SHORT-TERM CARBON DIOXIDE AND NITROUS OXIDE FLUX FOLLOWING TILLAGE OF THE CLAY SOIL IN THE RED RIVER VALLEY IN SOUTHERN MANITOBA

BY

ALEXANDER J. KOITER

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, Manitoba

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ABSTRACT

Koiter, Alexander J. M.Sc., The University of Manitoba, January, 2008. Short-term carbon dioxide and nitrous oxide flux following tillage of the clay soil in the Red River Valley in Southern Manitoba. Major Professor: Dr. David Lobb.

There has been resurgence in the interest of conservation tillage as a way to sequester carbon from the atmosphere, to help improve soil quality, and as a means to mitigate the increasing concentration of greenhouse gases (GHGs) in the atmosphere. However, the term conservation tillage is qualitative and quite ambiguous, and refers to a wide range of tillage practices. This makes the interpretation of information gathered from different tillage systems difficult. There currently exists a need for the quantification of soil surface properties following different tillage methods because surface properties are closely linked to soil surface processes. Previous research has focused on the long-term impacts of tillage systems and their effects on soil biological processes and properties, such as soil microbial populations and activity, soil organic matter fractions and their role in the production and emission of greenhouse gases. However, the more immediate impacts of tillage on soil physical processes and properties and their role in the production and emission of GHGs are not well understood and are often overlooked.

The first objective of this research addressed the need for better quantification of soil physical properties after tillage practices. This research demonstrated the use of a laser profiling system and digital imagery and image analysis software in measuring soil micro-relief and crop residue cover. Furthermore, comparisons of geostatistical and univariate procedures of quantifying surface roughness were also investigated. There was

a definite advantage in using a geostatistical approach to characterize soil topography as the indices they provide give insight into the characteristics of the surface roughness. Soil disturbance and the addition of corn residue were both found to be significant factors affecting the surface roughness, crop residue cover, exposed surface area, and near-surface porosity.

The second objective of this research focused on the quantification and characterization of the short-term effects of soil disturbance as a result of tillage on the carbon dioxide (CO_2) and nitrous oxide (N_2O) flux from the clay soils of the Red River Valley, Manitoba. The short-term CO_2 flux (up to 5 days) following a soil disturbance event was characterized by an immediate increase in the CO_2 flux following the soil disturbance event that quickly dissipated within the first 24 hours. Both the addition of residue and soil disturbance were found to be significant factors in the cumulative CO_2 loss over the 5-day observation period. However, the incorporation of the residue through the action of soil disturbance was found to be a more important factor than soil disturbance or the addition of residue alone. The effects of residue and soil disturbance on the N_2O flux were highly variable. However, there was some indication that the N_2O flux under certain soil conditions may have a response to soil disturbance similar to that of CO_2.

The third objective is a combination of the previous two objectives and deals with the need to better understand the underlying physical mechanisms that control the CO_2 and N_2O flux. This was accomplished by combining the detailed information on the changes in surface properties and the CO_2 and N_2O fluxes that occur due to soil disturbance. Generally, the soil disturbance treatments that resulted in a rougher surface,

greater exposed surface area, greater residue incorporation, and disturbed the greatest volume of soil had the highest initial CO_2 fluxes and the greatest cumulative CO_2 loss following the soil disturbance event. Due to the high variability in the N_2O fluxes following soil disturbance there was no significant relationship found between the N_2O flux and soil surface properties.

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FOREWORD

This thesis has been prepared in the manuscript format in adherence with the guidelines established by the Department of Soil Science at the University of Manitoba.

This research was conducted as part of the "Temporal dynamics of greenhouse gas fluxes linked to soil biophysical processes and management practices" funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) and BIOCAP Canada under the strategic grant initiative. As part of this overall project, measurements are being carried out using micrometeorological techniques, which are ideal for characterizing the temporal dynamics of greenhouse gas (GHG) fluxes. A tunable diode laser (TDL) trace gas spectroscopy is being used to obtain $^{13}CO_2$ and $^{12}CO_2$ fluxes for identification of the source of CO_2 (soil or crop residue), and relating these to N_2O emission episodes. This project is a comparison of the net GHG emissions (N_2O and CO_2 fluxes) in fields managed under conservation-till and conventional-till through year-round studies at the Elora, Ontario (humid) and Glenlea, Manitoba (semi-arid) research stations. Biophysical controls of GHG fluxes will be linked through an array of soil chemical, physical, and microbial measurements. Integration of project results will occur through a modeling approach. Project results will lead to increased understanding of seasonal carbon and nitrogen cycling and identification of strategies for net GHG reduction from agriculture in contrasting soil and climatic conditions. This project is a joint effort between the University of Manitoba, University of Guelph and Agriculture & Agri-Food Canada.

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1. INTRODUCTION

There has been growing concern among many Canadians about the increasing concentrations of greenhouse gases (GHGs) in the atmosphere and the role these gases play in global warming. In response to this concern, Canada, in 1992 joined an international treaty titled “the United Nations Framework Convention on Climate Change”. The objective of this treaty was the “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” (United Nations Framework Convention on Climate Change, 1992). More recently the Kyoto-protocol was added to the treaty; this is an international and legally binding agreement to reduce greenhouse gases emissions world wide. Canada’s ratification of the Kyoto-protocol requires Canada to reduce its GHG emissions to 6% below 1990 levels during the 2008-2012 commitment period.

In 2004, the agriculture sector in Canada accounted for an estimated emission of 55,000 kt CO_2-equivalent (7.2% of the total Canadian emissions of GHGs), and accounted for about 63% and 25% of the total nitrous oxide (N_2O) and methane (CH_4), emissions, respectively (Environment Canada, 2006). Consequently, part of Canada's plan for the achievement of Kyoto-protocol targets includes a substantial role for the agricultural sector. In particular, the adoption of conservation tillage techniques for field crop production has shown the potential for a net reduction of GHGs. The net reduction of GHG emissions through the adoption of conservation tillage is primarily accomplished through the accumulation of soil organic carbon, thereby sequestering carbon dioxide

(CO_2) from the atmosphere into the soil and through the reduction in the consumption of fossil fuels due to fewer field operations being needed (Cole et al., 1997).

Tillage is used in agroecosystems for a wide variety of reasons, predominately for seedbed preparation. Tillage is also used to control weeds, insects and diseases, manage soil moisture and temperature, increase nutrient mineralization and to improve soil structure by alleviating compaction and breaking up soil crusts. In conventional-till systems the soil is intensively disturbed, involving several field operations intended to completely invert the soil and incorporate most of the crop residues and to break up large soil clods to provide a homogeneous seedbed. Conservation-till systems, in comparison to conventional-till systems, use fewer and less intensive tillage operations that disturb a smaller volume of soil and leave a greater portion of the crop residues on the soil surface. In some conservation-till systems the crop is directly seeded into the soil (no-till/zero-till), however, even in these systems there will be some soil disturbance associated with the placement of the seed.

The effectiveness of conservation tillage for mitigating GHG emissions is still uncertain. For example, the effectiveness of these types of tillage systems on carbon (C) sequestration and reducing N_2O emissions varies across Canada, with western Canada showing a greater response compared to eastern Canada (VandenBygaart et al., 2003; Helgason et al., 2005). In addition, the benefits of sequestering C can be offset by relatively small increases in N_2O emissions, as N_2O has a global warming potential 298 times more than CO_2 (Solomon et al., 2007). Consequently, the role of tillage in agroecosystems on the global GHG balance must be fully understood if it is to be used effectively in mitigating the increasing concentrations of GHGs in the atmosphere.

The conversion of cropland from conventional-till systems to conservation-till systems can change many of the physical, chemical, and biological properties of the soil. The underlying assumption using conservation-till systems to sequester C is that these systems leave crop residues on the soil surface which can considerably slow decomposition, leading to an accumulation of organic matter over time (Reicosky et al., 1995). Tillage may also increase soil aeration, which can stimulate microbial respiration (Reicosky et al., 1995). Soils in conservation-till systems often have higher bulk densities and/or higher moisture contents which results in higher water-filled porosity compared to conventional-till systems (Linn and Doran, 1984). This higher-water filled porosity combined with the increase in organic C creates conditions that are more conducive to the production of N_2O through the process of denitrification and nitrification throughout the growing season (Lee et al., 2006). Conversely, conservation-till systems have shown to reduce N_2O emissions during the spring-thaw period due to a lower degree and intensity of freezing because of the insulating effects of the crop residues and snow cover (Wagner-Riddle et al., 2007).

One significant problem identified by Lobb et al. (2007), is the lack of detailed information on tillage systems. The use of qualitative terms such as conventional and conservation tillage to describe tillage practices can be quite problematic as it is ambiguous and a wide range of practices fall into these categories (Lobb et al., 2007). This makes the interpretation of information gathered from different tillage systems and regions difficult. Quantification of tillage practices is especially important in the prairie region of Canada where the different tillage practices used have a narrow range of intensities. Consequently, it is often difficult to differentiate between different tillage systems used in this region and quantification of surface properties will help to better distinguish one practice from another. Detailed information on tillage practices such as the changes in crop residue cover, near-surface porosity, surface roughness, and exposed surface area following a tillage event or sequence is one way the ambiguity of these qualitative terms can be minimized. Soil surface physical properties are closely linked to soil surface processes. Therefore, the characterization and quantification of surface properties may help in part to explain differences in crop growth, soil erosion, hydrology, gas exchange and energy balance between different tillage systems.

Detailed information on surface physical properties may in part be able to explain differences in observed fluxes of GHGs between different tillage systems. By having detailed information about the similarities and differences in soil physical properties and in the GHG flux arising from different tillage systems, the underlying physical mechanisms that control the GHG flux from agricultural soil can be better understood. Understanding these fundamental physical mechanisms will enable the agricultural sector to better identify strategies for the net GHG reduction from agriculture in contrasting soil and climatic conditions. In addition, relationships between the net GHG flux and soil physical properties will allow for the assessment of GHG fluxes based on changes in soil physical properties due to changes in management practices. Therefore, in order to get a national estimate of the net GHG flux from arable land, detailed information and quantification of tillage practices is needed throughout Canada to better quantify the effects of the tillage on the net GHG flux.

Previous research has focused on the long-term impacts of tillage systems (5 to 50 years) and their effects on soil biologic processes and properties, such as soil microbial populations and activity, soil organic matter fractions and their role in the production and emission of GHGs. However, the more immediate impacts of tillage (minutes to days) on physical processes and properties and their role in the production and emission of greenhouse gases are not well understood and are often overlooked. Many past and current C and nitrogen (N) studies neglect or miss these immediate losses following tillage as monitoring equipment often has to be removed to allow the field operations to occur; as well, there can be difficulty in making measurements on the rough and porous surface. The three to six tillage events that occur throughout the year will result in numerous days of unmeasured fluxes. These gaps in the data set can have serious consequences for the study and modeling of the C and N cycles as all C and N inputs and outputs must be accounted for. Quantification of the short-term effects of tillage on the CO_2 and N_2O flux will aid in the understanding of annual C and N cycles.

The gaps in the CO_2 and N_2O flux data set are often filled using interpolation or modeling techniques. Characterization of the short-term effects of tillage on the CO_2 and N_2O flux can provide information on the limitations of these interpolation or modeling techniques in estimating the CO_2 and N_2O flux around tillage events. This will lead to a more accurate estimation of the net GHG flux.

The goal of this research to better understand the cycling of C and N in agroecosystems under different tillage practices, and to identify possible strategies for the net GHG reduction from these systems in the Red River Valley of Manitoba. The three main objectives of this research were to: (1) to examine and characterize the effects of soil disturbance and crop residue and the interaction of these two factors on soil physical properties; (2) to examine and characterize the effects of soil disturbance and crop residue and the interaction of these two factors on the short-term (up to 5 days) CO_2 and N_2O flux; and (3) to relate changes in soil physical properties to the changes in CO_2 and N_2O flux from the clay soils of the Red River Valley, Manitoba. These objectives address the need for more detailed information about tillage systems, a better understanding of the short-term CO_2 and N_2O flux, and a better understanding of the underlying physical mechanisms that control the CO_2 and N_2O flux.

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2. CHARACTERIZATION OF SOIL SURFACE PROPERTIES FOLLOWING SOIL DISTURBANCE OF THE CLAY SOILS IN SOUTHERN MANITOBA

2.1 Abstract

There has been resurgence in the interest of conservation tillage as a way to sequester carbon from the atmosphere to help improve soil quality and as a means to mitigate the increasing carbon dioxide (CO_2) concentration in the atmosphere. However, the term conservation tillage is qualitative and quite ambiguous and refers to a wide range of practices. Currently, there exists a need for the quantification of surface properties following tillage as a means to differentiate among the different practices. In addition, quantification of surface properties may help to explain differences in CO_2 emissions among different tillage practices as surface properties are closely linked to soil surface processes.

This research demonstrated the use of a laser profiling system (LPS) and digital imagery as useful tools in measuring soil micro-topography and crop residue cover following a soil disturbance event. The soil micro-topography was characterized in terms of surface roughness using two geostatistical approaches; semivariance analysis and the mean absolute-elevation-difference method. A univariate statistical analysis was also used. All three procedures used to describe surface roughness were successful in detecting changes in surface roughness due to soil disturbance and the addition of corn residue. There was a definite advantage in using the geostatistical approaches to characterize surface roughness as the indices they provide give insight into the characteristics of the surface roughness. Crop residue cover was measured using digital images and image analysis software to contrast the soil and the crop residues.

The series of field experiments examined the roles of both soil disturbance and corn residue and their interactions on surface roughness, crop residue cover, exposed surface area, and near-surface porosity. Soil disturbance and the addition of corn residue were both found to be significant factors affecting the surface roughness, crop residue cover, exposed surface area, and near-surface porosity. Due to the interaction and added effects of crop residue, it was also demonstrated that the calculated surface area may not be a measure of exposed soil area, but rather it is a combination of soil and residue surface areas. Likewise, the roughness of a surface does not only reflect the soil clods produced during tillage but that of the residue itself. Furthermore, it was demonstrated that the information gathered by the LPS and digital imagery can be used to evaluate surface characteristics arising from different tillage practices.

Keywords Surface characterization; Tillage; Surface properties; Residue cover; Surface roughness

2.2 Introduction

There has been resurgence in the interest of conservation tillage as a means to sequester carbon from the atmosphere, to help improve soil quality, and as a practice to mitigate the increasing CO_2 concentration in the atmosphere. Conservation tillage has a wide range of definitions ranging from a broad definition such as "tillage practices specifically intended to reduce soil disturbance during seedbed preparation" (SOWAP, 2007) to a more site specific definition such as tillage systems that result in the amount of randomly distributed surface residue needed and the amount of surface soil disturbance allowed to reduce erosion, improve soil conditions, reduce CO_2 emissions, increase plant-available moisture, and provide food and cover for wildlife to planned objectives (NRCS, 2005; NRCS, 2006). The use of qualitative terms such as conservation tillage to describe tillage practices can be quite problematic as it is ambiguous and a wide range of practices fall into this category (Lobb et al., 2007). This makes the interpretation of information gathered from different tillage systems difficult. Lobb et al. (2007) have identified the need for better quantification of surface properties following a tillage event in order to better distinguish one practice from another. Detailed information on tillage practices is important in the modeling of environmental processes and in the use of environmental indicators (Lobb et al., 2007).

Tillage can result in immediate and dramatic changes in soil physical properties near the surface. The extent and duration of these changes will be closely related to the degree of soil disturbance and crop residue incorporation which will depend primarily on the implements being used and the soil conditions at the time of the tillage operation. A tillage event may result in changes in surface roughness, crop residue cover, surface area (exposed surface area per land area), near-surface porosity, soil moisture and temperature. Characterization of these properties may be an important component of distinguishing different tillage systems. Surface characterization and quantification may help in part to explain differences in crop growth, soil erosion, hydrology, gas exchange and energy balance between different tillage systems.

Clearly, two of the most important properties to consider in distinguishing tillage systems are surface roughness and crop residue cover. These surface properties play an important role in many soil surface processes. Measurements of surface roughness can provide an estimate of the depressional storage capacity (Kamphorst et al., 2000), which is an important factor in reducing runoff by retaining water and promoting greater infiltration (Freebairn et al., 1989). Surface roughness will also affect surface water flow because roughness elements within the field dissipate the energy of the flow reducing the erosive force of the water and ultimately reducing the amount of soil lost (Helming et al., 1998). Increasing the roughness of the soil surface will also increase the surface area, which can impact the energy balance by altering the amount of solar radiation being intercepted per unit horizontal land area, as well as the albedo (Matthias et al., 2000).

Measurements of crop residue cover can be used to estimate how well the soil is protected from rainfall impact, as the residue will intercept the rain and prevent the detachment of the soil particles. Crop residues will also intercept radiant energy, and effectively reduce the amount of energy available for evaporation at the soil surface; as well, crop residues will increase the resistance to gas exchange (Jolata and Prihar, 1998). In addition, crop residues and surface roughness can alter the wind profile near the surface, especially if there are standing senescent stems (standing stubble) (Jolata and Prihar, 1998). The greater the aerodynamic roughness of a surface, the less the amount of energy available for the convective exchange of water vapour and other trace gases (Jolata and Prihar, 1998) and the detachment and transport of soil particles by wind (Horning et al., 1998). The amount and configuration of crop residue is also an important component in the retention of snow (Smika and Whitfield, 1966).

Currently, there are no standard procedures or methods to measure and quantify crop residue cover and surface roughness following tillage. There are many different tools and techniques that can be used for assessing crop residue cover. The most common techniques include the visual-intercept methods and photographic techniques where the amount of residue is manually estimated (Morrison et al., 1993). These methods, however, can be quite subjective and results can vary among interpreters. More technical methods include sensor-based residue meters which use the difference in the fluorescence and reflectance properties of soil and residue to measure crop residue cover (Morrison et al., 1993). Digital imagery and analytical software can also be used to measure crop residue cover by contrasting the darker coloured soil from the lighter coloured residues (Morrison et al., 1993).

Techniques for obtaining soil micro-relief data include the drop-pin micro-relief meter (Kuipers, 1957), the chain method (Saleh, 1993), point-lasers (Huang and Bradford, 1990), laser profilers (Darboux and Huang, 2003; Bertuzzi et al., 1990a), and analytical photogrammetry (Merel and Farres, 1998). The main disadvantage of the first two methods is the lack of resolution and accuracy. The second disadvantage is that the measuring device comes into direct contact with the soil, and thereby alters the surface being measured. The point-laser method is a non-contact method that can provide accurate and high resolution soil micro-topography profiles. The main disadvantage of this system is that only one point can be measured at a time, so the laser system needs to be put onto a track system which will allow it to progressively move and scan a profile.

In addition to the various techniques in which soil micro-topography data may be obtained, there are several mathematical procedures that can be used to quantify soil roughness. The simplest is a univariate procedure, whereby the soil roughness is characterized by the distribution of soil heights about the mean soil height. The soil roughness can then be described by the range, standard deviation, and the standard error of soil heights. While this can be a useful in describing the changes in surface roughness following a soil disturbance event, the technique is very limited in describing the nature of the soil roughness, as there is no information on the spatial distribution of these soil heights. Alternatively, a geostatistical approach does take into account the spatial distribution of soil heights. A geostatistical approach calculates the variance between points at various spacing intervals. This technique can provide information on the orientation and configuration of roughness features.

Knowledge and standards are needed on instrumentation and methods of analysis used in the characterization of surface properties following tillage. The use of a laser profiler system (LPS) is a relatively new stationary, non-contact technique that can quickly provide accurate and high resolution soil profiles (Rahman et al., 2005). The use of digital images and image analysis software is a quick, easy, and accurate method of determining crop residue cover (Chen et al., 2004). In most cases this is easily accomplished due to the good colour contrast between the light-coloured residue and dark soil. Currently, there is little information on how crop residues affect and interact with tillage on surface properties. The objectives of this study were: (1) to assess the use of the LPS and digital imagery in characterizing surface properties including roughness, area, porosity, and crop residue cover following soil disturbance; (2) to investigate the role of soil disturbance and the addition of corn residue and the interaction of these factors on surface properties; (3) to compare three different mathematical procedures in characterizing soil micro-relief data; and (4) to characterize surface properties and compare a conventional-till system with a reduced-till system.

