

IMPACTS OF SOIL ACCUMULATION FROM EROSION ON
GREENHOUSE GAS PRODUCTION AND EMISSION FROM SOIL
WITHIN A COMPLEX AND CULTIVATED LANDSCAPE

BY

RUIFANG WANG

A Thesis
Submitted to the Faculty of Graduate Studies
In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

Department of Soil Science
University of Manitoba
Winnipeg, MB

©February, 2007

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ABSTRACT

In cultivated, topographically complex landscapes, soil erosion results in the redistribution of large amounts of soil. This soil redistribution changes the source materials and related soil properties within landscapes and within soil profile. These changes are expected to affect production and emission of greenhouse gases (GHG). To evaluate the effect of soil accumulation on CO₂ and N₂O production and emission, two laboratory experiments and one field experiment were carried out.

The column study was first conducted in a growth chamber to study the relationship between soil depth and GHG emission. Results showed soil depth had a great effect on CO₂ flux. CO₂ flux increased dramatically with soil depth. Regression analysis of data collected over 70 days showed the relationship between cumulative flux and soil depth can be described using a linear regression. However, as soil depth increased, emissions are not expected to increase proportionally. The effect of soil depth on N₂O flux was observed as well. Generally, N₂O flux increased with soil depth. Regression analysis of data collected over 70 days showed the cumulative flux also increased linearly. This experiment was limited in ability to determine the exact effect of soil depth due to limited numbers of depth treatments and the single replicate.

Based on the preliminary results of the column study, a detailed field experiment was conducted to study the effect of soil accumulation from soil erosion on GHG profile concentrations and surface emissions. This study was carried out in three depressions within a complex, cultivated landscape, 17 km north of Brandon, Manitoba. Results showed CO₂ flux and profile concentrations had obvious seasonal patterns. CO₂ flux and concentration changed dramatically as air and soil temperature varied, indicating that

temperature is the key factor controlling greenhouse gas production and emission. The highest variation in CO₂ concentration occurred during the growing season. Higher CO₂ concentration occurred at the greater depth in these depressions, probably resulting from high production and low diffusion rates. A thicker A horizon due to soil accumulation, root respiration, and microbial respiration resulted in higher CO₂ production. The high water table level and poor drainage in the depressions limited gas diffusion to the aboveground atmosphere as well. Significant soil accumulation was observed in each of the three depressions. The soil accumulation favored CO₂ production in that it increased quantities of soil organic carbon and nitrogen in the soil surface. However, the effect of soil accumulation on CO₂ flux was different in the three depressions due to soil moisture conditions. Results also showed N₂O profile concentrations and surface flux had significant seasonal patterns as well. High N₂O flux and profile concentrations only occurred during spring thaw periods. High soil moisture and available carbon and nitrogen during spring thaw periods might have contributed to the high production rates. Although soil accumulation enriched organic carbon and nitrogen in the soil profiles, the effect of soil accumulation on N₂O production and emission only occurred during the spring thaw events. The thickened A horizon increased N₂O production in soil profiles. However, this accumulation may have decreased N₂O emission due to the limited diffusion in the soil resulting in the conversion of N₂O to N₂. Thus, the effect of soil deposition from erosion on N₂O emission was complicated by hydrologic and pedologic conditions.

The potential production of CO₂ and N₂O at different soil depths from the field site was further studied with a microcosm experiment. This study revealed the potential gas production decreased with increased soil depth for both CO₂ and N₂O. The surface 25 cm of soil appeared to be the major potential source in CO₂ and N₂O production, in that this

layer was found to be rich in organic carbon and nitrogen, favoring microbial activity and microbial biomass. Therefore, the accumulation of soil on the surface rich in organic carbon should increase CO₂ and N₂O production within the soil profile, at least in the short-term.

In summary, the effect of the soil accumulation on GHG production and emission was complex. Its effect on CO₂ and N₂O flux was soil environment-specific. Soil accumulation increased GHG production in that it thickens the surface soil with high available carbon and nitrogen. However, this accumulation may have decreased CO₂ and N₂O emission due to the limited diffusion in the soil resulting in the further conversion of N₂O to N₂. The effect of soil deposition also could affect GHG flux through its effect on soil moisture, temperature and substrate availability.

ACKNOWLEDGEMENTS

I would like to thank Canadian Agri-Food Research Council-BGSS for the financial support of this project.

I wish to express my sincere thanks to my advisor, Dr. David Lobb. His guidance, support and encouragement are greatly appreciated. I want to thank my co-advisor, Dr. Brian McConkey, for his guidance, encouragement and kindness. I would also like to thank my advisory committee: Dr. David Burton, Dr. Alan Moulin and Dr. Tim Papakyriakou for their input and guidance.

Special thanks to Dr. Mario Tenuta for his most helpful advice and encouragement. Thank you to the technical support staff (Val Ward, Brad Sparling, Bo Pan, Rob Ellis, Michelle Erb, Sheng Li, Diane Smith, Clay Sawka, Tim Stem, Christine Cantello). Thanks to Barb Finkelman and Terri Ramm for their administrative support. I would also like to acknowledge Mr. Allan Meadows for providing the land and the Manitoba Zero Tillage Research Association. Thanks to all professors and graduate students in the Department of Soil Science for help and encouragement.

Very special thanks to my friends (Jude Liu, Zhifang Chen, Bo Pan, Shaohong Cheng and Yongshou Xie) for encouragement and help. Mom, Dad, Ruifeng and Ruili, I love and miss you! I appreciate your emotional support and encouragement throughout my study. My husband, Haifeng, you are my true love. I hope you know how much I appreciate your patience and support!

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1. INTRODUCTION

In the Canadian prairies, soil has undergone different rates of soil erosion since the first cultivation in 1900. As a consequence of soil erosion by wind, water and tillage, soil was redistributed within landscapes. In topographically complex landscapes where conventional tillage is used, severe soil loss is usually observed on hilltops (or convexities). Eroded soil remains in the field, transported to lower positions and deposited there, or is carried into the aquatic ecosystems by wind and water and/or is transported by wind onto other land outside of the field. In many cases, most of the eroded soil remains within the landscape or field (Lobb and Kachanoski, 1999; Lobb et al., 2002). The loss and accumulation of the topsoil often exceeds 50 cm in depth (Lobb et al., 2002).

The redistribution of soil within cultivated, topographically complex landscapes results in changes in soil organic matter (SOM) content and other soil properties. Changes in soil properties within landscapes are anticipated to affect the processes for greenhouse gases (GHG) production and emission. These effects are the result of three different changes with in the landscape.

First, erosion causes the loss of SOM-rich topsoil from upper slopes. Soil organic carbon (SOC) lost by erosion in the top 25 cm can exceed 65% of the original amount contained in the soil (Kimble et al., 2001). In the Canadian prairies, in excess of 75% of organic carbon and nitrogen can be lost from the upper slopes when severe erosion has occurred (Verity and Anderson, 1990). With less SOM due to erosional losses, there is less C and N available to drive CO₂ and N₂O production (Lobb et al., 2002). Moreover, due to the removal of SOM and exposure of carbonate-rich subsoil in upper slopes, soil has adverse properties including poor structure, reduced soil water holding capacity, loss of

nutrients and alkaline conditions due to the exposure of carbonates. Therefore, soil erosion decreases biological activity within landscapes. This will also affect plant growth and litter input, which further influence soil biological activity and the carbon flux in the agricultural system (Janzen et al., 2002).

Second, due to the loss of topsoil, subsoil is exposed at the surface. Since the soil of the Canadian prairies has developed on calcareous parent materials, the subsoil is rich in carbonate. Therefore, subsoil undergoes accelerated weathering by acidification. With the application of acid-forming fertilizers, acid rain and other sources of acid, subsoil will produce more CO₂. Moreover, due to the loss of topsoil, nutrients can be lost and soil structure can be deteriorated, which will adversely affect the plant growth.

Third, as the result of soil loss from upper slopes, eroded soil may deposit in lower slopes. Deposited soil increases total SOM in these positions. Accumulation of SOM may strengthen soil aggregation and increase physical protection of the carbon and nitrogen within micro-aggregates (Van Veen and Paul, 1981; Lal, 2001). At greater soil depths, the sequestration of carbon may be enhanced further because these layers are not subject to the disturbance by tillage. In these positions, the buried organic-rich soil is subject to more moderate temperature and moisture conditions. Also, the buried soil is subject to a reduced supply of oxygen due to the accumulation of surface soil. It has been estimated that the SOC sequestration in depressions is approximately 0.57 Pg C yr⁻¹ (Lal, 1995) to 1.0 Pg C yr⁻¹ (Stallard, 1998).

The increased frequency of occurrence of anaerobic conditions in depressions may result in more CH₄ and N₂O production and emission (Corre et al., 1996; Mosier, 1998; Meixner and Eugster, 1999). On the other hand, more moist conditions under aerobic conditions can also lead to increase CO₂ production and emission of the added SOM in

deposited soils. SOC deposited in these positions may be more biologically active than pre-existing SOC in that the soil is rich in the labile and light fraction (Gregorich et al, 1998), which is more easily used by microorganisms. Thus, accumulation of soil may increase CO₂ emissions.

Given the varied impacts of soil erosion on GHG emissions, there is growing interest in studying GHG production and emission affected by soil erosion. Several researchers have investigated the impacts of agricultural land management on emission and production of greenhouse gases. A few studies have been carried out on the effect of soil erosion on the redistribution of carbon with landscapes (Gregorich et al., 1998; Kimble, et al., 2001; Pennock and Frick, 2001). Other studies have evaluated the effect of soil erosion phases (e.g. slight erosion, moderate erosion and soil deposition) on CO₂ emissions and profile concentrations (Bajracharya et al., 2000a; Bajracharya et al., 2000b). Many researchers have focused on the delivery of organic carbon-rich material from the field and to water bodies. There is a need to study the potential effects of soil deposition within the field on GHG production and emissions to improve our understanding of the influence of soil erosion on climate change.

The purpose of this study is to assess the impacts of soil deposition from erosion on the production and emission of greenhouse gases from soils within a cultivated, hilly landscape. This was achieved through the quantification of the spatial and temporal variability of CO₂ and N₂O production and emission within an eroded soil-landscape. To fulfill the objectives of this study, two laboratory experiments and one field experiment were conducted. The column study was conducted in a growth chamber to study the relationship between soil depth and GHG emissions. Based on preliminary results of the column study, a more detailed field experiment was initiated to study the GHG profile concentrations and surface

emissions, and to determine soil loss and accumulation. A microcosm study was carried out related to the field study to assess the potential production of GHG of soil collected from different soil depths.

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2. IMPACTS OF SOIL DEPTH ON GREENHOUSE GAS EMISSION

2.1 Abstract

Soil redistribution caused by soil erosion within landscapes is expected to affect greenhouse gas production and emissions. The physical accumulation of soil changes source materials and soil environment for GHG production and emissions. To understand the influence of depth of soil accumulation on GHG emission, a preliminary column study was carried out in a growth chamber. In this investigation, a closed chamber method and sampling of the soil atmosphere was used to examine flux gas samples and profile concentrations, respectively. This column study showed soil depth had a great effect on CO₂ flux. CO₂ emission increased dramatically with increasing depth of soil. Regression analysis of data collected over 70 days showed the relationship between cumulative flux and soil depth can be described by linear equation ($R^2=0.83$). Soil depth also had an influence on N₂O flux. Generally, N₂O flux increased with soil depth. Regression analysis of data collected over 70 days showed a linear increase in cumulative flux with soil depth.

2.2 Introduction

Soil erosion is a significant form of soil degradation. The process involves the movement of surface materials, the transport, abrasion, sorting and deposition of the soil particles by water and wind (Brady and Weil, 2002). It also includes soil redistribution within landscapes by tillage (Lobb et al., 2002). Soil erosion results in soil redistribution within landscapes and causes many changes in chemical, physical and biological properties of soil. These changes include soil nutrient loss, soil organic matter loss, decreased soil water holding capacity and nutrient holding capacity, soil structure and aeration deterioration, and the increased variability of these properties across the landscape. These changes, particularly the increased variability, are most easily observed through their impact on plant productivity. These changes in these soil properties affect the conditions that contribute to greenhouse gas (GHG) production and emission (Lal et al., 1998; Lal, 2001; Lobb et al., 2002).

In topographically complex landscapes, tremendous soil redistribution occurs. The soil loss is usually observed on upper slope positions. This lost soil is relatively rich in organic carbon and nitrogen. Eroded soil accumulates in different landscape positions. Some are transported within the field and deposited in lower slopes, some are deposited in adjacent land, and some are carried into the aquatic ecosystems by water and wind. This significant soil redistribution is the result of water, wind and tillage erosion. The relative contribution of these three types of soil erosion to gross erosion is dependent on landforms and climate.

Soil erosion by water is one of most common forms of erosion. As a consequence of water erosion, soil is first lost where overland water flow starts.

Generally soil erosion rates are highest from back slopes followed by upper slopes. Since water erosion is selective, topsoil is always lost first. Usually, organic carbon concentrates near the soil surface and is of the relative low density. For this reason, redistributed sediments commonly enrich in organic carbon. As eroded soil is deposited in lower slopes, these positions may have relatively high organic carbon content. Moreover, this organic carbon is more active due to the high content of labile particulate fractions (Lal, 1995; Gregorich et al., 1998).

Wind erosion is another form of erosion with highest soil loss occurring in hilltops. The process of detachment, transportation and deposition by wind can result in a considerable soil loss, textural change, nutrient and productivity losses as well as sedimentation. Like water erosion, wind erosion is selective (Troeh et al., 1980). Fine and organic fractions are lost first by wind. Depending on the particle size, the transportation and deposition of soil ends up at different distances. Usually, the colloidal material, clay and humus, are easily carried as suspended sediment. The deposited part of soil in lower slopes may enrich organic carbon in these positions as well.

Different from patterns of water and wind erosion, tillage erosion causes soil loss from convex slopes (often upper) and accumulation in concave slopes (often lower). This type of soil erosion has only recently been recognized (Lobb et al., 1995; Lindstrom, 2002). The soil loss from tillage erosion is not selective regarding soil materials. As a consequence of tillage erosion, soil rich in organic matter is lost from upper slopes and accumulation in foot slopes and depressions. Within intensively-tilled complex landscapes, tillage erosion from hilltops can account for at least 70% of total erosion (Lobb and Kchanoski, 1999). As tillage erosion is the major form of soil erosion on

upper slopes, most soil lost from upper slopes remains in the field. The accumulation of soil can often exceed 50 cm in depth (Lobb et al., 2002).

As discussed above, soil loss and accumulation within landscapes greatly impact substrates and soil environment conditions for GHG production and emission (Gregorich et al., 1998; Lal, 2001). The physical accumulation of soil in lower slopes, especially from tillage erosion, thickens the organic matter layer. Accumulation of SOM may strengthen soil aggregation and increase physical protection of the carbon and nitrogen within micro-aggregates (Van Veen and Paul, 1981; Lal, 2001). At greater soil depths, sequestration of carbon may be enhanced further because these layers are not subject to disturbance by tillage. It was estimated that the worldwide SOC sequestration in depressions is approximately $0.57 \text{ Pg C yr}^{-1}$ (Lal, 1995) to 1.0 Pg C yr^{-1} (Stallard, 1998). However, buried soil is subject to a reduced supply of oxygen due to the accumulation of the surface soil. As well, in lower slopes, the buried organic-rich soil is subject to more moderate temperature and moisture conditions. The occurrence of anaerobic conditions in depressions may result in more CH_4 production and emission (Mosier, 1998; Meixner and Eugster, 1999) and more N_2O production (Corre et al., 1996; Meixner and Eugster, 1999). The amount of biologically active SOC in lower slopes may be more than other positions from additions of deposited topsoil that is rich in labile and light fraction (Gregorich et al., 1998) adding to that derived from plant residues from growth on the lower slopes themselves. This biologically active SOC is easily used by microorganisms and, therefore, accumulation of SOC in lower slopes may increase CO_2 emissions.

There are several studies which have investigated the impacts of agricultural and management on the emission of GHG (Burton et al., 1997; Billings et al., 1998). These

studies focused on the effect of cropping and tillage practices on carbon flux. The effect of soil erosion on GHG emissions has also been studied by other researchers, but their efforts have focused on water erosion and its removal of organic-rich material from cultivated landscapes. A few studies have been carried out on the effect of soil erosion on the redistribution of carbon with landscapes (Gregorich et al., 1998; Kimble et al., 2001; Pennock and Frick, 2001). However, the fate of accumulated soil and its effect on net GHG emission is not clear (Lal, 2001; Lobb et al., 2002), especially at landscape scales. To understand the interaction of these two processes, the primary question is to understand the influence of depth of soil accumulation on GHG emission. Therefore, the objective of this study was to establish the relationship between soil depth and GHG emission in a column study.

2.3 Materials and Methods

The accumulation of soil in depressions within landscapes is expected to affect GHG production and emission in that it buries source materials and brings in new source materials. To understand the relationship between increased soil depth resulting from soil accumulation and greenhouse gas emission, a preliminary column study was first carried out. This study was conducted in a growth chamber with repacked soils.

2.3.1 Experimental design

The experiment consisted of five treatments, which included five soil depths:

D0 - soil depth 0 cm (over 80 cm sand)

D20 - soil depth 20 cm (over 60 cm sand)

D40 - soil depth 40 cm (over 40 cm sand)

D60 - soil depth 60 cm (over 20 cm sand)

D80 - soil depth 80 cm (over 0 cm sand)

The height of columns was 85 cm with the soil surface maintained at 80 cm and with 5 cm headspace. The amount of soil used in each treatment varied, and the remainder of the height was comprised of silica sand.

2.3.2 Column preparation

Five poly-vinyl chloride (PVC) columns were constructed to accommodate soils. The bottom of PVC columns were glued to a plexi-glass plate using epoxy adhesive.

The height of columns was 85 cm and inner diameter was 20.3 cm (1.25-cm wall thickness) with a port fitted with a rubber stopper at the bottom to allow drainage. Before being packed with soils, the total weight of each column with screen, tubing rubber and stopper was recorded in order to allow gravimetric water addition to maintain constant soil moisture conditions.

2.3.3 Soil preparation, analysis and packing

Soils were collected from the Manitoba Zero Tillage Research Association farm (MZTRA) in November 2002. The MZTRA farm has been no-tilled since 1993. The depth of soil collection was 25 cm within the area of the vegetative buffer strip between the cropland and a permanent wetland. Soils were typical of the Newdale Association in the Parkland Region (Podolsky and Schindler, 1993). Soil series included Rufford and Cordova series. All soil was stored in the cooler at 4 °C after collection. Prior to the experiment, soil was air-dried and uniformly mixed using a commercial soil mixer and passed through a 6-mm mesh sieve. Soil for chemical analyses was collected after thorough mixing. Analyses included soil pH, %IC, %OC, %N, NH_4^+ -N, and NO_3^- -N. pH (1:2 extraction) was measured using a pH meter (Fisher Accumet). Total carbon (%C) and organic carbon (%OC) concentration were determined using a LECO CN-2000 analyzer (Laboratory Equipment Corporation, 1994) combustion procedure. To measure organic carbon, soil samples were predigested with 6 N HCl to remove inorganic carbon. Inorganic carbon (%IC) concentration was determined by subtracting %OC from %C. Total nitrogen (%N) was determined by combustion using a LECO CN-2000 analyzer (Laboratory Equipment Corporation, 1994). NH_4^+ -N and NO_3^- -N were measured following extraction with 0.5 M K_2SO_4 using Technicon Autoanalyser II (Technicon

Industrial System). Cadmium reduction method was used for NO_3^- -N analysis and automated phenate method was applied for NH_4^+ -N measurement. The results of analyses are listed in Table 2.1.

Table 2.1 Analyses of Soil

	pH	Organic C (%)	Inorganic C (%)	Total N (%)	NH_4^+ -N (mg/kg)	NO_3^- -N (mg/kg)
Soil	7.9	3.76	0.62	0.11	8.2	7.25

Before being packed, soils were brought to a moisture content of 70% Water-Filled Pore Space (WFPS) (assuming a soil bulk density of 1.20 Mg/m^3 and particle density of 2.65 Mg/m^3) by addition of the desired distilled water while constantly mixing with the soil. Silica sand was first washed using 10% HCl acid and then washed using distilled water until the pH of the solution reached 7. Silica sand was then air-dried and brought to the same water potential as the prepared soil. Silica sand was first packed into columns, mechanically compressed to a bulk density of 1.4 Mg/m^3 , and then soil to a bulk density of 1.2 Mg/m^3 to keep constant porosity. Sand and soil were packed in 5-cm increments in order to pack evenly. To prevent the mixing of soil and silica sand, a nylon screen (ID: 0.5 mm) was positioned between the two layers.

After being packed with soil, columns were placed in a temperature-controlled growth chamber where temperature was kept at $25 \text{ }^\circ\text{C}$. H_2O additions were made and

recorded when necessary to maintain soil moisture content at 70% WFPS. Relative humidity of the chamber was kept at 80%.

2.3.4 Gas flux sampling

Ten days were allowed before flux measurements were started in order to let soil cores stabilize following packing disturbance. Gas flux sampling was carried out using the static chamber technique (Hutchinson and Livingston, 2002), which include two-part static chambers. In this case, the two parts chamber consists of 5-cm collar defined by the headspace of the column (ID: 20.3 cm) and lids with a gas-sampling port that fits on the top of the column creating a chamber headspace of 5-cm in depth. Gas samples, withdrawn through the sampling port, were collected using a 20-ml plastic syringe (Beckton-Dickson) at 0, 30, 60 minutes intervals. The samples were injected into pre-evacuated vials 12-ml Exetainertm vials (Labco, UK) and transported to the laboratory and analyzed for CO₂ and N₂O using a Varian CP3800 gas chromatograph (GC) with three detectors (electron capture - ECD, flame ionization - FID and thermal conductivity - TCD). CO₂ was measured using a thermal conductivity detector. The TCD was operated at 130 °C with a prepurified helium carrier gas at 30 mL min⁻¹ (20 psi), Haysep D 80/100 analytical column (0.32 cm diameter x 183 cm length) maintained at 70 °C. An electron capture detector was used to measure N₂O. The ECD was operated at 300 °C, 90%Ar, 10%CH₄ carrier gas at flow rate of 30 mL min⁻¹ (13.0 psi), Porapak QS 80/100 precolumn (0.32 cm diameter x 46 cm length) and analytical columns (0.32 cm diameter x 183 cm length) in a column oven operated at 70 °C. A precolumn was used in combination with a four-port valve to remove water from the sample. Five replicates of two concentrations of standard gas mixtures (same concentrations as those used during

sampling) were included in each run and were used to construct standard curves. The standard gases collected during sampling were used to confirm sample integrity during sampling and storage.

Standard curves were used to convert peak areas derived from the GC into CO₂ and N₂O concentration in the sample. Standard gas samples were collected at the same time gas samples and were used for correction of background gas concentration in the vials and/or losses during storage. CO₂ and N₂O flux were calculated by regressing the linear change in gas concentration over sampling time (Rolston, 1986). The flux¹ of gas at the soil surface was calculated from:

$$f = (V/A) (\Delta c/\Delta t)$$

f = flux density of gas (g m⁻² s⁻¹)

V = volume of the chamber headspace (m³)

A = area of the chamber (m²)

$\Delta c/\Delta t$ = rate of change of gas concentration in the chamber headspace (g m⁻³ s⁻¹).

