CARBON DIOXIDE EMISSIONS FROM SOILS FOLLOWING ROTARY– AND NO-TILL SEED BED PREPARATION UNDER CONTROLLED LABORATORY AND FIELD CONDITIONS

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Abstract

Land use and land use change practices such as cultivation of cropping soils and deforestation contribute 20.1% of CO_2 emissions to total annual global anthropogenic GHG emissions (IPCC Report 2007). To reduce these losses conservation tillage namely no-tillage (NT; a seeding technique with least soil disturbance), has been recommended (Ussiri and Lal 2009). However, there is little New Zealand data comparing the CO_2 emissions from conventional tillage (CT) and no-tillage (NT) on a range of soils. We report the results of CO_2 emission from NT (using Cross Slot opener which causes least amount of soil disturbance) and CT (using rotary tiller to 10 cm depth) treatments under controlled laboratory and field conditions. Carbon-dioxide (CO_2) emissions were measured in the laboratory from four soils varying in physico-chemical properties and one soil in the field using the alkali trap method for up to 3-months following NT and simulated CT (ST) treatment. The total amount of CO_2 emitted under laboratory conditions from the four soils ranged between 1066 and 3077 kg CO_2-C ha^{-1} for ST, 924 and 2679 kg CO_2-C ha^{-1} for NT treatment. In general all the soils lost more CO_2 from ST (between 22 and 398 kg CO_2-C ha^{-1}) than NT treatment. Similarly, in field conditions total CO_2-C emissions were significantly higher under CT (2591 kg CO_2-C ha^{-1}) than NT (2226 kg CO_2-C ha^{-1}) treatment. Carbon dioxide measurements taken from both the field chambers and field in-situ soil cores following CT/ST or NT treatments were similar in magnitude (~2500 kg CO_2-C ha^{-1}). The CO_2 emissions were significantly higher from CT/ST than NT treatment. In the field NT treatment produced 365 kg CO_2-C ha^{-1} or 1.3 t CO_2 ha^{-1}lower emissions than CT. Overall the results of laboratory and field studies suggest that, depending soil type and the amount of crop residue, NT can conserve up to 1.5 t CO_2 ha^{-1}.

Introduction

Atmospheric concentration of CO_2 has increased from 280 ppmv in 1750 to 390 ppmv in 2010 and is currently increasing at the rate of 1.9 ppmv per year (www.globalcarbonproject.org). This rise in atmospheric CO_2 on planetary scale (Lal 2004) has increased the effort that is being devoted to explore the potential of agricultural land to store carbon (Wilson and Al-Kaisi 2008). The CO_2 emission from soil to the atmosphere, is attributed to the metabolism of plant roots, micro flora and fauna (Rastogi *et al.* 2002). Carbon dioxide emissions are influenced by tillage practices (Alvaro-Fuentes *et al.* 2008; Ussiri and Lal 2009) involving physical disturbance of the upper soil layers during seedbed preparation and incorporation of fertilizers and seeds. Conservation tillage namely no-tillage (NT; a cultivation technique without soil disturbance), in which seeds are sown in narrow slot cut into soil, has been recommended to reduce CO_2 emissions from the soil as more C stocks are generally observed in NT than in conventionally mouldboard ploughed soils (CT) (Puget and Lal 2005; West and Post 2002). Several researchers have studied the effect of soil tillage on soil CO_2 emissions; literature clearly demonstrates that CO_2 emissions after sowing are significantly less from NT than CT. However, there is little New Zealand data comparing the CO_2 emissions from CT and NT. Therefore, the objectives of this study were: i) to quantify CO_2 emissions from simulated tillage (ST) and NT on range of soils varying in physico-chemical properties and ii) to verify under field conditions the reliability of differences in CO_2 fluxes observed between ST and NT treatments from laboratory studies.

Material and Methods

Laboratory study

Soils, location and land use

The four soil sites are located in Manawatu region of North Island New Zealand. The study areas have a temperate humid climate with mean annual temperature and rainfall, 13.3^{o}C and 967mm, respectively. These sites under annual crop rotation of pasture and cereals were established for Cross-slot NT cultivation during the last 2 to 15 years to reduce CO_2 losses those occur during CT. These soils were sampled during December 2009 and January 2010 by collecting 24 in-situ soil cores (10 cm diameter, 0–10 cm depth) from 4 randomly selected areas following the cultivation of pasture in late spring/early summer for CO_2 measurements. All the four soil sites were sprayed with Roundup herbicide prior to seeding. The location, classification and physico-chemical characteristics of the soils are given in Table 1.

i) Site-1 Glen Oroua (40^{0}18’58.33”S and 175^{0}21’46.40”E), high fertility, sandy loam soil, 2–year NT, ii) Site-2 Tangimoana (40^{0}17’33.25”S and 175^{0}17’16.95”E), high fertility, sandy loam soil, 15–year NT, iii) Site-3 Kiwitea (40^{0}3’56.79”S and 175^{0}43’10.87”E), high fertility, silt loam soil, 7-year NT, and iv) Site-4 Feilding (40^{0}15’50.88”S and 175^{0}37’23.82”E), low fertility, silt loam soil, 8-year NT.

