THE EFFECTS OF LANDSCAPE RESTORATION ON GREENHOUSE GAS EMISSIONS AND PLANT SPECIES AND ABUNDANCE

BY

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A Thesis
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The Effects of Landscape Resotoration on Greenhouse Gas Emissions and Plant Species and Abundance

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Michelle M. Erb

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of

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of

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ABSTRACT

Erb, Michelle M. M.Sc., The University of Manitoba, October, 2005. The Effect of Landscape Restoration on Greenhouse Gas Emissions and Plant Species and Abundance. Major Professor: Dr. David Lobb.

The objective of this study was to investigate the effects of landscape restoration on two main parameters: greenhouse gas emissions (GHG; carbon dioxide, methane and nitrous oxide) and plants (species - including crop and weed species - and abundance). Two field experiments and two growth chamber experiments were completed over a two-year period to fulfill this objective. The two field experiments were similar in nature and examined the impacts of landscape restoration on both parameters under field-scale conditions. Greenhouse gases and plants were studied in separate growth chamber experiments. The growth chamber experiments complemented the field experiments but focused on one of the two parameters.

In the field, soil was removed from the lower slope riparian area of the landscape where soil had accumulated due to past tillage erosion, and was added to the eroded upper slope area. Nitrous oxide (N_2O), and methane (CH_4) emissions were not influenced by the removal of soil; however, carbon dioxide (CO_2) emissions were reduced in the first year following soil removal. In the upper slope area where soil was added, greenhouse gas emissions were not impacted. The growth chamber experiments assessed varying depths of soil removal and addition and the effects on GHG emissions. The depth of soil removal did not influence cumulative gas flux but in general, and similar to field results, soil removal reduced CO_2 emissions. Reductions in N_2O

emissions following soil removal were also found in the growth chamber. Soil addition did not impact GHG emissions by depth.

To address the question of landscape restoration effects on plants, plant emergence, abundance, and species composition was monitored in the field. In the first year following soil addition, weed emergence increased where soil was added. In one of the two study areas, crop yield was greater where soil was added despite the increase in weed emergence. The number of weed species present following soil addition remained the same as the controls. In year two following the addition of soil, weed emergence numbers where soil was added were similar to the control. The number of weed species present did increase. Because the area from which soil was removed was not part of the cropland, the type (weedy vs. native or wetland) of species revegetating the lower slope removal area was the primary interest. The species observed in the lower slope area were predominantly weeds and similar to those found in the adjacent cropland. In the growth chamber, the soil seed bank was examined to assess the viability of the seed bank within the soil profile and assess the species present; this information may be useful for predicting potential impacts of landscape restoration on weed populations in the restored cropland. It was found that the most viable seeds exist near the soil surface (within the top 5 cm of soil) and that the species were predominantly weeds. The species found in the seed bank correspond with those found in the field experiments in both the upper and lower slope areas.

In summary, this study demonstrated that in the medium-term, landscape restoration does not increase greenhouse gas emissions from soil. In fact, the removal of soil will benefit atmospheric CO_2 levels by reducing CO_2 emissions from the lower slope

removal areas. Weed emergence will likely increase in the first year following the addition of soil; which may or may not adversely affect crop yield depending on the crop type. The overall impact of increased weed pressures can be reduced by planting a competitive crop, and using the appropriate herbicide in correct rotation.

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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. The Canadian Journal of Soil Science was the reference style used in this document. Chapters 3 and 4 will be submitted to Journal of Soil and Water Conservation. For all papers, I will be the lead author and co-authorship will be designated accordingly.

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1. INTRODUCTION

Soil erosion by wind, water and tillage results in the redistribution of soil within the landscape. In topographically complex landscapes where conventional tillage is practiced, organic-rich topsoil becomes redistributed from hilltops (or convexities) to lower slope and depressional areas (or concavities). When hilltops become eroded they lose productivity while the lower slope and depressional areas often become more productive. The yield variability within the landscape resulting from soil erosion makes agricultural land management difficult and reduces the economic viability of the cropping system.

There are several ways hilltops can be managed to improve their productivity. These include increasing the fertility of the hilltop via chemical or organic fertilizers, increasing the organic matter content of the hilltop by using manure, green manures or altering the crop rotation, and by implementing conservation tillage practices. Adding fertilizer or manure may improve the short-term productivity of the eroded hilltops, but may have limited economic return. Using crop rotation or conservation tillage requires many years of implementation to improve soil productivity. An innovative approach to improving eroded hilltops quickly and effectively is landscape restoration.