Since the experiment was carried out at 25 °C, temperature correction was not necessary to calculate the flux. Under other temperature conditions, the ideal gas law was used to correct for temperature. Samplings were taken twice every week and the experiment lasted three months.

2.3.5 Soil atmosphere sampling

Soil atmosphere samples were collected at the same time flux samples were taken from the treatment D80. The profile depths included 20, 35, 50, 65 cm within 80-cm

¹ The term flux in this chapter and other chapters of this thesis refers to the flux density.

soil of A horizon. When soil was packed, PVC tubes (ID: 2 mm) were inserted into the middle of soil column horizontally. The end of the tube in the soil was protected using nylon screens. The other end out of the column was sealed with a rubber stopper and a silicone seal. A 20-cm syringe was used to draw gas through the rubber stopper by first drawing 1 mL to purge the volume of the tubing, and then 12 mL which was injected into a 6 mL pre-evacuated Exetainer. Gas samples were analyzed for CO₂ and N₂O with the same procedure as described in Section 2.3.4.

2.3.6 Data analysis

Regression analyses were used to estimate the relationship between soil depths and GHG emission. Data analysis was carried out using Statistical Analysis Software (SAS institute Inc., 2000).

2.4 Results

2.4.1 Effect of soil depth on CO₂ flux and profile concentrations

2.4.1.1 CO₂ surface flux and concentrations within soil profile

CO₂ flux from soil surface increased dramatically with soil depth from 0 to 60 cm and decreased from 60 cm to 80 cm (Figure 2.1). For the 0 cm depth (only sand), small negative values were observed. This was caused by the variability in the system. The highest CO₂ flux occurred on day 4 and day 14. There was no obvious difference between other dates. For a 71-day period, the cumulative CO₂ flux of each depth is shown in Figure 2.2. D60 appeared to have the highest CO₂ flux. Flux of other treatments followed the order D80>D40>D20>D0.

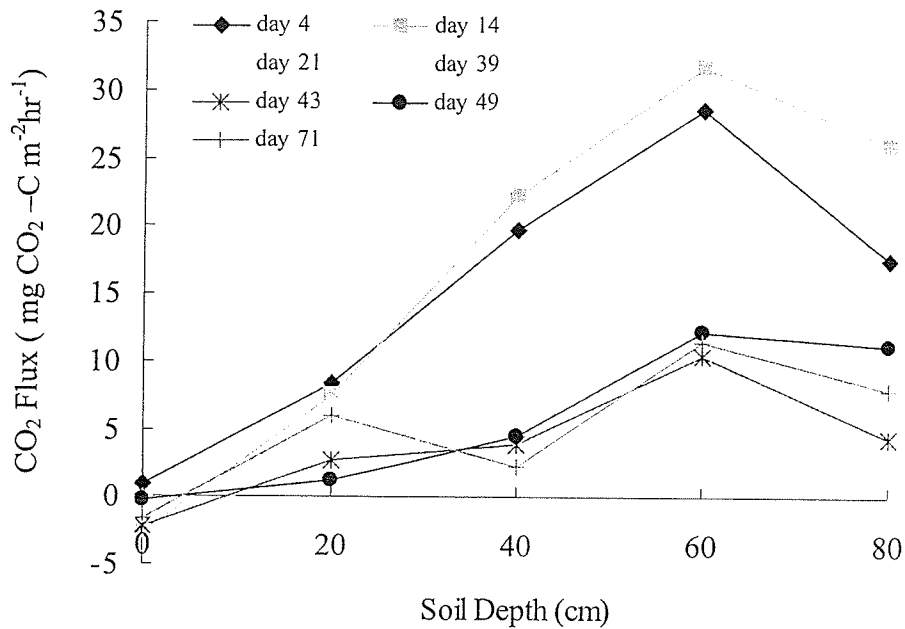


Figure 2.1 Surface CO₂ flux from the soil surface of columns of varying soil depths (7 of 14 dates shown).

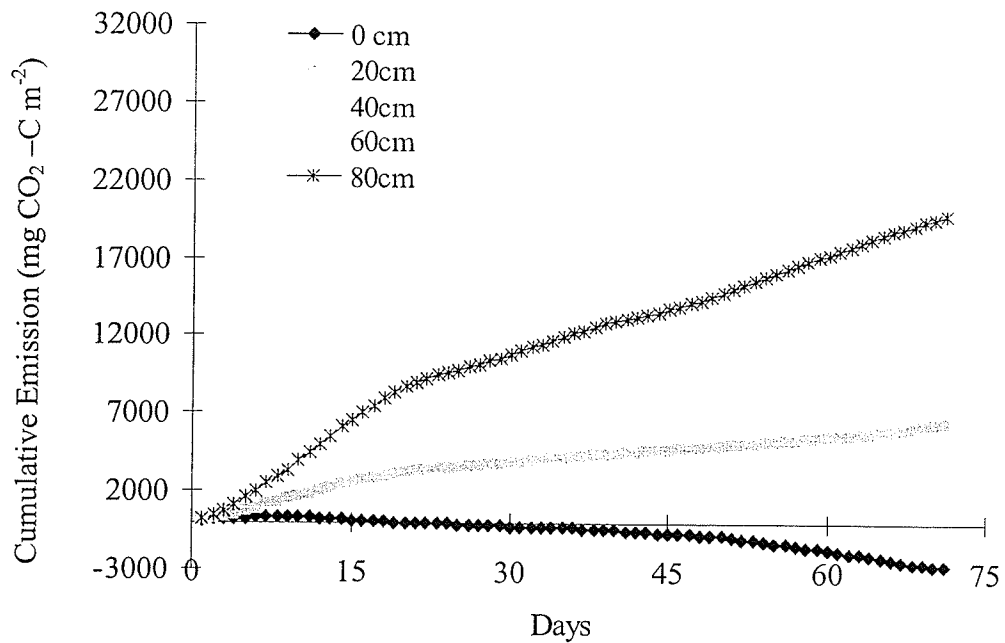


Figure 2.2 Cumulative CO₂ emission from the soil surface of columns of varying soil depths for a 71-day experimental period.

With treatment D80, CO₂ concentrations were measured of the soil profile. Results showed CO₂ concentrations increased with depth (Figure 2.3). The highest concentration occurred in 65-cm depth and CO₂ concentration was 120 mL L⁻¹.

2.4.1.2 Relationship between soil depth and CO₂ flux

The effect of soil depth on CO₂ flux was tested using regression analysis (Figure 2.4). With un-transformed CO₂ flux data, regression analysis of data collected over 71 days showed the relationship of cumulative flux and soil depth could be described using a linear equation ($Y = 322.24x - 371.6$, $R^2 = 0.83$, $P < 0.05$).

2.4.2 Effect of soil depth on N₂O flux and profile concentrations

2.4.2.1 N₂O surface flux and concentrations within soil profile

N₂O flux from the soil surface of columns, generally, increased with increasing depth of soil on all dates (Figure 2.5). The highest flux rate (216 µg N₂O-N m⁻² hr⁻¹) was observed on day 21 from columns with 80 cm of soil. Only for the columns containing 80 cm of soil was there an obvious difference between each date. N₂O flux increased from day 1 to day 21 and reached the highest value on day 21, then decreased dramatically after day 21. On day 14, high N₂O flux occurred for 40-cm soil depth while there was close to zero flux for 60-cm soil depth. For a 71-day period, the cumulative N₂O flux of each depth is shown in Figure 2.6. D80 had the highest flux rate, followed by D60. The flux of other treatments was closed to zero during the experimental period.

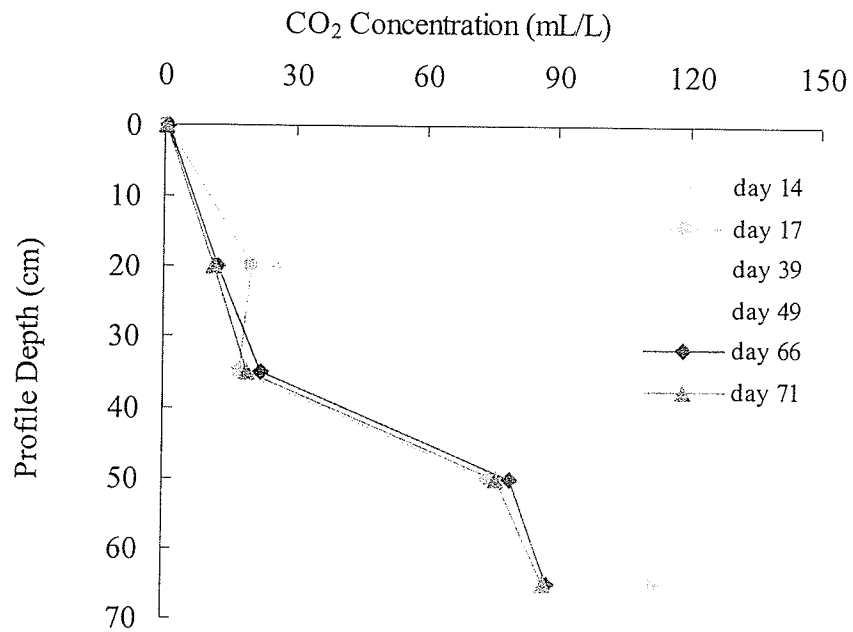


Figure 2.3 Profile of CO₂ concentrations within the column of 80 cm soil (6 of 14 dates shown).

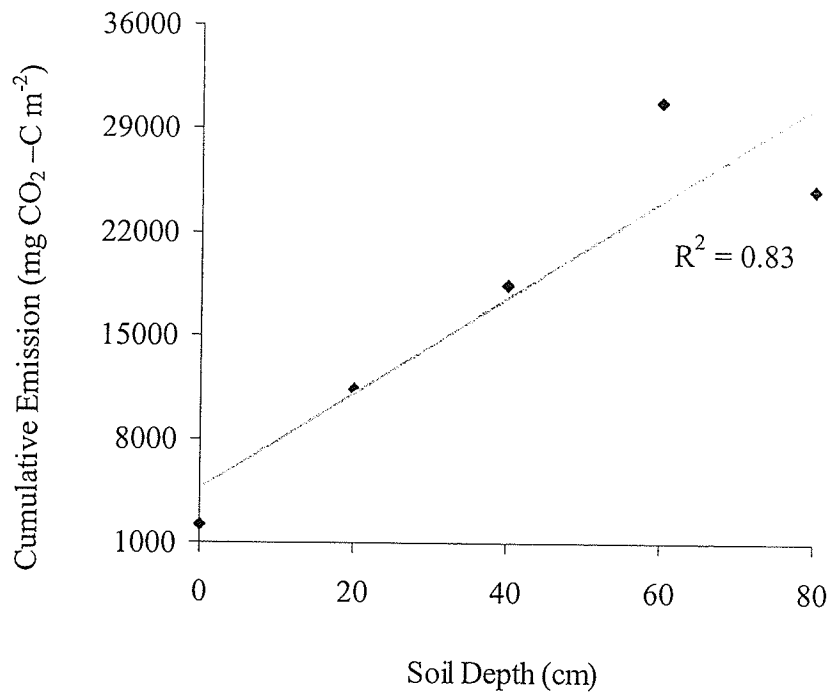


Figure 2.4 Relationship between cumulative CO₂ emission from the soil surface of columns for a 71-day period and soil depth.

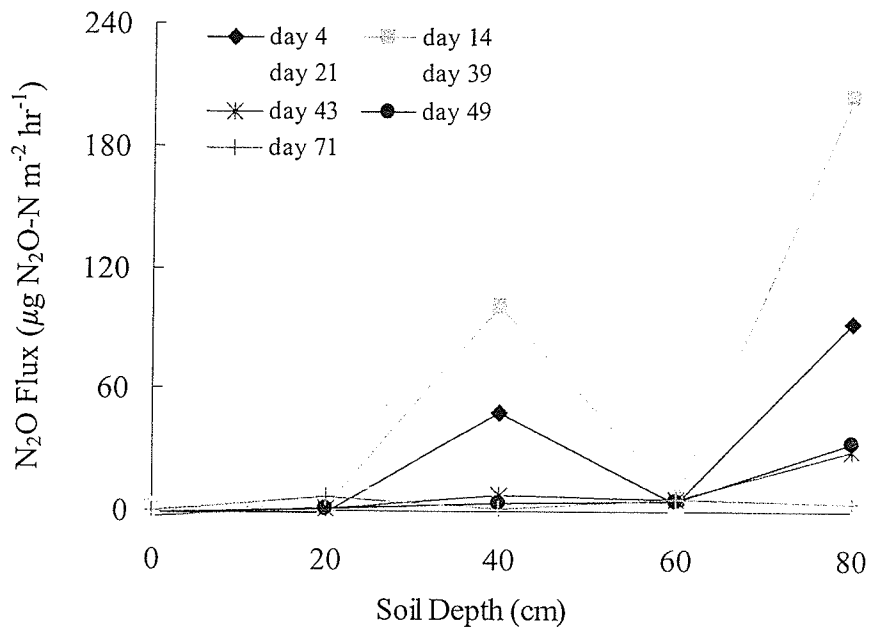


Figure 2.5 Surface N₂O flux the soil surface of columns of varying soil depths (7 of 14 dates shown).

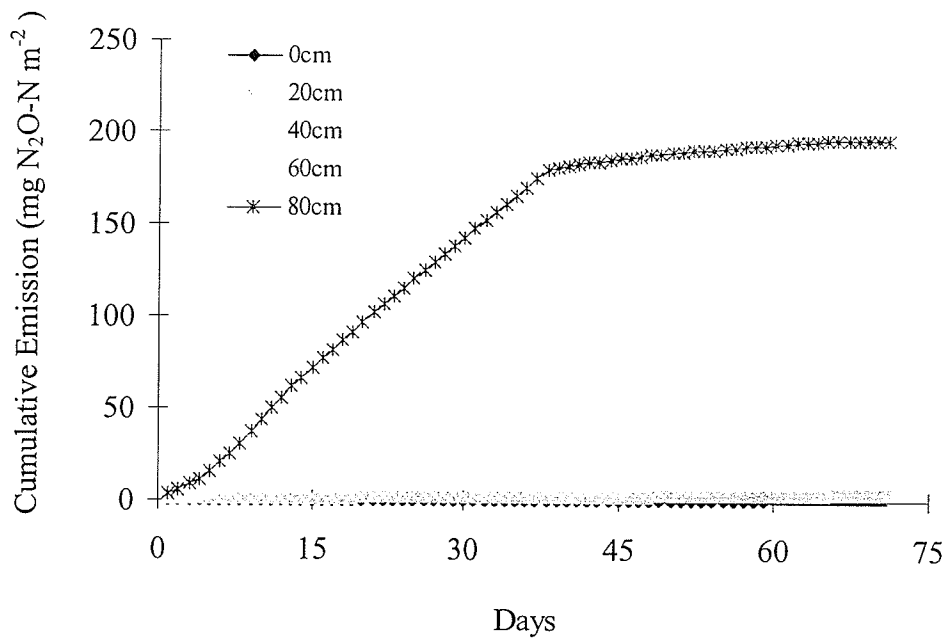


Figure 2.6 Cumulative N₂O emission from the soil surface of columns of varying soil depths for a 71-day period.

For the 80-cm soil profile, N₂O concentration increased with depth (Figure 2.7). N₂O concentrations near the surface (<15 cm) were low. Temporally, N₂O concentration profiles varied during the study period, especially at the greater depths. The highest concentration was observed on day 14 with the value of 240 ppm. This was very high comparing with concentrations observed by other researchers (Dowdell and Smith, 1974; Mosier and Hutchinson, 1981; Burton and Beauchamp, 1994), but not surprising given the depth of organic-rich disturbed soil contained in the column, relatively high moisture content (70% WFPS) and warm temperature (25 °C).

2.4.2.2 Relationship between soil depth and N₂O flux

The results of the column study indicated that soil depth had a marked effect on N₂O flux under controlled laboratory conditions. With 80 cm soil depth, highest N₂O flux was observed. The relationship of the untransformed N₂O cumulative flux data collected over 71 days was modeled using the linear regression: $Y = 2.0035x - 26.004$ (Figure 2.8).

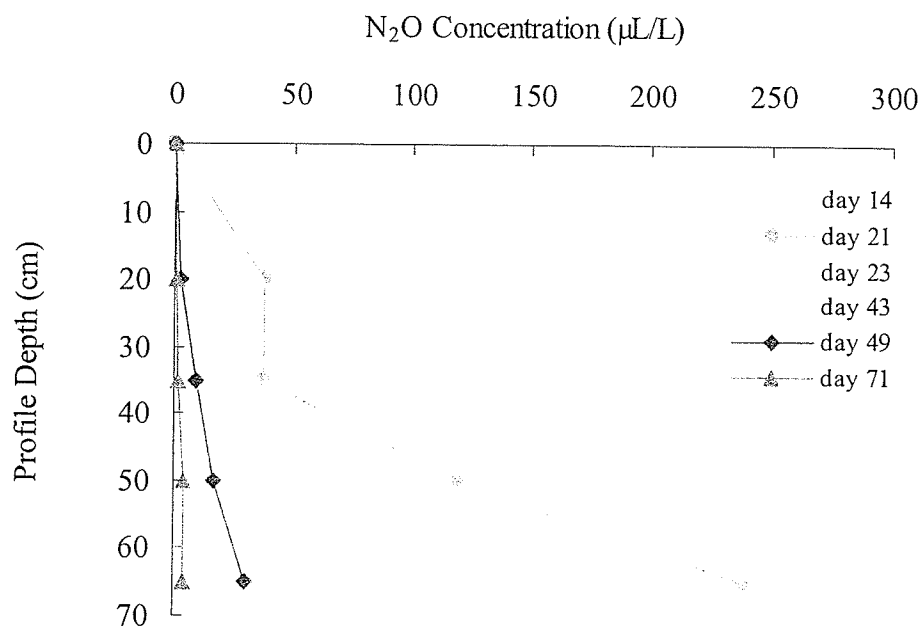


Figure 2.7 Profile N₂O concentrations within the column of 80 cm soil (6 of 10 dates shown).

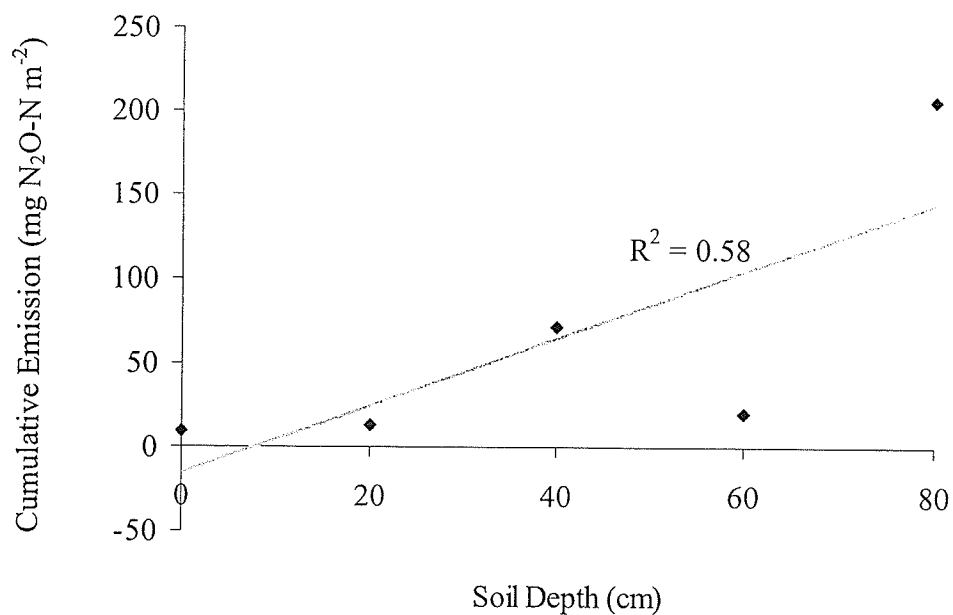


Figure 2.8 Relationship between cumulative N₂O emission from the soil surface of columns for a 71-days period and soil depth.

2.5 Discussion

2.5.1 Effect of soil depth on CO₂ flux and profile concentrations

Under controlled laboratory conditions, it is expected that soil depth will influence GHG emissions. Theoretically, the potential production of GHG is the same per unit of soil depth. If there is no effect of soil depth on surface GHG emission, CO₂ emission should increase proportionally to the depth. In reality, surface CO₂ emission is not only determined by production, but also by gas diffusion (Hojberg et al., 1994; Corre et al., 1996; Bajrachary, 2000a; Janzen et al., 2002; Toshie et al., 2002). Therefore, our assumption is that the relationship of CO₂ emission and soil depth should be non-linear. As well, the profile concentrations of CO₂ increase with the soil depth non-linearly. Therefore our hypothesis is that the proportion of production that is emitted at surface will depend on soil depth.

The results showed CO₂ flux increased with soil depth. The relationship between soil depth and CO₂ emission was tested using different regression models. The linear equation resulted in better fits to the data for the CO₂ emission (Figure 2.5) with R² = 0.83. It is known that gas diffusion in soil is affected mainly by air-filled pore size, soil diffusion, soil temperature and the concentration gradient. In this study, gas diffusion was mainly affected by the concentration gradient from increased soil depth as both soil moisture and temperature were constant. The depth from surface soil limited gas diffusion by affecting aeration and water movement. After certain depth, the change of gas diffusion and the change of gas production reach a constant level. Therefore, CO₂ flux should become stable. The reason for the contrary results is likely the high

variability of the data. As well, there was only one replicate for each treatment. More investigation is needed to clarify the impact of soil depth on CO₂ flux.

With depth increasing, CO₂ diffusion from greater depths was limited so there was an accumulation of CO₂ concentration in the greater soil depth. As well, O₂ diffusion to the deeper depths was reduced which restricted CO₂ production in that microbial activities were primarily controlled by O₂ concentration.

2.5.2 Effect of soil depth on N₂O flux and profile concentrations

Theoretically, potential N₂O production rate is same per unit of soil depth with uniform soil conditions. Therefore, N₂O emission should increase with soil depth but emission rate should decrease with increasing depth because emission is restricted by reduced diffusion at deeper depths and possible consumption of N₂O at shallower depths. Thus, N₂O emission is expected to increase following non-linear pattern and this exponential relationship is expected to be negative.

The results indicated that N₂O flux increased with soil depth linearly. The increased soil depth provided soil organic C and N for nitrification and denitrification, which are the main processes for N₂O production (Benckiser, 1995; Beauchamp, 1997; Bremner, 1997). Moreover, O₂ diffusion to the deeper soil depths was reduced which would favor N₂O production from denitrification since denitrification is an anaerobic process. Nevertheless, soil depth from surface limited N₂O diffusion in the soil as indicated by the accumulation of N₂O at depth. Also, under anaerobic conditions, the relative proportion of the denitrification process that results in N₂O production is controlled by the extent to which N₂O is further reduced to N₂, a relationship generally expressed as the ratio of N₂O/N₂ proportion (Weir et al., 1993). With depth increasing,

N_2O production rate increased though N_2O diffusion was limited. With further depth increasing, $\text{N}_2\text{O}/\text{N}_2$ proportion will decrease as a result of greater N_2O reductase activity. N_2O reductase is more inhibited by O_2 condition than N_2 reductase.