Treatments

Simulated-tillage (ST) and No-tillage (NT) were compared in a quadruplicate study with each replicate composed of three intact soil cores (diameter 100 mm, depth 100 mm). The ST treatment was formulated from three in-situ soil cores by emptying the soil, breaking it into pieces and thoroughly mixing in a plastic container. For the NT treatment 12 in-situ cores were collected immediately after the Cross-Slot No-till drilling. These soil cores representing NT treatment and the mixed soil of ST treatment in the container were incubated at room temperature (day 27.0 night 20.0) in the laboratory and CO_2 emissions were monitored. Soil moisture content in the cores and container were maintained throughout the experiment by weighing the soil cores and spraying required amount of deionised water onto the surface. Measurements continued for 92 days (Site-1 soil), 83 days (Site-2 soil), 81 days (Site-3 soil), and 54 days (Site-4 soil) until the emissions subsided and the differences between the treatments became negligible.

Field study

Soils, location and land use

The field experiment was carried out at a site near Sanson (40°14'34.33"S and 175°21'27.07"E), high fertility, silt loam soil, 11-year NT and planted in barley (*Hordeum vulgare* L.). Site was sprayed with Roundup herbicide prior to seeding. The classification and physico-chemical characteristics of the soil given in Table 1. Gravimetric soil water content at the time of tillage was 21.7%.

Experimental set up and CO_2 measurements

Field experiment was set up during autumn seeding of pasture. The treatments were:

i) tillage with rotary tiller (RT) to the depth of 10 cm followed by bar harrow and

ii) NT, pasture was direct drilled with Cross-slot NT drill.

In the RT plot 12 chambers and in NT plot 4 PVC chambers (Saggar *et al.* 2004) were inserted 5cm into the soil on one line perpendicular to the direction of the field operations and NaOH solution was placed in chamber to trap CO_2. Chambers were sealed with air tight lids to control the leakage of carbon dioxide. The soil surface in and 1.0m around the chambers was always kept free of vegetation to avoid the influence of plant on CO_2 measurements. Measurements continued for 110 days, taken regularly for the initial 27 days and intermittently on days 36, 43, 49, 76 and 110.

Cumulative CO_2 emissions

Soil CO_2-C emissions rate were integrated in order to calculate the cumulative soil CO_2-C loss during the whole measurement period.

Table: 1. Chemical and physical characteristics of the four field sites (0-10cms).

	Glen Oroua	Tangimoana	Kiwitea	Feilding	Sanson Field Site
pH (1:2.5)	5.79	5.68	6.08	6.01	5.98
CEC (cmol$_c$ kg^{-1})	19.4	19.0	35.0	21.3	19.8
Available P (mg kg^{-1})	33.9	45.8	14.7	14.2	21.5
Available S (mg kg^{-1})	11.0	10.8	31.5	14.0	8.25
Total C (g kg^{-1})	43.5	43.3	85.0	30.3	39.7
Total N (g kg^{-1})	3.7	3.7	8.7	2.8	3.5
Bulk Density (Mg m^{-3})	1.02	0.98	0.76	1.18	1.07
Volumetric SWC (%)	47.1	41.3	46.3	36.3	-
WFPS (%)	76.6	65.6	64.9	65.4	-
Soil type	Carnarvon black sandy loam	Carnarvon black sandy loam	Dannevirke silt loam	Ohakea stony silt loam	Ohakea silt loam
Soil Classification USDA	Typic Humaquept	Typic Humaquept	Typic Hapludand	Typic Epiaqualf	Typic Epiaqualf
NZ	Concretionary Sandy Gley soil	Concretionary Sandy Gley soil	Typic Orthic Allophanic soil	Typic Orthic Gley soil	Typic Orthic Gley soil
Particle size distribution Sand (%)	71	57	15	21	17
Silt (%)	18	31	55	51	59
Clay (%)	11	12	30	28	24
Duration under No-tillage (Years)	2	15	7	8	11

USDA Soil Classification (1998)
NZ Soil Classification (Hewitt 1992)
Clay <0.002mm; Silt 0.06-0.002mm; Sand 2.0-0.06mm

Soil Sampling and Analysis

Soils samples for chemical analysis were collected in triplicate from (0-10 cm) soil depth. The sample for each site was composed of 36 soil cores randomly collected across the field. Once in laboratory, the soils were air dried and ground to pass a 2mm sieve and analysed for pH (1:2.5), cation exchange capacity (CEC) according to Blackmore *et al.* (1987). A portion of each sample was ground to pass through 0.2mm for total carbon and nitrogen analysis using Leco induction furnace (Blackmore *et al.* 1987). Available P and S were determined according to Olsen *et al*. (1954) and Johnson and Nishita (1952). Particle size distribution was determined by pipette method of Claydon (1989). For soil bulk density determination, undisturbed soil cores (10 cm diameter, 10 cm depth) were taken in triplicate at 0-10cm depth. Soil bulk density was calculated by dividing the mass of oven dried soil by volume of the soil core.