2.3 Materials and Methods

2.3.1 Study Site

A series of studies was conducted in 2006-2007 at the Glenlea Research Station of the University of Manitoba, Winnipeg, Manitoba (49° 38' N, 97° 9' W). The research station is approximately 16 km south of the city of Winnipeg. The soils at the site consist largely of Red River and Osborne clays (Ehrlich et al.1953). The hydrology of the site ranges from poorly to imperfectly drained soil, largely dependent on micro relief of the landscape (Ehrlich et al., 1953). The surface soil (0-20 cm) has a bulk density of aproximately 1.2 Mg m^{-3} and has a texture of approximately 60 % clay, 35 % silt and 5 % sand. The entire study area was planted to corn (*Zea maize* L.) on 22 May, 2006 [day of year (DOY) 142].

2.3.2 Experiment design

Three separate studies were conducted to investigate the influence of soil disturbance and crop residues on surface roughness and crop residue cover. The first study (Study 1) consisted of simulated tillage with high, low, and no soil disturbance with and without corn residue. The corn plants including the near surface roots (root balls) were removed from the study area on 10 June, 2006 (DOY 161) to allow sufficient time for the soil to reconsolidate before the experiment was initiated. Each plot had an internal dimension (ID) of 1.2 m by 0.72 m and was separated by using frames constructed 0.04 m by 0.15 m (2-inch-by-6-inch) wood studs covered in polyethylene plastic sheeting. The frames were buried 0.10 m into the soil with 0.05 m protruding from the soil surface. During the installation of the frames, care was taken to minimally disturb the soil within each plot, soil was than back-filled against the frames. The frames were used as reference points and for calibration purposes. The treatments were replicated four times and arranged as a randomized complete block design. Each block was completed in its entirety before the next one was started. The study was initiated on 28 August, 2006 (DOY 240).

The high-disturbance treatments consisted of manually tilling the entire plot with a pointed-spade to a depth of 0.20 m and completely inverting the soil and breaking up any soil clods 0.20 m in diameter or larger. The low-disturbance treatments consisted of manually tilling two strips 0.20 m wide, 0.40 m between the centers of the strips, down the length of the plot to a depth of 0.075 m, with a square-mouth spade, taking care to loosen the soil but not to invert it. This was followed by a brisk raking of the entire plot area with a bow rake to produce soil clods 0.05 m or smaller in diameter. The no-disturbance treatments were left undisturbed. For the treatments that included corn residue, 1.74 kg m^{-2} of corn residue (approximately six plants, including roots per plot) was applied evenly by hand over the entire plot. The corn plants were hand chopped with hedge clippers and left to air dry; the length of corn residue ranged from 0.10 m to 0.20 m and the diameter of the corn stalks ranged 10 mm to 25 mm. The corn residue was applied immediately prior to the commencement of the soil disturbance event. Six evenly spaced surface profiles were measured on each plot; each profile was the entire width of the plot. In addition, digital images that encompassed the entire plot were taken.

The second study (Study 2) was a comparison between cultivated and not-cultivated plots. Two separate comparisons were made; the first in an area that had corn residues present, and the second in an area where corn residues were not present. Due to other experimental objectives, the cultivation where residue was present was initiated on 10 May, 2007 (DOY 130) and cultivation where residue was not present was initiated on 18 July, 2007 (DOY 199). The tillage implement used was a field cultivator with 0.20 m sweeps at 0.30 m spacing and 3 rows of spring-tine harrows at 0.10 m spacing and was pulled with a 70 kW tractor. Each plot was the width of one pass with the cultivator (2.3 m) and 20.0 m long. Six evenly spaced locations on each plot were selected and at each location a randomly orientated soil surface profile was measured and a digital image was taken.

The third study (Study 3) was an evaluation of two farm management practices which consisted of conventional-till and reduced-till treatments. Each treatment was subdivided into two field-scale plots each measuring 200 m x 200 m. Both treatments were planted to corn on 22 May, 2006 (DOY 142) and were harvested on 22 October, 2006 (DOY 295); the remaining residue and senescent stems were chopped using a flail mower on 25 October, 2006 (DOY 298). The conventional-till treatment had fall tillage that consisted of disking with a 6.1 m wide offset disk, and spring tillage consisting of a harrowing with a six bar spring-tine harrow. Both treatments were then seeded to faba beans (*Vicia faba* L.), on 11 May, 2007 (DOY 131) with a press-drill air seeder. After fall tillage, six locations on each plot were randomly selected and at each location a soil profile randomly orientated was measured and a digital image was taken. After seeding, 10 locations per plot were randomly selected and two soil surface profiles were measured, one parallel and one perpendicular to the direction of seeding. As well a digital image was taken.

2.3.3 Instrumentation and data analysis

2.3.3.1 Crop residue cover. The percent corn residue cover was measured using digital imagery and Assess: Image Analysis Software for Plant Disease Quantification (Lamari, 2002). A Kodak Easyshare C330® 4.0 mega pixel digital camera was vertically mounted on a tripod approximately 1.5 m from the surface. Each digital image covered an area of 1.8 m^2 and was analyzed for crop residue cover by contrasting the difference in light coloured corn residues with the dark coloured soil. An average residue cover value for each plot was determined by averaging the values obtained with each image.

2.3.3.2 Soil micro-topography. The laser profiling system (LPS) was developed and manufactured by the National Optics Institute (INO), Quebec, Canada. The instrumentation was initially designed for applications such as lumber measurement and classification, pavement rutting measurement, and iron ore pellet measurement. The instrument used was modified so that it could be oriented in such a way that it would be able to measure soil relief. The LPS was mounted on a stationary frame, such that the laser projector was 1.0 m from the surface. The LPS is based on laser profilometry. The laser projector projects a plane of light. When this plane of light crosses an object, the ground, the laser profile is reflected diffusely onto the charge coupled device (CCD) camera at the triangulation angle. The triangulation angle, the angle between the laser plane and camera axis, for this particular LPS was 32.5°. The location of the imaged profile on the camera is then a measure of depth. The manufacturer's standard configurations were a lateral resolution of 640 points per profile, lateral field of view of up to 2.0 m, depth accuracy of 0.1 to 1.0 mm and a depth range of 1.0 m. Figure 2.1

shows the coordinate system of the LPS. Figure 2.2 shows the basic geometry of the LPS and how laser profilometry is used to determine the height of two different objects.

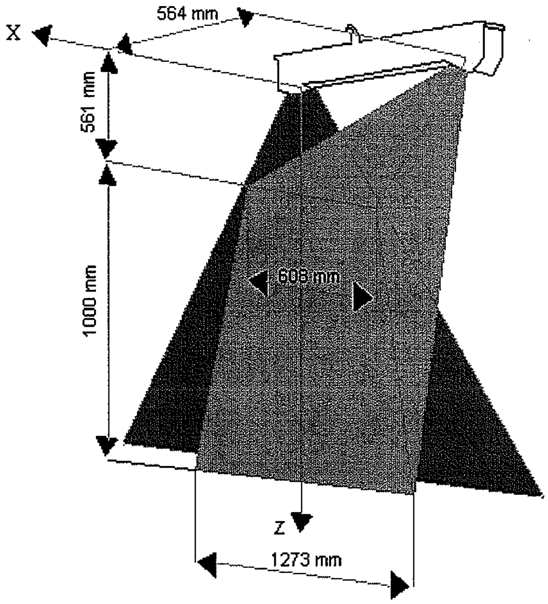

Figure 2.1 Laser profiler coordinate system

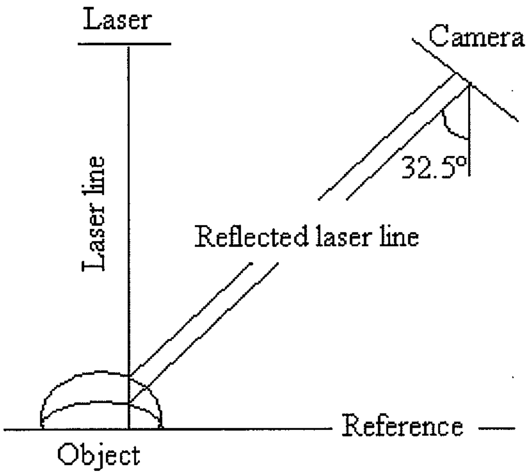

Figure 2.2 Laser profilometry schematic and geometry

Each profile recorded was checked for erroneous points caused by interference from sunlight or other factors. Elevation points that were 300 mm or more away from the average soil height were removed. A constant was then added to each elevation point (z-coordinate) within a profile to adjust the recorded profiles for a given plot to a common vertical reference plane. This ensured consistency for comparing the univariate statistical analysis between plots. For each profile within a plot, a constant was added to the x-coordinate, so that the horizontal spacing between profiles was greater than 200 mm. This ensured that the geostatistical methods would not compare points from different profiles.

The relative increase in soil volume in the top 0.20 m was used as an index of the increase in near-surface porosity. The relative increase in soil volume was determined by calculating the average soil height relative to the top of the frames and compared against the no-residue, no-disturbance treatment within each experimental block.

The soil micro-topography was characterized in terms of surface roughness using three separate procedures: semivariance analysis, mean absolute-elevation-difference method, and by univariate statistical analysis. The semivariance analysis was completed using GS+ 5.1 Geostatistics for the Environmental Sciences software (Gamma Design Software, 2000). The variogram is one of the most basic tools used in geostatistics. The semivariogram is a plot of the semivariance as a function of distance or lag between points of measurement. The semivariance is defined as $v_h = \sum_{i=1}^{n} (Z_i - Z_{i+h})^2 / 2n$, where n is the number of pairs at a given lag interval, Z_i is the elevation at a point and Z_{i+h} is the elevation at some lag number h (Isaaks and Srivastava, 1989). An active lag distance of 200 mm and a uniform lag distance interval of 20 mm were used in the analysis. An exponential model was then fitted to the data. This model is described by three parameters; sill, nugget, and the range, which can be used as roughness indices. The nugget variance represents the value of the variogram when the separation distance between points is equal to zero, although when the separation distance is zero, theoretically the variance should also be zero (Isaaks and Srivastava, 1989). Several factors, such as sampling error and small scale variability may cause the nugget to be larger than zero (Isaaks and Srivastava, 1989). The plateau the variogram reaches, or the model asymptote, is referred to as the sill. As the separation distance between points increases, the semivariance value increases as well, and at some separation distance the semivariance stops increasing with increasing separation distances, the point at which this is reached is referred to as the range (Isaaks and Srivastava, 1989). The range is the distance over which the spatial dependence is evident (Gamma Design Software, 2000)

The mean absolute-elevation-difference method is similar to the semivariance analysis and was developed by Linden and VanDoren (1986). This method produces two roughness indices, the limiting elevation difference (LD) and the limiting slope (LS). This method has been used successfully by Bertuzzi et al. (1990b) and Reicosky and Lindstrom (1993). The mean absolute-elevation-difference model is defined as $\Delta Z_h = \sum_{i=1}^{n} |Z_i - Z_{i+h}| / n$, where n is the number of pairs at a given lag interval, Z_i is the elevation at a point and Z_{i+h} is the elevation at some lag number h. Linear regression is used to relate the relationship between ΔZ_h and lag distance ΔX_h which is described by the equation $\Delta Z_h = 1/[(b(1/\Delta X_h)) + a]$ where a and b are fitted parameters. The parameters a and b were fitted by the regression of $1/\Delta Z_h$ and $1/\Delta X_h$. ΔX_h was limited to a minimum of 20 mm and a maximum of 200 mm, and the roughness index $LD = 1/a$ and

$LS = 1/b$ (Linden and Van Doren, 1986). The LD index gives information at large intervals and the LS index gives information at small intervals (Linden and Van Doren, 1986). In order to use the data collected by the laser profiler, the data needed to be presented in regular grid spacing. Interpolation using point kriging was used to provide values at regular 2-mm intervals. An estimate of surface area can be inferred directly from the trigonometric relationships of the slope parameter LS as $A_{s1} = \left[LS^2 + 1\right]^{1/2}$, where A_{s1} is the exposed surface area per unit horizontal area (Linden and Van Doren, 1986).

The univariate statistical analysis provided three roughness indices, the standard error (STERR), standard deviation (STDEV), and the range of soil heights. An index of exposed surface area, A_{s2}, was also estimated by summing the calculated hypotenuses between adjacent points along a profile and dividing by the horizontal length of the profile. This is very similar to the tortuosity index which is described by the equation $R = L/L_0$, where R is the tortuosity index, L is the actual length of the profile, and L_0 is the projected horizontal length of the profile (Boiffin, 1984).

2.3.4 Statistical analysis

Surface properties data were examined with SAS software (SAS Institute Inc., 2006) for statistical analysis. Analysis of variance was performed using the MIXED procedure with residue application and degree of soil disturbance analyzed as separate factors. Means of each factor were compared using Fisher's Least Significant Difference (LSD) when the F-Value was significant ($P<0.05$). The slice option was used within the MIXED procedure to test the significance of soil disturbance with and without corn residue on the different surface properties. Correlation analysis was performed using the PROC procedure.

2.4 Results

Treatment mean values for the percent corn residue cover following the soil disturbance event and the results from the statistical analysis for Study 1 are found in Table 2.1. The results show that increasing the intensity of soil disturbance results in a significant decrease in the percent corn residue cover. Treatment mean values for the relative increase in near-surface porosity following the soil disturbance event, and the results from the statistical analysis are found in Table 2.2. The results show that the addition of corn residue results in a significant increase in the relative volume. As well, as the intensity of soil disturbance increases there is also a significant increase in the near-surface porosity. The interaction between the residue and soil disturbance factors is not significant suggesting that the factors act in an additive fashion. In addition, each level of soil disturbance was also tested individually for the effect of corn residue addition. The results from this analysis demonstrate that the effect of soil disturbance on the increase in near-surface porosity is significant with and without the addition of corn residues. Only the no-disturbance treatments showed a significant difference between the residue and no-residue treatments.

Table 2.1
Percent corn residue following soil disturbance for Study 1. The mean values are significantly different (P<0.001)

Soil Disturbance	% Residue cover
High	22.7
Low	40.7
No	56.1

Table 2.2

Relative increase in surface porosity compared to the no-residue, no-disturbance treatment following soil disturbance and the addition of corn residue for Study 1

Residue	Relative increase in porosity (%)			
No-residue	11.0a			
Residue	20.1b			
Soil Disturbance		Residue	No-Residue	P-value[1]
High	27.1a	29.4a	24.8a	0.226
Low	11.8b	15.5b	8.1b	0.059
No	7.7c	15.4b	0.0c	0.001
P-values		0.002	<.0001	
Residue	<.0001			
Disturbance	<.0001			
R*D[2]	0.126			

*Means within a column followed by different letters are significantly different ($P<0.05$)

[1] Slice contrast P-value, no-residue vs residue

[2] Residue and soil disturbance interaction

Both the residue and soil disturbance factors were found to have a significant effect on the roughness indices and measurements of surface area with the exception of the nugget and range values calculated in the semivariance procedure (Table 2.3). For some of the roughness indices and measures of surface area, there was a significant interaction between the residue and the soil disturbance factors, indicating that the effect of residue must be looked at considering the level of soil disturbance, and vice versa.

The effect of soil disturbance with and without residue on the different roughness indices and measures of surface area are found in Table 2.4. For the no-residue treatments, all the roughness indices and measures of surface area calculated for the mean elevation difference method and for the univariate statistical analysis showed significant differences, while for the semivariance analysis only the sill index showed significant differences. For the residue treatments, only the semivariance analysis nugget index and the univariate statistical analysis indices, standard deviation, and the range showed significant differences among soil disturbance treatments.

In addition, each level of soil disturbance was also tested individually for the effect of corn residue addition and the results are found in Table 2.4. The results from this analysis show no clear pattern among the different roughness indices, measures of surface area, and methods of analysis. Generally the no-disturbance treatments showed the greatest number of significant differences between the residue and no-residue treatments and the high-disturbance treatments showed the fewest significant differences between the residue and no-residue treatments. For a particular level of soil disturbance where there is a significant difference between the residue and no-residue treatments, the addition of corn residue resulted in a rougher surface and greater surface area.

The correlation coefficients between the different roughness indices, measures of surface area, relative increase in near-surface porosity, and corn residue cover are found in Table 2.5. High correlation values were obtained between the two geostatistic indices LD and the sill, and both of these indices were highly correlated with, A_{s1}, STDEV, STERR, range, and the relative increase in near-surface porosity. In addition, high correlation values were observed between the LS index and the surface area measurements, A_{s1} and A_{s2}. There was also good correlation between the two methods of calculating surface area, A_{s1} and A_{s2}.

Table 2.3

Spatial analysis of surface roughness following soil disturbance and the addition of corn residue for Study 1

	Semivariance analysis			Mean absolute-elevation-difference			Univariate statistical analysis			
	Nugget	Sill	Range (mm)	LD[2] (mm)	LS	A_{S1} (m^2/m^2)	A_{S2} (m^2/m^2)	STERR (mm)	STDEV (mm)	Range (mm)
Residue										
No-residue	35.28a	186.67a	48.59a	13.88a	0.90a	1.73a	1.79a	0.36a	19.09a	118.32a
Residue	9.82b	413.57b	97.34a	24.05b	1.40b	1.40b	1.36b	0.22b	11.42b	67.26b
Soil Disturbance										
High	13.54a	407.44a	52.10a	24.79a	1.32a	1.66a	1.67a	0.39a	19.67a	122.64a
Low	18.20a	249.00b	91.76a	16.33b	1.25a	1.61a	1.56b	0.25b	13.24b	78.59b
No	35.91a	243.93b	75.04a	15.77b	0.89b	1.42b	1.50b	0.24b	12.87b	77.14b
P-values										
Residue	0.009	0.001	0.149	<0.001	<0.001	0.000	<0.001	0.000	<0.001	<0.001
Disturbance	0.110	0.045	0.608	0.003	0.001	0.020	0.002	0.001	<0.001	<0.001
[1]R*D	0.008	0.091	0.834	0.087	<0.001	0.001	<0.001	0.095	0.006	0.016

*Means within a column followed by different letters are significantly different ($P<0.05$)

[1] Residue and soil disturbance interaction

[2] LD; limiting elevation difference, LS; limiting slope, A_{S1}; surface area, A_{S2}; surface area, STERR; standard error, STDEV; standard deviation

Table 2.4

Spatial analysis for treatments with and without crop residue for Study 1

	Semivariance analysis								
	Nugget			Sill			Range (mm)		
Soil Disturbance	Residue	No-residue	P-value[1]	Residue	No-residue	P-value[1]	Residue	No-residue	P-value[1]
High	9.3a	17.8a	0.569	451.7a	363.2a	0.365	37.1a	67.1a	0.596
Low	27.2a	9.2a	0.241	344.4a	153.6b	0.062	54.0a	129.6a	0.194
No	69.4b	2.4a	<0.001	444.6a	43.3b	0.001	54.7a	95.4a	0.476
P-Value	0.003	0.589		0.467	0.013		0.938	0.544	

	Mean absolute-elevation-difference								
	LD[2] (mm)			LS			Surface Area (m^2/m^2)		
Soil Disturbance	Residue	No-residue	P-value[1]	Residue	No-residue	P-value[1]	Residue	No-residue	P-value[1]
High	27.4a	22.2a	0.145	1.4a	1.3a	0.344	1.7a	1.6a	0.402
Low	20.7a	12.0b	0.022	1.3a	1.2a	0.253	1.7a	1.6a	0.295
No	24.0a	7.5b	<0.001	1.5a	0.3b	<0.001	1.8a	1.0b	<0.001
P-Value	0.177	0.002		0.567	<0.001		0.534	<0.001	