Landscape restoration is a land management practice whereby soil that has accumulated in lower slopes and depressions is returned to the adjacent eroded hilltops. This technique has been practiced for many years by farmers in China and some parts of the U.S. and Canada, but has not been documented. Some researchers have looked at crop response to the application of soil and have found optimistic results, however, landscape restoration as a general management practice has not been studied. General agronomic, economic and environmental factors of landscape restoration should be considered. For example, there are many potential environmental impacts that may be associated with the movement of organic-rich soil within a landscape that have not been considered. These include pesticide fate, nutrient cycling as it relates to runoff, leaching, and greenhouse gas emissions, as well as impacts on plant species and abundance including crops, weeds, and native plants. The latter two topics are the focus of this study.

The purpose of this thesis project was to determine the medium-term effects of landscape restoration on greenhouse gas emissions and on plant species and abundance.

The objectives of this study were:

1) To study greenhouse gas emissions (carbon dioxide, methane and nitrous oxide) following landscape restoration comparing the restored areas to the eroded area in the upper slope area, and comparing removal areas to the accumulated areas in the lower slope area.
2) To study plant emergence (including crop and weeds) and examine weed composition in the area that is restored, and monitor plant species composition where soil was removed.

Several experiments were conducted to fulfill each of these objectives. Two field experiments were initiated to address both objectives, while one growth chamber experiment used intact soil cores to address objective 1, and a second growth chamber experiment looked at the seed bank within the soil profile to address objective 2. The findings from the growth chamber studies were compared with field experiment findings.

2. LITERATURE REVIEW

Erosion processes and erosion effects on crop productivity are outlined in this chapter. A review of the current methods for improving soil quality on eroded hilltops is included. Past research on landscape restoration and its effects on plant species and emergence, including crop, weeds and native plants, and on greenhouse gas emissions is summarized.

2.1 Soil Erosion in Topographically Complex Landscapes

The three predominant forms of soil erosion reported in the literature include water, wind and tillage erosion. Each form of erosion acts on the soil in different ways; each are predominant in different types of landscapes and may cause the redistribution of soil from and to different parts of the landscape. This section briefly describes the three types of soil erosion including soil and landscape factors affecting erosion.

2.1.1 Water and Wind Erosion

Water erosion occurs in moderately to strongly sloping landscapes and is most severe on soils of silty texture and with poor aggregate stability (Troeh et al.1980). When considering landform, soil tends to be lost from concave curvatures or backslopes (Lobb and Kachanoski 1999).

Wind erosion is most common on level landscapes. Fine sands and silts are prone to wind erosion, especially when soil moisture is low. When the landscape is topographically complex, wind erosion is most severe on exposed hilltops within the landscape (Lobb 1999). Although wind erosion is responsible for the loss of soil from hilltops, it is not the predominant erosion acting on hilltops of the prairie pothole region of Canada. The losses from hilltops are equally severe on a range of soil types on both sheltered and unsheltered hilltops indicating wind erosion cannot be the only cause (Lobb 1999).

Brady and Weil (2002) report 4 billion Mg soil per year is moved by water and wind erosion in the U.S. Both wind and water erosion are thought to be the predominant forces degrading agricultural soils, including the loss of soil from hilltops and ridges. However, there is little experimental or theoretical evidence that can adequately explain the degree of soil erosion on hilltops (Lobb et al.1995). Recent research has found that tillage erosion is in fact the cause (Govers et al. 1999).

2.1.2 Tillage Erosion

Tillage erosion is responsible for the loss of large quantities of soil from crest and shoulder slope landscape positions (Lobb et al.1995; Govers et al.1999;). Soil lost from these convexities accumulates in the concave footslopes and hollows (or depressions) downlsope (Govers et. al.1999). Slope gradient strongly affects tillage erosion (Van Muysen and Govers 2002) while other factors such as tillage depth, tillage speed, tillage direction (upslope vs. downslope tillage), and soil condition also play an important role (Lobb et al. 1995; Lobb et al. 1999; Govers et al. 1999; Van Muysen et al. 2002).

Tillage erosion has been reported to account for soil losses of 54 t ha^{-1} year^{-1} from upland shoulder slope positions in Southern Ontario (Lobb et al. 1995). This level far exceeds Canada's Agri-Environmental Indicator - Risk of Tillage Erosion tolerable level of 6 t ha^{-1} yr^{-1} (King et al. 2000). In Manitoba it was estimated that 56% of cropland fell under unsustainable soil conditions in terms of tillage erosion risk (King et al. 2000). It is clear that tillage erosion is an important process affecting soil quality and crop productivity in agricultural landscapes (Li and Lindstrom 2001).