Soil water content (SWC)

Gravimetric SWC was measured at 0-10 cm depth. Soil samples were collected from respective sites on the same date when soil cores were collected for carbon dioxide measurements. Field moist samples were weighed, oven-dried (105°C) to constant mass, and weighed again. The final mass *Ms*, and the difference between the field moist and dry masses *Mw*, were used to calculate the gravimetric SWC = (Mw/Ms) X 100. The volumetric SWC was then calculated by multiplying the gravimetric SWC by the soil bulk density.

Water-filled pore space (WFPS)

Soil bulk density was determined from three undisturbed soil core samples and particle density was assumed to be 2.65 g cm^{-3}. Total porosity (TP) was calculated for each soil, according to Equation (1):

$$\text{Total pore space (\%)} = 100\,[1- (\text{bulk density}/\ \text{particle density})] \qquad (1)$$

Water-filled pore space (WFPS) was then calculated as the ratio of the volumetric SWC to the total pore space.

Residue sampling

Pasture residues were collected from the above said sites. At each site three replicates measuring 1m X 1m were marked. Grass was cut to 2cm height and sprayed with Glyphosate spray. After 10 days, five soils cores (10 cm diameter) were taken to a depth of 10 cm from all the three replicates. Roots and above ground parts of the pasture grass were then separated by gentle shaking and wet sieving. Oven dried (65 ^{0}C) samples of above ground pasture and root biomass from each core were used to calculate the residue yield.

Statistical Analysis

A General Linear Models (GLM) procedure with SAS software (version 9.1) was used to analyze carbon dioxide emissions from two treatments. An analysis of variance, using *t*-test for least significant differences (LSD) at $P< 0.05$ was used to determine differences between the treatment means.

Results

For the laboratory study, the trend of the CO_2-C emissions were similar in both tillage treatments in all the soils, with high peaks of CO_2-C observed for first few days and low rather constant CO_2-C emissions afterwards. The daily CO_2-C emissions (kg CO_2-C ha^{-1} d^{-1}) for the ST and NT treatments from all 4 soils are shown in Fig. 1 a, b, c, d.

Daily emissions for ST treatment ranged from 101.1 to 8.2 kg CO_2-C ha^{-1} d^{-1}; 125.4 to 12.3 kg CO_2-C ha^{-1} d^{-1}; 145.5 to 11.6 kg CO_2-C ha^{-1} d^{-1}; 59.3 to 7.3 kg CO_2-C ha^{-1} d^{-1};and NT treatment ranged from 63.8 to 9.8 kg CO_2-C ha^{-1} d^{-1}; 105.7 to 10.5 kg CO_2-C ha^{-1} d^{-1}; 118.8 to 11.7 kg CO_2-C ha^{-1} d^{-1}; 42.5 to 6.4 kg CO_2-C ha^{-1} d^{-1} for Glen Oroua, Tangimoana, Kiwitea and Feilding soils throughout the measurement period, respectively. Amounts of pasture residue in these soils at the time of collecting in-situ soil cores were 7.5 t ha^{-1}, 8.3 t ha^{-1}, 7.9 t ha^{-1} and 3.1 t ha^{-1} for Glen Oroua, Tangimoana, Kiwitea and Feilding soils, respectively.

During 92 days measurement period for Glen Oroua soil (Fig.1.a), significantly higher CO_2-C emissions from ST than NT were observed for first 7 days; afterwards the differences in CO_2-C emissions under both treatments narrowed and became almost similar, with CO_2-C emissions from NT gradually becoming larger than ST. Significantly higher CO_2-C emissions from NT than ST were observed from 49th day onward till end. Among all 4 soils significantly higher CO_2-C emissions from NT than ST happened only in this soil.

During 83 days of measurement period for Tangimoana soil, ST emitted higher CO_2-C emissions than NT throughout the measurement period but significant differences were observed for 39 days (Fig.1.b). For Kiwitea soil, the CO_2-C emission on the first day of measurement was highest among all soils (Fig. 1.c). During 81 days of measurement period, the CO_2-C emissions from ST were higher than NT but significant differences were observed only for 13 days of measurement.

During 54 days measurement period for Feilding soil (Fig.1.d), the CO_2-C emissions were significantly higher from ST than NT for only 5 days of measurement and were similar from both treatments for rest of the period.

The cumulated CO_2-C emissions under ST and NT treatments from all 4 soils are shown in Fig. 2 a, b, c, d. The cumulated CO_2-C emissions ranged between 1066 and 3077 kg CO_2-C ha^{-1} for ST and 924 & 2679 kg CO_2-C ha^{-1} for NT among all the 4 soils. The Glen Oroua and Feilding soils did not show any significant difference in total CO_2-C emissions between the ST and NT treatments. However, the Tangimoana and Kiwitea soils emitted significantly larger CO_2-C for ST than NT treatment.

For the field study, CO_2-C emissions ranged from 17.5-44.1 kg CO_2-C $ha^{-1}d^{-1}$ in RT and 15.2-38.9 kg CO_2-C $ha^{-1}d^{-1}$ in NT. Significantly higher CO_2-C emissions were observed in RT than NT (Fig.3), 19 of 32 CO_2 measurements taken showed significantly higher emissions in RT than NT. The cumulated CO_2-C emissions were significantly higher in RT (2591±74.5 kg CO_2-C ha^{-1}) than NT (2226±90.8 kg CO_2-C ha^{-1}) (Fig.4).