	Univariate statistical analysis											
	Surface Area (m^2/m^2)			Standard Deviation (mm)			Standard Error (mm)			Range (mm)		
Soil Disturbance	Residue	No-residue	P-value[1]	Residue	No-residue	P-value[1]	Residue	No-residue	P-value[1]	Residue	No-residue	P-value[1]
High	1.8a	1.6a	0.001	21.5a	17.8a	0.074	0.4a	0.4a	0.112	140.2a	105.1a	0.007
Low	1.7a	1.4b	<0.001	16.1b	10.4b	0.010	0.3a	0.2b	0.061	96.9b	60.3b	0.006
No	1.9a	1.1c	<0.001	19.7ab	6.1c	<0.001	0.4a	0.1b	<0.001	118.0ab	36.3b	<0.001
P-Value	0.107	<.0001		0.039	<0.001		0.051	0.001		0.006	<0.001	

*Means within a column followed by different letters are significantly different ($P<0.05$)

[1] Slice contrast P-value, no-residue vs residue

[2] LD; limiting elevation difference, LS; limiting slope

Table 2.5

Calculated correlation coefficients between roughness indices, surface area, crop residue cover and the relative increase in surface porosity for Study 1

	Other parameters		Semivariance analysis			Absolute-elevation-difference			Univariate statistical analysis			
	Porosity[1]	% Cover	Nugget	Sill	Range	LD	LS	A_{S1}	A_{S2}	STDEV	STERR	Range
Porosity	1.00											
% Cover	0.18	1.00										
Nugget	0.16	**0.65**	1.00									
Sill	**0.63**	0.48	0.37	1.00								
Range	-0.35	-0.25	0.05	-0.10	1.00							
LD	**0.71**	0.46	0.30	**0.97**	-0.27	1.00						
LS	0.50	0.54	0.38	0.47	-0.34	0.50	1.00					
A_{S1}	0.45	0.54	0.37	0.43	-0.36	0.45	**0.99**	1.00				
A_{S2}	0.55	**0.77**	0.46	**0.73**	-0.33	**0.73**	**0.86**	**0.84**	1.00			
STDEV	**0.78**	0.41	0.33	**0.91**	-0.26	**0.97**	**0.53**	0.49	**0.71**	1.00		
STERR	**0.76**	0.50	0.36	**0.95**	-0.28	**0.98**	**0.60**	**0.56**	**0.79**	**0.97**	1.00	
Range	**0.80**	0.51	0.33	**0.89**	-0.32	**0.91**	**0.64**	**0.60**	**0.83**	**0.91**	**0.96**	1.00

Bold values indicates significance at $P<0.05$

[1] Porosity; relative increase in surface porosity, % Cover; % crop residue cover, LD; limiting elevation difference, LS; limiting slope, A_{S1}; surface area, A_{S2}; surface area, STERR; standard error, STDEV; standard deviation,

The summary of percent corn residue cover, roughness indices and measured surface area for Study 2 are found in Table 2.6. In comparison to the not-cultivated plots, the cultivated plots showed a dramatic reduction in the percent corn residue cover, when residue was present, and all the roughness indices showed an increase in both surface roughness and surface area. In comparison to the no-residue plots, the residue plots showed a rougher surface and greater surface area. These differences were more apparent for the not-cultivated plots.

The summary of percent crop residue cover, roughness indices, and measured surface area for Study 3 is found in Table 2.7. The measurements taken post-tillage in the fall of 2006 show some similarities with the measurement made in Study 2 including the reduction in crop residue cover following tillage and most of the roughness indices, with the exception of the LS index, show an increase in surface roughness. Both measurements of surface area showed little difference between treatments. The measurements taken post-seeding in the spring 2007 showed a difference in residue cover between the two treatments with the conventional-till treatment having lower residue coverage. The reduced-till treatment in comparison to the conventional-till treatment had a slightly rougher surface with greater surface area. However, the differences were very small and as much variation exists within replicates of the same treatment as between treatments.

Table 2.6

Summary of surface characterization measurements for Study 2

		Semivariance analysis			Mean absolute-elevation-difference			Univariate statistical analysis			
Treatment[1]	% Residue cover	Nugget	Sill	Range	LD[1] (mm)	LS	A_{S1} (m^2/m^2)	A_{S2} (m^2/m^2)	STERR (mm)	STDEV (mm)	Range (mm)
					Residue						
Cultivated	39.0	1.0	731.7	59.2	33.6	1.3	1.6	1.9	0.4	22.6	139.8
Not-cultivated	89.6	20.6	147.6	47.8	13.3	1.0	1.4	1.5	0.2	11.4	75.8
					No-residue						
Cultivated	0.0	8.0	526.9	71.5	29.5	0.8	1.3	1.6	0.2	20.0	129.3
Not-cultivated	0.0	0.6	23.7	40.9	5.1	0.3	1.0	1.1	0.1	4.8	61.7

[1] LD; limiting elevation difference, LS; limiting slope, A_{S1}; surface area, A_{S2}; surface area, STERR; standard error, STDEV; standard deviation

Table 2.7

Summary of surface characterization measurements for Study 3

			Semivariance analysis			Mean absolute-elevation-difference			Univariate statistical analysis			
Plot	Treatment[1]	% Residue cover	Nugget	Sill	Range	LD[2] (mm)	LS	A_{S1} (m^2/m^2)	A_{S2} (m^2/m^2)	STERR (mm)	STDEV (mm)	Range (mm)
						Fall tillage						
SE[3]	CvT	40.3	26.0	462.9	110.0	21.0	0.7	1.2	1.6	0.3	19.1	136.6
NE	CvT	45.9	26.0	762.0	130.4	28.2	0.8	1.3	1.7	0.4	22.0	132.7
SW	RT	90.7	57.9	255.4	97.3	13.4	1.2	1.6	1.7	0.2	12.5	99.2
NW	RT	89.5	25.1	325.2	84.7	15.9	0.6	1.2	1.5	0.2	15.1	127.4
						Spring tillage						
SE	CvT	10.3	0.1	288.4	57.9	19.6	0.7	1.2	1.5	0.1	14.7	125.0
NE	CvT	9.5	0.1	228.0	51.4	17.8	0.8	1.3	1.5	0.1	13.5	130.3
SW	RT	30.0	23.0	382.8	68.7	22.1	0.9	1.4	1.9	0.2	17.2	149.6
NW	RT	17.2	5.0	335.0	54.7	20.4	0.8	1.3	1.7	0.1	15.8	149.0

[1] CvT; conventional-till, RT; reduced-till

[2] LD; limiting elevation difference, LS; limiting slope, A_{S1}; surface area, A_{S2}; surface area, STERR; standard error, STDEV; standard deviation

[3] SE;south east, NE; north east, SW; south west, NW; north west

2.5 Discussion

2.5.1 Surface characterization for Study 1

2.5.1.1 Residue cover. The reduction in corn residue cover in relation to the level of soil disturbance, as seen in Study 1, is a direct result of the degree of inversion of soil that occurred during the soil disturbance event. The high-disturbance treatment which completely inverted the soil resulted in the burial of a large proportion of the residue. In contrast, the low-disturbance treatment, since only a small proportion of the soil was inverted, buried a smaller percentage of the residue.

2.5.1.2 Near-surface porosity. The effect of soil disturbance on the relative increase in volume is due to the disruption of the soil matrix and the creation of large voids that are a result of the poor reconsolidation of soil clods. The larger and more irregularly shaped soil clods will create larger voids because they do not pack together as well. This is consistent with the findings from Study 1, in which the high-disturbance treatments had the largest soil clods and the greatest relative increase in volume followed by the low-disturbance treatment. Soil disturbance has an immediate affect on inter-aggregate porosity (macro-porosity), whereas changes inter-aggregate porosity tends to reflect long-term tillage practices (Schafer and Johnson, 1982). The effect of corn residue burial can also be seen in the relative increase in near-surface porosity that occurred during the soil disturbance. The amount of the added residue is partially responsible for the increase, as well, depending on the nature of the residue, senescent stems will in part prevent the reconsolidation of soil clods as the stems will prop up soil clods. These effects of residue incorporation can be seen in this Study 1, as the statistical analysis showed that both soil disturbance and the addition of corn residue act in an additive fashion. The residue treatments consistently had a higher increase in the relative porosity due to the added amount of the corn residue. Theses immediate effects of the corn residue on the inter-aggregate porosity will begin to diminish over time as the corn residue begins to decompose.

2.5.1.3 Surface roughness. The semivariance analysis showed that the nugget index was able to detect changes in surface roughness as result of the addition of corn residue. This may be due to the fact that the nugget variance represents variation not spatially dependent over the range examined (Gamma Design Software, 2001). The placement of the corn residue on the soil surface was random and is reflected in the nugget value. As the intensity of soil disturbance increases, the amount of corn residue left on the surface decreases, and the random orientated roughness of the corn residue is being replaced by the more systematic roughness left by the soil disturbance.

The semivariance range index showed no significant difference among any of the treatments. This is primarily due to one plot having a range value that was an order of magnitude greater than the range value of the three other plots that received the same treatment. With the removal of this value, the statistical analysis then shows that both residue and soil disturbance factors and their interaction are significant. There were significant differences found only between the levels of soil disturbance for the no-residue treatments. The no-disturbance treatments had the highest range value followed by the high-disturbance and lastly the low-disturbance treatments. Both the high- and no-disturbance treatments with no residue had significantly higher range values than the residue treatments; there was no significant difference between the residue and no-residue low-disturbance treatments. Since the range value represents the distance over which the spatial dependence is evident, it should be indicative of the size of the roughness features in the horizontal plane (x-axis, Figure 2.1) (Isaaks and Srivastava, 1989).

Both the residue and soil disturbance factors were found to have a significant effect on the sill index with the residue treatments and the high-disturbance treatments having larger sill values. As well, there was no significant interaction between the residue and the soil disturbance suggesting that the factors act in an additive fashion. There were significant differences found only between the levels of soil disturbance for the no-residue treatments. The sill of the variogram model represents the spatially independent variance and is related largely to the variation in the vertical plane (z-axis, Figure 2.1) (Isaaks and Srivastava, 1989).

The no-residue, no-disturbance treatment probably had slight undulations due to the remnants of crop rows. These undulations would be long in the horizontal plane accounting for the higher range value, and small in the vertical direction accounting for the low sill value. The no-residue, low-disturbance treatment produced small and fairly uniform clods of soil. These clods would be small in the horizontal direction accounting for the small range value and medium in the vertical direction accounting for the mid sill value. The no-residue, high-disturbance treatment produced large clods; these large clods were medium in the horizontal direction accounting for the mid range value and large in the vertical direction accounting for the high sill value. The corn residue added additional roughness features in both the horizontal and vertical planes which resulted in the lower range and higher sill values. The interpretation of the geostatistical parameters was verified by the creation of hypothetical soil profiles that were derived from the same data set, but were transformed to alter the amplitude and period of the roughness features (Appendix B).

Analysis of the mean-absolute-elevation-difference data showed that the LD index displayed nearly identical results to that of the sill index and the statistical analysis of the LS index follows the same pattern and the range index. This is to be expected as both the LD and the sill indices give an indication as to the value at which the models plateau (Isaaks and Srivastava, 1989; Linden and Van Doren, 1986). Similarly, both the LS and the range indices give an indication as to what horizontal spacing the model reaches the plateau (Isaaks and Srivastava, 1989; Linden and Van Doren, 1986). However, smaller LS values would be representative of larger range values and vice versa. Both the LD and LS indices showed no significant changes between the residue treatments. However, within the no-residue treatments the LD index was able to detect significant differences between the high-disturbance treatment and the low- and no-disturbance treatments and the LS index was able to detect significant differences between the no-disturbance treatment and the high- and low-disturbance treatments. This suggests that the LS index is more sensitive to small-scale changes and the LD index is more sensitive to large-scale changes.

The standard deviation, standard error, and the range indices calculated in the univariate statistical analysis all demonstrate that both residue and soil disturbance are significant factors. The standard deviation and the range indices show a significant interaction between the residue and soil disturbance factors, while the standard error did not show a significant interaction between the two factors. Both the standard deviation and the range indices show similar patterns within the residue treatments where the low-disturbance treatment resulted in the smoothest surface. This pattern occurs with most other roughness indices but is most evident with the standard deviation and range indices. This pattern is a result of the breaking up and the partial incorporation of residue into the soil during the soil disturbance event, resulting in a more uniform surface. The standard deviation index was the most sensitive of the univariate indices for distinguishing between the different levels of soil disturbance. However, the range was the most sensitive univariate index for distinguishing between the residue and no-residue treatments.

The univariate procedure may be able to distinguish differences in roughness due to corn residue and soil disturbance; however, it is very limited in describing the nature of the soil roughness, as there is no information on the spatial distribution of these soil heights. As well, the standard deviation and the standard error indices are based on the assumption of normally distributed values of measured soil heights, which is often not the case. However, a geostatistical approach does take into account the spatial distribution of soil heights and can provide more information on the features and attributes of the roughness elements on the surface. The choice of the methodology chosen to quantify surface roughness will depend on its intended use (Schafer and Johnson, 1982). For example, directional characteristics, such as ridges, are important in predicting erosion and infiltration but not quantified by a univariate indices and geostatisical indices in this case may be more appropriate (Schafer and Johnson, 1982).

The lack of significant changes in surface roughness when corn residue was present indicates that the source of the roughness is changing from the corn residue to the soil clods being produced as a result of the soil disturbance. This needs to be taken into consideration as the two different sources of surface roughness, soil or residue, will have different behavioral properties. Due to these behavioral differences surface roughness arising soil or residue will impact erosional, hydrological and gas exchange processes that occur at the surface differently (Kamphorst et al., 2000; Horning et al., 1998).

2.5.1.4 Surface area. Both methods of calculating surface area, A_{s1} and A_{s2}, show similar results with the addition of residue and soil disturbance significantly increasing surface area. In addition, there was a significant interaction between the residue and soil disturbance factors. A_{s1} and A_{s2}, showed no statistical difference in surface area between the residue treatments even though the amount of residue on the surface varied between the different soil disturbance treatments. This indicates that as soil disturbance increases the source of the surface area shifts from residue to exposed soil even through there is no increase in total surface area. The fact that the soil disturbance results in greater expose soil surface has a large impact on the energy balance, evaporation and the exchange of trace gases at the surface (Matthias et al., 2000; Jolata and Prihar, 1998). The biggest difference between the two methods of calculating surface area is that the A_{s2} method found significant differences in the no-residue treatments between all three levels of soil disturbance, as well as significant differences between the residue and no-residue treatments within all levels of soil disturbance. A_{s2} may be a more robust way of estimating surface area as it is a direct measurement, whereas A_{s1} is inferred from a model parameter.

2.5.1.5 Correlation between surface characterization measurements. Between the two geostatistical approaches there was a high degree of correlation between LD and the sill indices. This was expected since both indices give the value at which the variogram plateaus. The LS and the range indices have a poor correlation; however, removal of the one anomalous range value greatly increases the correlation to -0.74 (significant at $P<0.05$). This again was expected as both indices give the horizontal spacing at which the plateau is reached (Isaaks and Srivastava, 1989; Linden and Van Doren, 1986). The lack of a perfect correlation between the two geostatistical approaches is likely due to poor fitting of the variogram model to the data and due to smoothing of the soil profiles as result of the interpolation needed so the data set could be used in mean absolute-elevation-difference analysis.

There was fairly good agreement between the two methods of calculating surface area. The differences arise due to the fact that A_{s1} is inferred from a model parameter and there is some error associated with fitting the model to the data set, whereas A_{s2} is a more direct measurement. There was also a correlation between A_{s2} and the percent residue cover. This is consistent with the analysis of variance which showed that the addition of residue was a significant factor affecting the surface area; as the amount of residue on the surface increases so does the surface area. There is also good correlation between A_{s2} and the LS index; this was to be expected since both indices use information gathered at small intervals and are dependent on both clod size and frequency (Bertuzzi et al., 1990b).

The high degree of correlation between the geostatistical indices; LD and sill and the univariate indices; standard deviation, standard error, and range; is due to the fact that all of these indices measure the scale or magnitude of surface roughness (Bertuzzi et al., 1990b). As well, the above indices are also fairly well correlated with the relative increase in near-surface porosity. This demonstrates that these indices can be used to provide insight into the increase in near-surface porosity after tillage when pre-tillage reference points are not available.

2.5.2 Surface characterization for Study 2

The findings of the second study are similar to those of the first. The cultivated plots were very similar to the high-disturbance treatments and the not-cultivated plots were similar to the no-disturbance treatments. In both studies, the disturbance event increased surface roughness and surface area. Also, the role of corn residue was similar in both studies, with the presence of residue increasing both surface roughness and surface area. The biggest difference between the two studies was that the residue, not-cultivated plot showed a smoother surface in comparison to the residue, cultivated plot. This is not consistent with Study 1 where no significant difference was found between the high- and no-disturbance treatments when residue was present. This difference may indicate that residue addition or soil disturbance in Study 1 did not accurately reflect field conditions and operations.

2.5.3 Surface characterization for Study 3

The surface characterization measurements taken post-fall tillage for Study 3 are similar in many aspects to the results found in Study 2, especially with respect to the roughness indices indicating that the reduced-till treatment was smoother and had a higher percentage of residue cover than the conventional-till treatment. It is unclear as to why there is little difference in the LS values and surface area measurements between the two treatments. After planting, the differences between the two treatments become less obvious, as much of the corn residue had decomposed since the fall and both treatments were planted using the same equipment. The largest difference seen between the two treatments was the amount of residue cover. However, there was large variation in the residue measurements made in the reduced-till treatment. This was a result of spring flooding during the snow melt which caused a lot of residue to float away and collect in localized depressions both within and outside of the study area. For the reduced-till treatment the crop residue cover ranged from greater than 50% to less than 10%. This type of information is important to consider as it represents a redistribution of carbon and nitrogen and other nutrients within the experimental area. Furthermore, subsequent sampling schemes need to take into consideration the non-uniform conditions that exist in order to avoid bias results.

The small differences seen in the surface roughness measurements and surface area measurements may have two explanations. Firstly, the greater levels of crop residues on the conventional-till treatment, as demonstrated previously, can increase both roughness and surface area. Secondly, the harrowing on the conventional-till treatment broke up and loosened the soil prior to planting and smaller clods were produced as a result of the planting operation.

The major difference between the study using manual tillage and the studies using tillage equipment is the smaller LS and larger range values that are associated with the latter. These values may represent the furrows that are created by the tillage implements and wheel tracks or in the cases of the plots that received no tillage it may represent the corn rows. These are more prominent features in comparison to the soil clods which are being reflected in the range and LS values. These features were not present in the initial study due to the manual tillage.

2.5.4 Implications and areas for further research

This research has demonstrated that the LPS can be a useful tool in measuring changes in soil micro-topography following tillage. Similarly, digital imagery and image analysis software can be useful tools in measuring changes corn residue cover following tillage. These measurement techniques can be used to evaluate different conservation tillage implements as well as farm management practices. For this to be a feasible endeavor some of the technical challenges of taking the LPS into remote areas, including issues of mobility and power supply, must first be overcome. In addition, the LPS software needs to be improved, primarily to record surface elevation points at a uniform spacing. This improvement would eliminate the need for the interpolation of the data set to be used in mean absolute-elevation-difference method. However, if the data are not collected at regular intervals, the use of the semivariance analysis can provide similar results to the mean absolute-elevation-difference method without having elevation data presented at a regular spacing. This research also identifies that corn residues are an important factor to consider when looking at both surface roughness and surface area. This signifies the importance of not only the tillage intensity and its effect of surface properties but also the interaction or added effects of corn residue.

Due to the fine textured soils and periodic episodes of excessive soil moisture that exist in the Red River Valley, there is a narrow range of tillage practices that are used. However, the techniques demonstrated in this research were still able to detect difference in surface properties between tillage practices. Therefore, in regions where more diverse tillage practices exist, differences in surface properties observed among tillage practices may be more pronounced. Measurements of surface properties may, in part, be able to explain differences in crop growth, soil water content, soil temperature, snow retention, and the net GHG flux observed among different tillage systems and regions as these factors are related to surface conditions (Linden and Van Doren, 1986).

