N_2O uptake somewhat lower in the more disturbed communities and that N_2-fixing cyanobacteria could both produce and consume N_2O (http://gane.ceh.ac.uk/award3.shtml). In this study, N_2O uptake was observed in soybean field. Soybean is a N_2-fixing legume in symbiosis with bacteria living in its roots. Even though we did not investigate the nature of bacterial flora in our soil, it may be also thought that soybean, through its bacterial symbiosis, contributed to this phenomena. Another explanation may be a temporal N deficit in the soil. In fact, the soybean crop received a starter dose of N of 32 kg N. This amount might have been taken up by the soybean plants during early growth when the root nodules were not established and the rhizobium bacteria where not actively fixing N_2. During such periods with low nitrate availability, the soil may consume atmospheric N_2O. All soil physical properties studied were significantly correlated with either CO_2, CH_4, N_2O or NO with correlation coefficients ranging from 0.30 to 0.70. Correlation between soil physical properties and gas fluxes have also been reported by Ball *et al*. (1997) who found significant relationships between N_2O fluxes and air permeability, the soil gas diffusion coefficient and tortuosity. Hu *et al*. (2001) also reported a significant relationship between the soil gas diffusion coefficient and CH_4 fluxes.

SUMMARY

Tractor compaction increased soil resistance to penetration, water, bulk density and pore tortuosity while reducing air-filled porosity, total pore space and the soil gas diffusion coefficient. Changes in soil physical properties resulted in increased CO_2, NO and N_2O emissions. This work helped identify rarely measured soil physical properties such as D_s/D_0 and τ which significantly influence soil gas exchange. More studies are needed to determine if these effects are permanent or only temporary on both soil and gas fluxes.

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