2.5.3 Method discussion

The variability of the results indicated the need for improvement in this column study. Firstly, in this study, treatments only included five depths (0, 20, 40, 60, 80 cm). To better understand the effect of soil depth on GHG production, more depth treatments are needed for further study. Treatments should include from 0 to 120 cm with 10 cm increments. Secondly, each treatment only included a single replicate. The experiment should include at least three replicates based on the variability measured in the experiment. Thirdly, with sand as control and comprising for the remainder of the height, it affected soil water movement and gas transport which may have affected the GHG flux. For future study, sand/bentonite mixture should be used to provide similar conditions to soil. As well, soil moisture control during the experimental period was difficult. Due to high evaporation, soil cracking at the soil surface was a concern for gas exchange with atmosphere because this will result in mass flow. Soil moisture should be monitored using TDR hourly or daily.

2.6 Summary and Conclusions

Under controlled laboratory conditions, a column study showed that cumulative CO_2 flux over 70 days increased linearly with soil depth ($R^2 = 0.83$). Likewise, cumulative N_2O flux increased linearly with soil depth ($R^2 = 0.58$). These were attributed to increased depth of soil increasing production of both CO_2 and N_2O . The

experiment was limited in ability to determine the exact effect of soil depth due to limited number of depth treatments and single replicate. Also, although soil moisture was controlled, the variability of soil moisture within the soil profile, due to soil water movement and surface evaporation, likely affected CO₂ and N₂O production and subsequent emission.

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3. IMPACTS OF SOIL ACCUMULATION ON GREENHOUSE GAS PROFILE CONCENTRATION AND EMISSION

3.1 Abstract

A field experiment was carried out in three depressions within a complex, cultivated landscape, 17 km north of Brandon, Manitoba. The effect of soil accumulation on profile CO₂ and N₂O concentrations as well as emissions from the soil surface were examined. Soil atmosphere was sampled using silicone tube probes positioned horizontally into the soil profile in 5-cm increments to a depth of 100 cm or 10 cm into the C-horizon. Surface gas flux was measured using the closed-chamber method. Soil accumulation was estimated using ¹³⁷Cs analysis.

Results showed CO₂ flux and profile concentrations had obvious seasonal patterns. CO₂ flux and concentration changed dramatically as the temperature varied, indicating that temperature is the key factor controlling gas production and emission. Soil CO₂ profile concentrations had high variations within depths. Higher CO₂ concentrations at the greater depths in these depressions probably resulted from high production and low diffusion rates. A thicker A horizon due to soil accumulation, root respiration, and microbial respiration resulted in high CO₂ production. The high water table level and poor drainage in the depressions limited gas diffusion to the soil surface as well. Significant soil accumulations were observed in three depressions. The soil accumulations favored CO₂ production in that it increased quantities of soil organic carbon and nitrogen to greater depths in the soil profile. The effect of soil accumulation on CO₂ flux was different in the three depressions due to soil moisture conditions.

Results indicated N₂O profile concentration and surface flux had significant seasonal patterns as well. The high N₂O flux and profile concentrations only occurred during spring thaw periods. Peak concentrations appeared to accumulate at 10-25 cm at the start of the thaw events. High soil moisture, available carbon and nitrogen during spring thaw periods are likely to have contributed to the high N₂O production rates. Although soil accumulation increased quantities of organic carbon and nitrogen in the soil profiles, the effect of soil accumulation on N₂O production and emission was only expressed during spring thaw events. The increased organic matter content associated with the thickened A horizon is consistent with increased biological activity and increased N₂O production in soil profiles. Restricted gaseous diffusion in the soil at depth might have resulted in greater the conversion of N₂O to N₂ decreased emissions of N₂O from the soil surface. Thus, the effect of soil erosion on N₂O emission was complicated by hydrologic and pedologic conditions.

The potential production of CO₂ and N₂O at different soil depths from the field site was further studied with a microcosm experiment. This study demonstrated that potential for gas production decreased with increased soil depth for both CO₂ and N₂O. The surface 0-25 cm of soil appeared to be the major potential source in CO₂ and N₂O production, in that this layer was found to be rich in organic carbon and nitrogen, favoring microbial activity and microbial biomass. Therefore, the accumulation of soil on the surface rich in organic matter should increase CO₂ and N₂O production within the soil profile, at least in the short-term.

3.2 Introduction

Soil plays a major role in emission of greenhouse gases (GHG) such as CO₂ and N₂O, as well as in the sequestration of carbon. The potential of soils to be sources or sinks for these gases is recognized as an important issue (Duxbury et al., 1993; Burton and Beauchamp, 1994; Mosier, 1998). Recently, the enhanced greenhouse gas effect resulting from increasing concentrations of anthropogenic greenhouse gases (e.g. CO₂, N₂O and CH₄) has led to further deterioration of our environment. According to the Intergovernmental Panel on Climate Change (IPCC, 2001), the concentrations of CO₂, N₂O and CH₄ have increased by 30%, 145% and 15%, respectively, since the preindustrial period. A doubling of CO₂ concentration is expected to raise global mean surface temperature by about 2 degrees by the end of this century (IPCC, 2001; Mosier, 1998). Of all these changes, production of CO₂, N₂O and CH₄ in the soil and emission to the atmosphere contribute to about 50%, 40%, 75%, respectively, of total anthropogenic emissions (IPCC, 2001). These gases are mainly produced as a result of microbial processes in the soil. Within a soil profile, variability of substrates, moisture, temperature, aeration and other soil properties affects GHG production and consumption (Smith et al., 2003; Jacinthe and Lal, 2004). Variations of these components of soil, especially as influenced by anthropogenic activities (e.g. tillage) within landscapes, contribute to the varying of GHG production and emission spatially and temporally. GHG emissions are the function of production, consumption and diffusion processes within the soil profile (Hojberg et al., 1994; Toshie et al., 2002). Among these processes, production of GHG in the surface soil layer plays a key role in their emission. The subsurface production is also a potential source of emission. Understanding the

temporal variability of GHG concentration within the profile as well as the production, consumption and transport of gas within the profile can provide insight on how to reduce the loss of these gases to the atmosphere (Terhune and Harden, 1991; Burton and Beauchamp, 1994).

Production and emission of greenhouse gases are not only determined by pedogenic soil characteristics, but are also strongly affected by land use and soil management practices (e.g. soil erosion). Enhanced soil erosion by wind, water and tillage can redistribute considerable amounts of soil, and thus influence the distribution of organic C and N within landscapes. Soil redistribution resulting from erosion is more severe in hilly and cultivated landscapes. In these landscapes, a larger amount of soil is lost from upper slopes and accumulated in low slopes or carried into river systems (Lal, 1995; Lobb et al., 2002). The physical removal of organic- and nitrogen-rich materials from upper slope landscapes can account for 75% of total organic carbon and nitrogen lost from these positions (Verity and Anderson, 1990). Soil redistribution is likely to affect the dynamics of carbon and nitrogen through its effect on soil properties and processes within landscapes. Firstly, it removes the surface soil and exposes the carbonate-rich subsurface soil. Secondly, it deteriorates soil structure because of the depletion of organic matter and the exposure of carbonates. Thirdly, it buries soil in lower slopes due to accumulation/deposition. Finally, it changes soil hydrology and temperature regime within landscapes (Corre et al., 1996; Bajrachary, 2000a; Janzen et al., 2002; Lobb et al., 2002). The impact of variations in these properties and processes caused by soil erosion within landscapes is to alter the physical and chemical nature of the soil thus affecting soil microbial activities and plant growth, which are the major factors controlling GHG production in the soil.

In addition, soil redistribution affects the variation of organic carbon and nitrogen within the soil profile. As tillage erosion is a major form of soil erosion within cultivated landscapes, most eroded soil accumulates in lower slopes. The depth of accumulation of soil in depressions often exceeds 50 cm and sometimes even 100 cm (Lobb et al., 2002). The accumulated soil is rich in organic carbon and nitrogen which may enhance soil aggregation. Thus this position may be a carbon sink. However, there may be increased CO₂ production in these soils as a result of increased microbial activity in response to the additional organic carbon (Voroney et al., 1981). Due to the soil accumulation, the buried soil may be isolated from further tillage disturbance. As well, located in depressions, these soils are subjected to moderate temperature and higher moisture conditions. Thus, the formation of anaerobic conditions may result in increased N₂O and CH₄ production (Lobb et al., 2002).

Many studies have investigated greenhouse gas production and emission from forestlands, pasture, and crop land (Burton and Beauchamp, 1994; Billings et al., 1998; Burton et al., 2004; Burton and Lobb, 2004). The effect of soil erosion on GHG emission has been studied by other researchers (Kimble et al., 2001; Lal, 2001), but their efforts have focused on water erosion and its removal of organic-rich material from cultivated landscapes. A few studies have examined the effect of soil erosion on the redistribution (loss and accumulation) of carbon with landscapes (Gregorich et al., 1998; Kimble et al., 2001; Pennock and Frick, 2001). In addition, a few studies have examined the effect of erosion phases (loss) on CO₂ flux and profile concentration (Bajracharya et al., 2000a; Bajracharya et al., 2000b). These studies showed that soil erosion phases had no direct effect on CO₂ flux from soil. They concluded that the impact of soil erosion phases on soil CO₂ concentration occurs primarily through its

impact on soil temperature. The weakness of these studies was that the erosion phases were estimated qualitatively based on Ap horizon thickness and profile characteristics. Moreover, CO₂ concentration was monitored only at a depth of 10cm. A study carried out by Erb (2005) indicated landscape restoration (application of topsoil to areas of soil loss and removal of topsoil from areas of soil accumulation) does not increase GHG emission from soil. Her conclusion suggested the removal of soil will benefit atmospheric CO₂ level by reducing CO₂ emission from the lower slope removal areas, while N₂O and CH₄ emissions were not influenced by the removal of soil. However, this study only focused on the effect of landscape restoration on GHG emission, not the effect of soil erosion. To understand the specific effect of soil loss and accumulation on soil air CO₂ concentration and emission to the atmosphere, more detailed monitoring CO₂ concentration in the soil profiles is needed. Determining the effect of loss and accumulation is improved by measuring erosion quantitatively. The fate of accumulated soil within landscapes and its effect on net GHG emission is not clear (Lal, 2001; Lobb et al., 2002), especially within the soil profile of cultivated landscapes. To date, there is limited information relating the magnitude of soil accumulation from erosion processes within landscapes to GHG production in the soil profile and surface emissions.

3.3. Objectives

3.3.1 Field study

- 1) To estimate the amount of soil accumulation that has occurred in the lower slope positions of selected depressions within a cultivated landscape due to soil erosion.
- 2) To measure the concentration of N₂O and CO₂ with depth in the soil of these landscape positions, and to measure the surface emission of N₂O and CO₂ from the soil of these landscape positions.
- 3) To assess the impact of soil accumulation on N₂O and CO₂ production and emission.

3.3.2 Microcosm study

- 4) To determine the CO₂ and N₂O production potential of soils collected from various depths from the lower slope positions of depressions within the landscape to further understand the impact of accumulated soil on CO₂ and N₂O production and emission.

3.4 Materials and Methods

Field and microcosm experiments were carried out to study the effect of soil erosion on greenhouse gas production and emission, as well as the potential production of greenhouse gas from soils collected from different soil depths. This section presents the detailed description of the site where the field experiments were conducted, and from where soil was collected for the laboratory experiment. The methodology for the field study and microcosm study are described as well.

3.4.1 Site selection and description

The study area is north of Brandon, in southwestern Manitoba, legal location SE32-12-18. This area is a part of the Prairie Pothole Region. The mean annual temperature is 1.4 °C. The mean annual precipitation is 340 mm. The landscape is an undulating to hummocky ground moraine with wetlands which are defined as any land which is covered by water for extended periods (weeks, months, years) affecting vegetation and soils. The slope steepness ranges from 3-5% and the slope length varies from 30 to 50 m. The soil has developed on moderately to strongly calcareous, loamy morainal till (Podolsky and Schindler, 1993). Major soils are of the Newdale Association, which includes Newdale series in the middle to upper slope positions and Rufford and Cordova series appearing in the lower slope positions. This area has been conventionally tilled for about 100 years. The land has been under flax and wheat in rotation for the last 10 years.

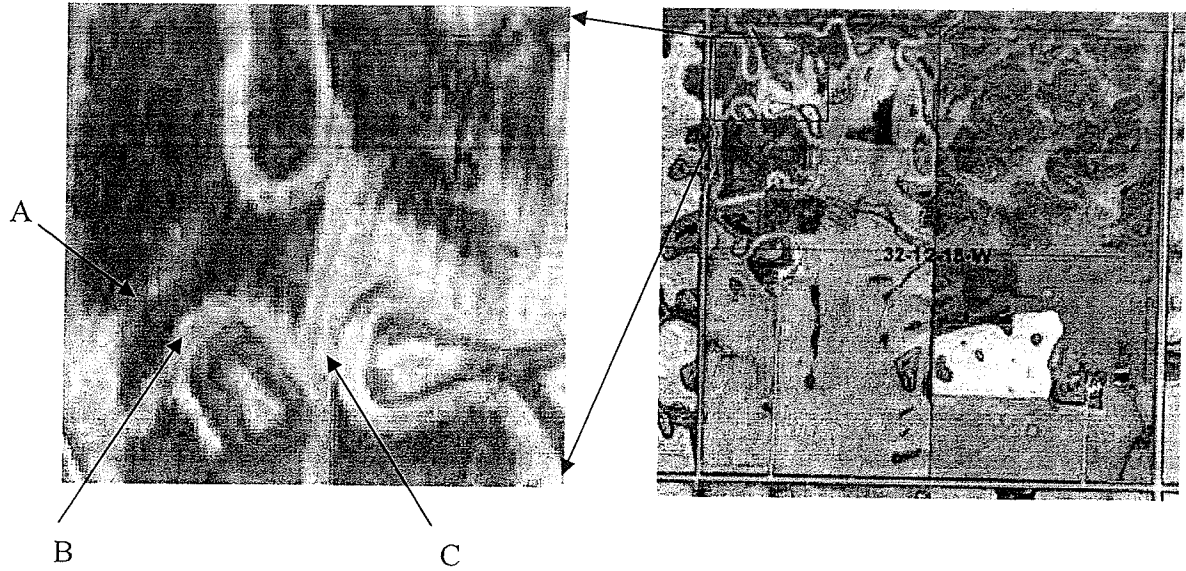


Figure 3.1 The study site (Depressions A, B and C) in a conventionally-tilled field, Brandon, MB (1995, scale:1: 25,300).

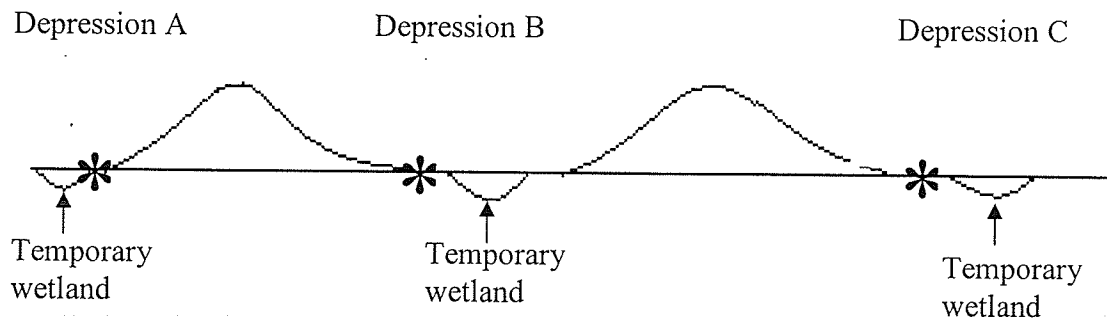


Figure 3.2 A diagram of the field site (*-sampling area)

In this topographically complex and intensively-tilled landscape, soil redistribution by water and tillage erosion is obvious on these hillslopes. On the tops of hillslopes, the soil has a thin A horizon, high carbonate content and low soil organic matter content. The base of the slopes is concave with soil accumulation due to erosion. These lower slope positions have a thick A horizon and high organic matter content.

3.4.2 Field experiment

The site selected for the field experiment was moderately eroded. Three depressions (A, B and C) were selected within < 1km radius (Figure 3.1-2). All three depressions are discharge areas. The typical soil series in these depressions belong to the Rufford and Cordova series. The soil texture is clay loam.

3.4.2.1 Measurements and devices

In each depression, three plots were set up on the edge of the field and in the foot slope positions. The area of the plots was 3-m x 3-m. In each plot, gas flux was collected from the soil surface, and soil atmosphere was collected over the depth of the soil profile. Probes constructed from silicone tubing were installed into desired soil depths to collect soil atmosphere and closed-chambers were used to measure gas flux at the soil surface. Soil redistribution within the three depressions was estimated using ¹³⁷Cs analysis. As well, ancillary measurements including soil moisture, soil and air temperature, water table level, precipitation, soil properties analyses and above-ground plant biomass were measured during the study period.

3.4.2.1.1 Soil atmosphere collection within soil profiles

Soil atmosphere CO₂ and N₂O concentrations were sampled using probes constructed from silicone tubing inserted into the ground at desired depths. The silicone probe was adapted from sampling techniques developed by Kammann et al. (2001). Each probe consisted of a PVC pipe (22-cm-long x 1.6-cm-internal diameter) with silicone tubing (18-cm-long, 1.2-cm-internal diameter, 0.24-cm-wall thickness, Cole Parmer # 06411-19) inside (Figure 3.3). The silicone tubing was closed at one end with septa (ID: 13 mm, OD: 13 mm, Sigma Aldridge #Z-51, 250-8) and silicone seal, and with the other end fitted with a septa with a hole through which the Tygon tubing (ID: 1/32", OD: 1/32", wall: 1/32", Cole Parmer # EW-06408-60) was threaded 2 cm into the silicone tubing. The other end of Tygon tubing was fitted with a male luer with a locking nut and a barb (Cole Parmer # EW-30504-02). When sampling, the luer was connected with a three-way stopcock and air sample was taken using a syringe. Both ends of the PVC pipes were sealed with triple-expanding urethane foam to avoid mass flow. To allow gas exchange with silicone tubing, there were 18 holes (1-cm diameter) distributed evenly along PVC pipe. Before installation, each sampler was tested for leaks and time to equilibration with the atmosphere.

The silicone probes were inserted into one vertical face of a 100 m deep excavated pit. Horizontal holes were made into the face using a drill with a drill bit of the same size as the probes. Sampling probes were then placed into soil horizontally at 5-cm depth increments within the profile down to 100 cm or 10 cm into the C horizon. To avoid soil collapse or vertical cracking extending between probes, the position of probes was staggered over the depth of the profile (Figure 3.4). The pit was then refilled with soil, horizon by horizon, in the reverse sequence as it was excavated.

Gas samples were analyzed for N₂O and CO₂ using CP 3800 gas chromatography (CH₄ was also analyzed as a standard operating procedure) with the same procedure as described in Section 2.3.3.

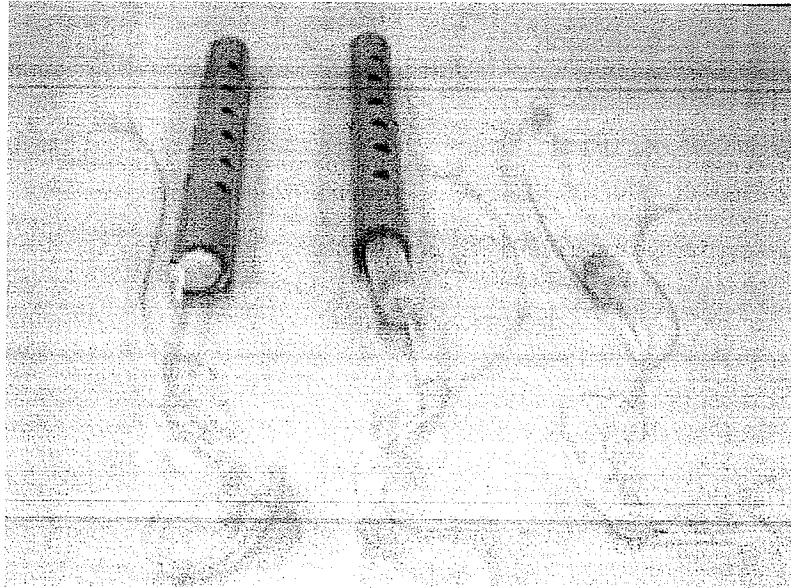


Figure 3.3 Construction of silicone tube probes.

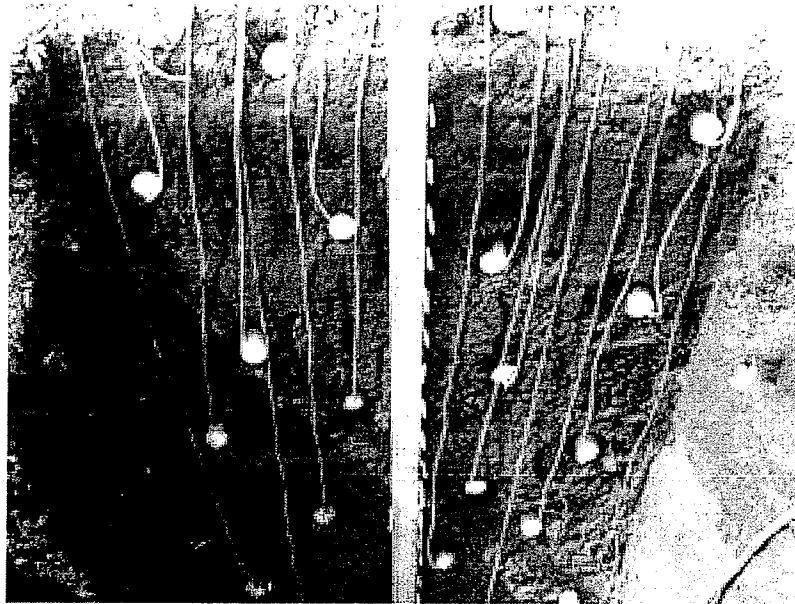


Figure 3.4 Installation of silicone probes within soil profile.

3.4.2.1.2 Gas flux measurement

Greenhouse gas (CO₂ and N₂O) emissions were measured at the same time gas samples were taken within soil profiles. Flux samples were taken from all plots with duplicate samples in each plot. Gas samples were taken using a non-steady state vented chamber (Hutchinson and Livingston, 2002), which employed a two-piece static chamber. The two parts chamber consisted of a base collar (ID: 20.3 cm, height: 10 cm) and a lid (ID: 20.3 cm). Lids had a 0.4-cm-internal-diameter x 7.5-cm-long vent tube and a gas-sampling port with a serum stopper. Collars were installed 5 cm into soil with another 5-cm headspace for gas sampling. The installation of chambers was completed at least 2 weeks prior to gas sampling. The depth of insertion of the collar was corrected when necessary to keep the same height (5 cm). Samples were collected at 0, 15, 30 and 60 minutes after closure. Samples were collected at 0, 30 and 60 minute intervals for CO₂ measurement and 0, 15 and 30 minute intervals for N₂O measurement. At time zero, atmosphere samples were collected for background corrections as well. Gas samples were injected into pre-evacuated vials with 20 ml disposal syringes and transported to the laboratory. Gas samples were analyzed for CO₂, CH₄ and N₂O using the procedure described in Section 2.3.4. Standard gas samples were collected at the same time and used for correction of background gas concentration in the vials and to correct for losses during storage. CO₂, N₂O and CH₄ flux were calculated according to the method described by Rolston (1986).