In this series of experiments, surface characterization was only carried out immediately after a soil disturbance event; the surface properties would likely change over time due to precipitation, freeze-thaw cycles, biological activity and other field operations (Bertuzzi et al., 1990b). As such, surface characterization measurements may be needed throughout the year to better understand how surface properties change over time and how it may affect soil surface processes. The results from Study 1 demonstrated that soil disturbance had little effect on measurements of surface roughness and surface area when residue was present. However, soil disturbance changed the source of the surface roughness and surface area moving from being dominated by residue to being dominated by soil as the soil disturbance intensity increased. Due to the behavioral differences in surface processes of the residue and soil, an important research objective would be to combine the crop residue cover and micro-topography measurements to be able to determine the proportion of surface area and surface roughness attributed to either soil or the residue.

2.6 Conclusions

This research demonstrates that information gathered by the LPS and digital imagery can be used to assess and evaluate surface characteristics arising from soil disturbance, the presence of crop residue, and the interaction of these two factors. Both soil disturbance and presence of crop residue were found to be significant factors in determining the surface roughness, surface area, crop residue cover, and the relative increase in near-surface porosity. Due to the interaction and added effect of crop residue on soil disturbance, it was also demonstrated that the calculated surface area may not be a measure of exposed soil area, but rather, it is a combination of both soil and residue. Likewise, the roughness of the soil surface does not only reflect the soil clods produced during tillage, but that of the residue itself. The relationship between the relative increase in near-surface porosity and the roughness indices enables estimates of the increase in near-surface porosity to be made after tillage without establishing reference points.

All three statistical procedures used to describe surface roughness were successful in detecting changes in roughness due to soil disturbance and the addition of corn residue. There was a definite advantage in using a geostatistical approach to characterize soil topography as the indices they provide have more physical meaning and provide insight into the nature of the surface roughness. Although the univariate procedure was able to detect significant changes due to soil disturbance and the presence of corn residue, unlike the geostatistical procedures, it is dependent on the distribution of soil heights. Furthermore, it was demonstrated that the information gathered by the LPS and digital imagery can be used to quantify and evaluate surface characteristics arising from different tillage practices.

An important future research objective would be the continued integration of the measurements of surface roughness, surface area, near-surface porosity, and of crop residue cover into models to be able to predict the fluxes of greenhouse gas (GHG) from agricultural ecosystems. Detailed information on surface properties following tillage will enable researchers to better understand the observed differences or similarities in the fluxes of GHG arising from different tillage systems. Relating changes in fluxes of GHG to changes in soil physical properties resulting from tillage will allow deeper study of the principles that govern the exchange of these gases. This information will allow the development of tillage equipment and practices for the net reduction of GHG from agriculture.

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3. SHORT-TERM CARBON DIOXIDE AND NITROUS OXIDE FLUX FOLLOWING TILLAGE OF CLAY SOILS IN THE RED RIVER VALLEY IN SOUTHERN MANITOBA

3.1 Abstract

The immediate impacts of soil disturbance through tillage on soil physical properties and processes and their role in the production and emission of greenhouse gases are not well understood. There has been some research investigating the short-term effects of tillage on the flux of carbon dioxide (CO_2), however, the short-term effects of tillage on the flux of nitrous oxide (N_2O) have not been studied. The immediate impacts of tillage on the N_2O flux are important to understand as N_2O has a larger global warming potential compared to CO_2. The objectives of this series of experiments were to characterize the short-term (5 days) effects of soil disturbance and corn residue on the CO_2 and N_2O flux and to relate the changes in the fluxes to changes in soil physical properties. The short-term CO_2 flux following a soil disturbance event was characterized by an immediate increase in the CO_2 flux following the soil disturbance and quickly dissipated within the first 24 hours. Disturbing the soil to a depth of 0.2 m resulted in an immediate 3- to 4-fold increase in the CO_2 flux after which the soil system reaches a new equilibrium with a higher CO_2 flux than if the soil had not been disturbed. The addition of corn residue was found to be a significant cause of the CO_2 lost throughout the 5-day observation period regardless of the level of soil disturbance. However, the incorporation of the residue through the action of soil disturbance was found to be a more important factor than either soil disturbance or the addition of residue in the cumulative loss of CO_2. The initial CO_2 flux following soil disturbance and the cumulative CO_2 loss were closely related to changes in surface roughness, surface area, crop residue cover, and depth of soil disturbance. Generally, the soil disturbance treatments that resulted in a rougher surface, greater surface area, greater residue incorporation, and disturbed the greatest volume of soil had the highest initial fluxes of CO_2 and the greatest cumulative CO_2 loss following soil disturbance event. The effects of residue and soil disturbance were much stronger for the CO_2 flux than N_2O flux. The N_2O flux following soil disturbance was highly variable; however, there was some indication that the N_2O flux, under certain soil conditions, can result in an immediate increase in the N_2O flux which will quickly dissipate over time.

Keywords Tillage; Carbon dioxide; Nitrous oxide; Soil surface properties; Greenhouse gas fluxes

3.2 Introduction

Agriculture has been identified as a source of atmospheric carbon dioxide (CO_2) and nitrous oxide (N_2O). The manner in which agricultural land is managed can have an appreciable impact on the gaseous loss of both carbon (C) and nitrogen (N) (Cole et al., 1997). Due to the concerns over the increasing concentrations of CO_2 and N_2O in the atmosphere and their global warming potential, there is a need to better understand agriculture's role in the cycling of C and N. Understanding how different farm management practices affect the C and N dynamics is important in developing best management strategies to help mitigate the emission of CO_2 and N_2O to the atmosphere.

Tillage has been identified as a key management practice in controlling CO_2 emissions from agricultural ecosystems (Kern and Johnson, 1993; Reicosky and Lindstrom, 1993). Previous research has focused on the long-term impacts of tillage systems (5 to 50 years) and their effects on soil biological processes and properties, such as soil microbial populations and activity and soil organic matter fractions and their role in the production and emission of greenhouse gases (GHGs) (Flach et al., 1997). However, the more immediate impacts of tillage on physical processes and properties and their role in the production and emission of GHGs are not well understood and are often overlooked.

A few studies have investigated the immediate losses of CO_2 and water vapour (H_2O) following tillage and have focused primarily on quantifying the influence of tillage operations on the fluxes of these gases. The short-term tillage induced losses of CO_2 and H_2O were characterized by a large and pronounced initial peak in the flux; within 10 hours to 5 days the flux had returned to approximately the rates observed prior to the tillage event (Reicosky and Lindstrom, 1993; Ellert and Janzen, 1999; Calderón et al., 2001). There have been few studies investigating the short-term impacts of tillage on the N_2O flux (Carmo et al., 2007; Baggs et al., 2006; Yamulki and Jarvis, 2002). While there are many similarities between the physical mechanisms of CO_2 and N_2O gas exchange at the surface, the chemical and biological processes of nitrification, denitrification, and respiration, and their responses to environmental conditions, are quite different. The short-term impact of tillage on the production and emission of N_2O is not well understood. Many past and current C and N studies neglect or are unable to capture these immediate losses following tillage as monitoring equipment often has to be removed to allow the field operations to occur. As well, there can be difficulty in making chamber measurements on the rough and porous surface. This information is vital in the study and modeling of C and N cycles, as all C and N inputs and outputs must be accounted for.

Crop residue in agricultural ecosystems has primarily been studied from the biological perspective. The effect of crop residue incorporation through tillage adds a fresh source of organic matter for the microbial population. However, the incorporation of crop residue into the soil will also have an immediate effect on the physical properties of the soil. Reicosky and Lindstrom (1993) and Ellert and Janzen (1999) both suggested that the changes in physical properties within the tilled-layer played a key role in the tillage-induced flush of CO_2 that was observed. Therefore, crop residues may also have some effect on the tillage-induced flush of CO_2 above and beyond the effect of adding new sources of organic matter. Tillage incorporation of residue will likely have a bigger impact on the longer term CO_2 loss as the residue decomposes.

Little attention has been given to how changes in soil physical properties from tillage relate to the short-term CO_2 flux. The immediate changes to soil physical properties that may influence the short-term GHG fluxes from agricultural soils following a soil disturbance event include effects on surface roughness, surface area (exposed surface area per land area), near-surface porosity, and crop residue cover. The extent of these changes is largely related to the method of tillage and the presence of crop residues. Reicosky and Lindstrom (1993) reported that the magnitude of the short-term CO_2 flux was more related to the depth of soil disturbance and the surface roughness than to the degree of residue incorporation. However, the techniques used in the characterization of the surface properties had poor spatial resolution and accuracy. In addition, there was no in-depth examination of how the surface properties related to the short-term CO_2 flux.

Understanding how changes in soil physical properties affect the short-term GHG flux will enable the agricultural sector to develop tillage implements and management practices that minimize the losses of C and N from the soil.

The Red River Valley region in southern Manitoba, is characterized by a level to very gently sloping (0-<2%), clayey glaciolacustrine plain. The soil properties, landscape, and climatic conditions of the Red River Valley region create a unique agricultural environment which is reflected in the farm management practices. The largest management constraints in this region arise primarily from the high clay content and frequent episodes of excessive moisture in the spring. Consequently, extensive tillage is common, and conservation tillage methods have not been widely used in the region (Huffman et al., 2005). It is therefore important to understand how tillage affects C and N dynamics in this unique environment.

Soil disturbance can considerably alter soil physical properties near the surface and, thereby, dramatically change the distribution within the soil and the emission of CO_2 and N_2O from the surface. A tillage-induced loss of CO_2 or N_2O may be the result of several factors including changes in surface roughness, crop residue cover, surface area, and near-surface porosity that occur following a soil disturbance events. The extent of these changes in surface properties, and therefore, the magnitude of the fluxes will depend on the nature of the soil disturbance event including the type of implements used and the speed and depth at which they are operated. The physical properties of the soil and the amount and type of crop residue on the surface prior to tillage may also have an impact on the extent of the changes in soil surface properties following tillage event. In addition, the soil physical and biological properties prior to the soil disturbance event will also have an effect on the magnitude of the tillage induced loss of CO_2 and N_2O. In this study, the focus is on the short-term effects (minutes to days) on the GHG flux following a soil disturbance event. The objectives of this study were: (1) to characterize the short-term CO_2 and N_2O flux (5 days) following a soil disturbance event on the clay-rich soils of the Red River Valley, Manitoba, Canada; (2) to investigate the role of soil disturbance and corn residue, and their interaction on short-term CO_2 and N_2O flux; and (3) to link changes in surface properties, including surface roughness, surface area, near-surface porosity, and crop residue cover that occur as a result of soil disturbance and the addition of corn residue, to the short-term CO_2 and N_2O flux.

3.3 Materials and Methods

3.3.1 Site description

A set of studies was conducted in 2006-2007 at the Glenlea Research Station of the University of Manitoba, Winnipeg, Manitoba (49° 38' N, 97° 9' W). The research station is approximately 16 km south of the city of Winnipeg. The soils at the site consist largely of Red River and Osborne clays (Ehrlich et al., 1953). The hydrology ranges from poorly to imperfectly drained soils, which is largely dependent on micro relief of the landscape (Ehrlich et al., 1953). The soil (0-20 cm) had a bulk density of 1.2 Mg m^{-3} and a texture of 60 % clay, 35 % silt and 5 % sand. The dominate clay mineral group found at the site are 2:1 smectites. The average (0-20 cm) soil organic carbon content was 3.2 % as determined by the loss-on-ignition method (Nelson and Sommers, 1996). The average NO_3^-/NO_2^--N and NH_4^+-N content was 71.2 mg N $kg^{-1}_{\text{oven dried soil}}$ and 7.4 mg N $kg^{-1}_{\text{oven dried soil}}$, respectively as determined by the 2 M KCL extraction method (Mulvaney, 1996).

The entire study area was planted to corn on 22 May, 2006 (DOY 142). Daily climatic data including precipitation, air temperature, solar radiation, and wind speed were collected from an onsite weather station (Appendix B). The last major rainfall prior to the initiation of Study 1 occurred on 12 August, 2006 (DOY 224) with a total of 43.3 mm. Following the rainfall event the experimental plots for Study 1 were covered with a polyethylene tarp to reduce evaporation and prevent soil rewetting during subsequent rainfalls. The average daily air temperature during the measurement periods for Study 1 was 15.5 °C with a standard deviation of 4.8 °C.

3.3.2 Experiment design

Two separate studies were conducted to investigate the influence of soil disturbance and crop residues on the short-term CO_2 and N_2O flux. The first study (Study 1) consisted of measuring the CO_2 and N_2O flux immediately, 2, 6, 24, 48 and 120 hours following a soil disturbance event. The treatments consisted of high, low, and no soil disturbance with and without corn residue. An additional two plots with half (0.5X) and twice (2X) the amount of corn residue, both receiving the high-disturbance treatment, were also included. The living corn plants were removed from the study area on the 10th of June, 2006 (DOY 161). Each plot had an internal dimension of 1.20 m by 0.72 m and were separated by frames constructed with 0.04 m by 0.15 m (2-inch-by-6-inch) wood studs covered in polyethylene plastic sheeting. The frames were buried 0.10 m into the soil with 0.05 m protruding from the soil surface. During the installation of the frames, care was taken to minimize disturbance of the soil within each plot and soil was than back-filled against the frames. The frames were used as reference points for the surface characterization measurements and served as collars for the flux chambers. The treatments were replicated four times and arranged as a randomized complete block design. Each replicate was completed in its entirety before the next one was started. The study was initiated on 28 August, 2006 (DOY 240).

The high-disturbance treatments consisted of manually tilling the entire plot with a pointed-spade to a depth of 0.20 m and completely inverting the soil and breaking up any soil clods 0.20 m in diameter or larger (Figure 3.1a). The low-disturbance treatments consisted of manually tilling two strips 0.20 m wide, 0.40 m between the centers of the strips, down the length of the plot to a depth of 0.075 m, with a square-mouth spade, taking care to loosen the soil but not to invert it. This was followed by a brisk raking of the entire plot area with a bow rake to produce soil clods 0.05 m or smaller in diameter (Figure 3.1b). The no disturbance treatments were left undisturbed (Figure 3.1c). For the treatments that included corn residue, 1.74 kg m^{-2} of corn residue (approximately six plants, including roots per plot) was applied evenly by hand over the entire plot. The corn plants were hand chopped with hedge clippers and left to air dry; the length of corn residue ranged from 0.10 m to 0.20 m and the diameter of the corn stalks ranged 10 mm to 25 mm. The corn residue was applied immediately prior to the commencement of the soil disturbance event.

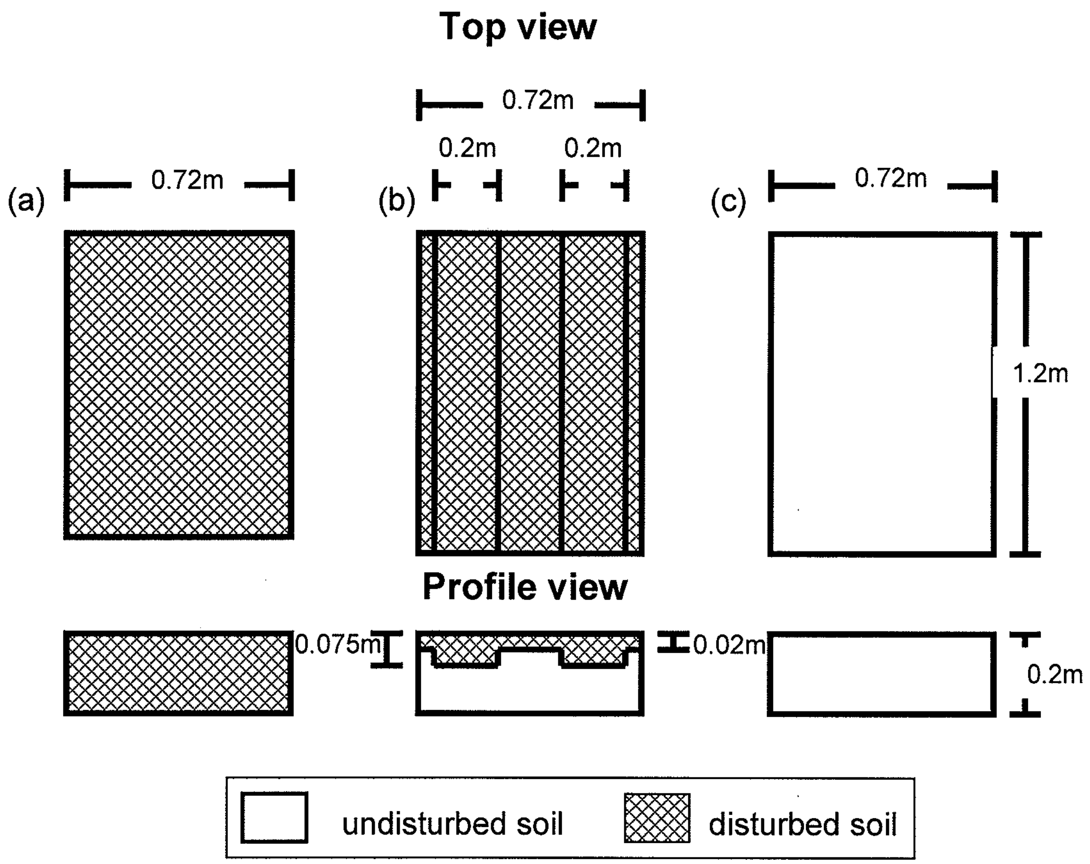

Figure 3.1 Soil disturbance methods diagram for Study 1 (a) high-disturbance, (b) low-disturbance and (c) no-disturbance

The corn plants were air dried and hand chopped to pieces that ranged from 0.10 m to 0.20 m. For the treatments that included corn residue, 1.74 kg m^{-2} of corn residue (approximately six plants, including roots per plot) was applied evenly by hand over the entire plot. The plots were left bare until the commencement of the soil disturbance event or the flux measurements. The high-disturbance treatments took 12 minutes to till and the low-disturbance took 6 minutes to till. The flux chambers were set in place within one minute of the completion of the soil disturbance event and the first measurement taken is referred to as time-zero in the context of this research. Due to experimental design restraints, the initiation of the different treatments within a replication was randomized and occurred between 1000 h and 1100 h.

Soil water content and temperature at 0.05 m were measured after the flux measurements were completed. Soil temperature was measured with a soil thermometer (Traceable® Long-Stem Thermometer, Control Company) and soil water content was measured with a capacitance moisture probe (Hydra Probe Soil Sensor®, Stevens Water Monitoring Systems, Inc.). To characterize the soil topography following the soil disturbance event, six evenly spaced soil surface profiles were measured on each plot; each profile was the entire width of the plot. In addition, to measure crop residue cover following the soil disturbance event, digital images that encompassed the entire plot were taken. The surface roughness, surface area, relative increase in near-surface porosity, and the percent crop residue cover were measured and calculated using the procedures and equipment described in Section 2.

The second study (Study 2) was a comparison between cultivated and not-cultivated plots. The plots received 200 kg ha^{-1} of urea-N broadcast by hand on 10 October, 2006 (DOY 283). The urea was solubilized by subsequent rainfall and the cultivation was initiated on 26 October, 2006 (DOY 299) at 1030 h. The average soil water content in the top 0.05 m at the time of cultivation was 0.38 m^3 m^{-3} and the average soil temperature at 0.05 m was 5.0 °C. The tillage implement used was a field cultivator with 0.20 m sweeps at 0.30 m spacing and 3 rows of spring tine harrows at 0.10 m spacing and was pulled with a 70 kW tractor. Each plot was the width of one pass with the cultivator (2.3 m). Pairs of flux chambers were deployed within 1 minute after the tillage equipment had passed with one chamber on the cultivated plot and one chamber on the not-cultivated plot immediately adjacent. Two passes were made with the field cultivator one hour apart and 2 pairs of observations were made with each pass. Due to weather constraints, surface characterization was not completed at that time.