Overall, ~16% more CO_2 emission was measured in the field from the RT than NT treatment.

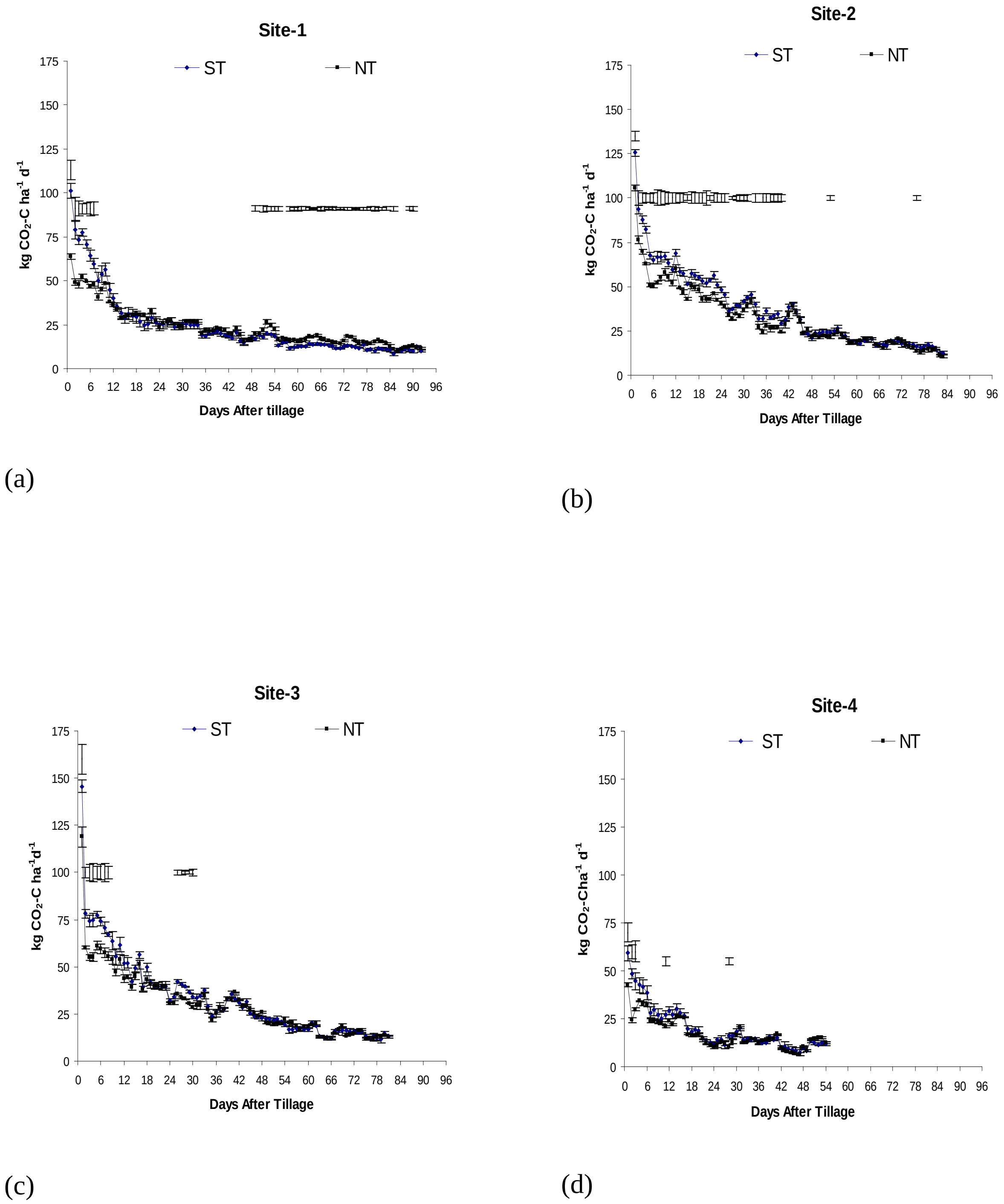

Fig 1: Daily CO_2-C emissions as influenced by tillage (ST, Simulated tillage; NT, No-tillage) from (a) Glen Oroua, (b) Tangimoana, (c) Kiwitea and (d) Feilding soils. Each value represents the mean of four replicates with standard errors (±) shown by vertical bars and vertical bars above represent LSD ($P < 0.05$) for comparison among tillage treatments where significant differences were found.