3.4.2.1.3 Estimation of soil redistribution

Soil redistribution in the depressions was estimated using ¹³⁷Cs analysis (Lobb, 1991). The ¹³⁷Cs technique is based on radioactive fallout from the use of nuclear

weapons during the 1950's and 1960's. The amount and distribution of ^{137}Cs reflects atmospheric deposition of Cs and its strong adsorption to the soil. Consequently, ^{137}Cs is mostly concentrated in the surface of soil. The half-life of Cs is 30.2 years and its decay constant is 0.023 year^{-1} . The distribution of ^{137}Cs in the landscapes is measured to evaluate soil redistribution since about 1960. To evaluate soil redistribution using ^{137}Cs , a baseline activity of ^{137}Cs was first identified. Based on the baseline, the rate of soil accumulation and loss at the eroded slopes were estimated. In this experiment, a baseline value of 2400 Bq m^{-2} was used based on estimates reported by Lobb and Kachanoski (1999).

^{137}Cs activity was measured using a Canberra Broad Energy Canberra Gamma Spectrometer. Soil for ^{137}Cs activity measurement was collected at the time when silicone probes were installed in soil pits. On two sides of soil pits, different from the side for the installation of probes, soil samples were taken in 5-cm increments of the same depths as the gas collection. The soil samples were analyzed for ^{137}Cs activity and other soil attributes described below. Bulk density of each layer was measured using the 5-cm-high x 5-cm-internal-diameter soil core. Prior to measurements, the samples were air dried, and milled to pass through a 2-mm sieve. Stones were separated from soil and weighed because they will affect a volume absent of ^{137}Cs activity (Lobb, 1991). For analysis, about 0.5 kg of the processed sample was placed in Marinelli beakers, and then these beakers placed on the gamma detector. The net ^{137}Cs activity photopeak area of each sample was then translated into an activity unit in Bq kg^{-1} using the method described by Lobb (1991).

3.4.2.1.4 Ancillary measurements

At the time of gas sampling, air and soil temperatures, soil moisture, and water table level were also measured. Air temperature was recorded using a thermometer (Fisher). Soil profile temperature was measured using thermocouples installed at 5, 10, 15, 20, 25, 30, 40, 70, 100 cm of soil depths. Soil moisture was measured using Time-Domain Reflectometry (TDR) at 15, 30, 50 cm in depth. Water table level was measured using 100-cm wells (5-cm-internal diameter plastic tube). When present, snow depth was measured using a metre stick. Daily precipitation was obtained from MZTRA farm records.

Soil collected for ^{137}Cs analyses was also used for analyzing soil organic carbon, inorganic carbon, ammonia, nitrate, microbial biomass, soil pH and soil salinity. Soil organic carbon, inorganic carbon, ammonia, and nitrate content of each layer were analyzed using the same procedure described in Section 2.3.2. Soil pH and soil salinity were analyzed using 1:2 extraction and 1:1 extraction, respectively, by AgVise laboratories. Microbial biomass was measured using a chloroform fumigation extraction method-Standard Operation Procedure of Department of Soil Science revised by D. L. Burton (Appendix 5.1).

Above-ground plant biomass was measured three times during the growing seasons by harvesting 0.5 m² sampling quadrats. The fields were cropped to flax for the duration of the experiment. Depressions B and C were seeded with flax on June 9, 2004 with a garden seeder. The seeding rate was 45 kg ha⁻¹ and row spacing was 25 cm. However, Depression A had ponded water from spring until early summer so was not seeded. In upslope positions, flax was seeded on May 28 with conventional seeding equipment.

3.4.2.2 Experimental procedure

The field experiment was carried out from October 2003 to May 2005. The first stage of this experiment initiated in October 2003 in Depressions A, B and C with three replicates in A and one replicate in B and C. The second stage of this experiment initiated in April 2004 with the addition of two replicates in Depressions B and C. Gas samples were taken monthly from January 2004 to May 2005 with intensive sampling focused on rainfall, snowmelt and spring thaw events. The initial sampling of the first stage installation was on January 23, 2004 and June 18, 2004 for the second stage. At the time of gas sampling, ancillary measurements described in Section 3.4.2.1.4 were carried out as well.

3.4.3 Microcosm study

The field experiment evaluated GHG production and emission *in situ*. To further understand production processes of GHG, a microcosm incubation experiment was carried out under controlled laboratory conditions. This study was designed to study the potential production of GHG (N_2O and CO_2) from soil collected from different depths. The treatments of this study were 20 soil depths from 0 to 100 cm with 5-cm increments. Each treatment included three replicates.

3.4.3.1 Soil sampling

All soils were collected in the three sampling plots at Depression A. The detailed site description was presented in Section 3.4.1. Soil for incubation was air dried and uniformly mixed, then ground to pass through a 2-mm mesh sieve. Soils for

chemical analyses were collected after thorough mixing. Analyses included soil pH, C, IC, OC, N, NH_4^+ -N and NO_3^- -N. The procedures for measuring pH, C, IC, OC, N, NH_4^+ -N, NO_3^- -N are described in Section 2.3.3. Fresh soil was used for the measurement of microbial biomass. The chloroform fumigation extraction method (Voroney et al., 1999) was applied to measure microbial biomass (Appendix 5.1).

3.4.3.2 Soil incubation

Soil samples were incubated in a 1.2-L mason jar with a rubber septum fitted in the top of lids and a 125-ml glass jar. 138 grams of oven-dry equivalent soil was put into 125-ml glass jar in a 1.2-L mason jar. Prior to the initialization of the study, soils were brought to 60 % WFPS and packed to a bulk density of 1.2 g cm^{-3} . Mason jars were covered by gas-permeable Parafilm to maintain soil moisture during the incubation period. H_2O addition was made when necessary based on weight (date, time, weights and amount of water were recorded). Incubating temperature was kept at 25°C and relative humidity was 80 %.

3.4.3.3 Gas measurement

Prior to gas sampling, 10-day pre-incubation time was applied to the re-establishment and stabilization of the soil microbial population following disturbance. For sampling period, the Parafilm was removed and lids with septum were used to seal 1.2-L jars. Gas samples were taken using a 20-ml syringe inserted through the septum. Gas samples were taken at time zero and 24 hr. After the removal of the 24 hr sample the lids were removed and Parafilm replaced on the jars. Gas samples were collected three times a week for the first week and twice a week for the remainder of the incubation period.

For weeks three and four, samples were taken at 0, 48 hr, and the rest of the time samples were collected at 0, 72 hr. The gas samples were injected into pre-evacuated vials and transported to the laboratory. Gas samples were analyzed for CO₂ and N₂O using a Varian CP 3800 gas chromatograph described in Section 2.3.4.

3.4.4 Data analysis

Analysis of variance was performed using the statistical Analysis Software System (SAS Institute Inc. 2000). Gas flux data were analyzed as repeated measures in analysis of variance (ANOVA) with depressions as the treatment factor and sampling dates as the repeated measure factor. The data on gas concentration in soil air were not normally distributed and were log-transformed prior to ANOVA. Sampling dates were considered as repeated measures. Selected dates of typical CO₂ and N₂O flux and concentration were examined. Statistics analysis was carried out in Depression A, B and C separately.

Production of CO₂ and N₂O in the incubation experiment was expressed in $\mu\text{g CO}_2\text{-C g}^{-1}$ dry soil hr^{-1} and $\text{ng N}_2\text{O-N g}^{-1}$ dry soil hr^{-1} , respectively. Relationships between CO₂ evolution and organic carbon and microbial biomass were tested using linear regression models. Relationships between N₂O and organic carbon, nitrate and microbial biomass were also tested using linear regression models.

3.5. Results

3.5.1 Field experiment

3.5.1.1 Site characteristics

3.5.1.1.1 Environmental factors

During the study periods, the differences in environmental conditions {temperature, rainfall (amount and distribution), water table level and snow depth} resulted in contrasting patterns in gas production and flux. As shown in Figure 3.5, air temperature increased above zero on Mar 26, 04 and soil temperature increased accordingly. Snow began to melt on this date and disappeared on April 7, 2004 (Table 3.1). During this period, spring thaw and snow melt affected GHG production and emission, resulting in peak N₂O and CO₂ flux. These results are presented in Section 3.5.1.2. Soil profile temperature exhibited seasonal and spatial patterns. During the winter, profile temperature increased with soil depth. In contrast, soil temperature decreased with depth during the summer. Temperature near the surface layer was quite variable as compared to temperature at greater depth. Snow accumulation reached its greatest depth on Feb 25, 04 in the three depressions with 51, 40, 70 cm, accumulating in A, B and C, respectively (Table 3.1). Greater snow accumulation was observed in Depression C than in other two depressions. On April 5, 2005, Depression C was covered by 23 cm snow while the other depressions there were no longer any snow accumulation on the ground. Soil moisture content was high during the experimental period (Table 3.2), especially in Depression A. There was no obvious difference between 15, 30 and 50 cm three depths due to wet conditions. Water table level in Depressions A and C was higher than that in

Table 3.1 The measurement of the snow depth (cm) during winter and spring time.

Depressions	Jan 13,04	Feb 25,04	Mar 26,04	Dec 15,04	Apr 5,05
A	31	51	29	9	water-logged
B	23	40	25	4	2
C	42	70	49	12	23

Table 3.2 Soil volumetric moisture content ($m^3 m^{-3}$) during experimental periods on select dates.

	Depression A			Depression B			Depression C		
	15 cm*	30 cm*	50 cm*	15 cm	30 cm	50 cm	15 cm	30 cm	50 cm
Jun.18	0.53	0.51	0.51	0.44	0.41	0.37	N/A**	N/A	N/A
Jul.27	0.52	0.52	0.52	0.41	0.28	0.32	0.54	0.37	N/A
Aug.30	0.51	0.50	0.51	0.44	0.41	0.36	0.51	0.36	N/A
Sep.28	0.46	0.46	0.49	0.40	0.40	0.35	0.51	0.34	0.44
Nov.02	0.46	0.45	0.48	0.34	0.36	0.33	0.47	0.32	0.42

* Depth from the soil surface.

**N/A: not available.

Table 3.3 Water table level (cm) from soil surface during experimental periods in Depressions A, B and C.

Depressions	Apr 14,04	Apr 27,04	May 7,04	May 28,04	Jun 18,04	Jul 27,04	Aug 30,05	Oct 26,04	Apr 8,05	Apr 24,05	May 9,05
A	87	88	26	23	12	52	38	57	N/A *	31	ponded at surface
B	70	86	70	64	71	92	Below 100	92	N/A	80	63
C	ice	80	63	21	28	75	86	84	74	88	69

* N/A: not available.

Table 3.4 Soil properties of top 30 cm in Depressions A*, B and C.

Variables	Soil depth (cm)					
	5	10	15	20	25	30
Depression A						
Bulk Density (g cm ⁻³)	1.17	1.13	1.00	1.11	1.30	1.54
pH	7.7	7.6	7.6	7.4	7.4	7.6
Salts (mmhos cm ⁻¹)	1.22	0.82	0.67	0.52	0.41	0.37
TKN (%)	0.43	0.48	0.44	0.35	0.23	0.15
Total Organic Carbon (%)	4.64	5.25	4.75	3.32	1.78	1.20
Inorganic Carbon (%)	0.24	0.19	0.08	0.03	0.08	0.02
Depression B						
Bulk Density (g cm ⁻³)	0.97	0.99	1.03	1.00	0.98	1.07
pH	7.6	7.8	7.8	7.9	8.0	8.2
Salts (mmhos cm ⁻¹)	1.16	2.01	2.06	2.45	2.61	3.63
TKN (%)	0.53	0.48	0.44	0.43	0.37	0.29
Total Organic Carbon (%)	5.21	5.19	4.71	4.54	4.04	3.04
Inorganic Carbon (%)	0.02	0.08	0.20	0.29	0.47	0.75
Depression C						
Bulk Density (g cm ⁻³)	0.97	0.96	0.82	0.87	0.97	0.86
pH	7.9	7.8	7.6	7.5	7.4	7.4
Salts (mmhos cm ⁻¹)	1.39	1.79	2.06	1.60	1.42	1.27
TKN (%)	0.63	0.60	0.84	0.94	0.92	0.64
Total Organic Carbon (%)	5.98	6.46	7.75	7.85	7.41	5.27
Inorganic Carbon (%)	0.42	0.39	0.23	0.11	0.05	0.05

* Soil properties of 30-100 cm are available in Depression A.

Table 3.5 Above-ground plant biomass (g m⁻²) during growing seasons in three depressions.

Depressions	Dates		
	Jul 27,04	Aug 24,04	Sep 21,04
A	15	121	241
B	199	537	456
C	117	369	882

Depression B, especially during the summer (Table 3.3).

3.5.1.1.2 Nutrient status

Soil properties in three depressions are listed in Table 3.4. At the top 30 cm, pH ranged from 7.4 to 7.8 in the three depressions. Salt in Depression A decreased with depth, while in B it increased with the increased depth. High salt accumulation in C occurred in 15 cm soil layer. The different patterns of salt distribution reflected the varied soil moisture and drainage conditions in the three depressions.

TKN and organic carbon generally decreased with soil depth. Comparing the three depressions, TKN and total organic carbon in Depression C was higher than that in the other two depressions (Table 3.4). Inorganic carbon contents were lower in A and C comparing with that in B (Table 3.4). It was hypothesized that the different contents of TKN, total organic carbon and inorganic carbon will have an impact on GHG production and emission.

Corresponding with the trend of organic carbon and TKN, microbial biomass decreased with soil depth as well (Figure 3.6). High microbial biomass in the top 30 cm soil layers was observed, and with greater depths, the amount of microbial biomass decreased dramatically. Ammonium and nitrate content in each soil layer followed the same trend as soil organic carbon and microbial biomass, but the contents near the surface were quite variable (Figure 3.7 and 3.8).

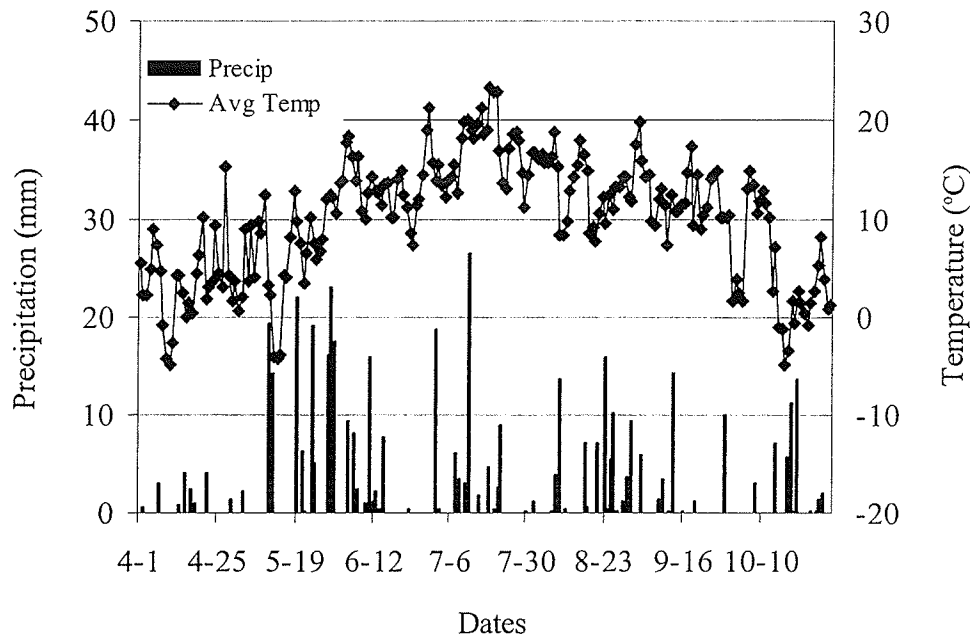


Figure 3.5 Precipitation and air temperature at the experimental site.

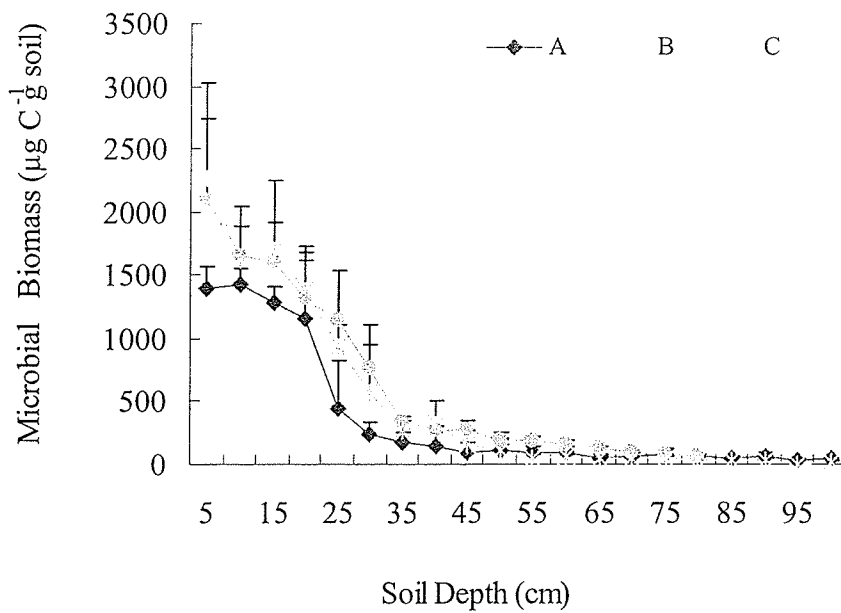


Figure 3.6 Microbial biomass C of soils removed from soil profiles of Depression A, B and C (Oct.15, 2003).

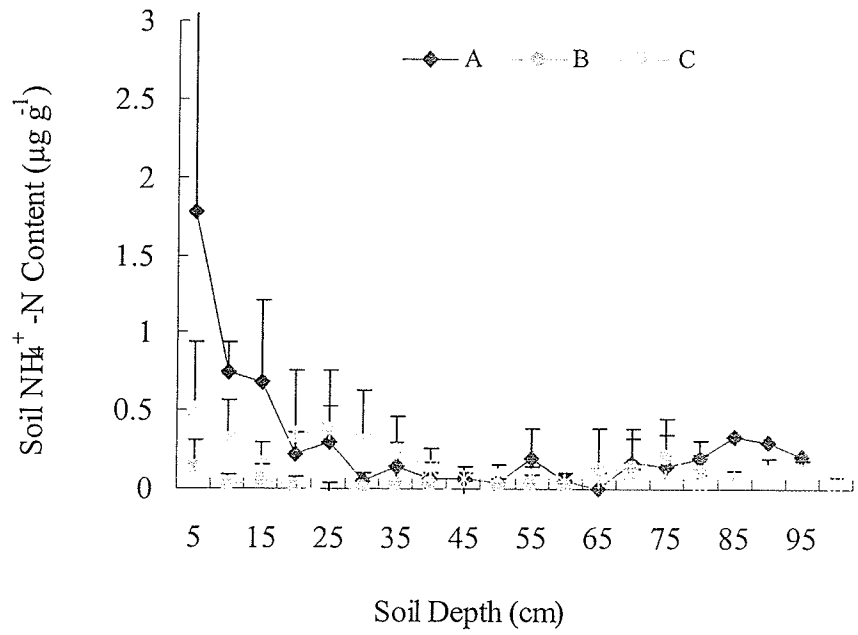


Figure 3.7 NH₄⁺-N content of soils removed from soil profiles of Depression A, B and C (Oct.15, 2003).

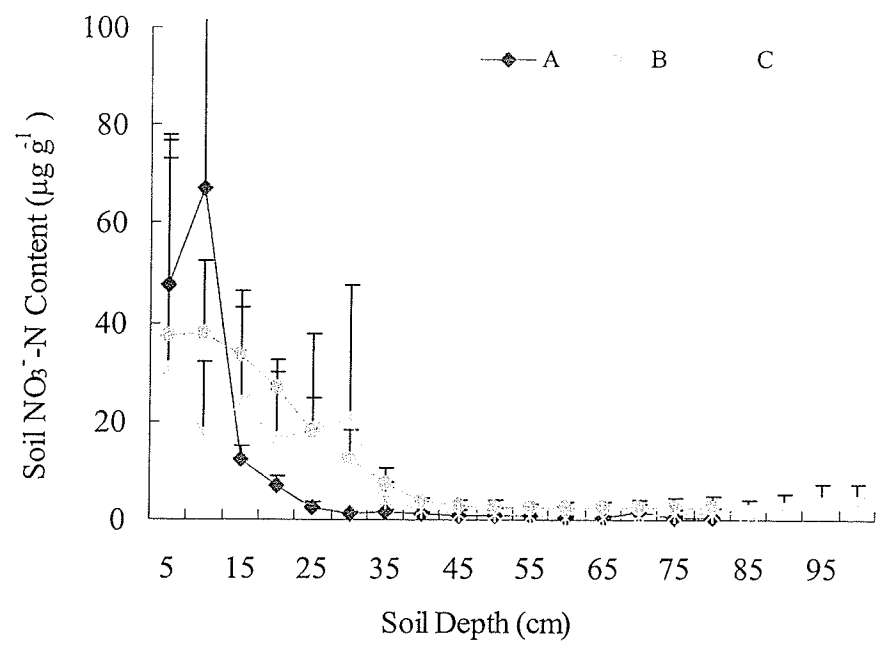


Figure 3.8 Soil NO₃⁻-N content of soils removed from soil profiles of Depression A, B and C (Oct.15, 2003).

3.5.1.1.3 Plant growth

Above-ground plant biomass, including weeds and seeded flax, are shown in Table 3.5. The above-ground plant biomass increased over the growing season. Depression C had higher biomass than other depressions. In Depressions A and C, most of the plant biomass was weeds.

3.5.1.2 CO₂ flux and profile concentrations

During the study period, CO₂ flux from the clay loam soil had a significant seasonal pattern in the three depressions (Table 3.6 and Figure 3.9). CO₂ flux increased from near zero during January and February to high of 14.18 kg CO₂-C ha⁻¹ day⁻¹ in July 2004. From this high, CO₂ flux decreased over the late summer and autumn to winter minimum. In the following year, 2005, the same CO₂ trends were observed during the spring period. The general trend of CO₂ flux in three depressions corresponded with the temperature pattern (Figure 3.5). The relationship of CO₂ flux and soil temperature (0-10cm), and air temperature was predicted using polynomial regressions (Figure 3.10 and 3.11). Results showed CO₂ flux is corresponded with the change of soil temperature and air temperature. There was the significant difference of CO₂ flux on selected dates though there is no significant difference on dates during the winter time. Compared with depressions, Depression B had the lowest flux.

A temporal trend of CO₂ profile concentration was also significant (Table 3.8 and Figure 3.12). CO₂ concentration increased in soil air from spring to summer and decreased from autumn to winter in 2004 in the three depressions. As well, in 2005, CO₂ concentration increased from April to May at all soil depths. The pattern of CO₂

concentration in soil air corresponded to seasonal changes of soil temperature (Table 3.7).

With soil depth, CO₂ concentration had high variation.

Table 3.6 CO₂ flux (kg CO₂-C ha⁻¹ day⁻¹) from the soil surface in Depressions A, B and C on selected dates.

Dates	Jun. 18,04	Jul. 27,04	Aug. 30,04	Oct. 26,04	Dec. 15,04
Means	8.33a	11.28 ab	6.15 b	1.08 c	-0.12 c

Depressions	A	B	C
Means	6.60 a	3.49 c	5.94 ab

* Lowercase letters indicate significant differences <0.05.