The following spring on 10 May, 2007 (DOY 130), in an area that received no fall tillage, the same cultivator was used to till a 20 m long strip to obtain surface characterization measurements. The soil water content at 0.05 m prior to cultivation was 0.42 $m^3\ m^{-3}$. Six evenly spaced locations on the cultivated plot and six evenly spaced locations on the not-cultivated plot immediately adjacent was selected and at each location a soil surface profile randomly orientated were measured to characterize the soil topography. A digital image, covering approximately 1.8 m^2, was taken to measure crop residue cover. The surface roughness, surface area and crop residue cover were measured and calculated using the procedures and equipment described in Section 2.

3.3.3 Instrumentation and data analysis

Four 1.22 m x 0.74 m x 0.25 m (ID) insulated, dark, vented static chambers equipped with a mixing fan were used to measure the flux (Appendix C). The chambers were slightly larger than the experimental plots to ensure a good seal with the plot frames and were held in place with elastic cords. The chambers were constructed using 6.3 mm acrylic glass cemented together and sealed using silicone. Metal brackets were used for structural support. One 0.09 m (ID) fan was installed 0.20 m from the ceiling of the chamber orientated in such a way so that the flow of air was directed upward toward the top of the chamber. The air flow rate of the fan was 4 L s^{-1}. The bottom edge of the chamber was lined with closed cell foam weather stripping to ensure a tight seal with the plot frames. The vent consisted of a 0.63 m (ID) plastic tube, with a volume equal to that of one sample (20 mL). The flux chambers were modified for Study 2, so the chambers could be used without installing collars, by the removal of the foam, and was fitted with a 0.30 m windbreak constructed from polyethylene plastic sheeting similar to the design of Matthias et al. (1980). Soil was piled on the windbreak in an effort to minimize leakage. Chamber headspace was sampled with a 20 mL syringe through a rubber septum centrally located on the top of the chamber.

Headspace samples were extracted using a syringe at 0, 15, 30, and 45 minutes after the initial placement of the flux chamber for Study 1, and 0, 1, 2, 3, 4, 5, 7, and 10 minutes after the initial placement of the flux chamber for Study 2. The samples were injected into pre-evacuated 12 mL Exetainers® (Labco) and transported to the laboratory and analyzed for CO_2 and N_2O using a Varian CP3800 gas chromatograph (GC). A thermal conductivity detector (TCD) was used to measure CO_2. The TCD was operated at 130 °C with a purified helium carrier gas at 30 mL min^{-1} (137.9 kPa), Haysep D 80/100 analytical column (3.20 mm diameter x 1.83 m length) maintained at 70 °C. An electron capture detector (ECD) was used to measure N_2O. The ECD was operated at 300 °C, 90 % Ar, 10 % CH_4 carrier gas at flow rate of 30 mL min^{-1} (89.6 kPa), Porapak QS 80/100 precolumn (3.20 mm diameter x 0.46 m length) and analytical columns (3.20 mm diameter x 1.83 m length) in a column oven operated at 70 °C. Three replicates of two concentrations of standard gas mixtures were included in each run and were used to construct standard curves. The standard gases collected during each sampling period were used to confirm sample integrity during sampling and storage.

Standard curves were used to convert peak areas derived from the GC into CO_2 and N_2O concentration in the sample. The CO_2 and N_2O fluxes were calculated by converting the volumetric concentration of CO_2 and N_2O to a mass basis and then linearly regressed as a function of sampling time (Rolston, 1986). The slopes of the regression lines, which represent the rate of accumulation of CO_2 and N_2O within the chamber, are expressed on a unit horizontal land area basis. The CO_2 and N_2O flux, however, could be adjusted to be expressed on an exposed soil surface area. The regression coefficients for the CO_2 data were quite high with an average of 0.97 ± 0.06 (standard deviation). The regression coefficients for the N_2O data were not as high with an average of 0.76 ± 0.28 (standard deviation). The cumulative loss of C and N was calculated using the trapezoidal rule; the 2 hour and 6 hour measurements in Study 1 were not included in the calculation to remove the diurnal effects.

3.3.4 Surface characterization

Characterization of surface properties following soil disturbance is described in a previous study (Section 2) using the same experimental plots used for this study. Each plot was characterized in terms of surface roughness using two different geostatistical procedures, semivariance analysis and mean absolute-elevation-difference method. A univariate statistical analysis was also used. Surface area (exposed surface area per land area) was calculated two ways. Firstly, surface area (A_{s1}) was calculated using a trigonometric relationship between the mean absolute-elevation-difference method slope parameter (LS). Secondly, an index of surface area (A_{s2}) was calculated by summing the hypotenuses from adjacent points along a surface profile and dividing by the horizontal length of the profile. Near-surface porosity was measured as the relative increase in volume compared to the no-residue, no-disturbance treatment. Crop residue cover was measured by dividing the land area covered by residue by the total land area of the experimental plot. For a complete description of the materials and methods used in the surface characterization and the results refer to Section 2.

3.3.5 Statistical analysis

Flux and surface properties data were examined with SAS software (SAS Institute Inc., 2006) for statistical analysis. Analysis of variance was performed using the MIXED procedure with the residue addition and soil disturbance analyzed as separate factors. Means of each factor were compared using Fisher's Least Significant Difference (LSD) when the F-Value was significant ($P<0.05$). The slice option was used in the MIXED procedure to test the significance of soil disturbance with and without corn residue on the CO_2 and N_2O flux. To further investigate the effect of residue on the short-term CO_2 and N_2O flux, a one-way analysis of variance was performed using the MIXED procedure with the amount of residue application as the main factor. Means were compared using Fisher's Least Significant Difference (LSD) when the F-Value was significant ($P<0.05$). An analysis of repeated measures was performed using the MIXED procedure with the flux measurements for a treatment within a block as the subject repeatedly measured over time. Heterogeneous compound symmetry was used as the variance structure for the repeated measures analysis. Comparison of treatment means in Study 2 was preformed using the t-test procedure with the cultivated and not-cultivated as paired comparisons. The REG procedure was used to relate the initial CO_2 and N_2O flux to the measured surface properties.

3.4 Results

The addition of residue had a significant effect on the CO_2 flux at every sampling period, except the first (Figure 3.2). The residue treatments had a consistently higher CO_2 flux compared to the no-residue treatments. The level of soil disturbance was also found to have a significant effect on the CO_2 flux at every sampling period with the high-disturbance treatments resulting in a significantly higher flux compared to the low- and no-disturbance treatments. There was no significant difference between the low- and no-disturbance treatments, even though fluxes were generally higher under low- than under no-disturbance. There was no significant difference between the low- and no-disturbance treatments. There was no significant interaction between soil disturbance and the addition of corn residue.

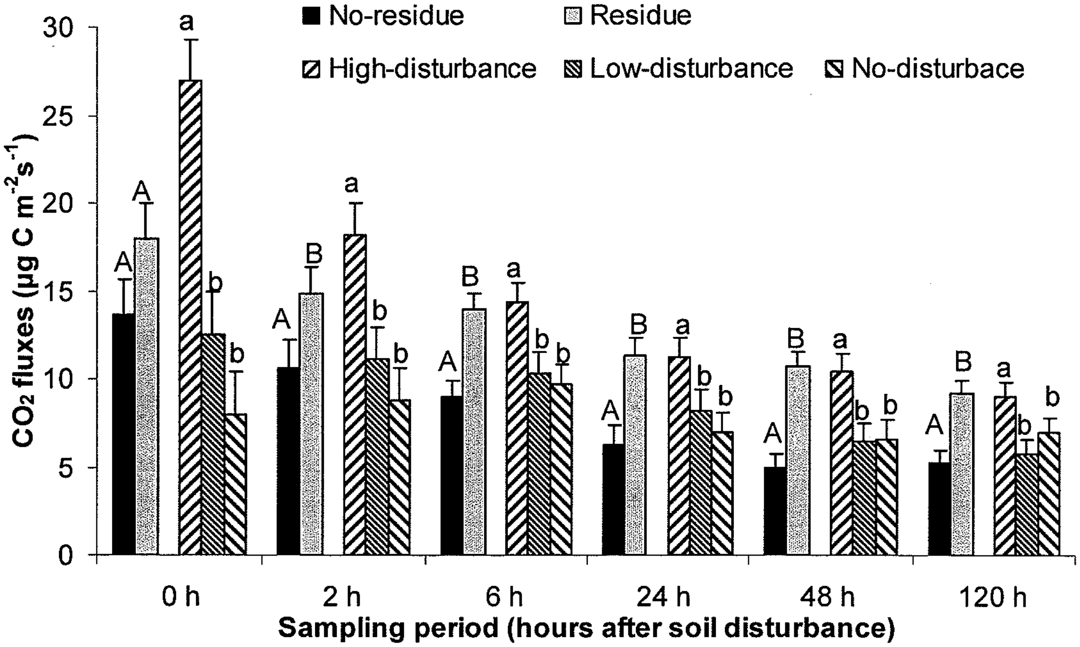

Figure 3.2 Soil disturbance and residue treatment mean CO_2 fluxes for Study 1. Residue means within a sampling period followed by different uppercase letters are significantly different at $P<0.05$. Soil disturbance means within a sampling period followed by different lowercase letters are significantly different at $P<0.05$. Soil disturbance occurred at 10:30 am. Error bars represent ± 1 standard error (residue n=12; soil disturbance n=8).

The effect of soil disturbance with and without residue addition on the CO_2 flux is found in Table 3.1. For the no-residue treatments, significant differences were only found within the first two sampling periods, with the high-disturbance treatments resulting in higher flux compared to the low- and no-disturbance treatments. For residue treatments, significant differences were found at every sampling period with the exception of the measurements made 6 hours following soil disturbance. Generally, the CO_2 flux resulting from the high-disturbance treatments were greater than the flux from the low- and no-disturbance treatments. Each level of soil disturbance was also tested individually for the effect of residue addition (Table 3.1). Significant differences between the residue and no-residue treatments did not occur until 6 hours after the soil disturbance event and the differences generally persisted throughout the remainder of the experiment.

Table 3.1

Mean CO_2 fluxes (µg C m^{-2} s^{-1}) for treatments with and without residue for Study 1.

Sampling period[2]	0 h			2 h			6 h		
	No-residue	Residue	P-value[1]	No-residue	Residue	P-value[1]	No-residue	Residue	P-value[1]
Disturbance									
High	24.3 a	29.5 a	0.264	17.3 a	19.1 a	0.534	11.6 a	17.0 a	0.030
Low	10.8 b	14.4 b	0.433	8.1 b	14.1 ab	0.056	7.8 a	12.8 a	0.043
No	5.9 b	10.1 b	0.369	6.5 b	11.1 b	0.133	7.4 a	12.0 a	0.057
P-value	0.003	0.002		0.004	0.045		0.148	0.087	

Sampling period[2]	24 h			48 h			120 h		
	No-residue	Residue	P-value[1]	No-residue	Residue	P-value[1]	No-residue	Residue	P-value[1]
Disturbance									
High	8.3 a	14.2 a	0.002	6.0 a	14.9 a	0.001	6.4 a	11.6 a	0.0014
Low	5.7 a	10.7 b	0.005	4.1 a	8.8 b	0.036	4.3 a	7.1 b	0.0531
No	4.9 a	9.0 b	0.016	4.8 a	8.4 b	0.097	5.1 a	8.8 b	0.0136
P-value	0.100	0.012		0.642	0.011		0.331	0.015	

*Means within a column followed by different letters are significantly different ($P<0.05$)

[1] Slice contrast P-value, no-residue vs residue

[2] Hours after soil disturbance, soil disturbance occured at 10:30 am

The results for the repeated measures analysis for the CO_2 flux over time are found in Table 3.2. The no-disturbance treatments did not show any significant changes over time. However, with the low-disturbance treatments, only the residue treatment showed a significant change in the CO_2 flux over time. All the high-disturbance treatments showed similar trends regardless of the amount of residue added. The high-disturbance treatments resulted in significant changes over the first 24 hours following the soil disturbance event, with the flux considerably declining by a factor of 2 or more during that period. There was little change in the flux after24 h.

Table 3.2
Repeated measures analysis for the mean flux of CO_2 (μg C m^{-2} s^{-1}) over time for Study 1.

Residue amount	0X			0.5X	1X			2X
Disturbance	High	Low	No	High	High	Low	No	High
Sampling period[1]								
0 h	24.3 a	10.8	5.9	27.2 a	29.6 a	14.4 a	10.1	39.6 a
2 h	17.3 b	8.1	6.5	17.6 b	19.1 b	14.1 ab	11.1	25.9 b
6 h	11.6 c	7.8	7.4	12.1 c	17.0 bc	12.8 ab	12.0	21.5 c
24 h	8.3 d	5.7	4.9	9.2 cd	14.2 cd	10.7 bc	9.0	18.0 cd
48 h	6.0 d	4.0	4.8	8.0 d	14.9 c	8.8 cd	8.4	17.6 d
120 h	6.4 d	4.3	5.0	7.5 d	11.6 d	7.1 d	8.8	16.5 d
P-value	<0.001	0.081	0.714	<0.001	<0.001	0.002	0.365	<0.001

*Means within a column followed by different letters are significantly different ($P<0.05$)

[1] Hours after soil disturbance, soil disturbance occured at 10:30 am

The statistical analysis for treatment means of the cumulative loss of CO_2 following soil disturbance and the addition of corn residue are found in Table 3.3. Both the addition of corn residue and soil disturbance were significant factors in the cumulative loss of C over the 5 days following the soil disturbance event. The addition of corn residues resulted in twice the amount of CO_2 being lost. Similarly, the high-disturbance treatment also resulted in nearly twice the amount of C loss compared to the no-disturbance treatments. There was no significant interaction between the soil disturbance and the addition of corn residues, indicating the effects of soil disturbance and residue are additive. The results of soil disturbance with and without residue on the cumulative loss of CO_2 are found in Table 3.3. Significant differences were only found between the residue treatments. Each level of soil disturbance was also tested individually for the effect of residue addition and the results (Table 3.3). There were significant differences between the residue and no-residue treatments at every level of soil disturbance.

Table 3.3

Cumulative CO_2-C loss (kg C ha^{-1}) following soil disturbance and the addition of corn residue for Study 1.

Residue				
No-residue	26.7a			
Residue	48.0b			
Disturbance		No-residue	Residue	P-value[1]
High	51.1a	36.3a	65.8a	0.001
Low	31.0b	22.1a	39.9b	0.021
No	29.9b	21.6a	38.2b	0.029
P-values		0.085	0.002	
Residue	<0.001			
Disturbance	0.001			
[2]RxD	0.363			

*Means within a column followed by different letters are significantly different ($P<0.05$)

[1] Slice contrast P-value, no-residue vs residue

[2] Residue and soil disturbance interaction

Treatment means and statistical analysis for the effects of amount of corn residue added on the CO_2 flux are found in Figure 3.3. There was no significant difference between the 0X and the 0.5X added amounts of corn residue on the CO_2 flux at each sampling period. The CO_2 flux in the 2X added corn residue treatment was significantly higher than that in all the other treatments during the first two sampling periods. The differences between 2X, 1X, and 0.5X added corn residue treatments became more apparent as the experiment progressed.

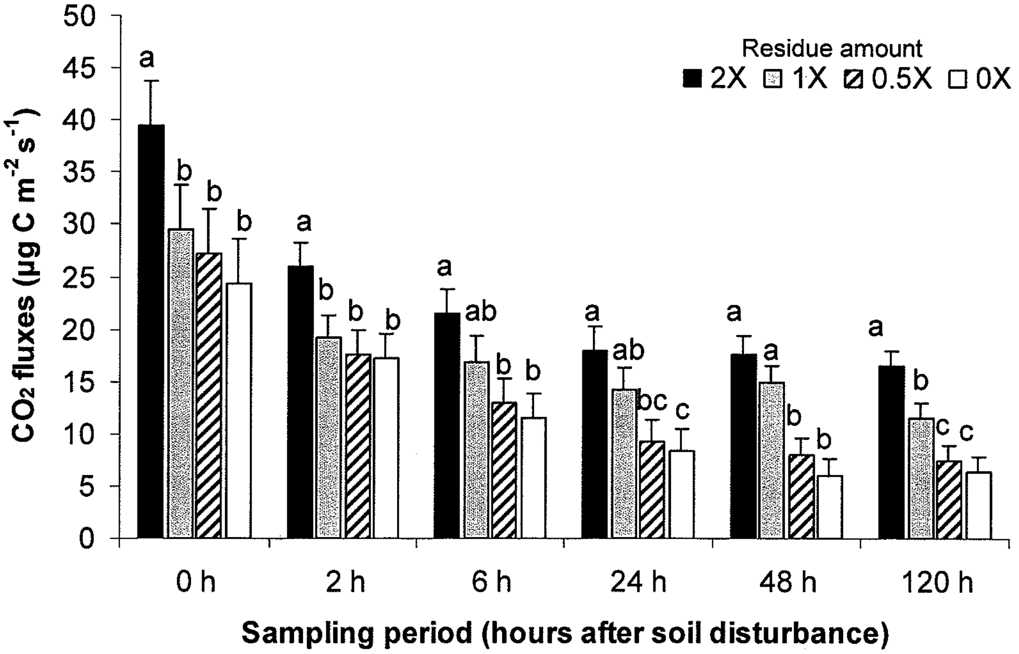

Figure 3.3 Residue treatment mean CO_2 fluxes for Study 1. Means within a sampling period followed by different letters are significantly different at $P<0.05$. Soil disturbance occurred at 10:30 am. Error bars represent ± 1 standard error (n=4).

The effects of corn residue added on the cumulative loss of C over the 5 days following the soil disturbance are found in Figure 3.4. Significant differences were found between all treatments with the exception of 0.5X and 0X added corn residue, with increasing amounts of corn residue resulting in a greater loss of CO_2 over the 5-day observation period following the soil disturbance event.

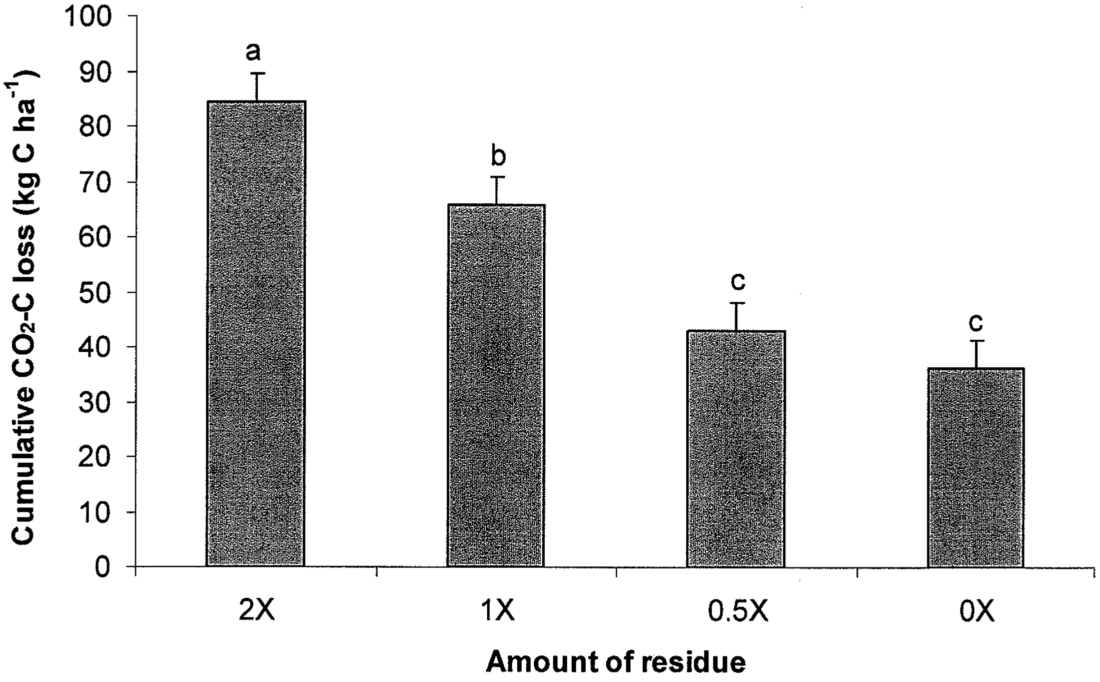

Figure 3.4 Residue treatment mean cumulative CO_2-C loss. Means followed by different letters are significantly different at $P<0.05$. Error bars represent ± 1 standard error (n=4).