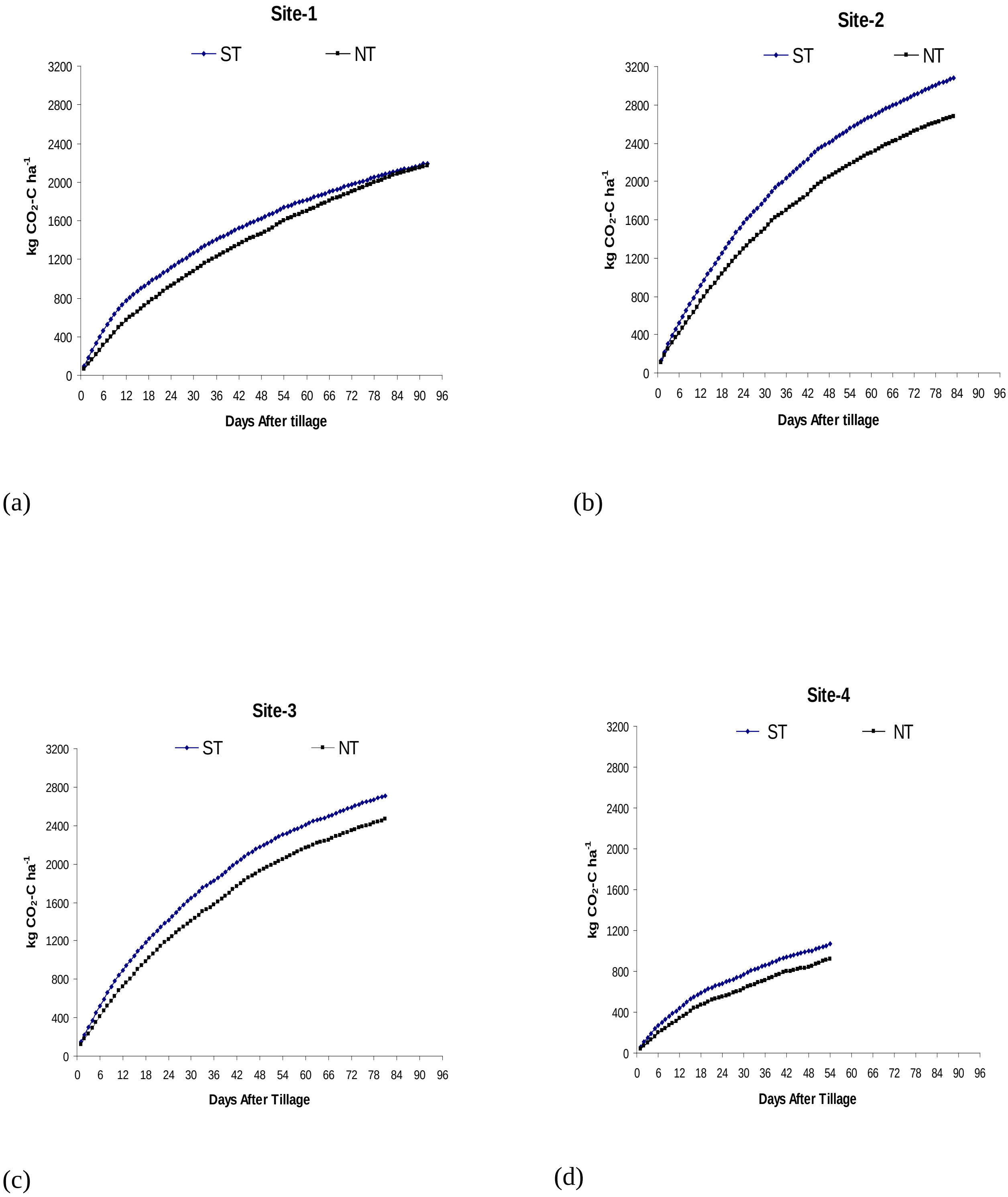

Fig 2: Cumulative CO_2-C emissions from simulated tillage (ST) and No-tillage (NT) treatments from (a) Glen Oroua , (b) Tangimoana, (c) Kiwitea and (d) Feilding soils.

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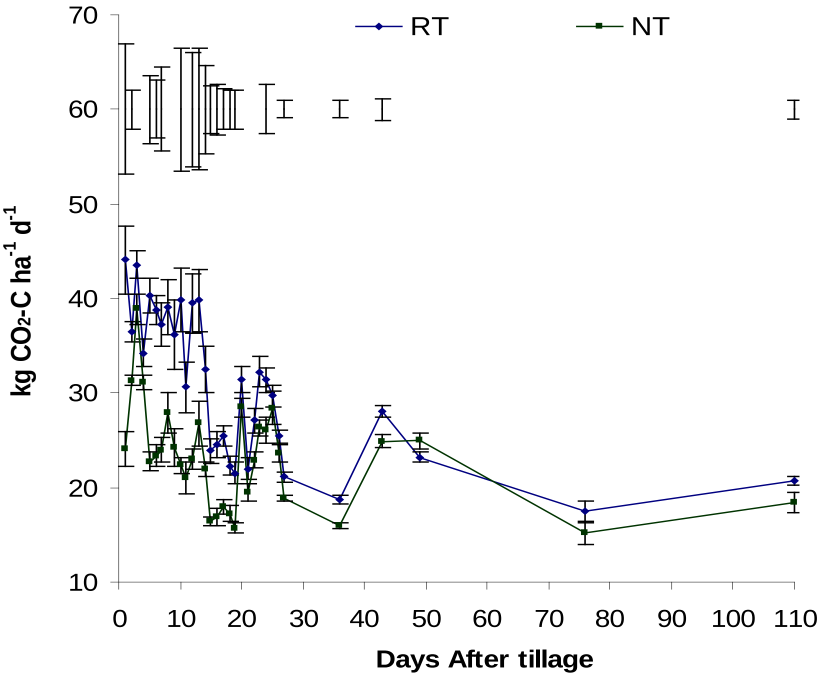

Fig 3: Daily CO_2-C emissions as influenced by tillage (RT, Rotary tillage; NT, No-tillage). Each value represents the mean of four replicates for NT and twelve replicates for RT with standard errors (±) shown by vertical bars and vertical bars above represent LSD ($P < 0.05$) for comparison among tillage treatments where significant differences were found.