Table 3.7 Profile temperature during the experimental period in Depressions A, B and C.

Depth	Dates															
	Jan 13, 04	Feb 25, 04	Mar 26, 04	Apr 07, 04	Apr 14, 04	Apr 27, 04	May 17, 04	May 28, 04	Jun 18, 04	Jul 27, 04	Aug 30, 04	Oct 26, 04	Dec 15, 04	Apr 5, 05	Apr 24, 05	May 9, 05
Depression A																
10 cm	-4.3	-1.0	0.5	1.8	0.3	7.7	7.4	7.9	10.1	18.8	13.3	2.4	-0.2	N/A	6.1	11.4
20 cm	-3.3	-1.0	1.0	2.1	1.0	5.4	5.9	7.4	11.4	18.5	13.6	3.7	0.2	N/A	5.3	8.9
30 cm	-2.9	-1.0	1.0	1.9	1.7	4.9	5.6	7.2	12.0	18.3	13.6	4.5	1.0	N/A	5.5	8.0
40 cm	-2.5	-1.0	1.5	1.4	2.1	4.5	5.3	7.4	12.4	17.8	13.9	5.6	1.2	N/A	5.1	7.4
70 cm	-1.5	0.0	1.5	-0.1	1.3	3.0	5.1	6.2	10.8	15.4	13.2	6.8	2.6	N/A	3.9	5.7
100 cm	-0.6	1.0	1.5	0.8	1.4	2.7	5.0	5.7	9.5	13.7	12.8	7.8	3.5	N/A	3.3	4.4
Depression B																
10 cm	-4.3	-1.0	-2.0	4.4	1.6	17.6	13.0	11.3	9.6	18.9	13.7	2.8	-2.3	0.2	4.7	8.1
20 cm	-3.3	-1.0	-1.0	-1.3	-0.8	7.0	6.2	7.8	9.3	17.8	13.2	3.2	-1.2	-0.3	3.5	8.0
30 cm	-2.7	-1.0	-1.0	-0.6	1.5	4.2	4.3	7.6	10.1	17.2	13.2	3.2	-1.2	-0.3	3.5	8.0
40 cm	-2.2	-1.0	-1.0	-0.3	-0.4	3.3	4.3	7.3	9.9	16.7	13.0	5.4	0.5	-0.2	2.1	6.8
70 cm	-1.3	0.0	-1.0	-0.1	0.1	1.5	4.1	5.9	8.6	14.8	13.0	5.4	0.5	-0.2	2.1	6.8
100 cm	-0.5	0.0	0.0	0.7	0.6	1.2	4.1	5.1	7.4	13.1	12.0	8.2	3.4	0.5	0.4	3.4
Depression C																
10 cm	-5.1	N/A*	-2.0	3.2	0.9	9.9	8.7	9.1	10.9	18.8	18.8	14.1	3.8	-0.4	2.8	1.7
20 cm	-4.5	N/A	-1.0		0.6	4.0	5.3	8.1	10.9	17.6	17.6	13.5	4.0	0.2	1.9	-0.2
30 cm	-3.9	N/A	-1.0	1.3	1.7	3.7	4.7	7.6	10.8	16.9	16.9	13.2	5.6	0.8	2.1	0.5
40 cm	-3.2	N/A	-1.0	1.9	1.8	3.5	4.7	7.3	10.7	16.3	16.3	13.2	6.4	1.5	2.0	0.6
70 cm	-1.7	N/A	0.0	2.0	1.7	3.2	4.8	5.7	8.4	14.7	14.7	12.4	7.9	2.5	2.8	0.8
100 cm	-0.7	N/A	0.0	2.7	2.2	3.1	4.8	5.3	8.1	13.1	13.1	11.9	8.7	3.3	2.8	1.7

*N/A: not available.

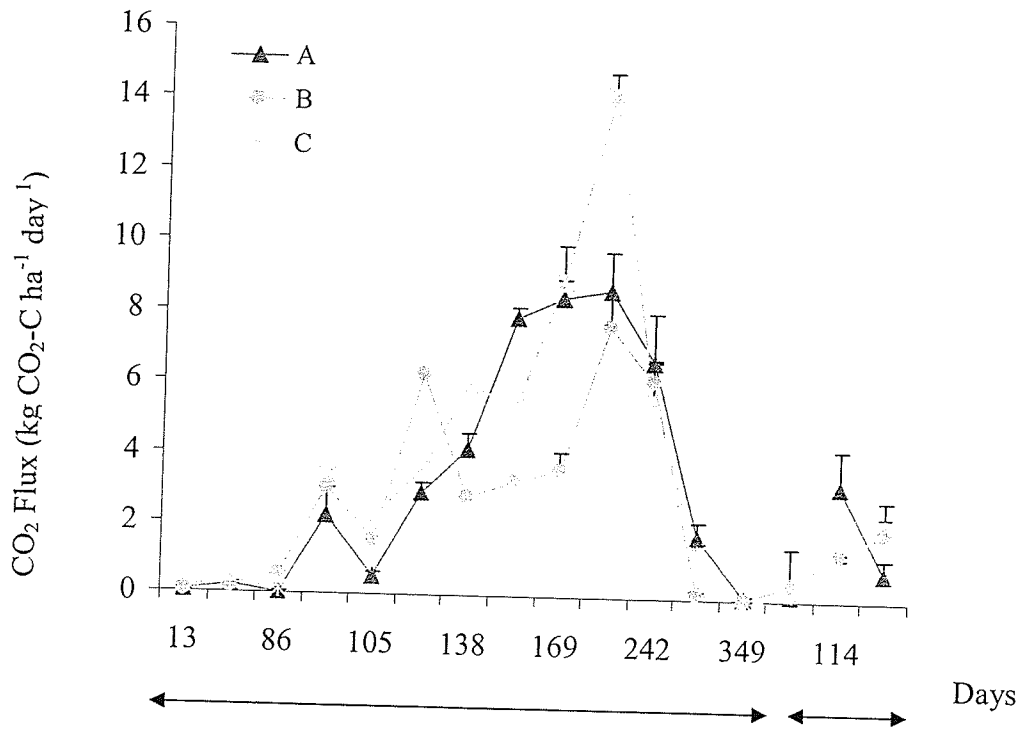


Figure 3.9 CO₂ flux from soil surface in Depressions A, B and C during 2004-2005 (the bar represents standard error).

During the winter period CO₂ concentration generally increased with depth on all dates. During the growing season soil CO₂ concentrations were highly variable. However, the distribution of CO₂ in the soil profile was very different in three depressions. The averaged CO₂ concentration of A and C was much higher than B on each date, especially on July 17. Peak CO₂ accumulation occurred at 20-40 cm and 40-60 cm depth on July 17, while in Depression B, the highest CO₂ concentration was observed at greater depth. Statistical analysis showed there is no significant difference among depths from 15-80 cm for Depressions A and C. In Depression B, higher concentrations were below 40 cm.

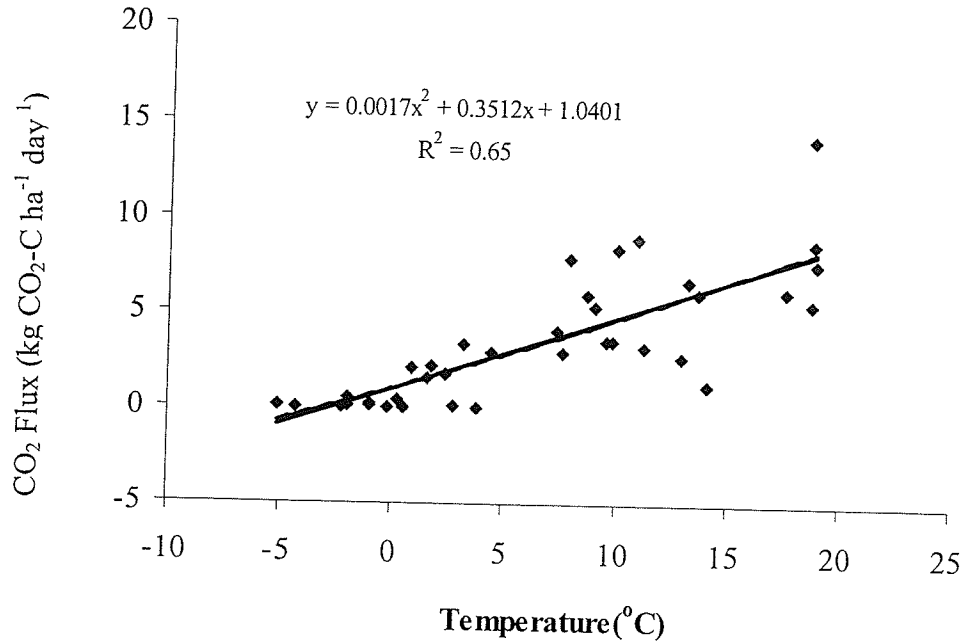


Figure 3.10 Relationship between CO₂ flux and soil temperature (10 cm).

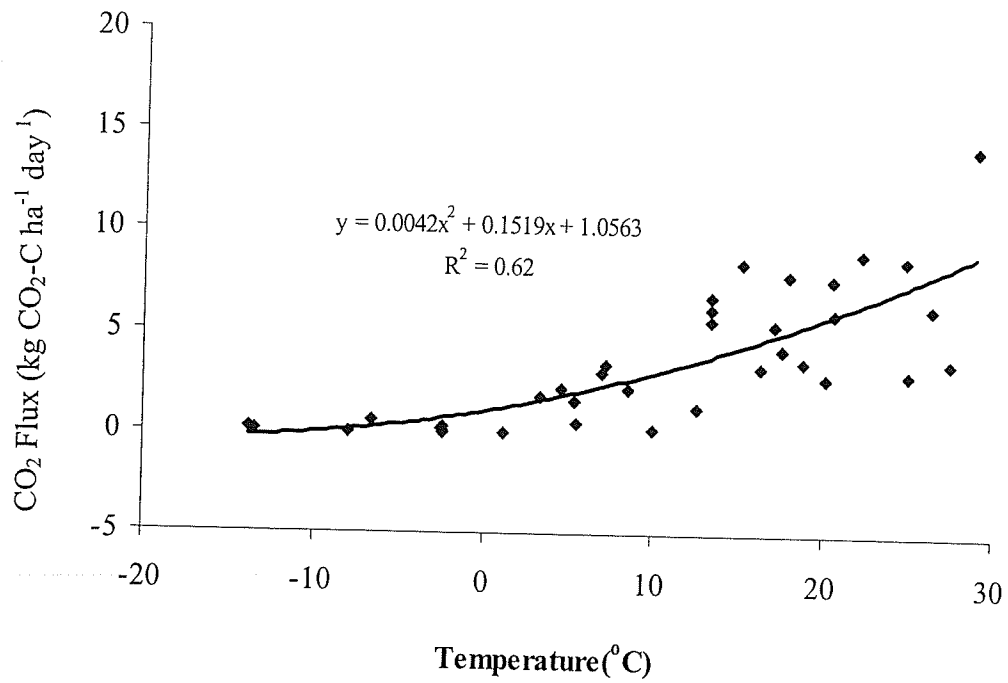


Figure 3.11 Relationship between CO₂ flux and air temperature.

Table 3.8 Average CO₂ concentration (uL CO₂ L⁻¹) of selected dates at different depths measured in soil profiles of Depressions A, B and C * during 2004.

Depth (cm)	Depression A	Depression B	Depression C
	CO ₂ Concentration (uL CO ₂ L ⁻¹)		
0-5	339 d**	350 h	334 c
5-10	11962 c	2272 fg	11472 b
10-15	15490 bc	1867 g	13685 ab
15-20	15080 abc	2102 fg	12982 ab
20-25	18421 abc	2647 efg	17385 a
25-30	16003 abc	3311 def	18938 a
30-35	19877 ab	4036 cde	16424 a
35-40	14135 abc	4335 bcd	18108 a
40-45	16140 abc	4738 abc	16819 a
45-50	17901 ab	4648 abc	21033 a
50-55	16198 abc	4557 abc	20704 a
55-60	19389 ab	5806 ab	19129 a
60-65	20579 ab	5720 ab	19400 a
65-70	19055 ab	5293 abc	20584 a
70-75	20855 ab	5507 ab	14693 a
75-80	24947 ab	5202 ab	15990 a
80-85	25975 a	6328 a	16027 a

*Dates include Jun.18, 04, Jul.27, 04, Aug. 30, 04, Oct. 26, 04, Dec. 15, 04.

** Statistics analysis was carried out in Depression A, B and C separately. Lowercase letters indicate significant differences <0.05 (LSD test) between depths. Significant differences are based on log-transformed data but non-transformed data are presented.

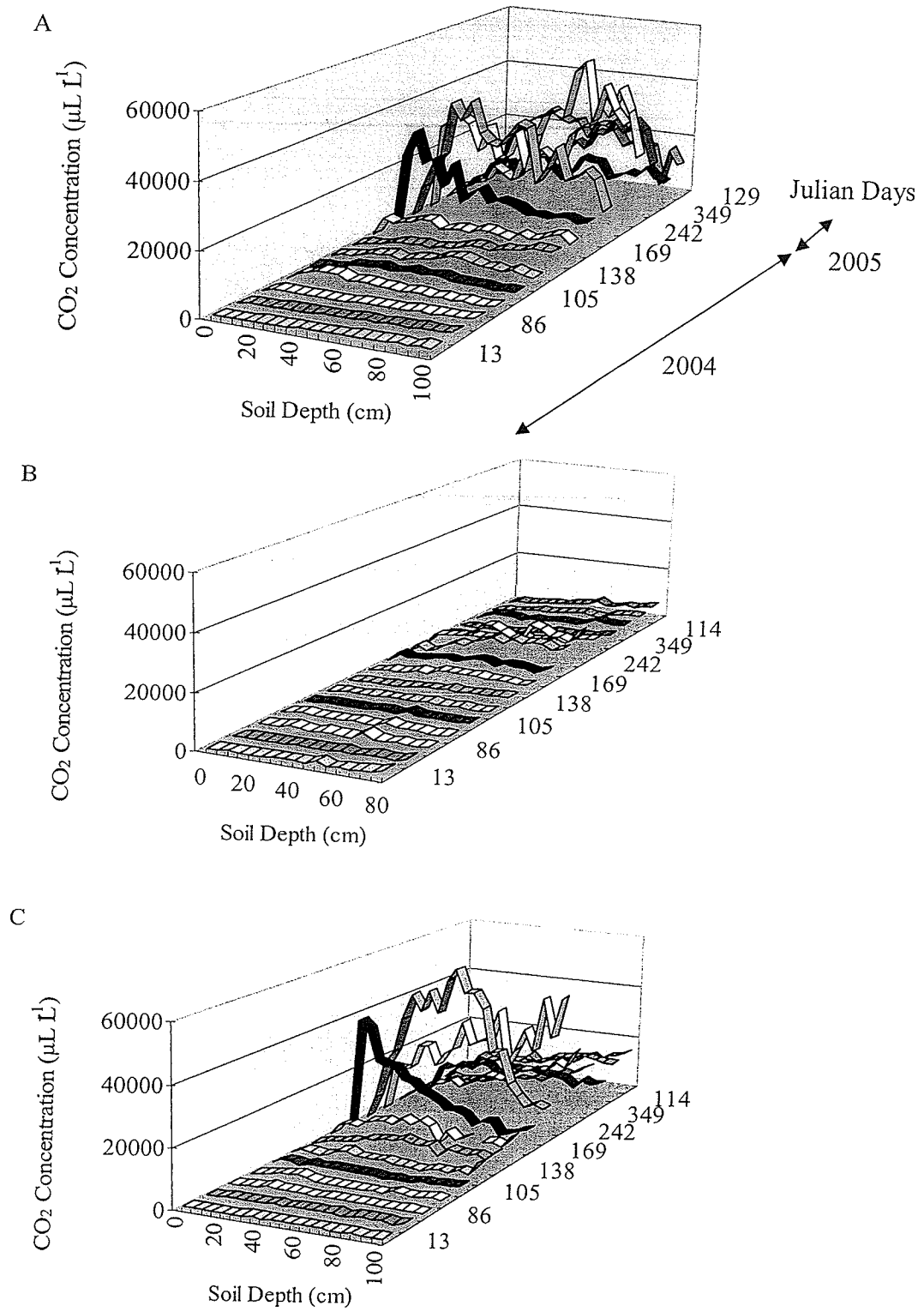


Figure 3.12 CO₂ concentrations measured in soil profiles of Depressions A, B and C during 2004-2005.

3.5.1.3 N₂O flux and profile concentrations over soil depths

N₂O surface flux and profile concentration had quite a different pattern from CO₂ (Table 3.9-10 and Figure 3.13 and 3.16). Unlike CO₂, the levels of N₂O flux did not appear to be dependent on air and soil temperature (Figure 3.14-3.15). During the thaw period (Figure 3.5), there was peak flux on April 7 for all three depressions in 2004. After the thaw, N₂O flux decreased markedly. Depression A had a second peak on May 28 in 2004 while Depressions B and C did not. At other times, there was zero or very low N₂O flux. In 2004, Depression B had highest flux (85.3 g N₂O-N ha⁻¹ day⁻¹) compared with the other two depressions with value of 22.3 g N₂O-N ha⁻¹ day⁻¹ in Depression A and 20.4 g N₂O-N ha⁻¹ day⁻¹ in Depression B on April 7, 2004 (Table 3.9). While on April 24, 2005, only C had obvious flux (8.12 g N₂O-N ha⁻¹ day⁻¹) during the thaw period, and A and B only had a flux of 0.05, 0.6 g N₂O-N ha⁻¹ day⁻¹, respectively. During the spring of 2005, there was a peak flux on April 24 in Depression A during the thaw period, while no similar flux occurred in Depressions B and C. On other dates, N₂O flux was low.

Soil atmosphere N₂O concentration profiles varied temporally and with depth (Figure 3.16). In winter, profile N₂O concentration was uniform at all depths. At the time of thaw (starting March 26, 2004), peak concentrations were observed between 5 to 25 cm in depth cm in three depressions with values of 75 ppm, 53 ppm and 105 ppm in Depressions A, B and C, respectively. At this time, the flux of N₂O increased dramatically as well. Once the soil had thawed, profile N₂O concentration and flux decreased quickly. The same trend was observed in Depressions B and C during the spring of 2005. The highest peak occurred on April 5, 2005 with the value of 49 ppm and 113 ppm, respectively. Data for Depression A was not collected due to the waterlogged condition of the soil at that time.

Table 3.9 N₂O flux (g N₂O-C ha⁻¹ day⁻¹) from soil surface in Depressions A, B and C on selected dates.

Depression	Jan.13,04	Mar.26,04	Apr.07,04	Apr.27,04	May 17,04
A (6.38b)*	0.10**	-0.02	22.35	2.59	0.62
B (17.81a)	0.08	-0.08	85.29	3.35	0.39
C (4.84b)	0.36	0.03	20.39	2.69	0.74

*Lowercase letters indicate significant differences (<0.05) between depressions.

** For dates measured, N=3 for Depression A, N=1 for Depressions B and C.

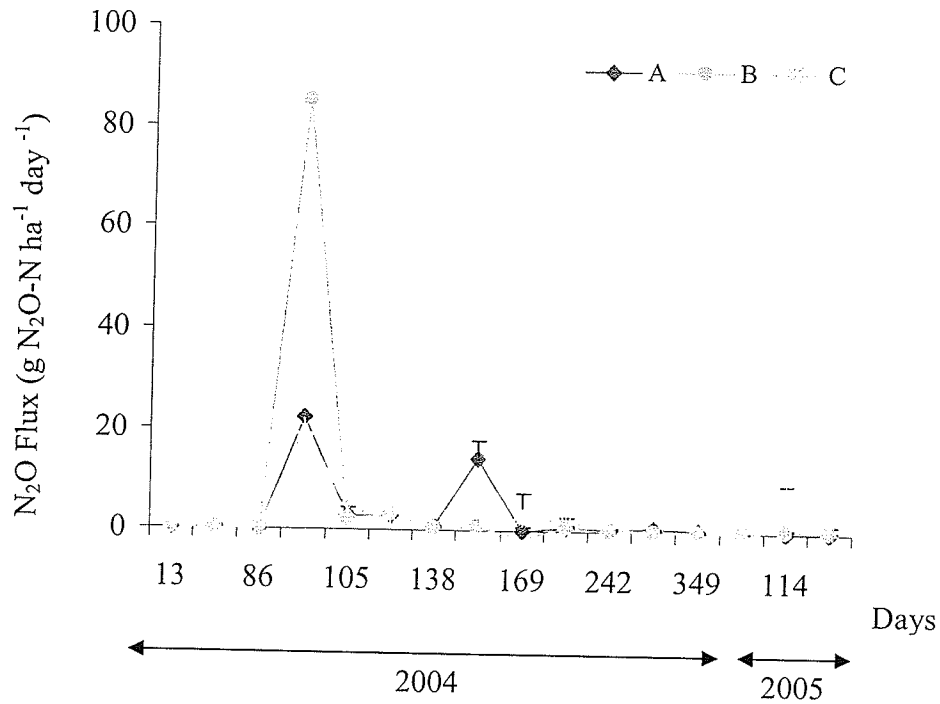


Figure 3.13 N₂O flux from soil surface in Depressions A, B and C during 2004-2005 (the bar represents standard error).

During the two years of study, peak accumulation of N₂O occurred between 10 to 25 cm in depth during the spring thaw period. Before the thaw, concentration was low and, after the thaw period, N₂O concentration decreased dramatically. N₂O accumulation resulted from the high production rate in this layer during the thaw period. There is no evidence that the flux with spring thaw was the result of outgassing upon soil surface thawing of N₂O produced at deeper depths over the winter. At this time, the flux from the soil surface increased markedly on the same time that profile N₂O concentration was observed to increase, while in 2005 spring, the peak surface flux was delayed (April 24) relative to the peak in N₂O accumulation in the soil profile in Depression C. There was no peak flux occurring on April 24 and other dates corresponded with high N₂O

accumulation within soil profile in Depressions A and B. Profile N₂O concentration of individual depression had no significant difference between depths (Table 3.10).

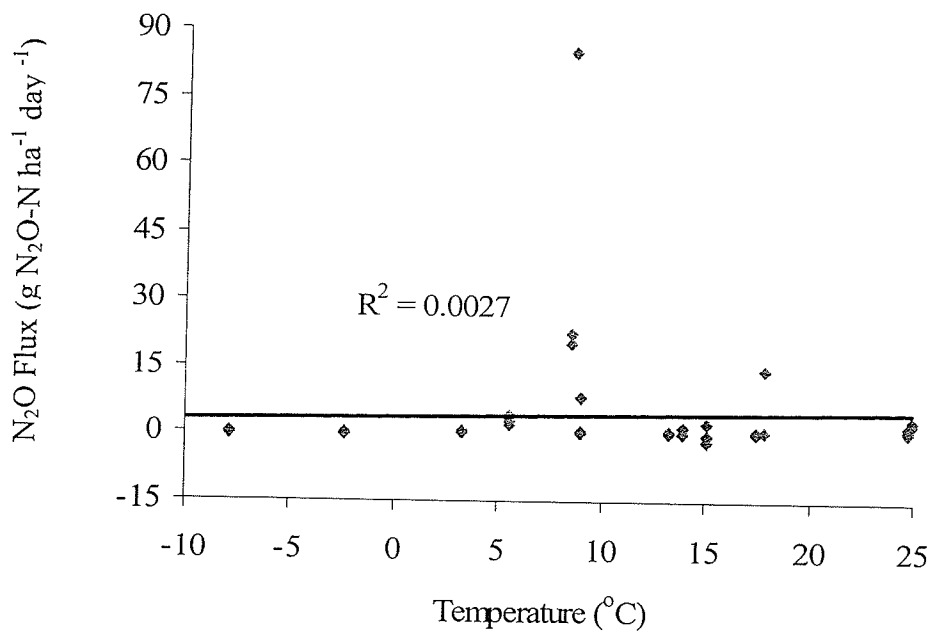


Figure 3.14 Relationship between N₂O flux and air temperature.