The effects of corn residue and soil disturbance on the volumetric water content of the soil are found in Figure 3.5. Residue was not found to be a significant factor affecting the soil water content over the entire 5-day observation period. Soil disturbance on the other hand was a significant factor at every sampling period, with the high- and low-disturbance treatments having significantly lower soil water content compared to the no-disturbance treatments over the entire 5-day observation period. Differences in soil water content among the different treatments became greater as the experiment progressed.

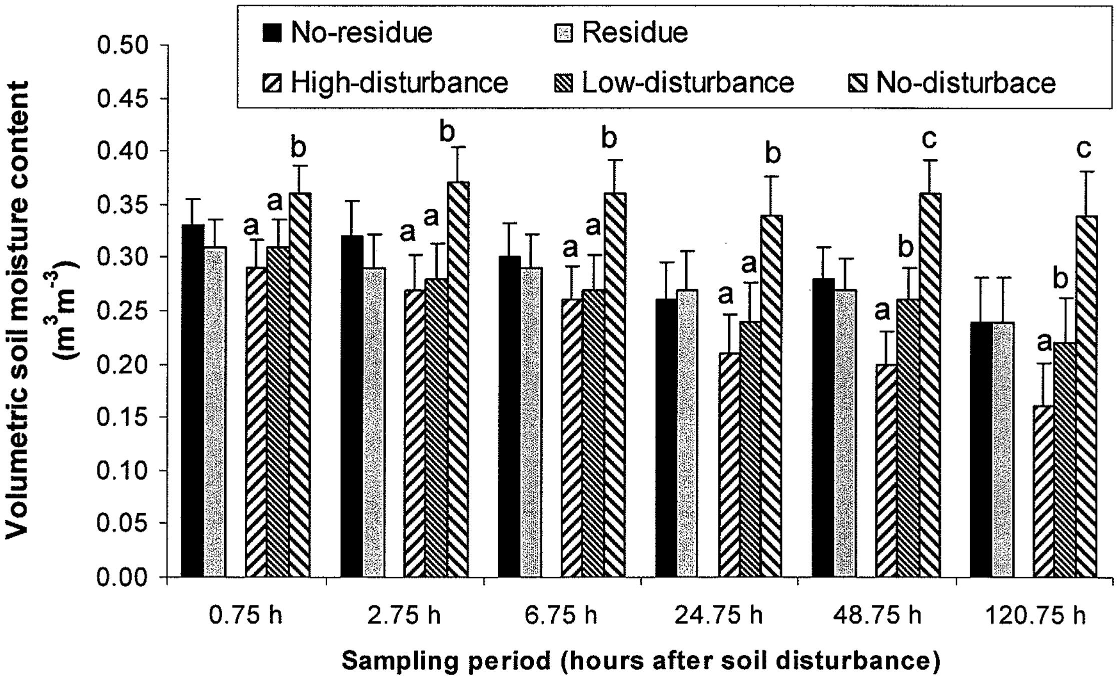

Figure 3.5 Soil disturbance and residue treatment mean soil water contents for Study 1. Soil disturbance means within a sampling period followed by different lowercase letters are significantly different at $P<0.05$. Soil disturbance occurred at 10:30 am. Error bars represent ± 1 standard error (residue n=12; soil disturbance n=8).

Results for the repeated measures analysis for soil water content are found in Table 3.4 and the results are very similar to what was observed for the CO_2 flux with most of the significant changes in soil moisture occurring within the first 24 hours. There was no significant effect of residue or soil disturbance on soil temperature, nor were there any significant changes in soil temperature over time (Appendix D).

Table 3.4

Repeated measures analysis for the mean soil water content (m^3m^{-3}) over time for Study 1.

Residue amount	0X			0.5X	1X			2X
Disturbance	High	Low	No	High	High	Low	No	High
Sampling period[1]								
0 h	0.32a	0.3a	0.37	0.29a	0.26a	0.30	0.36	0.30a
2 h	0.29ab	0.30ab	0.37	0.31a	0.25a	0.26	0.37	0.27a
6 h	0.2bc	0.29ab	0.37	0.24b	0.26a	0.26	0.36	0.28a
24 h	0.23c	0.22c	0.34	0.22bc	0.20b	0.27	0.35	0.26a
48 h	0.22c	0.25bc	0.36	0.21bc	0.18b	0.26	0.35	0.21b
120 h	0.15d	0.23c	0.35	0.18c	0.17b	0.21	0.34	0.17b
P-value	<0.001	0.001	0.656	<0.001	0.001	0.114	0.948	<0.001

*Means within a column followed by different letters are significantly different ($P<0.05$)

[1] Hours after soil disturbance, soil disturbance occured at 10:30 am

Addition of residue and soil disturbance had no significant effects on N_2O flux during any measurement period or on cumulative loss of N. There was also no significant change in the N_2O flux over the 5-day observation period. The average N_2O flux values throughout the 5-day observation period within the no-disturbance treatments ranged from 0.006 to 0.0006 μg N m^{-2} s^{-1} with an overall average of 0.002 μg N m^{-2} s^{-1}. Theses values agree reasonably well with the onsite micrometeorological measurements where the daily average N_2O fluxes ranged from -0.002 to 0.005 μg N m^{-2} s^{-1} with an overall average of 0.002 μg N m^{-2} s^{-1} for the entire Study 1 period (DOY 240 - 266) (Appendix F) (Glenn, 2007, unpublished). The high-disturbance treatments generally showed a downward trend in the N_2O flux over time with values ranging from 0.007 to 0.003 μg N m^{-2} s^{-1} immediately after soil disturbance to values ranging from 0.002 to 0.001 μg N m^{-2} s^{-1} 5-days following soil disturbance. The N_2O flux data for Study 1 is shown in Appendix E.

The mean CO_2 and N_2O flux and the cumulative CO_2 and N_2O loss difference between the tilled and not tilled plots from Study 2 are found in Table 3.5. On average the single pass with the cultivator resulted in approximately twice the amount of CO_2 and N_2O being released 10 minutes following cultivation compared to the not-cultivated plots. The differences in surface characteristics between the cultivated and not-cultivated showed that cultivation resulted in a 56 % decrease in residue cover, 27 % increase in surface area and both the mean absolute-elevation-difference method and univariate statistical analysis method roughness indices showing an increase in surface roughness. For complete surface characterization measurements refer to Section 2.

Table 3.5
Average CO_2 and N_2O flux and carbon and nitrogen loss difference between not-cultivated and cultivated plots after 10 minutes for Study 2.

Treatment	[1]Flux	[2]Loss difference	% loss increase	P > |t|
		CO_2		
Not-cultivated	22.1	15300.0	53.6	0.001
Cultivated	47.5			
		N_2O		
Not-cultivated	0.007	3.8	46.9	0.049
Cultivated	0.014			

[1] $\mu g\ C\ m^{-2}\ s^{-1}$; $\mu g\ N\ m^{-2}\ s^{-1}$
[2] $\mu g\ C\ m^{-2}$; $\mu g\ N\ m^{-2}$

In relating soil physical properties to the initial CO_2 and N_2O flux from Study 1, the results from the 2X and 0.5X added corn residue treatments were not included for simplicity. In Section 2 it was demonstrated that both the addition of residue and soil disturbance had a significant effect on many of the surface properties; due to this phenomenon, the initial CO_2 flux from residue and no-residue treatments were regressed against surface characterization measurements independently of one another. Due to the high variability in the N_2O fluxes, there was poor correlation between the initial flux and cumulative loss of N_2O and the measured surface properties and the data are not included in this report.

The relationship between the initial CO_2 flux and the geostatistical roughness indices limiting elevation difference (LD) and the sill are found in Figures 3.6a and 3.6b, respectively. The relationship between the initial CO_2 flux and the univariate roughness indices standard deviation (STDEV), standard error (STERR), and the range are found in Figures 3.6c, 3.6d, and 3.6e, respectively. Finally, the relationship between the initial CO_2 flux and the volume of soil disturbed, surface area (A_{s2}), and the amount of corn residue cover are found in Figures 3.6f, 3.6g, and 3.6h, respectively. There was a positive correlation between the initial CO_2 flux and all the roughness indices, when corn residue was not present, with higher fluxes resulting from rougher surfaces. The initial CO_2 flux from both the residue and no-residue treatments were well correlated to the volume of soil disturbed, with larger initial fluxes resulting from the treatments in which larger volumes of soil were disturbed. The initial CO_2 flux from the residue treatments was negatively correlated with the percent corn residue cover, with larger initial fluxes occurring with lower residue cover. The initial fluxes of CO_2 from both the residue and no-residue treatments was not significantly correlated to the relative increase in near-surface porosity, or the other measures of surface area and surface roughness.

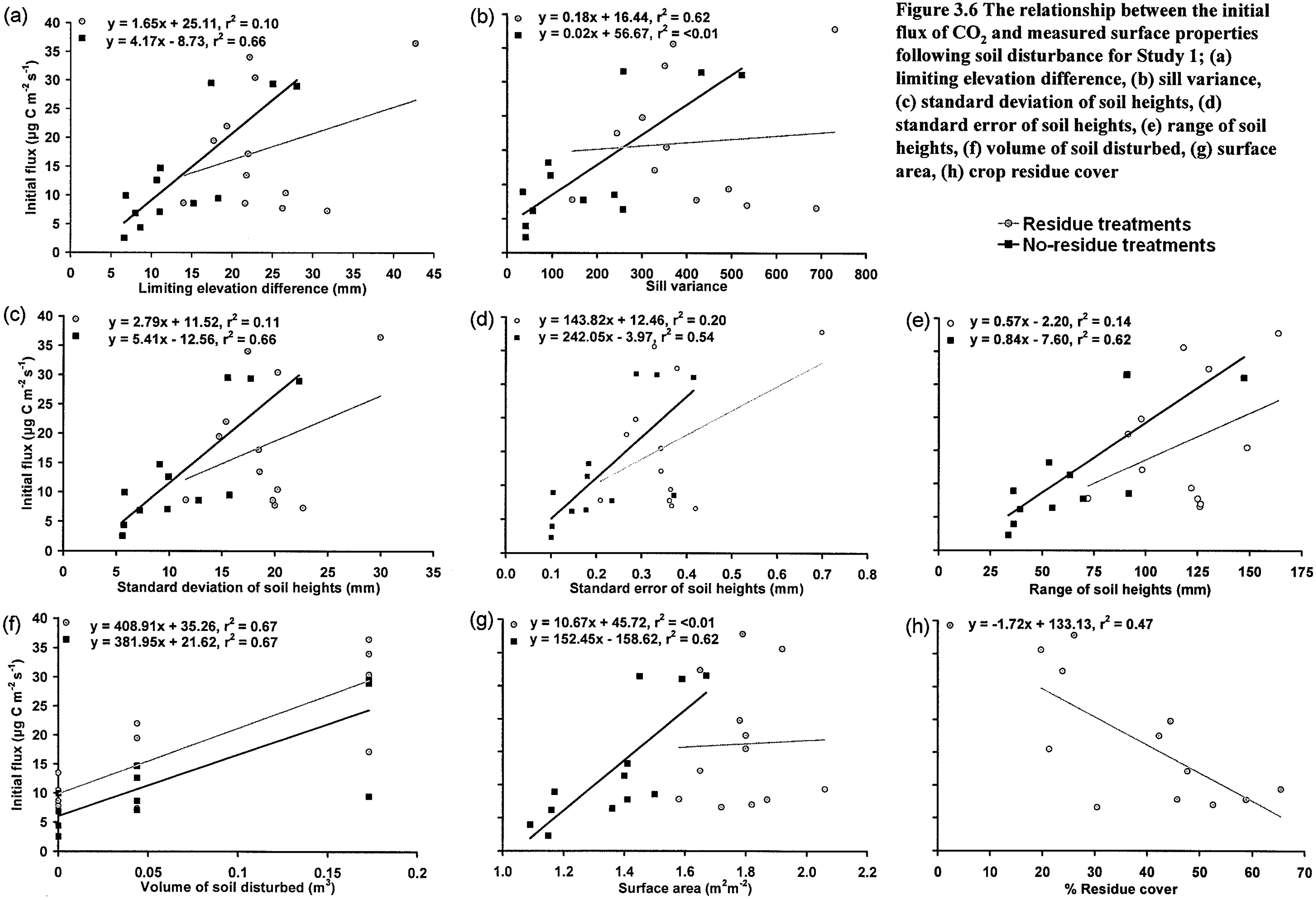

Figure 3.6 The relationship between the initial flux of CO_2 and measured surface properties following soil disturbance for Study 1; (a) limiting elevation difference, (b) sill variance, (c) standard deviation of soil heights, (d) standard error of soil heights, (e) range of soil heights, (f) volume of soil disturbed, (g) surface area, (h) crop residue cover

3.5 Discussion

3.5.1 CO_2 flux following soil disturbance

The corn residue may have more than one effect; the residue is not only an additional C source but the residues also have an impact on the soil physical properties as was demonstrated in Section 2. Likewise, soil disturbance not only incorporates the corn residue making it more available for decomposition, it too has an effect on the soil physical properties near the surface (Section 2). These interactions and similarities between the residue and the soil disturbance make it difficult to separate the causes and effects of each individual factor. In addition, soil disturbance was found to have a significant effect on soil water content, which has been identified as one of the major driving forces in the production of CO_2 (Linn and Doran, 1984).

Soil disturbance had a significant effect on the CO_2 flux in Study 1 and Study 2. The short-term CO_2 flux following the high-disturbance treatments is characterized by a 3- to 4-fold increase in the CO_2 flux compared to the no-disturbance treatments that quickly dissipates within 24 hours following the soil disturbance event. This initial flush of CO_2 observed in Study 1 and Study 2 could, however, be attributed to either physical or biological processes. The physical processes involved may include the release of 'trapped' soil gas when soil pores are ruptured during the soil disturbance process (Wuest et al., 2003). This process would be almost instantaneous and due to the experimental design was likely not captured in Study 1 and only partially captured in Study 2. Soil clods produced and brought towards the surface during the soil disturbance have a higher surface area for gas exchange to occur and a smaller distance from the center of a clod to the atmosphere. During soil disturbance, 'fresh' soil is brought to the surface and CO_2

dissolved in the soil water may come out of solution due to the change in the partial pressure of CO_2 with its surroundings (Reicosky and Lindstrom, 1993). Finally, soil disturbance changes the structure and porosity of the soil, which in turn can change the effective diffusion coefficient in soils. The soil gas concentration gradient within the soil will automatically decrease to compensate for the change in the effective diffusion coefficient until a new equilibrium is met. This process results in a loss of gas from both within and below the till layer (Kimball, 1983).

The biological component of the tillage-induced CO_2 flush may include an immediate increase in microbial respiration due to the increase in O_2 concentration, which may have been a limiting factor prior to the tillage event. The increase in O_2 concentration within the soil may be due to the same phenomenon described above with the release of CO_2, but acts in the opposite direction, as there is no net change in the total pressure of the soil atmosphere. The second biological response to the tillage event may be due to the incorporation of crop residues which increases the soil-residue contact, making the residue more readily available for decomposition (Reicosky and Lindstrom, 1993). In study 1, residue was not a significant factor during the first measurement period, which suggests that the latter biological response may not be an important process in the initial flush of CO_2. It is difficult to separate the physical and biological effects on the CO_2 flux as previous research has shown that the soil microbial community can respond very quickly, within minutes to hours, to soil disturbance (Calderón et al., 2000) and the addition of carbon substrates such as glucose and amino acids (Jones and Murphy, 2007).

The rate and extent to which these processes contribute to the initial flush of CO_2 would be largely related to the initial state of the soil, the type of tillage and to climatic factors both before and after the tillage event. The soil physical, chemical and biological properties and climatic condition prior to tillage control the concentration, amount and distribution of CO_2 within the soil (Buyanovsky and Wagner, 1983). The initial conditions will dictate the concentration and total volume of soil gas available for physical release during tillage. The type of tillage implements and the manner in which they are operated will control the degree and extent of the soil disturbance in terms of the depth of tillage, the size and distribution of soil clods, and the amount of crop residue being incorporated (Reicosky and Lindstrom, 1993). These changes in physical properties are likely to control the actual amount and the rate of CO_2 physically released during tillage (Reicosky and Lindstrom, 1993; Reicosky and Archer, 2007). Climatic conditions, especially wind, will also control the flux as wind moving over porous surfaces can induce mass flow (Kimball and Lemon, 1971). As a result, the flux may be increased above that which would be observed if diffusion was the only process of gas exchange.

Within the high-disturbance treatments, at the 24-hour sampling period the CO_2 flux reaches a plateau and the soil system appears to have reached equilibrium as there is little change in the CO_2 flux past this point. The CO_2 fluxes past the 24-hour sampling remain higher than the no-disturbance treatments. This may be result of the greater inter-aggregate porosity that exists after soil disturbance (Section 2) allowing for a greater amount of surface area of soil to be exposed to the atmosphere allowing for more rapid gas exchange.

The main difference between the residue and no-residue treatments is that the no-residue treatments CO_2 flux plateaus at approximately one-half of the residue treatments. This phenomenon is also observed with the different amounts of applied residue where increasing the amount of residue resulted in the CO_2 flux reaching a progressively higher plateau. These trends may be the result of either physical and/or biological processes. Firstly, as demonstrated in Section 2, the addition of residue was found to be a significant factor affecting the near-surface porosity, so the greater increase in porosity due to the presence of residue would result in a greater effective diffusion coefficient causing larger decrease in the CO_2 concentration profile than if residue was not present (Kimball, 1983). This phenomenon would cause more CO_2 being physically released at the surface and a greater diffusion of O_2 into the soil which would then stimulate microbial activity resulting in a greater production of CO_2. Secondly, the addition of residue would have increased the amount of organic C available for respiration (Holland and Coleman, 1987; Abiven and Recous, 2007).

The observed pattern in the CO_2 flux over time may be due, in part, to the loss of soil water that occurred as a result of the soil disturbance, which follows a similar trend to that of the CO_2 flux. Previous studies have demonstrated that CO_2 production is well correlated with the water-filled porosity of a soil (Linn and Doran, 1984). However, differences in soil water and temperature cannot explain differences in the observed CO_2 flux between the residue and no-residue treatments, as no significant differences were found in the soil water content and soil temperature.

There was evidence of some diurnal effects, especially in the no-disturbance treatments. The CO_2 flux increases within the no-disturbance treatments, although not statistically significantly, over the first 6 hours of measurements (Table 3.2). This is mostly likely a response to the increase in soil temperature, as microbial respiration is strongly influenced by soil temperature (MacDonald et al., 1995). On average there was a non-statistically significant increase in the soil temperature at a depth of 0.05 m of 4.2 °C between the initial sampling period and the 6-hour sampling period. The relationship between microbial respiration and soil temperature may have partially obscured the effect of soil disturbance on the CO_2 flux. The increase in soil temperature over the first 6 hours following soil disturbance likely lessened the difference observed between the disturbed treatments and the no-disturbance treatments. The effect of soil disturbance on the CO_2 flux may have been more apparent had the soil been held at a constant temperature for the duration of the experiment.