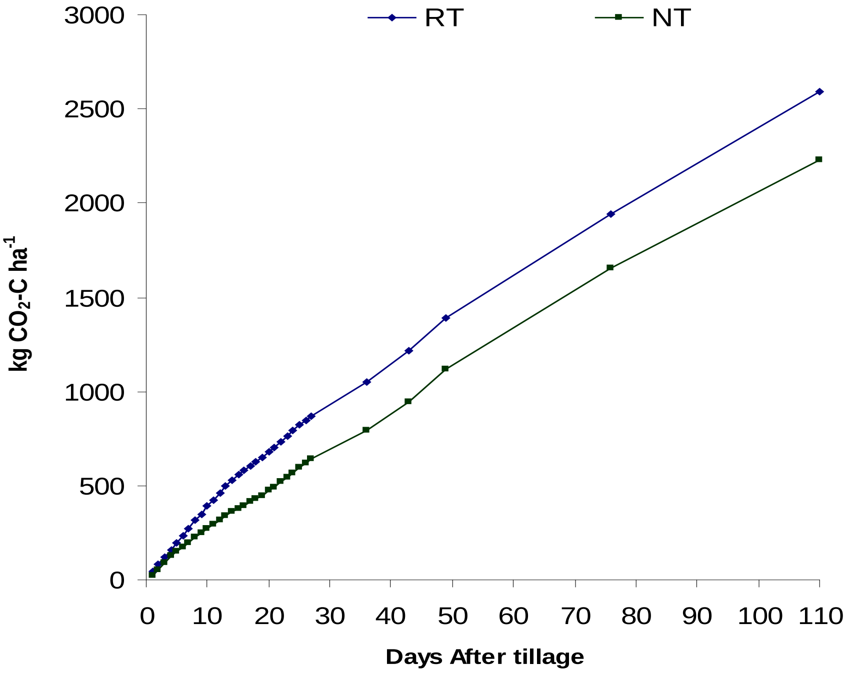

Fig 4: Cumulative CO_2-C emissions from Rotary tillage (RT) and No-tillage treatments.

Discussion

Different CO_2-C emissions among sites were the result of differences in soil organic carbon content, texture, moisture content and crop residues incorporated as soils were selected to have these contrasts. Higher initial CO_2-C emissions from ST/RT than NT treatment may be due to the physical release of the CO_2 entrapped and accumulated in soil pores from previous microbial activity (Reicosky and Lindstrom 1993 and Reicosky *et al.* 1997). The subsequent response depends on the rate of microbial decomposition of easily decomposable organic matter in ST soils. Tillage breaks soil macro-aggregates and exposes protected organic matter, incorporates crop residues into soil thereby increasing soil and crop residue contact (Reicosky *et al.* 1997; Curtin *et al.* 2000; Ussiri and Lal 2009). Differences in CO_2-C emissions between ST and NT treatments ceased when tillage stimulated decomposition processes deceased due to exhaustion of easily decomposable residue substrates (Rochette and Angers 1999).

The laboratory study was carried out under controlled temperature and moisture conditions in the laboratory. Therefore, the differences in emissions among the four soils are attributed to differences in soil texture, soil organic carbon content, amount & nature of plant and root residues incorporated. Cumulated CO_2-C emissions for Glen Oroua, Tangimoana, Kiwitea and Feilding soils from ST were 2196, 3077, 2712, 1066 kg CO_2-C ha^{-1}; and NT were 2174, 2679, 2464, 924 kg CO_2-C ha^{-1}. Among the four soils, Tangimoana soil lost the most CO_2-C. This soil has higher amount of residue (8.3t ha^{-1}) incorporated followed by Kiwitea (7.9t ha^{-1}), Glen Oroua (7.3t ha^{-1}) and Feilding (3.1t ha^{-1}) soils. Feilding soil accounted for least cumulative CO_2-C loss amongst all sites probably due to low amount of residue incorporated (3.1t ha^{-1}).One can argue that it might be due to shorter measurement period of 54 days but if we compare the total CO_2-C lost from all the soils till 54th day i.e. cumulated CO_2-C emissions on 54th day for Glen Oroua, Tangimoana, Kiwitea and Feilding soils from ST were 1737, 2553, 2303, 1066 kg CO_2-C ha^{-1}; and NT were 1601, 2175, 2048, 924 kg CO_2-C ha^{-1} even than the CO_2-C loss was minimum in Feilding soil. Results suggest that total amount of CO_2 losses from soils are affected by the amount of residue incorporated.