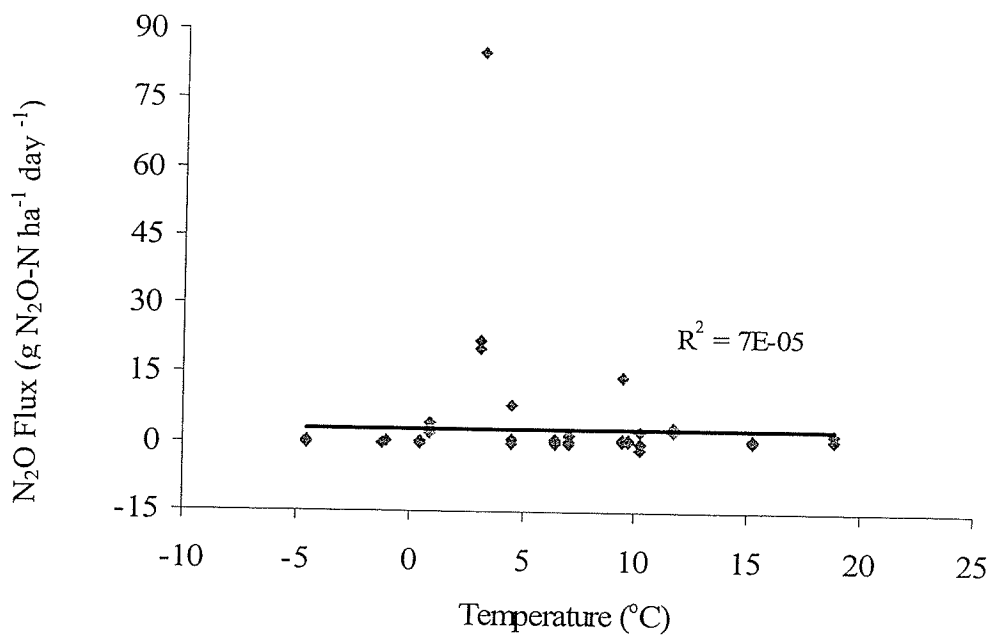
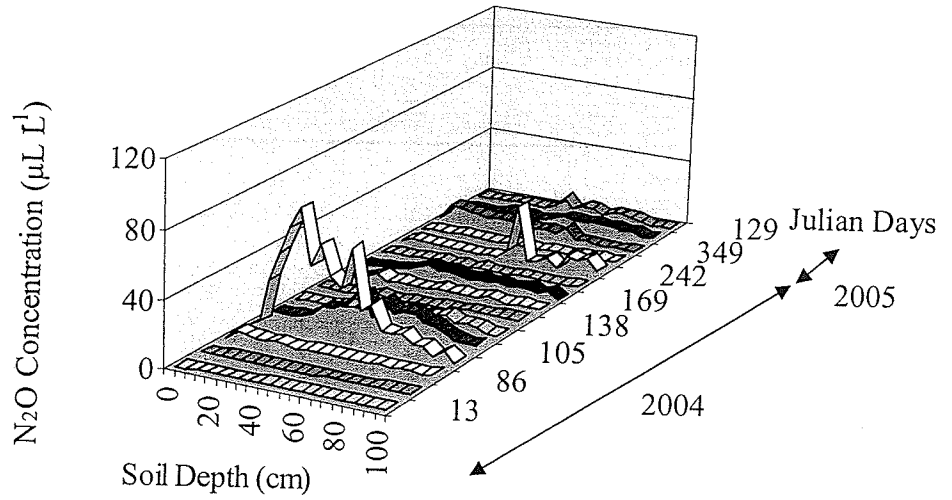
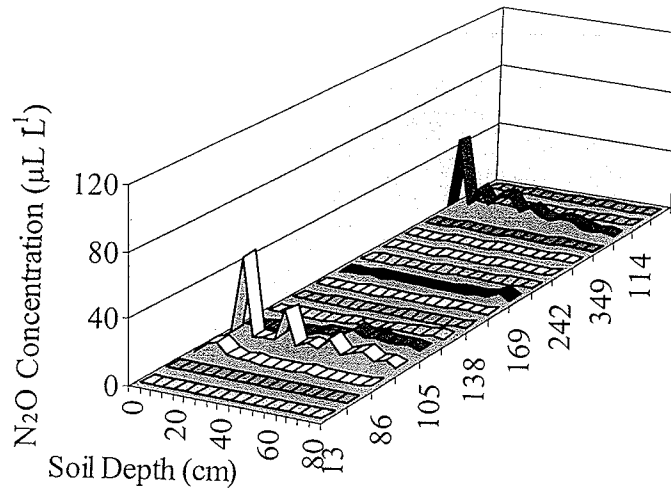


Figure 3.15 Relationship between N₂O flux and soil temperature (10 cm).

A



B



C

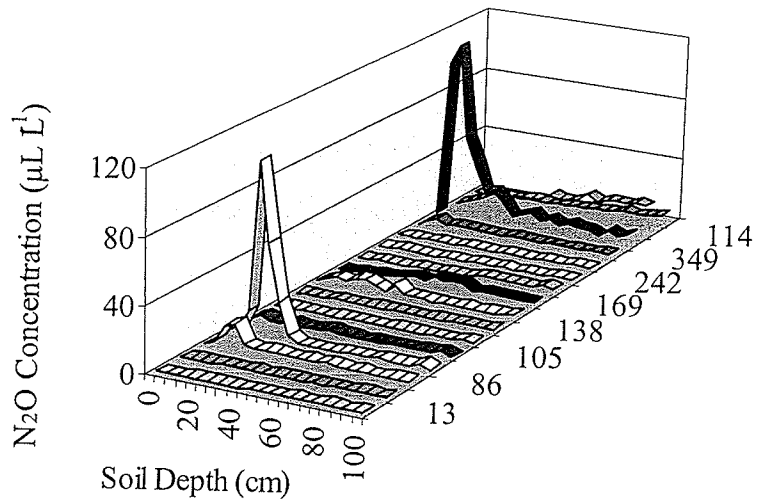


Figure 3.16 N₂O concentrations measured in soil profiles of Depressions A, B and C during 2004-2005.

Table 3.10 Average of N₂O concentration (uL N₂O L⁻¹) of selected dates at different depths measured in soil profiles of Depressions A, B and C * during 2004.

Depth (cm)	Depression A	Depression B	Depression C
	N ₂ O Concentration (uL N ₂ O L ⁻¹)		
0-5	0.31c**	0.32b	0.32c
5-10	1.92b	2.34a	1.83abc
10-15	6.17ab	10.78a	5.05ab
15-20	9.04ab	1.53a	20.56a
20-25	12.18ab	1.54ab	11.09ab
25-30	15.46a	1.76a	4.69ab
30-35	10.12a	4.99a	1.74ab
35-40	12.67a	1.89ab	1.19abc
40-45	11.36a	2.57a	1.23bc
45-50	10.76a	2.26a	0.99abc
50-55	13.14a	4.82a	1.05abc
55-60	8.85a	2.43a	0.95 abc
60-65	8.58a	3.10a	1.15abc
65-70	6.61a	3.47a	0.95abc
70-75	6.96a	2.56a	0.88abc
75-80	6.86a	3.17a	1.02abc
80-85	5.00a	2.39a	0.94abc

*Dates include Jan.13,04, Mar.26,04, Apr.07,04, Apr27,04, May 17,04.

** Statistics analysis was carried out in Depression A, B and C separately. Lowercase letters indicate significant differences <0.05 (LSD test) between depths. Significant differences are based on log-transformed data but non-transformed data are presented.

3.5.1.4 CH₄ flux and profile concentrations

CH₄ flux varied from -1.88 to 7.73 g CH₄-C ha⁻¹ day⁻¹ during the study period (Figure 3.17). High flux only occurred on Jun 18, 2004 in Depression A and May 9, 2005 in Depression B. During other times, very low or negative flux was observed.

Soil atmosphere CH₄ concentration profiles behaved differently in three Depressions (Figure 3.18). Profile CH₄ concentration in Depressions B and C behaved uniformly and had lower concentration (below 10 ppm). No obvious seasonal and depth patterns were observed. Profile CH₄ concentration in Depression A was uniform in the winter, while has higher variation in the summer with highest value of 100 ppm.

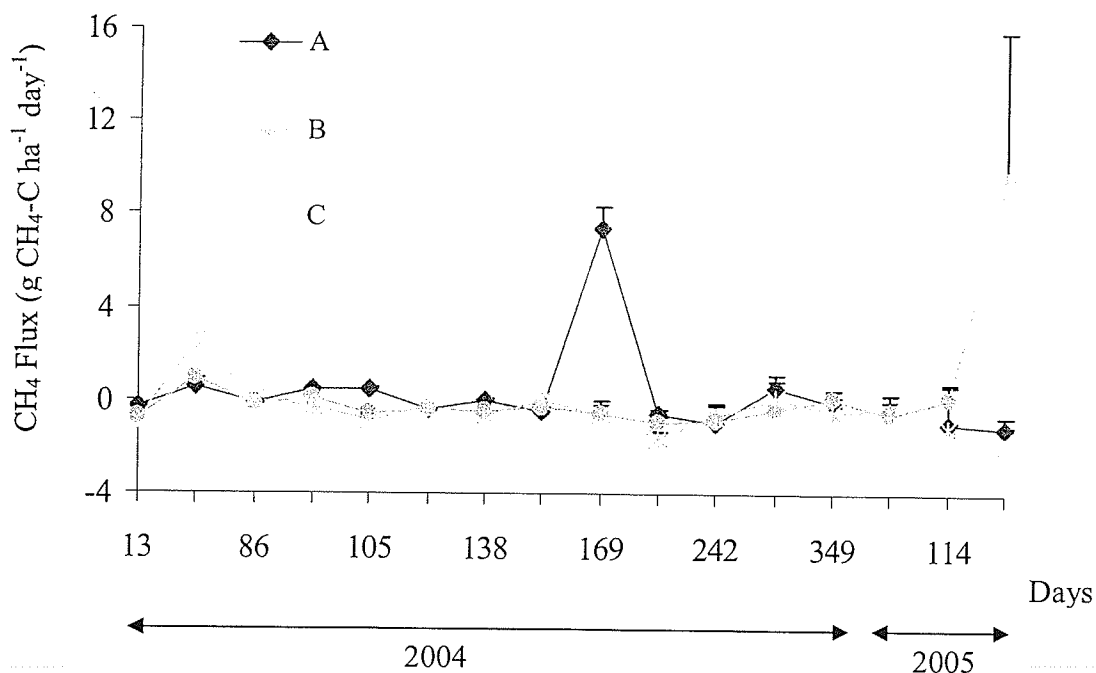
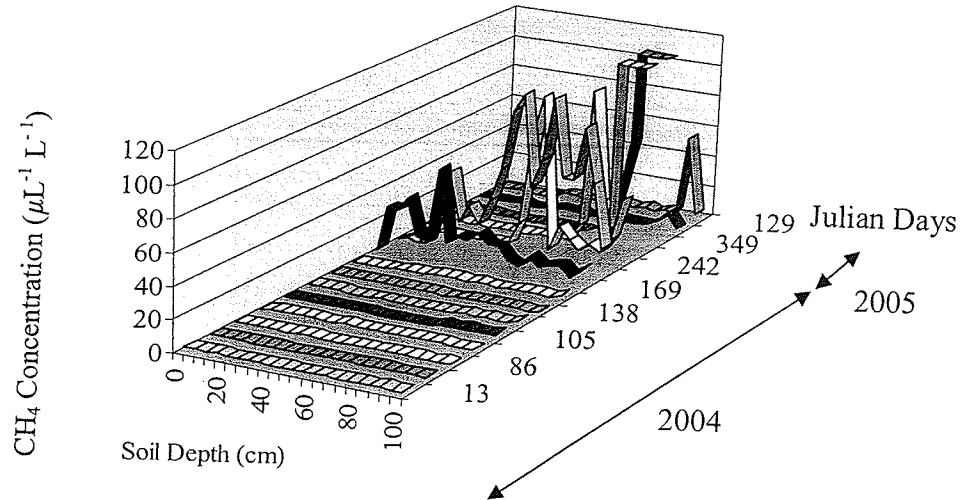
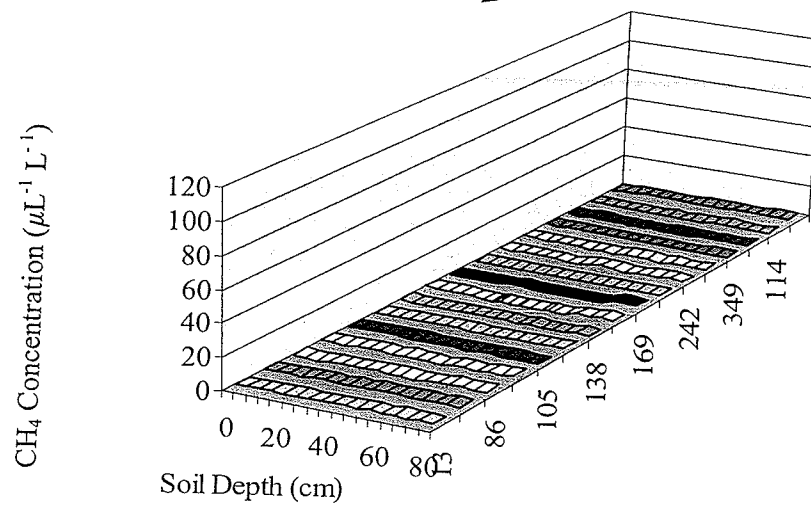


Figure 3.17 CH₄ flux from soil surface in Depressions A, B and C during 2004-2005.

A



B



C

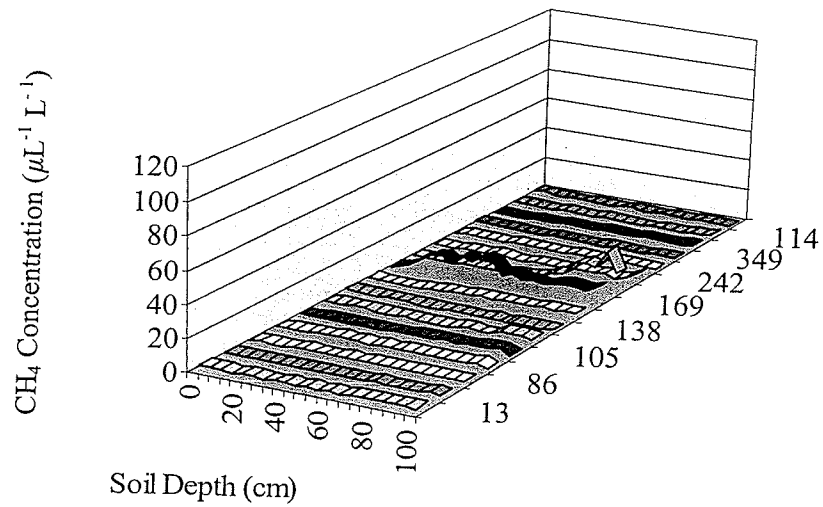


Figure 3.18 CH₄ concentrations measured in soil profiles of Depressions A, B and C during 2004-2005.

3.5.1.5 ^{137}Cs activities within soil profile and estimation of soil accumulation

^{137}Cs distributions within the profiles of the three depressions exhibited the same trend (Figure 3.19). Generally, ^{137}Cs activity decreased with depth dramatically at top 20 cm, then declined to zero at depth of 25 cm for Depressions A and B, 30 cm for Depression C. For depressions A and B, the low ^{137}Cs activity at surface 0-5 cm indicated soil accumulation diluted the ^{137}Cs -rich soil in the soil surface. Highest ^{137}Cs activity in Depression A was at 10 cm with value of 1084 Bq m^{-2} , B at 10 cm with value 1746 Bq m^{-2} and C at 5 cm with 1615 Bq m^{-2} .

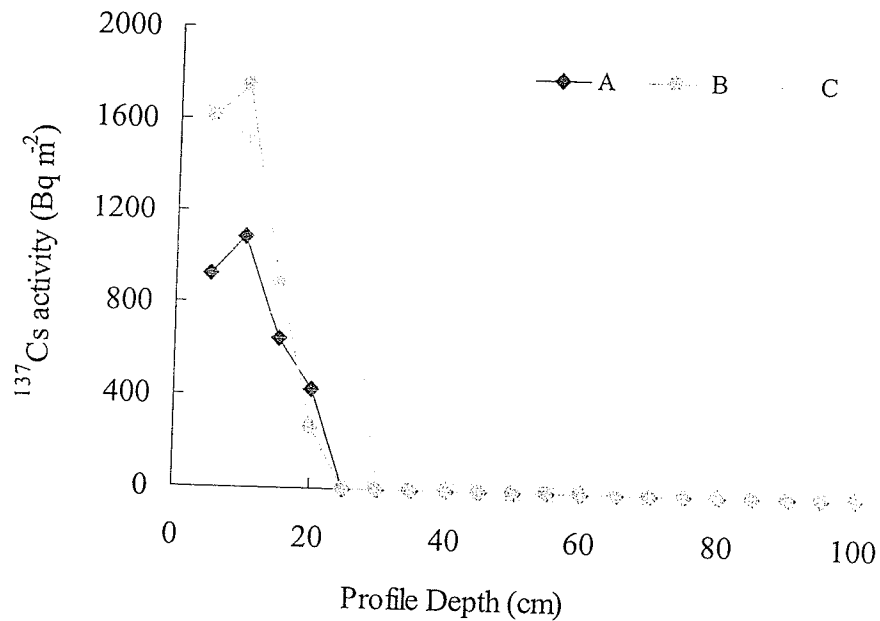


Figure 3.19 Profile of ^{137}Cs activity in soil of Depressions A, B and C (activity of 5-cm depth increments of soil).

Table 3.11 Estimated soil loss in Depressions A, B and C.

Site	Soil Loss* (t ha ⁻¹ yr ⁻¹)
A	-16.7
B	-38.8
C	-73.3

* Negative values represent soil accumulation.

The estimated total annual soil loss and accumulation showed significant soil accumulation in all three depressions (Table 3.11). The highest degree of soil accumulation was in Depression C with 73.3 t ha⁻¹ yr⁻¹. In Depression C, total organic carbon content was also higher than the other two depressions. These observations are consistent with more topsoil, rich in organic matter, accumulating in this depression. This accumulated soil provided the greater potential for C and N transformation due to high total nitrogen and organic carbon contents.

3.5.2 Microcosm study

3.5.2.1 Potential production of CO₂

Under laboratory conditions, the rate of CO₂ evolution from incubated soils differed with depth. The top 5-cm soil had the greatest initial rates of respiration. The rate of evolution decreased with increasing soil depth (Figure 3.20). Greatest rates of CO₂ evolution were from 5, 10, 15, 20, 25 cm depths. There was no significant difference between CO₂ evolution among depths greater than 25 cm. The CO₂

Table 3.12 Soil properties of the microcosm study*.

Variables	Soil depth (cm)																			
	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
pH	7.7	7.6	7.6	7.4	7.4	7.6	N/A**	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total N(%)	0.43	0.48	0.44	0.35	0.23	0.15	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total Organic Carbon (%)	4.64	5.25	4.75	3.32	1.78	1.20	0.87	0.79	0.70	0.77	0.81	0.83	0.76	0.68	0.73	0.74	0.77	0.63	0.55	0.54
Inorganic Carbon (%)	0.24	0.19	0.08	0.03	0.08	0.02	0.19	0.15	0.19	0.21	0.12	0.07	0.07	0.08	0.07	0.04	0.00	0.06	0.13	0.39
NH ₄ ⁺ -N (mg kg ⁻¹)	1.77	0.75	0.68	0.22	0.29	0.05	0.15	0.06	0.06	0.04	0.20	0.05	N/A	0.17	0.14	0.20	0.33	0.30	0.21	1.11
NO ₃ ⁻ -N (mg kg ⁻¹)	47.36	67.10	12.14	6.83	2.45	1.36	1.47	1.06	0.78	0.65	0.64	0.57	0.35	1.52	0.40	0.46	0.39	1.06	0.49	0.30

* Samples were collected from Depression A.

**N/A: Not Available.

evolution corresponded with the trend of total organic carbon content and microbial biomass of each soil with depth (Table 3.12 and Figure 3.21). The relationship of the evolution rate and total organic carbon content, microbial biomass were analyzed using linear regression models (Figure 3.22 and Figure 3.23). The rate of CO₂ production significantly correlated with total organic carbon ($R^2 = 0.87$, $P < 0.05$) and microbial biomass ($R^2 = 0.89$, $P < 0.05$). However, in Figure 3.22 and 3.23, it appears to be one data point which contributes significantly to the regressions. This indicates data points cluster in one end of the regression line. More data points which distribute evenly are need to obtained for regression analysis.

3.5.2.2 Potential production of N₂O

Under laboratory conditions, the rate of N₂O evolution from incubated soils varied with depth. The rate of evolution decreased with increasing soil depth (Figure 3.24). High rates of N₂O evolution were from 0-5, 5-10, 10-15-cm depths. Below 15 cm, there was no effect of depth on N₂O evolution. The N₂O evolution was consistent with the trend of total organic carbon content, microbial biomass, ammonium and nitrate nitrogen content with depth (Table 3.5 and Figure 3.21). Using linear regressions (Figure 3.25-28), the rate of N₂O production was related to total organic carbon ($R^2 = 0.61$, $P < 0.05$), microbial biomass ($R^2 = 0.61$, $P < 0.05$), ammonium ($R^2 = 0.68$, $P < 0.05$) and nitrate nitrogen ($R^2 = 0.63$, $P < 0.05$). However, in Figure 3.25-28, it appears to be one data point which contributes significantly to the regressions. This indicates data points clusters in one end of the regression line. More data points which distribute evenly are need to obtained for regression analysis.