The additive effect of soil disturbance and residue can be seen as there were no significant differences found within the no-residue treatments, but there were significant differences found within the residue treatments, with the high-disturbance treatment having significantly higher CO_2 fluxes than the low- and no-disturbance treatments. This is likely a biological response to the more intimate contact between the residue and the soil as a result of the incorporation of the residue. Previous research has demonstrated that incorporated residues decompose faster than surface applied residues (Holland and Coleman, 1987; Abiven and Recous, 2007). At any given level of soil disturbance, fluxes in the residue treatments were consistently significantly higher than in the no-residue treatments. In addition, increasing the amount of residue also increased the cumulative loss. This implies that the residue was a significant cause of the C lost throughout the 5 day observation period.

Within the high-disturbance treatments, the proportion of immediate flush of CO_2 (0 to 24 hours following soil disturbance) relative to the total cumulative loss over the 5-day observation period was quite small. On average, the immediate flush of CO_2 accounted for approximately 28 % and 38 % of the total CO_2 lost for the residue and no-residue treatments, respectively. The cumulative loss over the same period for the no-disturbance treatments accounted for approximately 21% of the total CO_2 lost. The lower proportion attributed to the residue treatments suggests that incorporation of residue into the soil and the subsequent effects on the biological activity and the production of CO_2 may be a more important factor than the soil disturbance event itself on the cumulative loss of CO_2 over the 5-day observation period.

3.5.2 N_2O flux following soil disturbance

The results from Study 1 show no statistically significant differences in the N_2O flux among treatments or over time. However, some plots did show similar trends to those of CO_2 with soil disturbance causing an immediate increase in the N_2O flux which quickly dissipated over time. Firstly, these results may in part be due to the fact that the conditions at the time of the study (low inorganic-N and low soil water content) were not favorable for the production of N_2O (Lee et al., 2006), and there was no N_2O within the soil atmosphere to be released during soil disturbance. Secondly, previous studies have shown the production and emission of N_2O has large spatial and temporal variability (Röver et al., 1999) and because of this, the statistical analysis did not reveal any significant response among the different treatments or over time. In Study 2, the trend in the N_2O flux was similar to that of the CO_2 flux. This N_2O flush following cultivation resulted in a 2-fold increase in the loss of N_2O over the 10-minute observation period.

The addition of 200 kg ha^{-1} of urea-N 16 days prior to the cultivation and the 25 mm of rain received during that period would have stimulated nitrification and denitrification processes leading to a potential increase in the production of N_2O (Lee et al., 2006). The increase in the N_2O production would have led to an N_2O accumulation within the soil atmosphere.

The immediate increase in the N_2O flux following cultivation would largely be a physical response as the biology of the system would not be able to respond that quickly to the changes in the physical environment, due to the cool soil temperatures (5.0 °C) at the time of cultivation. The physical processes involved in the tillage-induced loss of N_2O may be very similar to that of CO_2 as discussed previously. However, there is limited data to support this. These preliminary results demonstrate that soil disturbance can have a similar effect on the N_2O flux and CO_2 flux. These results also indicate that the effect of soil disturbance on the N_2O flux is highly variable and may only be significant under certain soil conditions such as high soil N, C and water content (Lee et al., 2006).

3.5.3 Relationship between soil physical properties and the initial CO_2 flux

Only the no-residue treatments had a significant relationship between the initial CO_2 flux and soil roughness. This is consistent with finding is Section 2 where it was demonstrated that there were no significant differences in surface roughness between the different levels of soil disturbance when residue was present. All of the roughness indices that were found to have significant relationship to the initial CO_2 flux relate to the scale or magnitude of surface roughness (Bertuzzi et al., 1990). These indices provide some insight to the size of the voids and soil clods produced during the disturbance event. This information gives an indication of the porosity of the soil which, as described earlier, is an important component of the degassing phenomenon. As the size of the voids increases, the porosity increases which considerably changes the diffusion coefficient and allows CO_2 from depth to easily diffuse to the surface (Kimball, 1983). In addition, with higher porosity the effects of wind on mass flow may become more evident (Kimball and Lemon, 1971). The lack of a significant relationship between the initial CO_2 flux and the relative increase in near-surface porosity was unexpected since these roughness indices were significantly correlated to the relative increase in near-surface porosity measurement. This may be due to the measurement procedure, as direct measurements of the change in near-surface porosity may have yielded better results in comparison to the relative measurements of the change in near-surface porosity that were made in Study 1.

The positive correlation within the no-residue treatments with surface area measurement, A_{s2}, and the initial CO_2 flux supports the idea of the increase in surface area allowing for a greater gas exchange to occur. The poor correlation between surface area and the initial CO_2 flux within the residue treatments was expected because soil disturbance was previously found not to significantly affect surface area and surface roughness (Section 2). The poor correlation between the surface area measurement, A_{s1}, and the initial CO_2 flux may be due to the fact that A_{s1} is inferred from a model parameter and A_{s2} is a more direct measurement.

The negative correlation between the crop residue cover and the initial CO_2 flux was expected since the same amount of residue was applied to every treatment and the lower crop residue cover measurement indicated that more of the residue was incorporated into the soil. The greater amount of residue incorporated into the soil will increase the near-surface porosity, as the residue will prevent the soil from reconsolidating. Again, this will affect gas exchange by changing the effective diffusion coefficient and will allow CO_2 from depth to easily diffuse to the surface (Kimball and Lemon, 1971). The greater incorporation of residue also increases the amount of residue in contact with soil and this may have provided additional C sources (Holland and Coleman, 1987; Abiven and Recous, 2007).

The volume of soil disturbed was the only property that was positively correlated to the initial CO_2 flux, regardless of the presence of residue. The positive correlation indicates that as the depth of soil disturbance increases, the CO_2 loss increases as well. This may be due to two reasons; firstly, the fact that the CO_2 concentration increases with depth and as the depth of soil disturbance increases it will have reached deeper into soil where the concentration of CO_2 is greater (Buyanovsky and Wagner, 1983). Secondly, as the depth of soil disturbance increases, a greater volume of soil is disturbed, rupturing a greater amount of pores releasing a larger volume of soil atmosphere (Wuest et al., 2003).

3.5.4 Implications and areas for further research

This research has demonstrated both the addition of residue and soil disturbance are significant factors affecting the short-term CO_2 flux and the cumulative CO_2 loss from the clay soils of the Red River Valley, Manitoba, Canada. Similarly, this research demonstrated that soil disturbance can be a significant factor affecting the short-term N_2O flux from the clay soils of the Red River Valley. However, the experiments conducted demonstrated that the response of the N_2O flux to soil disturbance was highly variable both spatially and temporally. It may be that soil disturbance is only an important factor under soil conditions favourable for the production of N_2O, such as high soil N, C and water content (Lee et al., 2006). These results suggest that the immediate losses of CO_2

and N_2O following soil disturbance need to be measured for a complete and accurate C and N budget. Measurement and quantification of disturbance-induced losses of CO_2 and N_2O may help to explain differences and similarities in the N and C dynamics observed between different tillage systems within clay soils of the Red River Valley.

The magnitude of the initial flush of CO_2 following the soil disturbance event and the cumulative CO_2 loss were related to the depth and volume of the soil disturbed and changes in the physical properties of the soil including surface roughness, surface area, and the amount of crop residue incorporated. The results from this research indicate that tillage methods used in the Red River Valley, that reduce the depth and volume of soil disturbance, do not considerably increase surface roughness, near-surface porosity, and surface area and which leave crop residues on the surface have potential to reduce agriculture's contribution of CO_2 and N_2O to the atmosphere. This will not only help mitigate the effects of climate change but also improve soil quality by increasing the amount of organic matter in the soil.

Further research is still needed to understand whether the initial flush of CO_2 and N_2O observed is a purely physical release of trapped gas or whether there is an immediate biological response contributing to the observed flush. It is also necessary to better understand how the soil conditions, including soil temperature, water content, and structure prior to soil disturbance, will affect the short-term losses of CO_2 and N_2O, especially N_2O, as the response to soil disturbance was highly variable. This is important as these soil properties will affect physical and biological processes in the soil which will control the concentration, volume, and distribution of soil gas (Buyanovsky and Wagner, 1983). As well, the initial soil conditions also play a role in the extent of the changes in physical properties following soil disturbance (Dexter and Bird, 2001). Further research will also be needed to determine the role of the microclimate both prior and post-tillage on the tillage-induced losses of both CO_2 and N_2O. Microclimatic factors, including solar radiation, wind, precipitation and air temperature, can have a significant impact on physical and biological properties which can affect the both production of CO_2 and N_2O and its release at the soil surface.

The closed static chamber method used in this set of studies to measure the CO_2 and N_2O flux following soil disturbance has several limitations (Rolston, 1986). These limitations of the closed static chamber method often result in the under-estimation of the flux from the soil (Rochette et al., 1997; Rolston, 1986). Another limitation of the closed static chamber method is that this method measures an average flux over the deployment period over a relatively small area. These restrictions provide a coarse spatial and temporal resolution (Rochette and Hutchinson, 2005). Consequently, an important research objective would be the use of continuous monitoring equipment and techniques, such as the eddy covariance method, to better capture and characterize the tillage-induced losses of CO_2 and N_2O.

Information on the short-term effects of soil disturbance on the CO_2 and N_2O flux is important in C and N modeling and budgeting. Gaps in data sets often occur around tillage operations because monitoring equipment needs to be taken down to allow these operations to be completed. These gaps in data sets are often filled by using interpolation or modeling techniques. The information presented in this research can provide an indication as to the limitations of these interpolation or modeling techniques in estimating the CO_2 and N_2O flux around tillage events on clay soils in the Red River Valley.

3.6 Conclusions

The short-term CO_2 flux following the high-disturbance treatment was characterized by an immediate 3- to 4-fold increase in the CO_2 flux immediately following the tillage event that quickly dissipated within the first 24 hours. After this point the soil system reaches a new equilibrium with the CO_2 flux being greater than the no-disturbance treatments. The relative contribution of the peak was an average 28 % and 38 % of the total CO_2 lost for the residue and no-residue treatments, respectively. It is still unclear as whether the immediate response to soil disturbance is a physical degassing of the soil, biologically-mediated response, or a combination of both physical and biological processes. The addition of crop residue was found to be a significant cause of the CO_2 lost throughout the 5-day observation period, regardless of the level of soil disturbance. However, the incorporation of the residue through the action of soil disturbance was found to be a more important factor than soil disturbance or the addition of residue alone in the cumulative loss of CO_2 over the 5-day observation period.

There was no statistically significant response from soil disturbance or the addition of residue on the N_2O flux in Study 1. However, results from Study 2 showed a significant increase in the N_2O flux following cultivation compared to the not-cultivated plots. This information provides some indication that the N_2O flux may have a response to soil disturbance similar to that of CO_2 under certain conditions or that it is a reflection of the more variable nature of N_2O emissions.

The initial and cumulative CO_2 flux following soil disturbance was closely linked to changes in surface properties. Treatments that resulted in high surface roughness and exposed surface area, and the greatest residue incorporation resulted in the largest initial and cumulative CO_2 flux. The initial and cumulative CO_2 flux was also well correlated to the depth and volume of soil disturbed. These relationships are a reflection of the size of the voids and soil clods produced, and the amount of residue incorporated during the soil disturbance event. These changes in soil physical properties resulted in greater diffusion and convective flow of CO_2 out of the soil and greater diffusion of O_2 into the soil as well as increased residue-soil contact. There was some difficulty in relating changes in surface roughness and exposed surface area to the initial and cumulative CO_2 flux when residue was present due to effects of the residue on the measured surface properties.

This research demonstrates the importance of capturing the short-term CO_2 and N_2O flux following soil disturbance. Soil disturbance during periods of peak emissions (spring and fall) may lead to several days of elevated (but unmeasured emissions) emissions, which could be a considerable portion of the total annual emissions. Not accounting for the short-term losses can have serious consequences in C and N modeling and budgeting. The relationships between soil surface properties and GHG emissions are important in the understanding of production and emission processes. It may also be possible to make assessments of GHG emissions based on changes in soil surface properties due to changes in management practices.

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4. OVERALL SYNTHESIS

This research was conducted as part of the "Temporal dynamics of greenhouse gas fluxes linked to soil biophysical processes and management practices" funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) and BIOCAP Canada under the strategic grant initiative. The goal of this overall project was to increase the understanding of seasonal carbon (C) and nitrogen (N) cycling, and to identify strategies for net greenhouse gas (GHG) reduction from agriculture in contrasting soil and climatic conditions. This is being accomplished by comparing the net carbon dioxide (CO_2) and nitrous oxide (N_2O) fluxes in fields managed under conservation-till and conventional-till through year-round studies in Elora, Ontario (humid) and Glenlea, Manitoba (semi-arid) and linking the biophysical controls of GHG fluxes through an array of soil chemical, physical, and microbial measurements.

This research has contributed to the overall project by providing detailed information on the two tillage systems compared at the Glenlea, Manitoba site. The soil physical properties near the surface, including surface roughness, near-surface porosity, exposed surface area, and crop residue cover, have large direct and indirect influences on soil physical and biological processes. These surface properties can influence hydrology, soil erosion, gas exchange, soil-residue contact, and the energy balance (Kamphorst et al., 2000; Freebairn et al., 1989; Matthias et al., 2000; Helming et al., 1998; Jolata and Prihar, 1998; Linden and Van Doren, 1986; Smika and Whitfield, 1966). The detailed surface characterization that was conducted at the site may, in part, be able to explain differences in crop growth, soil water content, soil temperature, snow retention, and the net GHG flux observed between the conservation-till and conventional-till systems as these factors are related to surface conditions. In addition, the detailed information obtained about the tillage practices from the Glenlea site will also allow for better comparisons with other sites. This is important as tillage systems vary greatly from region to region. For example, a zero-till system in the Canadian prairies compared to a zero-till system in eastern Canada is quite different in terms of the soil disturbance associated with the seeding operation (Lobb et al., 2007). This will aid in the understanding of how other factors, such as climate and soil type, affect the GHG flux.

The results from Study 1 demonstrated that soil disturbance had little effect on measurements of surface roughness and surface area when residue was present. However, soil disturbance changed the source of the surface roughness and surface area moving from being dominated by residue to being dominated by soil as the soil disturbance intensity increased. Due to the behavioral differences of the residue and soil in surface processes, an important research objective would be to combine the crop residue cover and micro-topography measurements to be able to determine the proportion of surface area and surface roughness attributed to either soil or the residue. In this series of experiments surface characterization was only carried out immediately after a soil disturbance event; the surface properties would change over time due to precipitation, freeze-thaw cycles, biological activity, and other field operations (Bertuzzi et al., 1990). Consequently, surface characterization measurements will be needed throughout the year to better understand how surface properties change over time and how it may affect soil surface processes.

Examination of the effects of soil disturbance and crop residue, and the interaction of these two factors, on the short-term CO_2 and N_2O flux, and the relationship between changes in soil physical properties the CO_2 and N_2O flux has contributed to the overall project in three ways. Firstly, this research has shown that, in the short-term, tillage results in a significant loss of CO_2, and in some instances, N_2O as well. Not capturing these events will have serious consequences for C and N budgeting and modeling, as all C and N inputs and outputs must be accounted for. In this series of experiments, the CO_2 and N_2O fluxes were only measured following a single soil disturbance event. Conventional-till systems in the Red River Valley often have a series of tillage events in the spring and fall. The relationship between the timing and intensity of a series of tillage events and tillage-induced losses of CO_2 and N_2O are not well understood. The first tillage event within a series would likely have the largest effect on the CO_2 and N_2O fluxes as the changes in the soil physical properties would be the greatest. Subsequent tillage events will have less of an effect on the CO_2 and N_2O fluxes as changes in soil physical properties would be smaller and subsequent tillage may even smooth the soil surface. Several tillage operations during periods of peak emissions (spring and fall) may lead to several days of elevated (but unmeasured) emissions, which could be a considerable portion of the total annual emissions.

Secondly, this research has increased the understanding of some of the physical and biological mechanisms that control the CO_2 and N_2O flux. The relationships found between the CO_2 flux and soil physical properties demonstrate that tillage implements and practices that minimize soil disturbance will reduce the net GHG emissions from arable land within the Red River Valley. These results are consistent with similar studies investigating the impacts of tillage on the short-term CO_2 fluxes (Reicosky and Lindstrom, 1993; Ellert and Janzen, 1999). Strengthening our understanding of this relationship between soil physical properties and the GHG flux is important as it may lead to estimates of the net GHG flux based on changes in soil physical properties due to changes in management practices. In addition, the relationships found between the CO_2 flux and soil physical properties have partially confirmed hypothesis about the mechanisms surrounding the physical release of 'trapped' gas that occurs immediately after tillage (Reicosky and Lindstrom, 1993). Further research is still needed to fully understand whether the initial flush of CO_2 and N_2O observed is a purely physical release of 'trapped' gas or whether there is an immediate biological response contributing to the observed flush. It is very difficult to separate the physical and biological processes contributing the tillage-induce loss of CO_2 and N_2O as the different processes occur simultaneously and are often interconnected.

Lastly, the information presented in this research provides an indication as to the limitations of gap filling techniques used in estimating the CO_2 and N_2O flux around tillage events at the Glenlea, Manitoba site when the continuous monitoring equipment had been taken down. The results from this research show that the tillage-induced CO_2 flux was characterized by a large peak immediately following tillage that quickly dissipated within 24 hours. After this point the soil systems appear to have reached a new equilibrium with the tilled treatments having a greater CO_2 flux than the not-tilled control. Using mathematical interpolation techniques, such as curve fitting, or modeling fluxes based on other environmental data, such as air temperature, to fill gaps in the data set will fail to capture the large and dynamic fluxes following tillage. Continued research may lead to better estimates of the CO_2 fluxes following a tillage event based on changes in surface characteristics due to the tillage.

Not capturing the short-term CO_2 flux following tillage may not have a significant effect on an annual net CO_2 flux. For example, Hollinger et al. (2005) reported annual net CO_2 fluxes over a no-till corn (*Zea maize* L.) crop ranging between -6918 kg-C ha^{-1} to -5322 kg-C ha^{-1} (negative represents net C sink). The data from this research showed that one tillage event resulted in an average increase in CO_2 loss above the not-tilled control of 27.6 kg-C ha^{-1} over the 5-day observation period. Not accounting for the short-term losses around one tillage event would have resulted in an over estimation as a net C sink by only 0.4 % to 0.5 %, well within the margins of error associated with the measurements. Furthermore, not capturing the short-term losses, even considering multiple tillage events within a year, would still only represent a small percentage of the annual net CO_2 flux. However, the tillage-induced losses may represent a larger proportion of the total soil respiration, as the annual net CO_2 flux is dominated by the plant component of the system, through photosynthesis (C sink) and root respiration (C source) (Hanson et al., 2000). The tillage-induced losses of CO_2 in fields with long histories of continual intensive tillage, may in part explain, the gradual decline in soil organic matter compared to virgin land (Reicosky and Lindstrom, 1993).

The results from this research have demonstrated that the N_2O flux following tillage is highly variable. The experimental results provide some indication that the N_2O flux may have a response to soil disturbance similar to that of CO_2 under certain soil conditions such as high soil C, N or water content or that they reflect the more variable nature of the N_2O flux (Röver et al., 1999; Lee et al., 2006). Continued research is needed to better understand under what soil and climatic conditions and management practices tillage will have a significant effect on the short-term N_2O flux. An equally important research objective is to better understand why the N_2O flux is so spatially and temporally variable.

The soil properties, landscape, and climatic conditions of the Red River Valley region in southern Manitoba create a unique agricultural environment. The Vertisolic soils found in this region are not very common within Canada or the world (Brady and Weil, 2002). The research presented applies to arable land within the Red River Valley in southern Manitoba and caution needs to be taken in applying these results to other areas including the Elora, Ontario research site. The topography at the Elora site is more variable and complex and this creates spatial variability in soil properties as wind, water and tillage erosion redistributes soil and its constituents within the landscape (Reicosky et al., 2005). This can complicate the determination of tillage-induced losses of C loss across the landscape (Reicosky et al., 2005). The different soil physical properties and climate conditions at the Elora site will also affect the magnitude of the tillage-induced losses of CO_2 as these abiotic are significant factors controlling CO_2 fluxes (Lee et al., 2006). Results may also differ between the Elora and Glenlea site as the no-till systems have been established for different lengths of time. The Elora site is comparing conventional tillage treatments against a well-established no-till system, whereas at the Glenalea site is comparing against a recently-established no-till system. Well-established no-till compared to recently-established no-till systems will have differences in soil organic C (West and Post, 2002) and physical properties (Voorhees and Lindstrom, 1984) which can affect the CO_2 and N_2O fluxes (Lee et al., 2006).