Soil texture also influences CO_2 losses mainly through its effects on soil porosity, moisture and fertility (Dilustro *et al.* 2005). In the present study Glen Oroua & Tangimoana soils were sandy loam in texture and Kiwitea & Feilding soils were silt loam in texture. Based on soil texture, Glen Oroua & Tangimoana sandy loam soils lost more CO_2-C in comparison to Kiwitea & Feilding silt loam soils. In a laboratory incubation study to assess the affect of soil textures on CO_2 concentration, McInerney and Bolger (2000) observed 20 to 40% less CO_2 production from clayey soils than silt loam soils; similarly under controlled laboratory conditions, Bouma and Bryla (2000) found reduced CO_2 emissions from fine texture soil in comparison to coarse texture soil, as higher sand content would provide more micro and macro pores, allowing easier oxygen supply for aerobic respiration by microorganisms on crop residues and CO_2 exchange between the soils and the atmosphere.

Results from field study have shown that RT had significant effect on the CO_2-C emissions throughout the measurement period. When the differences were not significant, either the soil under RT treatment was quite dry or the variability among measurements was high. Most of the significant differences between the two tillage systems were observed during first 19 days of the study suggesting a rapid rate of mineralization of labile organic substrates followed by a slower rate of mineralization of more recalcitrant C substrates. These results are similar to those of Reicosky and Lindstrom (1993) who found that soil CO_2 emissions were higher under mouldboard plough than no-tillage even 19 days after tillage operation. Carbon dioxide emissions were similar to those reported by Aslam *et al.* (2000) under contrasting tillage systems in New Zealand conditions using absorption technique. The magnitude of CO_2 emissions from RT/ST and NT treatments both in field and laboratory conditions were similar (~2500 kg CO_2-C ha^{-1}) (Fig 5), showing the reliability of the CO_2-C fluxes measured from field in-situ cores under controlled laboratory conditions. In the laboratory studies we used soils varying in texture, moisture content, and residue input. Therefore, there are various reasons for the observed differences in CO_2 emissions from these soils. For example the Feilding soil with the least residue input (3.1 t DM ha^{-1}) resulted in least emissions. This soil has similar texture and soil moisture during the incubation as the Kiwitea soil but lower residue input (Table 1). Similarly, residue inputs for Tangimoana (8.3 t DM ha^{-1}) and Glen Oroua (7.3 t DM ha^{-1}) soils having similar texture resulted in higher CO_2 losses for Tangimoana than Glen Oroua soils. Comparing the Glen Oroua and Tangimoana, sandy loam texture soils, Glen Oroua soil did not show any significant difference in total CO_2-C emissions between the ST and NT treatments. It might be due to duration under NT system as Tangimoana has been under NT system from last 15 years and Glen Oroua for last 2 years; it was the decay of old weathered crop residues that explained the significant differences in CO_2 emissions between the ST and NT treatments from Tangimoana soil. Curtin *et al.* (1998) found a small difference between the decomposition of recently harvested and weathered wheat straw concluding that weathered field residues can also contributes significantly to CO_2 emissions. Similarly, comparing Feilding and Kiwitea soils, Feilding soil did not show any significant difference in total CO_2-C emissions between the ST and NT treatments. It could be due to exhaustion of easily decomposable residue substrates as the Feilding soil has lower residue input than Kiwitea. Overall the results of both laboratory and field studies suggest that, depending soil type and the amount of crop residue, NT can conserve up to 1.5 t CO_2 ha^{-1}.

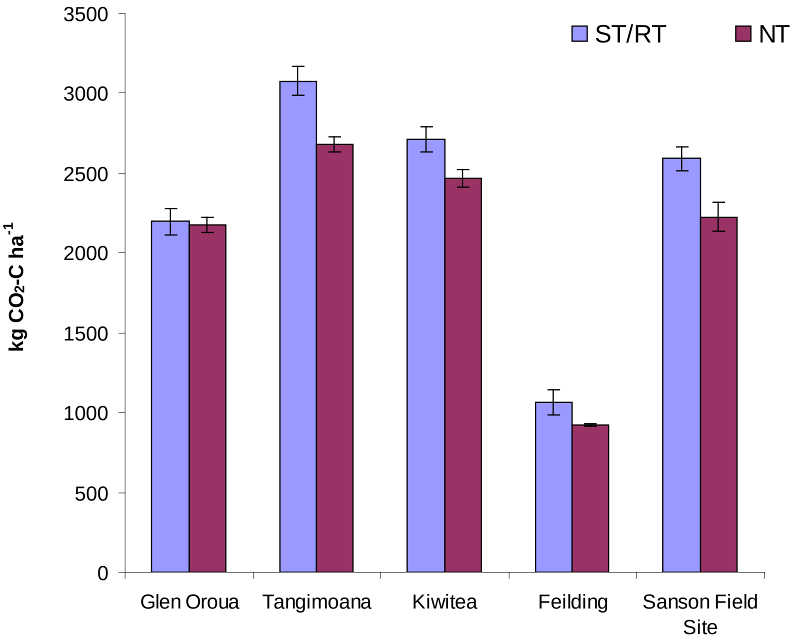

Fig 5. Cumulative CO_2-C emissions from Simulated /Rotary tillage (ST/RT) and No-tillage (NT) treatments from Glen Oroua (a), Tangimoana (b), Kiwitea (c) and Feilding (d) & Sanson Field site.