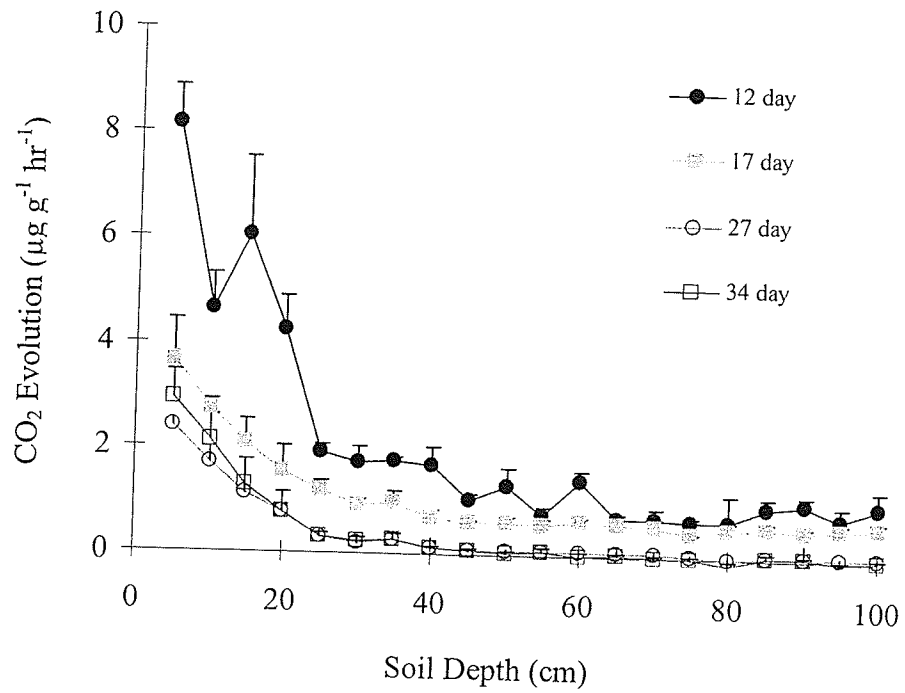


Figure 3.20 CO₂ evolution from soils removed from the soil profile under laboratory conditions (4 of 10 dates shown).

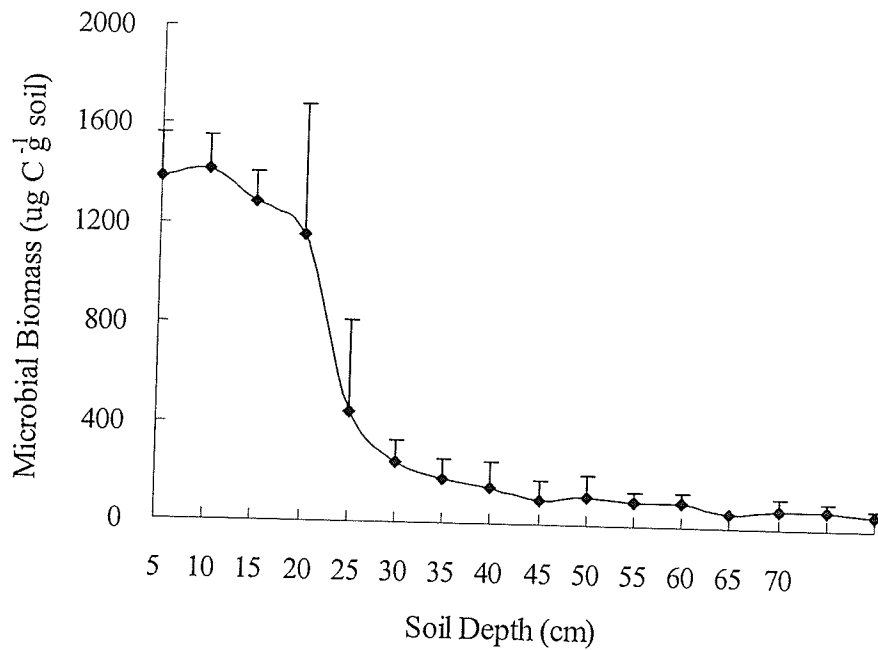


Figure 3.21 Microbial biomass C at soils removed from the soil profile at varied depths (Oct.15, 2003).

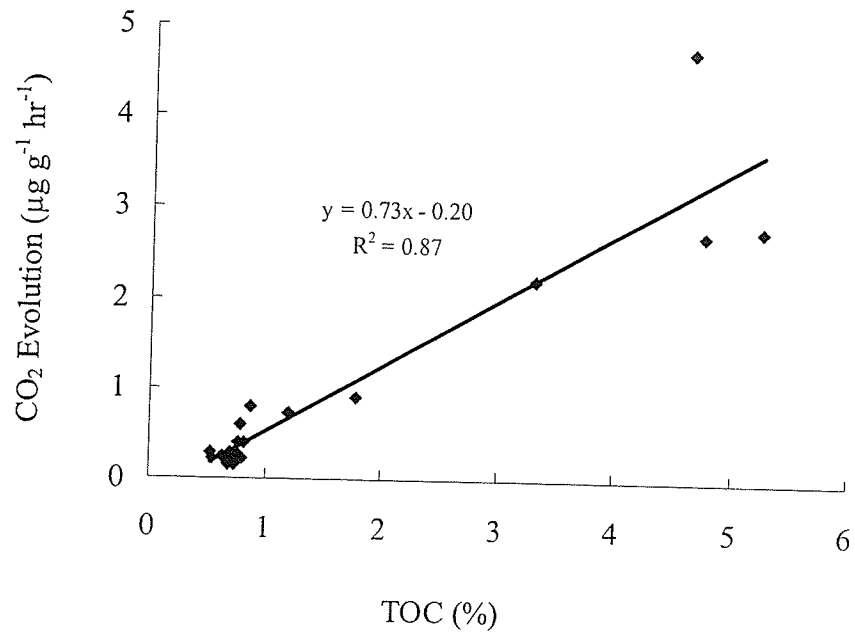


Figure 3.22 Relationship between CO₂ evolution and total organic carbon.

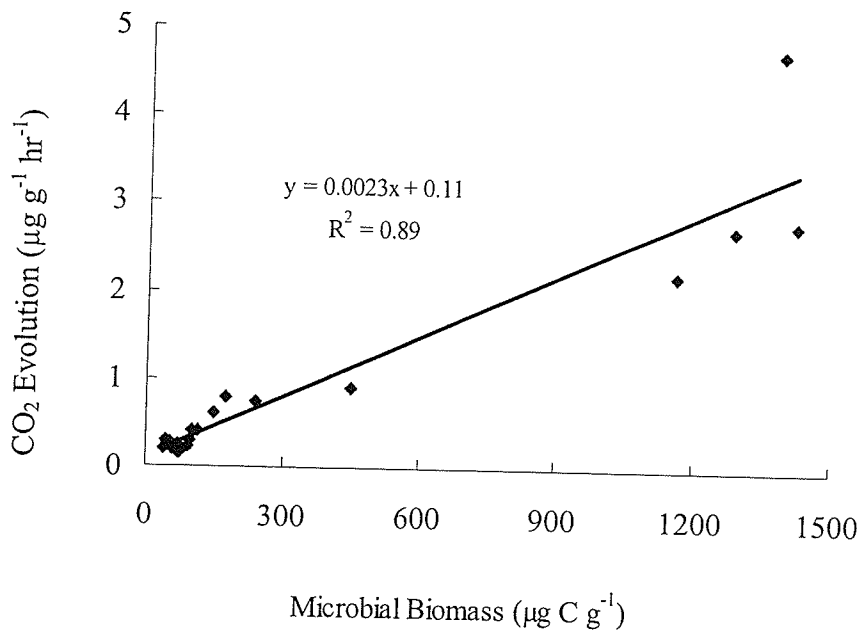


Figure 3.23 Relationship between CO₂ evolution and microbial biomass C.

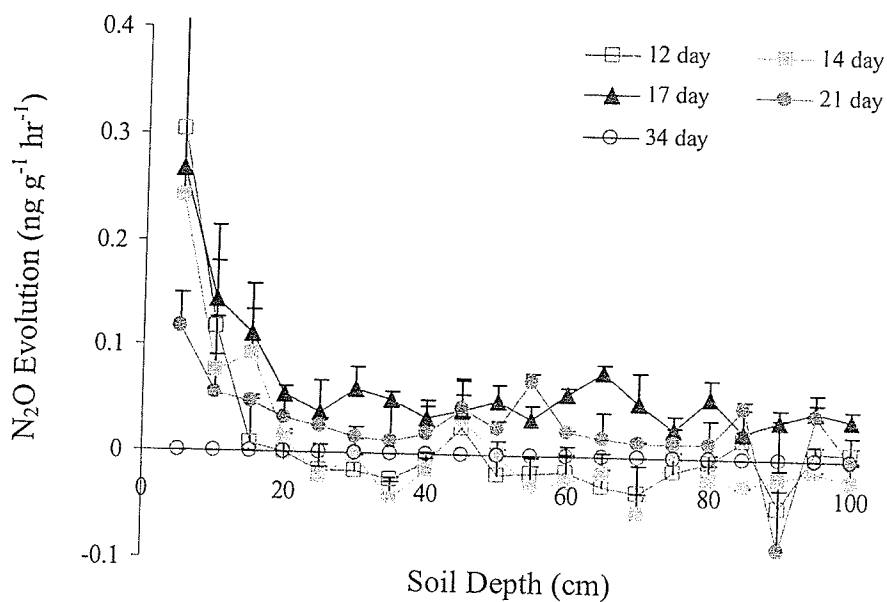


Figure 3.24 N₂O evolution from soils removed from soil profiles under laboratory condition (4 of 10 dates shown).

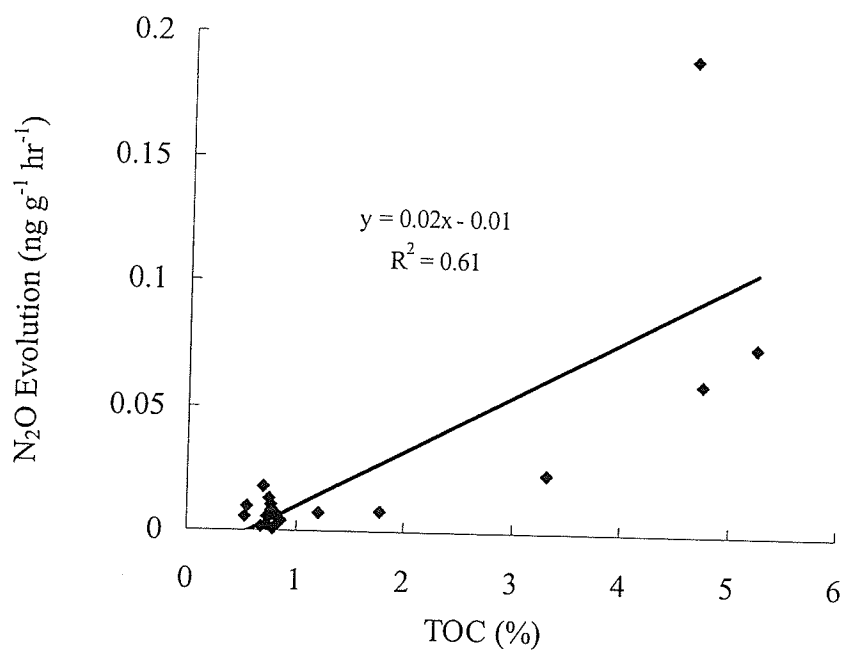


Figure 3.25 Relationship between N₂O evolution and total organic carbon.

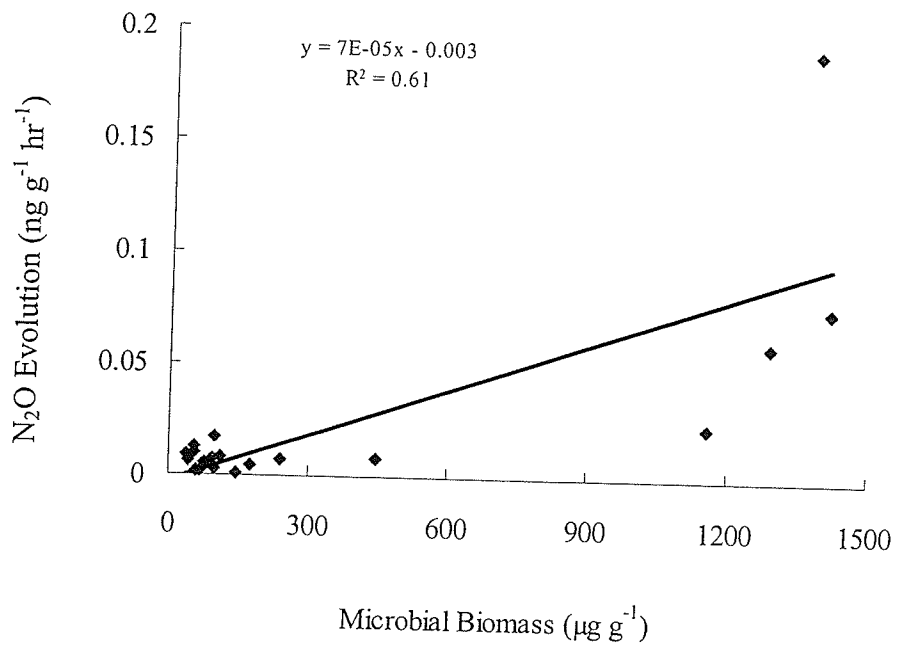


Figure 3.26 Relationship between N_2O evolution and microbial biomass C.

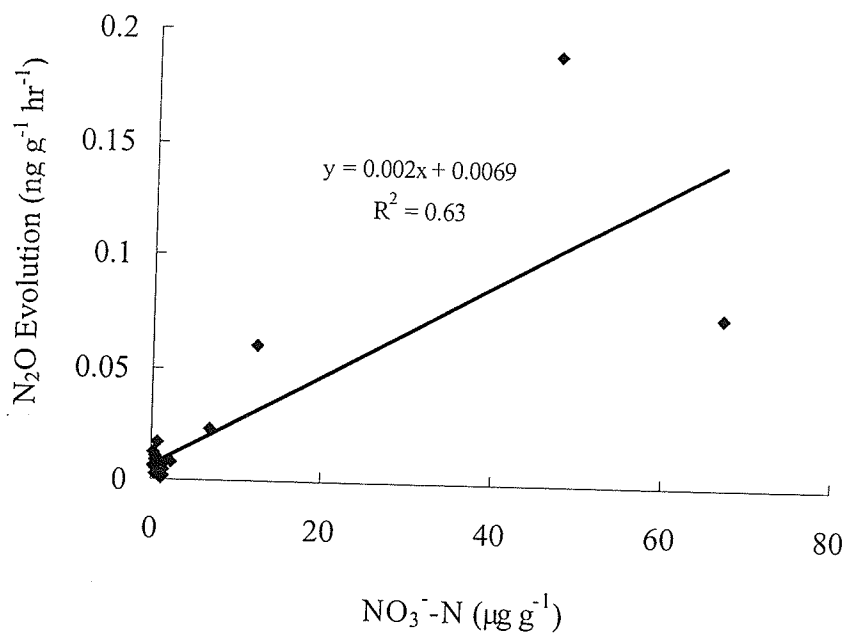


Figure 3.27 Relationship between N_2O evolution and NO_3^- -N.

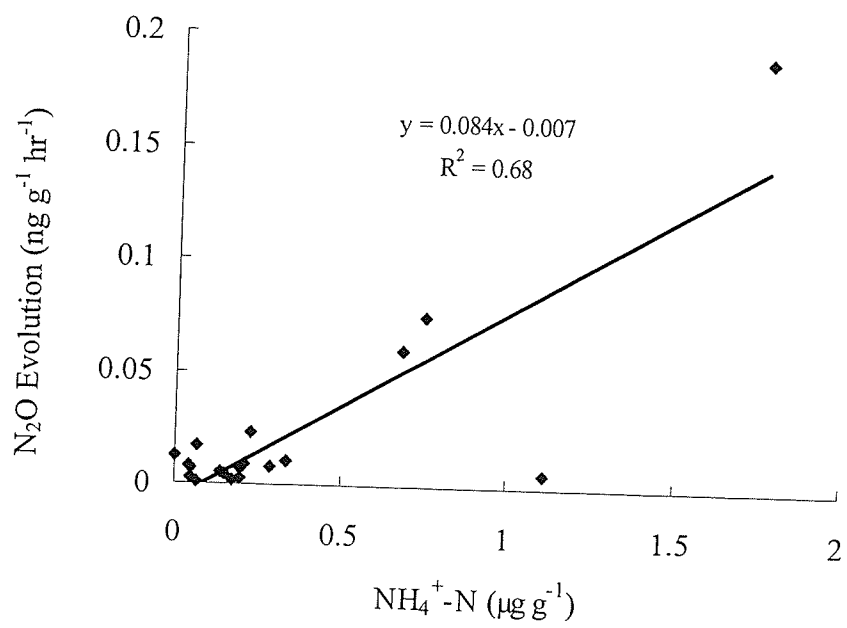


Figure 3.28 Relationship between N_2O evolution and $\text{NH}_4^+\text{-N}$.

3.6. Discussion

3.6.1 Field experiment

3.6.1.1 CO₂ emission and profile concentration

3.6.1.1.1 Variation of CO₂ emission

In the field study, it was found that CO₂ flux had an obvious seasonal pattern and followed the change of both soil and air temperature pattern closely in all three depressions (Figure 3.5 and 3.9). The close correlation between CO₂ flux and soil temperature has been observed by others (Mielnick and William, 2000; Fang et al., 2001; Smith et al., 2003; Jacinthe and Lal, 2004). Primarily soil temperature governed seasonal variations in CO₂ emission with the highest flux on July 27, 2004 and lowest value on January 13, 2004. During the winter, air and soil temperatures were below zero when soil biological activities were minimal or zero, due to freezing. Thus, CO₂ flux was low. With the increase of temperature, the release of CO₂ from microbial respiration and plant root respiration increased which led to high CO₂ flux during the growing season at a moderately high soil temperature. Then, with the decrease of temperature after the autumn, the activities of microorganisms and root respiration decreased resulting in the decline of CO₂ flux accordingly.

The release of CO₂ from soil organic carbon decomposition and vegetation root respiration generally increases exponentially with soil or air temperature (Winkler et al., 1996; Bajracharya et al., 2000a). However, other relationships (such as linear, quadratic, polynomial, logistic) have been described (Holthausen and Caldwell, 1980; Jenkinson, 1990; Bowden et al., 1998; Jacinthe and Lal, 2004). In this study, CO₂ flux was predicted with

polynomial regression models ($R^2 = 0.65$) of soil surface temperature (10 cm), and air temperature with $R^2 = 0.62$.

In addition a flush of CO₂ emissions was observed during the spring thaw period. On April 07, 2004, snow began to melt and soil temperature increased above zero. The increase of available carbon and high soil moisture due to thaw may have contributed to the enhanced CO₂ production and emissions.

Unlike temperature, the effect of soil moisture on CO₂ flux was not obvious. This is in agreement with the findings of others (Bajracharya et al., 2000b; Hamada and Tanaka, 2001). Bajracharya et al. (2000b) found soil moisture only influence CO₂ flux under very dry or very wet (saturated) conditions. In this study, the three depressions were subject to wet conditions due to runoff from upslope, especially at Depression A. The collected TDR data indicated high values of moisture content in the surface 15 cm (Table 3.2). This is also consistent with the observed depth to the water table during the summer. In May 2004 and 2005 standing water was observed in Depression A but not in Depressions B and C. Therefore, insufficient soil moisture was not a factor limiting CO₂ production. This was the reason why rainfall events did not result in the flush of CO₂, which differs from other studies (Burton and Beauchamp, 1994; Mielnick and William, 2000). Under very wet conditions, high moisture content limits aeration and O₂ diffusion, restricting soil respiration, resulting in reduced CO₂ flux. In this study there was not clear relationship between soil moisture and CO₂ flux. Patterns in CO₂ production and consumption within soil profiles were markedly affected by soil moisture content. This will be discussed in the following section.

3.6.1.1.2 Temporal and vertical variations of profile CO₂ concentrations

During the experimental period, CO₂ concentration increased in all soil depths from January to July 2004 as temperature increased, then decreased as soil temperature declined (Figure 3.12). The concentration of CO₂ ranged over 2 orders of magnitude from low of 416 uL CO₂ L⁻¹ during the winter to peak of 58, 879 uL CO₂ L⁻¹ during the summer. The high variation of CO₂ concentration in these soil profiles resulted, in part, from the varying of biological activity, including microbial respiration and plant root respiration (Schlentner and Cleve, 1985; Buyanovsky et al., 1986; Burton and Beauchamp, 1994; Hamada and Tanaka, 2001). Any factor influencing these two biological processes results in variation of CO₂ concentration in the soil profile. Soil temperature, moisture, substrate availability and aeration appear to be most important factors affecting CO₂ production and concentration (Terhune and Harden, 1991; Howard and Howard, 1993; Wang et al., 1999).

During the winter, low observed CO₂ concentration corresponded to almost dormant microbial and plant root activities resulting from low soil temperature during this period. As temperature increased during the spring thaw higher CO₂ production was observed, resulting in an increase in CO₂ concentration in topsoil as well as the flush of emissions of CO₂ from the soil surface on April 7. Freezing and thawing of the soil results in the disruption of soil structure and the release of available carbon and nitrogen for microbial respiration (Groffman and Tiedje, 1989; Soulides and Allison, 1961). Freezing also results in the rupture of microbial cells further releasing soluble C and N (Soulides and Allison, 1961). Thawing coincided with a flush of CO₂ as has been observed in other studies (Burton and Beauchamp 1994; Skogland et al., 1998). During the spring and summer, increasing soil temperature and plant growth stimulated microbial

and root respiration and resulted in CO₂ production exceeding CO₂ losses as was also noted by Anderson (1995) and Dudziak and Halas (1996). CO₂ concentration reached its highest value of 58,879 uL CO₂ L⁻¹ in depressions in late July. Although this value was high compared with those reported in other studies in agricultural systems (Terhune and Harden, 1991; Hamada and Tanaka, 2001; Toshie et al., 2002), the value was similar with those reported for forest soil and grassland soils (De Jong and Schappert, 1972; Marion et al., 1993b; Billings et al, 1998). Peak CO₂ accumulation in these depressions probably resulted from high production rate and low diffusion and consumption rates, which will be discussed later in greater detail.

CO₂ concentration tended increased with increasing soil depth during winter, but the concentration differences in the soil profile were not statistically significant. During the summer CO₂ concentration were highly variable. The accumulation of CO₂ at greater depths results from the downward diffusion of CO₂ produced in near the surface as soil microbial activity and microbial biomass is greatest in the topsoil (Figure 3.6 and Figure 3.12). The downward diffusion is further enhanced by restricted diffusion at the soil surface as a result of high soil water contents.

During the winter, this trend was not obvious due to low CO₂ production rates. However, during the summer, high fluctuations of CO₂ concentration were observed in the soil profile. This happened more markedly in Depressions A and C where high variation was observed at 40-60 cm depths on July 27, 2004. Depression B had a uniformly low concentration during the study period. The difference of CO₂ concentration between three depressions provided an interesting contrast. Depression C had high organic carbon content in upper 30 cm soil layer (Table 3.4) and above-ground plant biomass (Table 3.5) on July 27, which resulted in high CO₂ production. As well,

this led to high flux in Depression C. However, high CO₂ concentration occurred at greater depths because it was controlled by diffusion and consumption processes as well. These processes were mainly affected by soil water. Elevated soil water content at the soil surface reduces soil aeration and gas diffusion contributing to the redistribution of CO₂ to the lower profile and CO₂ accumulation at greater depths (Moore and Dalva, 1993; Oechel et al., 1998). Water table level at 75 cm limited CO₂ diffusion downward and lower aeration status of the soil results in redox conditions that favor methanogenesis which results in the conversion of CO₂ to CH₄ and a resulting CH₄ accumulation (Figure 3.17). CH₄ production at depth resulted in CH₄ accumulation in the soil profile on several days (Figure 3.18). Although soil organic carbon content of Depression B was higher than A in the surface, CO₂ concentration in soil profile was much lower during the summer. Two possible reasons resulted in low CO₂ concentrations. The first reason was water table level. The low water table level in Depression B indicated good aeration and high profile temperature in comparison to that in other two depressions, which would allow more quick diffusions of CO₂ up-downward or laterally. The second one was the depth of A-horizon soil. The depth of A-horizon soil was only at 70 cm at B while at A it was below 100 cm. As well, Depression B had high inorganic carbon content with depth (Table 3.4).