To better understand the role of tillage on the CO_2 and N_2O flux on a national or global scale continued research will be needed encompassing a wide range of soil types and climates. Future research should be focused on understanding the underlying factors and processes that control CO_2 and N_2O fluxes. By knowing these fundamental factors and processes the nature of the temporal and spatial variability of GHG fluxes can be better understood. This will allow for the agricultural sector to develop strategies for the net reduction of GHGs better suited for a particular region.

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5. APPENDICES

Appendix A

Experimental plot layout

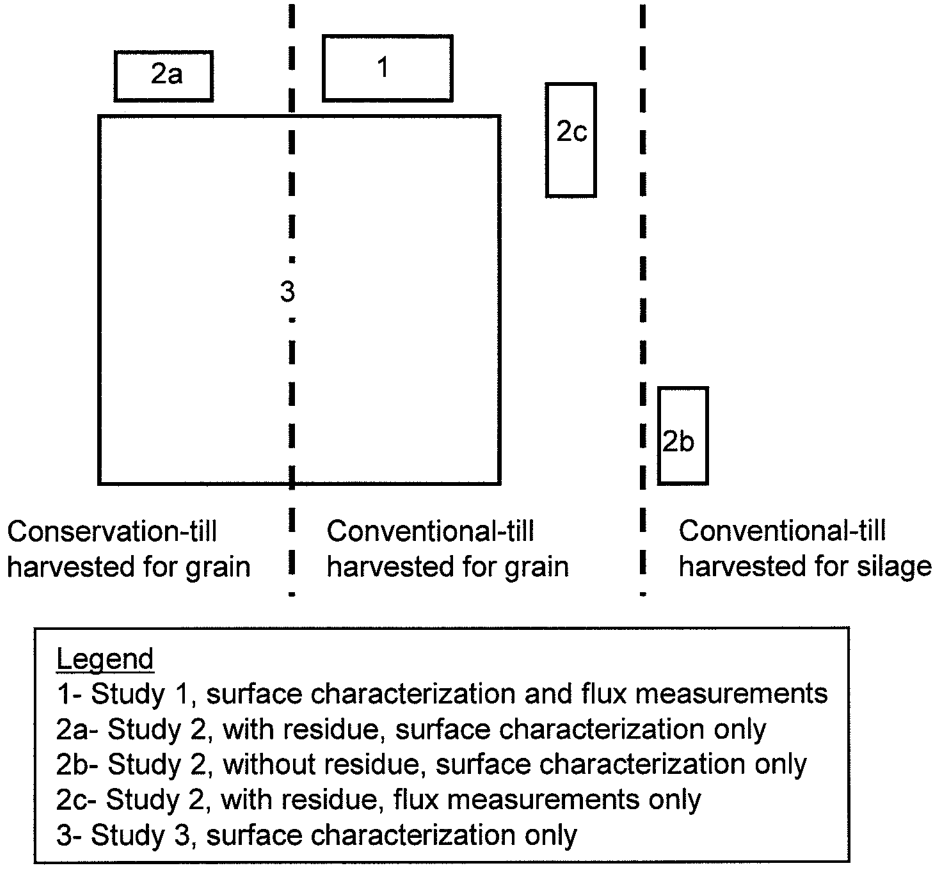

Figure A.1 Experimental plot layout

Appendix B

Demonstration of how variations in micro-topography affect surface roughness measurements

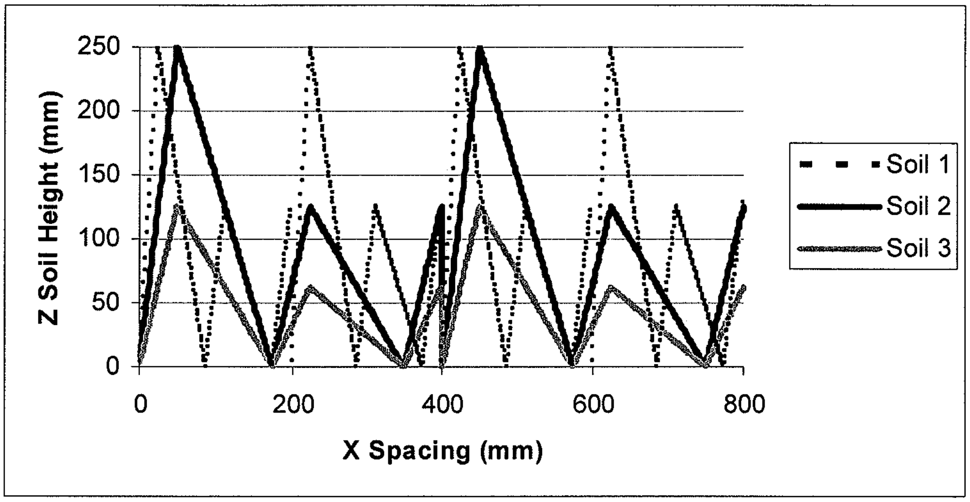

Figure B.1 Three hypothetical soil profiles

Appendix C
Summary of daily microclimatic data during the study

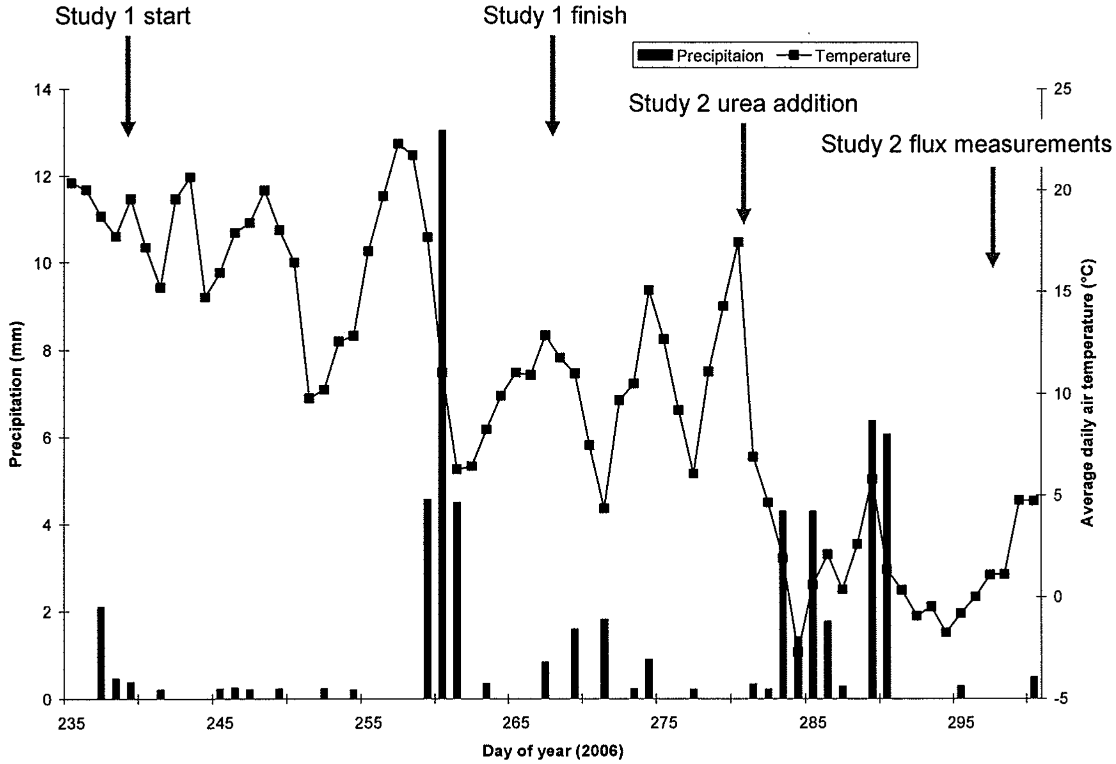

Figure B.1 Summary of daily precipitation and average air temperature data during the flux measurements, collected 500 m from the experimental areas.

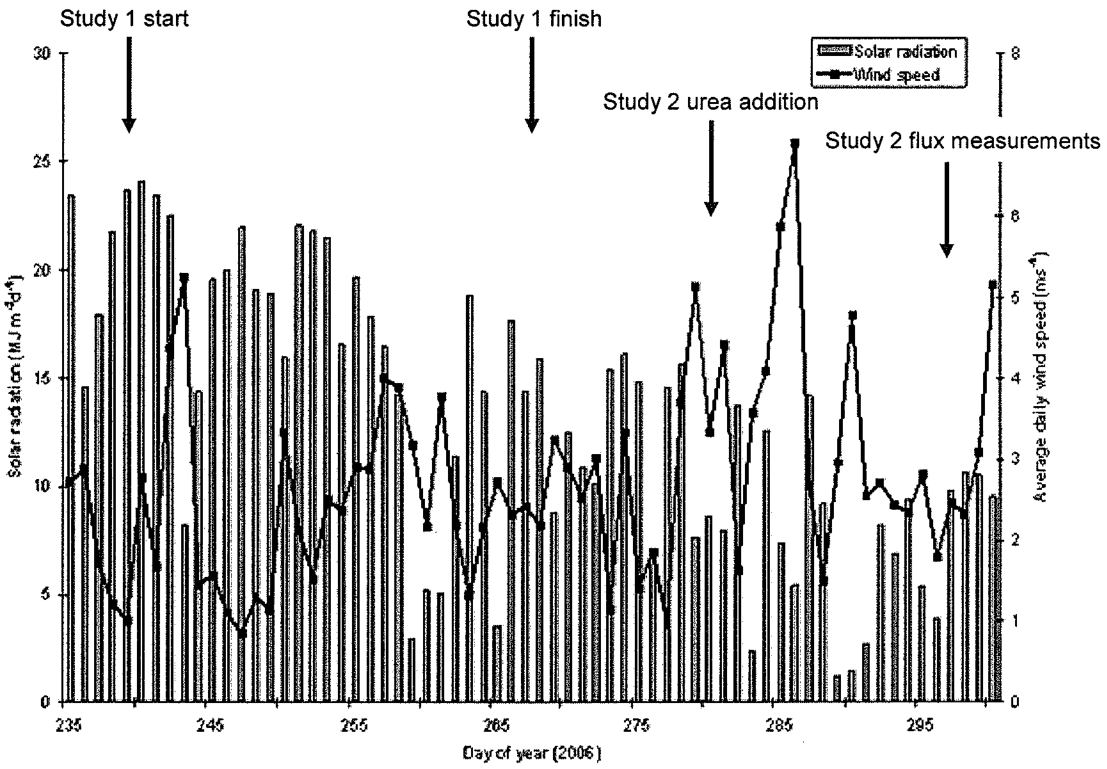

Figure B.2 Summary of daily solar radiation and average wind speed data during the flux measurements, collected 500 m from the experimental areas.

Appendix D

Diagram of closed chamber used for measuring gas flux at the soil surface

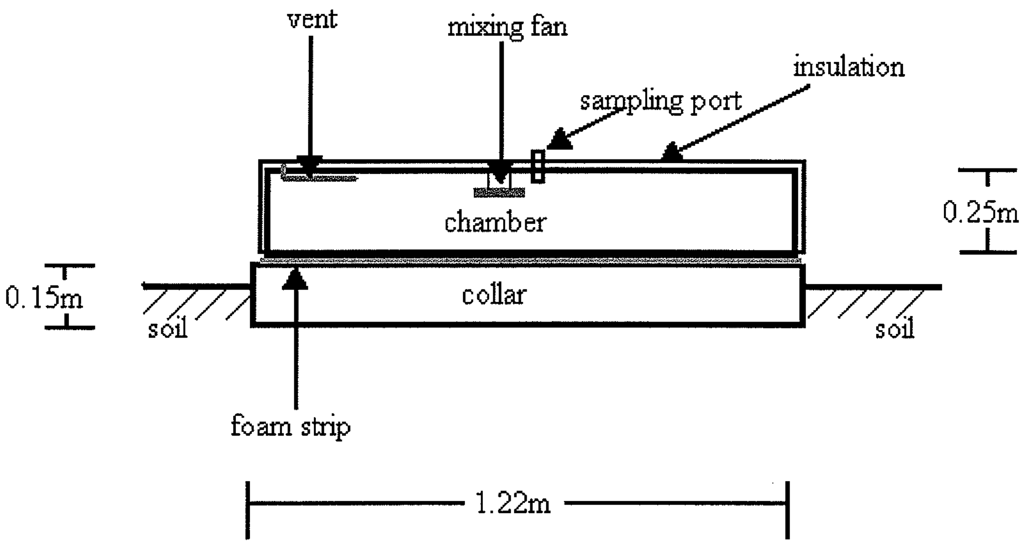

Figure D.1 Flux chamber used in Study 1.

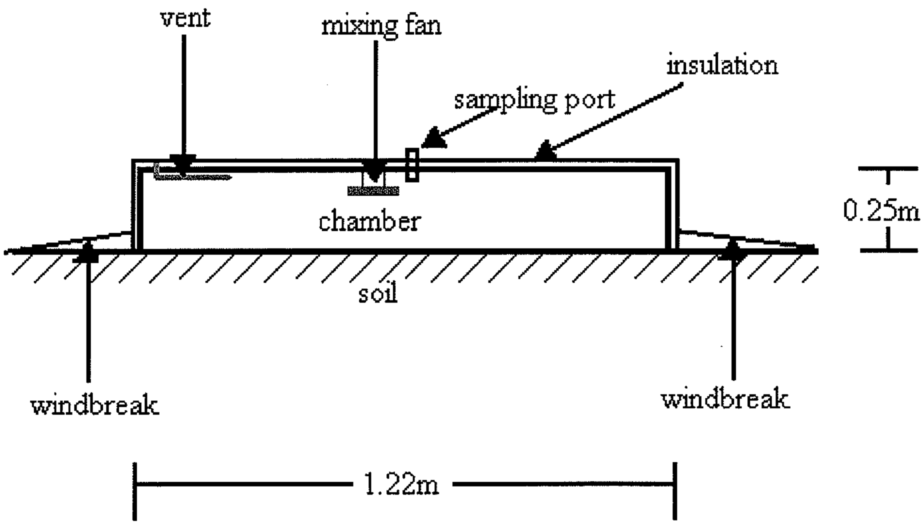

Figure D.2 Modified flux chamber used in Study 2.

Appendix E

Summary of the N_2O flux and soil temperature data for Study 1

Table E.1

Mean N_2O (μg N m^{-2} s^{-1}) fluxes for Study 1.

Residue amount	0X			0.5X	1X			2X
Disturbance	High	Low	No	High	High	Low	No	High
Sampling period[1]								
0 h	0.003	0.004	0.004	0.007	0.005	0.004	0.001	0.006
2 h	0.005	0.003	0.003	0.004	0.003	0.006	0.002	0.003
6 h	0.005	0.004	0.006	0.004	0.004	0.005	0.001	0.003
24 h	0.003	0.002	0.002	0.004	0.004	0.003	0.002	0.002
48 h	0.001	0.001	0.003	0.004	0.003	0.002	0.003	0.002
120 h	0.001	0.001	0.002	0.002	0.001	0.002	0.001	0.001

[1] Hours after soil disturbance, soil disturbance occured at 10:30 am

Table E.2

Mean soil temperatures (°C) (5 cm below soil surface) for Study 1.

Residue amount	0X			0.5X	1X			2X
Disturbance	High	Low	No	High	High	Low	No	High
Sampling period[1]								
0 h	15.6	15.6	14.8	15.5	14.7	15.2	14.1	15.3
2 h	17.1	17.0	17.1	16.6	16.0	16.7	15.7	16.6
6 h	18.3	18.3	19.7	18.2	17.6	18.0	17.7	17.9
24 h	14.8	15.8	16.6	14.8	14.7	16.3	15.4	15.0
48 h	25.1	25.5	26.8	25.7	24.7	25.7	25.6	23.7
120 h	15.3	16.4	17.9	15.4	15.2	15.9	16.2	15.0

[1] Hours after soil disturbance, soil disturbance occured at 10:30 am

Appendix F

Summary of daily micrometeorological flux measurements during the study

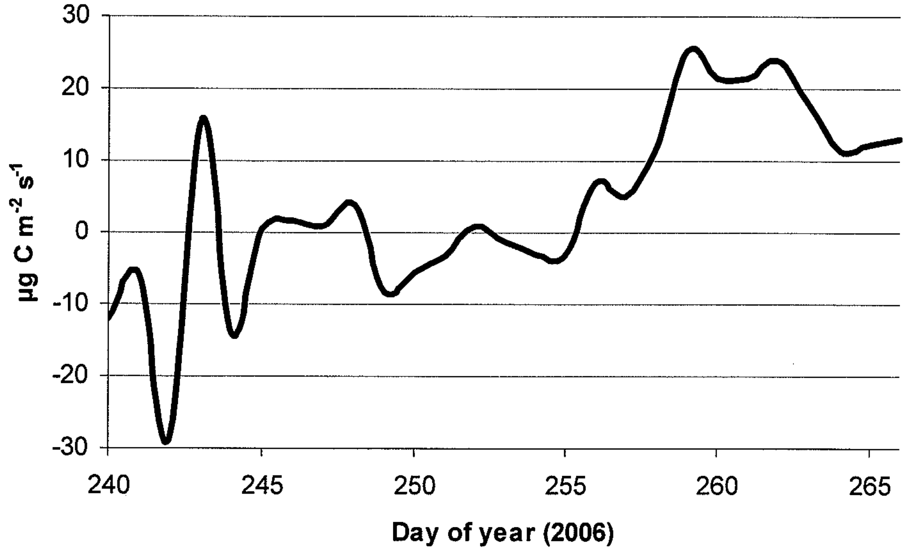

Figure F.1 Daily average CO_2 Flux measurements. Positive flux values represent emissions from the soil surface to the atmosphere.

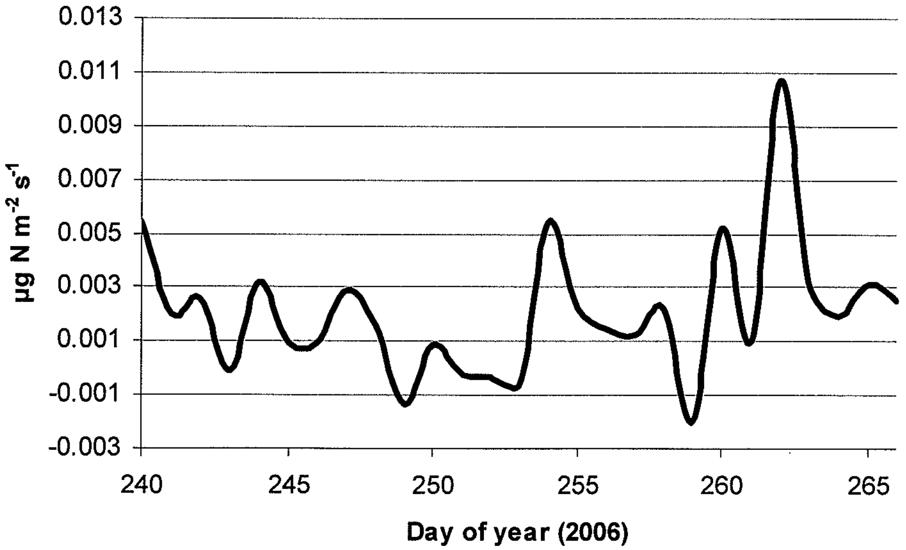

Figure F.2 Daily average N_2O flux measurements. Positive flux values represent emissions from the soil surface to the atmosphere.