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References

Alvaro-Fuentes, J., Lopez, M. V., Arrue, J. L., & Cantero-Martinez, C. (2008). Management effects on soil carbon dioxide fluxes under semiarid Mediterranean conditions. *Soil Science Society of America Journal, 72*(1), 194-200.

Aslam, T., Choudhary, M. A., & Saggar, S. (2000). Influence of land-use management on CO2 emissions from a silt loam soil in New Zealand. *Agriculture Ecosystems & Environment, 77*(3), 257-262.

Bouma, T. J., & Bryla, D. R. (2000). On the assessment of root and soil respiration for soils of different textures: interactions with soil moisture contents and soil CO_2 concentrations. *Plant and Soil, 227*(1-2), 215-221.

Blackmore, L. C., Searle, P. L., & Daly, B. K. (1987). *Methods of chemical analysis of soils*: New Zealand Soil Bureau Scientific Report 80.

Claydon, J. J. (1989). *Determination of particle size distribution of fine grained soils-Pipette method.*: DSIR Division of Land and Soil Sciences Technical record LH5.

Curtin, D., Selles, F., Wang, H., Campbell, C. A., & Biederbeck, V. O. (1998). Carbon dioxide emissions and transformation of soil carbon and nitrogen during wheat straw decomposition. *Soil Science Society of America Journal, 62*(4), 1035-1041.

Curtin, D., Wang, H., Selles, F., McConkey, B. G., & Campbell, C. A. (2000). Tillage effects on carbon fluxes in continuous wheat and fallow-wheat rotations. *Soil Science Society of America Journal, 64*(6), 2080-2086.

Dilustro, J. J., Collins, B., Duncan, L., & Crawford, C. (2005). Moisture and soil texture effects on Soil CO2 efflux components in southeastern mixed pine forests. *Forest Ecology and Management, 204*(1), 85-95.

Hewitt, A. E. (1992). New Zealand Soil Classification. *DSIR Land Resources Scientific Report No.19.*

IPCC (2007). *Climate change: Synthesis Report*. Cambridge UK: Cambridge Univ. Press.

Johnson, C. M., & Nishita, H. (1952). Microestimation of sulfur - in plant materials, soils, and irrigaiton waters. *Analytical Chemistry, 24*(4), 736-742.

Lal, R. (2004). Soil carbon sequestration to mitigate climate change. *Geoderma, 123*(1-2), 1-22.

McInerney, M., & Bolger, T. (2000). Temperature, wetting cycles and soil texture effects on carbon and nitrogen dynamics in stabilized earthworm casts. *Soil Biology & Biochemistry, 32*(3), 335-349.

Olsen, S. R., Cole, C. V., Watanabe, F. S., & Dean, L. A. (1954). Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *USDA Department Circular,* 939.

Puget, P., & Lal, R. (2005). Soil organic carbon and nitrogen in a Mollisol in central Ohio as affected by tillage and land use. *Soil & Tillage Research, 80*(1-2), 201-213.

Rastogi, M., Singh, S., & Pathak, H. (2002). Emission of carbon dioxide from soil. *Current Science, 82*(5), 510-517.

Reicosky, D. C., & Lindstrom, M. J. (1993). Fall tillage method - effect on short-term carbon-dioxide flux from soil. *Agronomy Journal, 85*(6), 1237-1243.

Reicosky, D. C., Dugas, W. A., & Torbert, H. A. (1997). Tillage-induced soil carbon dioxide loss from different cropping systems. *Soil & Tillage Research, 41*(1-2), 105-118.

Rochette, P., & Angers, D. A. (1999). Soil surface carbon dioxide fluxes induced by spring, summer, and fall moldboard plowing in a sandy loam. *Soil Science Society of America Journal, 63*(3), 621-628.

Saggar, S., Andrew, R. M., Tate, K. R., Hedley, C. B., Rodda, N. J., & Townsend, J. A. (2004). Modelling nitrous oxide emissions from dairy-grazed pastures. *Nutrient Cycling in Agroecosystems, 68*(3), 243-255.

Ussiri, D. A. N., & Lal, R. (2009). Long-term tillage effects on soil carbon storage and carbon dioxide emissions in continuous corn cropping system from an alfisol in Ohio. *Soil & Tillage Research, 104*(1), 39-47.

USDA (1998). Keys to soil taxonomy, 8th edn. *Soil Resources Conservation Service, Washington D.C.*

West, T. O., & Post, W. M. (2002). Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. *Soil Science Society of America Journal, 66*(6), 1930-1946.

Wilson, H. M., & Al-Kaisi, M. M. (2008). Crop rotation and nitrogen fertilization effect on Soil CO_2 emissions in central lowa. *Applied Soil Ecology, 39*(3), 264-270.