Although CO₂ may be produced from carbonate dissolution (Billings et al., 1998; Burton and Beauchamp, 1994), in Depression B, CO₂ was consumed probably due to high pH and formation of carbonates (Lindsat, 1979; Langmuir, 1997; Ming, 2002). Therefore, carbonates may be a sink of CO₂ in this study, although the role of carbonates in CO₂ production and consumption is not well understood (Langmuir, 1997).

3.6.1.1.3 Effect of soil accumulation on CO₂ production and emission

The profile ¹³⁷Cs activities in the three depressions showed the significant soil accumulation by erosion within this landscape (Figure 3.19). This is a result of intensive tillage in the past. The high activity of ¹³⁷Cs in the top 0-25 cm layer indicated this layer is composed of soil that was formerly at the surface during period of ¹³⁷Cs fallout. The thickened organic-rich A-horizons which have formed in these lower slope positions is presumed to have altered greenhouse production and emission from these profiles presumably as a result of two processes.

Firstly, the soil accumulation affected CO₂ production as a result of the additional substrates (C and N) added to the profile. Changes in ¹³⁷Cs content are consistent with the accumulation of soil organic carbon and nitrogen in the soil profile. Depression C had highest activities of ¹³⁷C indicating high soil accumulation in this position. Similarly, soil organic carbon content was highest in Depression C relative to the two other depressions. The thick accumulated A horizons provided larger amounts of substrate for biological activity, which resulted in high profile CO₂ concentrations and surface flux in 2004.

Secondly, the effect of soil accumulation on CO₂ production and emission was complicated by environmental factors. Similar results were also investigated by Bajracharya et al. (2000a, b). Soil accumulation in Depression B was higher than that in Depression A. This reflects that organic carbon and nitrogen contents in Depression B were higher than that in Depression A. Therefore, higher CO₂ production and surface emission in Depression B is expected. However, in our field study, Depression A had higher concentration and flux. The reason was that Depression A had high moisture contents and thicker A-horizon, while Depression B had shallow A-horizon even though

it had more soil accumulation since 1960. In Depression B, low water table level indicated good aeration, thus a more rapid change of profile temperature. This was also seen from the soil moisture content. This resulted in high rate of organic matter turn over, therefore, even Depression B had higher rate of soil accumulation, it developed a more shallow A horizon. This result indicated soil accumulation influence soil respiration through affecting soil moisture and soil temperature (Gregorich et al., 1998; Bajracharya et al., 2000b; Lindstrom, 2002). Moreover, soil loss from upper slopes was rich in organic carbon and nitrogen, which favored CO₂ production. But it might have enhanced soil aggregation and decreased CO₂ production (Van Veen and Paul, 1981; Lal, 2001). Therefore, soil accumulation could be the source of CO₂ production but also the sink of CO₂ in the depressions, which depended on its interaction with soil moisture, soil temperature, soil substrates and other factors.

3.6.1.2 N₂O emission and profile concentrations

3.6.1.2.1 Variation of N₂O emission

We observed the high N₂O emission during spring thaw events (Figure 3.13). The changes of N₂O flux at the three depressions during these periods are consistent with past reports confirming the effect of freeze - thaw events on N₂O emission (Goodroad and Keeney, 1984; Groffman and Tiedje, 1989; Burton and Beauchamp, 1994; Corre et al., 1996; Muller et al., 2002). In this study, the peak flux occurred on April 7, 2004 in all three depressions. This date corresponded with the date at which the air and soil surface temperature first exceeded zero in 2004. The soil surface was free of snow as well. The melting snow and thawing soil provided the high soil moisture and available C and N resulting in a large pulse of N₂O. There was both an increase in surface N₂O flux as well

as an increased soil profile N_2O concentrations (Figure 3.16). There was also a flush of CO_2 during this period confirming the increase in biological activity resulting from the release of substrates and improved conditions for biological activity. In the spring of 2005 the only observed peak in N_2O flux was observed on April 24 and only in Depression C. Peak N_2O accumulation in the soil profile was observed on April 5 in Depressions B and C. There were two possible reasons for these results. The first one was that the soil surface was covered by snow in 2005 (Table 3.1). The snow cover would reduce gas exchange between the soil atmosphere and the surface.

The effect of rainfall events on N_2O flux was not obvious during the experimental period, which was not consistent with results from Burton et al. (1997), Cannavo et al. (2004), and Corre et al. (1996). This indicated that other factors other than soil moisture limited N_2O production and diffusion. From May 1 to May 26, 2004, there was 88 mm rainfall in this area. Soil water accumulated in the depressions from runoff from upslope as evidenced by high water tables. Under this condition, N_2O flux was low probably because any N_2O produced during denitrification was completely reduced to N_2 (Meixner and Eugster, 1999; Smith et al., 2003). On May 28, there was a flush of N_2O in Depression A, but little or no emissions seen in Depressions B and C. The flush of N_2O in Depression A might have resulted from the fluctuation of water table level, which affect N_2O/N_2 ratio and denitrification rate (Klemedtsson et al., 1997; Smith et al., 2003) in Depression A.

3.6.1.2.2 Temporal and vertical variation of profile N_2O concentrations

The N_2O concentration in all soil depths indicated the markedly seasonal patterns (Figure 3.16). Unlike the CO_2 concentration, the levels of N_2O concentration were not

dependent on soil temperature (Figure 3.14 and Figure 3.15). The only significant N_2O accumulation occurred during spring thaw events. This seasonal variation of N_2O concentrations has been observed by others (Goodroad and Keeney, 1984; Groffman and Tiedje, 1989; Burton and Beauchamp, 1994; Corre et al., 1996; Muller et al., 2002). The high N_2O accumulation of N_2O in the soil profile during spring thaw indicates that N_2O production occurred not only at the soil surface, but also within the soil profile. High N_2O production during spring thaw may result from different processes, including: 1) stimulated microbial activities due to newly-increased levels of available C and N including microorganisms killed by freeze-thaw; and 2) accumulation of labile substrates due to reduced microbial activities during the winter time. Once temperature increased, these substrates were readily used by microbes leading to high N_2O production. As discussed in Section 3.6.1.1, available C and N from the above processes and high soil moisture might favor N_2O production from nitrification and denitrification in the soil profile.

N_2O concentrations in the soil profile are the result of the net effect of production, diffusion as well as consumption processes (Hojberg et al., 1994). In this study, generally, seasonal changes in N_2O concentration were greatest in the topsoil though as a result of high variability these differences are not significantly different between depths. Peak N_2O concentrations were observed in upper 10-25 cm at the start of the thaw event (Figure 3.16). This is consistent with observations reported by others (Goodroad and Keeney, 1984; Sitaula et al., 1995). Concentrations of N_2O as high as $113 \mu L N_2O L^{-1}$ were observed in the upper 0-25-cm soil layers, while mean concentration of all soil depths was $< 10 \mu L N_2O L^{-1}$. High N_2O concentration in surface soil layers implies a high rate of production at these depths. N_2O production might either be from

denitrification in anaerobic conditions or nitrification in aerobic conditions in the soil profile (Linn and Doran, 1984; Davidson, 1992; Corre et al., 1996). According to the reports of Linn and Doran (1984) and Meixner and Eugster (1999), N_2O is mainly from nitrification when WFPS < 60%, and mainly from denitrification when WFPS > 60%. At a depth of 15 cm, the average WFPS observed in Depressions A, B and C were 79%, 58% and 80%, respectively, from June to November 2004. Therefore, N_2O was mainly from denitrification in Depressions A and C, while N_2O was produced by nitrification on Depression B. The magnitude of N_2O production is not only determined by the rate of nitrification and denitrification, but the proportion of NO/N_2O and N_2O/N_2 . In this study during the spring thaw period, snow melt and runoff from upslopes resulted in higher soil moisture contents in the depressions. It is assumed N_2O production resulted mainly from the denitrification process. However, due to the failure of TDR during this time, no data of soil moisture was measured during the spring thaw period. The pattern of N_2O distribution in soil profile showed the rate of N_2O production decreased markedly with depth. This trend indicated either denitrification rate decreased with depth or the proportion of N_2O/N_2 decreased with depth. Substrates including organic carbon, ammonium and nitrate nitrogen resulted in high microbial biomass and potential production rate at the surface layer. Freezing and thaw events provided soluble carbon and net nitrogen mineralization, which is likely to have resulted in significant denitrification in the surface soil layers (Soulides and Allison, 1961; Deluca et al., 1992; Muller et al., 2002). With greater soil depths, N_2 might be the dominant end product of denitrification under completely anaerobic conditions. As well, due to the decrease of available substrates, total denitrification rate might decrease. Moreover, the decrease in the size of microbial community with depth might have contributed to a lower

denitrification rate (Luo et al., 1998). This was observed in microcosm study where the N_2O production potential decreased with soil depth.

Different from the results of this study, other studies evaluating N_2O distribution with depth have shown peak concentrations occurring at the greater depth, often 50-100 cm below the soil surface (Burton et al., 1997). This suggested the process of N_2O production and emission was complex, which might be highly variable due to variability of substrates, changes in environment as well as land management (e.g. soil loss and accumulation).

3.6.2 Microcosm study

3.6.2.1 Potential production of CO_2 under laboratory conditions

Under laboratory conditions, the rate of CO_2 evolution from incubated soils decreased with the increase of soil depth (Figure 3.20). The same result has been observed by others (Doran, 1987; Fraser et al., 1988; Winkler et al., 1996). The average CO_2 evolution at the 5-cm soil layer was $4.74 \mu g CO_2 g^{-1}h^{-1}$ while in 100 cm was only $0.29 \mu g CO_2 g^{-1}h^{-1}$. Decreases in CO_2 evolution paralleled the decreases in microbial biomass, organic carbon and total N with soil depth (Table 3.12). In this study, CO_2 production was from microbial respiration which is driven by substrate availability as influenced by soil temperature and moisture (Linn and Daron, 1984; Doran, 1987; Leiros, et al., 1999). Under controlled temperature ($25^\circ C$) and soil moisture (60% WFPS), microbial activities and population were mainly affected by substrate availability. Close correlations between microbial activities and organic carbon and nitrogen were observed (Figure 3.22-23).

This study showed the surface 0-25 cm of soil appeared to be the major potential source of CO₂ production, because this layer was found to be rich in mineralizable organic carbon and nitrogen, favoring microbial activity and supporting a larger microbial biomass. High activities of ¹³⁷Cs in this layer indicated accumulation of topsoil from upslope which added organic carbon that would increase CO₂ production.

3.6.2.2 Potential production of N₂O under laboratory conditions

Our laboratory experiment showed the rate of N₂O evolution from soil decreased with increasing soil depth (Figure 3.24). Similar decreases in N₂O production rate with depth have been observed in other laboratory or field experiments (Staley et al., 1990; Luo et al., 1998). High rates of N₂O evolution were mainly from 0-25 cm soil depths. The topsoil layers were rich in available carbon and nitrogen which provided the source materials for microbial growth and activity (Burford and Bremner, 1975; Weier et al., 1993). Luo et al. (1998) also pointed out that the decrease in the size of denitrifier community with depth limited the production rate rather than being solely a function of substrate limitation. Regression analyses showed the rate of N₂O evolution correlated with total organic carbon content, ammonium and nitrate content, and microbial biomass of soil with depths (Table 3.12 and Figure 3.21), but these relationships were not strong in comparison with results reported by others. It has been reported N₂O production rate is highly correlated with water-soluble carbon (Burford and Bremner, 1975; Burton and Beauchamp, 1985).

As discussed in Section 3.6.2.1, the surface 0-25 cm soil also appeared to be the major source in CO₂ production. This meant the topsoil, rich in organic carbon and nitrogen, favored both N₂O and CO₂ production, at least in the short-term. Thus, soil

accumulation in the depressions should increase N_2O and CO_2 production during and shortly after erosion events.

3.7 Summary and Conclusions

The field study demonstrated CO_2 flux and profile concentration had obvious seasonal patterns. CO_2 flux and concentration changed dramatically as temperature varied, indicating that temperature is the key factor controlling gas production and emission. CO_2 profile concentrations behaved differently in the three depressions. High CO_2 concentrations occurred at the greater depth in these depressions, probably resulting from high production and low diffusion rates to atmosphere. High water table levels and poor drainage in the depressions limited gas diffusion from soil to the aboveground atmosphere as well. Significant soil accumulation was observed in the three depressions. Soil accumulation favored CO_2 production in that it increased quantities of soil organic carbon and nitrogen. The effect of soil accumulation on CO_2 flux was different in the three depressions, attributed to differences in soil moisture and water table level.

Results showed N_2O profile concentration and the surface flux had significant seasonal patterns as well. High N_2O flux and profile concentration only occurred during spring thaw periods. Peak concentrations accumulated at 10-25 cm at the start of the thaw events. High soil moisture and available carbon and nitrogen during spring thaw periods contributed to high production rates. Although soil accumulation increased quantities of organic carbon and nitrogen in the soil profile, the effect of soil accumulation on N_2O production and emission only occurred during spring thaw events. Accumulation of topsoil increased N_2O production in the soil profile. However, this accumulation might

decrease N_2O emission due to limited diffusion in the soil or the conversion of N_2O to N_2 . Thus, the effect of soil erosion on N_2O emission was complicated by hydrologic and pedologic conditions.

Further laboratory conditions confirmed the potential CO_2 and N_2O production decreased with the increase in soil depth. Surface 0-25-cm soil was the major source in CO_2 and N_2O production in that this layer was rich in organic carbon and nitrogen favoring microbial activities.

3.8. References

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4. OVERALL SYNTHESIS

In topographically complex, intensively tilled landscapes, soil is often severely eroded. Soil erosion redistributes vast quantities of soil, and, thus, organic carbon and nitrogen within landscapes (Gregorich et al., 1998; Lobb et al., 2002; Lobb et al., 2003). Soil redistribution results in variation of soil biological, physical and chemical properties which affect carbon and nitrogen mineralization, immobilization, reduction and oxidization processes and, thus, greenhouse gas production and emission. There is limited information directly relating soil erosion processes to greenhouse gas (GHG) production and emission within landscapes. The objective of this study was to evaluate the impacts of soil erosion on GHG production and emission within landscapes. To achieve this objective, two laboratory experiments and one field experiment were conducted.

A preliminary column study examined the effect of soil depth (uniform soil) on GHG emission using repacked soil under controlled soil temperature and moisture conditions. Under these conditions, the column study showed the soil accumulation had a great effect on GHG emission. Physical accumulation of soil is presumed to affect GHG production and emission since it provides more source materials and limits gas diffusion in the soil. Increasing the depth of surface soil resulted in increased GHG production, most likely as a result of the greater amount of substrate to support microbial activity. But, the emission and production rate decreased with increasing depths of surface soil and, therefore, it was concluded that emission is limited by reduced diffusion at deeper depths and possibly consumption within soil profile. Diffusion of O₂ is also

limited by increasing amounts of soil accumulated on the surface which also affects GHG production.

Based on the understanding of the column study, a further field experiment was carried out in lower slopes within a landscape to evaluate the effect of soil accumulation on GHG production and emission. The results indicated the production and emission of CO₂ and N₂O are highly variable in the field, highly variable in both time and space. CO₂ concentration in the soil and emission were greatest during the summer, coincident with high soil temperature, low soil moisture, low water table levels and maximum plant growth. Seasonal patterns of CO₂ flux and profile concentration revealed that temperature is the primary factor controlling CO₂. With depth, peak accumulation of CO₂ at certain depths showed soil water content limited gas diffusion and soil aeration which contributed to CO₂ accumulation at depth. Under anaerobic conditions, more CO₂ may be converted to CH₄, raising another issue, the increase of CH₄ production while CO₂ production was decreased. N₂O concentrations in soil profile and surface emission were greatest during the early spring, coincident with rapid soil warming and thawing, high soil moisture content and high water table level.

Under the field condition, it is not possible to isolate the relationship between the rate of soil erosion and the rate of CO₂ and N₂O emission due to the high degree of variability and the large number of factors controlling production and emission. The effect of soil accumulation, based on estimates using ¹³⁷Cs, on CO₂ emission was different between lower slopes examined in this study. Soil accumulation did increase the amount of organic carbon and nitrogen and thus resulted in high CO₂ emission and CO₂ production in soil profile in Depression C. This differs from the observations in the Depressions A and B where the effect of soil accumulation was affected by different soil

moisture and temperature regimes. This indicated soil erosion may have affected GHG production through affecting soil temperature, moisture, substrates and other factors.

To further understand the impacts of soil accumulation on the production of GHG, a microcosm study was conducted. The microcosm study showed the potential production of CO₂ and N₂O decreased with the soil depth. This corresponded with the trend of organic carbon decreased with the soil depth. High levels of ¹³⁷Cs in the top 25 cm soil layer indicated soil had accumulated in lower slopes. The accumulated soil was rich in organic carbon and nitrogen. Consequently, soil accumulation increased CO₂ and N₂O production. However, in the long-term, CO₂ production appears not to have increased proportionally to the degree of accumulation as indicated by the column study.

As discussed above, this study examined the interaction of the soil accumulation process and GHG production and emission processes within the cultivated landscape. The effect of soil accumulation on GHG production within soil profile and its net production resulting in emission was thoroughly evaluated. This study first investigated the relationship between soil depth and the GHG emission. In the field study, further understanding was gained of the production and accumulation of N₂O and CO₂ over the depth of 100 cm. The study demonstrated that the effect of the soil accumulation on GHG production and emission was complex. The effect of soil accumulation could affect GHG flux through its effect on soil moisture, temperature and substrates. Therefore, it is difficult to establish the relationship between soil accumulation and GHG emission. This study also provided information of the fate of the buried soil caused by soil accumulation. It was concluded that soil accumulation increased GHG production in depositional area, at least in the short term. The effect of soil accumulation on flux was more complex and soil specific.

Although this study was successful in examining the interaction of soil accumulation process and GHG production and emission processes, it had limitations.

Future studies should address the following areas of concern:

- More detailed laboratory column studies on the relationship between soil depth and GHG emission are needed with higher soil depths and more replications.
- Additional field studies on GHG profile concentrations and the surface flux on upper slope positions should be evaluated, and soil erosion should be evaluated as well.
- On both upper slopes and lower slope positions, detailed soil moisture measurements are needed, especially at the spring thaw events.
- The contribution of inorganic carbon to CO₂ production within soil profile should be studied. The effect of soil erosion on GHG emission should be evaluated on a CO₂- equivalent basis at a landscape scale.

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5. APPENDIX

I. Standard Operation Procedure of Department of Soil Science

Soil Microbial Biomass Extraction Methodology

Equipment per soil sample:

- 2 square French bottles
- 2 #5 stoppers
- 2 Whatman No. 5 filter papers
- 4 30mL scintillation vials
- CHCl_3
- must be purified, dried, and distilled in glass
- must not be stabilized with ethanol
- boiling chips
- 150mL beaker
- desiccators able to withstand a high vacuum without implosion
- vacuum pump
- fumehood
- 10% HCl acid bath
- 0.5 M K_2SO_4 solution

Procedure

Solutions

- Prepare 0.5 M K_2SO_4 solution by dissolving 87.135g K_2SO_4 crystals in 1L distilled water.
- Use moderate heat to help expediate the process.

Soil

- Weigh out two 25g portions of soil into the square French bottles.
- one sample will be fumigated for 24h and then extracted
- one sample will be extracted immediately

Fumigation

1. Prepare the desiccator for fumigation by lining it with moistened paper towels.
2. Place samples in desiccator with a 150mL beaker containing approximately 50mL of CHCl_3 and boiling chips.
3. Seal and evacuate the desiccator, taking care to vent the fumes released by the vacuum pump into the fumehood, until the CHCl_3 boils vigorously, and continue evacuating for approximately 1 minute.
4. Seal the desiccator under vacuum by turning collar, and leave for 24 hours.
5. After 24 hours, release the vacuum by turning the desiccator collar; a hissing noise should be heard. Remove the beaker of CHCl_3 and the paper towels.
6. Remove the residual CHCl_3 vapour from the soil samples by repeatedly evacuating the chamber 3 times for about 30 seconds each time.

Extraction

- Unfumigated samples are extracted immediately after weighing, while fumigated samples are extracted after 24 hours of fumigation.
1. Add 50mL of 0.5M K₂SO₄ to the square French bottles using a repipettor. Stopper the bottles using #5 stoppers. For each set of extractions, prepare two solution blanks containing only K₂SO₄.
 2. Place the bottles on a lateral shaker set at high speed for 1 hour.
 3. After shaking, pass the soil suspension through Whatman No. 5 filter paper.
 - Funnels are not necessary; filter paper is folded and placed in the funnel rack directly.
 - Filter paper should be rinsed with approximately 50mL deionised water prior to filtration.
 4. Collect filtrate in 30mL scintillation vials.
 - Two sets of filtrate samples are collected – A set and B set.
 - Vials should be switched when the A vial is about 3/4 full.
 - Vials should be labelled with the site name, original date of sampling, sample code, “F” or “U” for fumigated or unfumigated, and “A” or “B.”
 5. Cap vials and placed in the freezer as soon as possible. The B set may be left overnight if the filtration time prolonged.

Analysis

- Analyse filtrate for N, C, NO₃⁻, and NH₄⁺ using the Technicon Auto-Analyser.

Calculations

1. Calculate the mass of C (μg g⁻¹ soil)

$$= \frac{[(\mu\text{g mL}^{-1}\text{ C})_{\text{fumigated}} - (\mu\text{g mL}^{-1}\text{ C})_{\text{blank}}] \cdot [\text{mL K}_2\text{SO}_4 + (\text{mass wet soil} \cdot \text{GMC})]}{(\text{mass of wet soil}/(1 + \text{GMC}))}$$

- μg mL⁻¹ C comes from the Auto-Analyser
- mass of wet soil/(1 + GMC) gives the mass of oven dry soil
- mass wet soil • GMC gives the mass of water in the sample
- * to calculate the mass of C in the unfumigated sample, substitute the appropriate data value for (μg mL⁻¹ C)_{unfumigated}

2. Calculate the mass of microbial biomass C (μg C g⁻¹ soil)

$$= \frac{\text{CO}_2\text{-C (fumigated)} - \text{CO}_2\text{-C (unfumigated)}}{(0.25) \cdot (\text{mass dry soil})}$$

- where 0.25 is a correction factor

- * To calculate microbial biomass N, substitute the Auto-Analyser N data into the above steps, and use 0.18 as the correction factor in Step 2.

Safety

- All technicians are responsible for familiarising themselves with the Materials Safety Data Sheets for all chemicals used in this procedure.
- If WHMIS control products must be stored in containers other than their originals, a workplace label must be prepared for the new container. Control products include both pure decanted chemicals and prepared solutions.

Notes

- Square French bottles should be acid-washed for 24 hours, then rinsed with distilled water and allowed to dry prior to use.
- If more or less soil is used in the analysis, adjust the amount of K_2SO_4 added so that the ratio of soil:solution remains 1:2.