2.2 Effects of Soil Loss on Crop Productivity

'The effects of erosion depend largely on the thickness and the quality of the topsoil (being lost) and the nature of the subsoil' being exposed (Frye et al.1985). The loss of topsoil from hilltops can dramatically reduce the productivity of those hilltops for various reasons.

When topsoil is lost, the total amount of soil organic matter[1] is reduced on the eroded areas (Lal 2000; Frye 1985; Lobb1995; Tanaka 1989). The loss of organic matter brings with it altered chemical and physical properties, such as reduced fertility and lower soil water holding capacity (Lal 2000; Langdale 1982).

Soil fertility is reduced in eroded soils (Fry et al. 1985). With each Mg ha^{-1} of lost organic matter, approximately 60 kg of nitrogen (N) is also lost (Frye et al. 1985). Phosphorus concentrations of soil may also be lowered. Larney et al. (2000a) found the extractable phosphorus (P) concentration decreased with increasing depth of soil removal at two of three sites while Tanaka and Aase (1989) also found extractable P significantly decreased when soil was removed.

In addition to influencing soil fertility, soil organic matter content influences the soil's water holding capacity by retaining water that is much more plant available than that held in the mineral fraction (Brady and Weil 2002). When organic matter is lost, so is

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[1] The term organic matter refers to the organic fraction of soil consisting of all organic elements including carbon, nitrogen, phosphorus, sulphur, hydrogen and oxygen; the terms organic matter and organic carbon are sometimes used interchangeably in the literature but here, when the term organic matter is used, the organic compounds in general are being reported; when the term organic carbon is used, the measured organic carbon fraction is being reported.

the soil's ability to retain moisture for plants. Organic matter indirectly affects plant available water by stabilizing soil structure and increasing pore space (Brady and Weil 2002; Lal 2000). Soils with higher organic content, therefore, show better water infiltration.

Finally, loss of topsoil may result in soil profile mixing. Any remaining topsoil becomes mixed with subsoil material through further tillage thereby diluting the topsoil's organic matter content (Frye et al. 1985; Tanaka and Aase 1989). When subsoil becomes mixed with topsoil, the inorganic carbon content will increase (Larney et al. 2000b) when subsoils are rich in carbonates. When calcium carbonates are present in the subsoil, this profile mixing may in turn cause problems with soil fertility since small amounts of P can be adsorbed by and/or precipitated with calcium especially when P concentrations in the soil are low (Havlin et al. 1999). A co-precipitation reaction can also occur with sulphate ions and $CaCO_3$ (Havlin et al. 1999). The availability of P and S is therefore reduced. Subsoils are often stony, lending to undesirable seedbeds and problems with seedling emergence. The subsoil is often less friable and less permeable to air, water and roots (Troeh et al.1980).

These changes in soil physical and chemical properties ultimately reduce productivity in eroded areas. There is a significant relationship between grain yield and organic C content of soil (Larney et al. 2000b) and grain quality may also be affected (Tanaka and Aase 1989). The negative effect of topsoil loss on soil quality and productivity has been well documented over the past two decades and started as early as 1944 (Horner et al. 1944; Lyles 1977; Langdale and Shrader 1982; Sadler 1984; Burnett et al.1985; Meyer et al. 1985; Carter et al.1985; Battiston et al. 1987; Larney et al. 1998;

Schumacher et al.1999;Larney et al 2000 a and b; Lal et al. 2000). The effects of erosion are not always recognized, however, due to the use of fertilizers and other restorative amendments.

2.3 Current Methods for Improving Soil Quality and Productivity

Producers often deal with poor soil quality on hilltops by increasing fertilizer use, adding organic amendments, and changing cropping and soil management practices. There are several studies that looked at the effects of one of, or combinations of, these practices on previously eroded or artificially eroded soils.

2.3.1 Fertilizer Use

Since nutrient deficiency is a common problem of eroded soils, it makes sense to increase fertilizer inputs in eroded areas. The introduction of precision farming has made variable rate application of fertilizer possible (Beckie et al. 1997). Adding increased amounts of fertilizer, however, may not be sustainable in the long-term both agriculturally and economically. In fact, it has been well documented that fertilizer addition alone will not return crop yields to pre-erosions states (Massee and Waggoner, 1985; Mielke and Schepers, 1986; Dormaar et al. 1988; Robbins et al. 1997; El-Swaify 2000). Massee and Waggoner (1985) found that large amounts of N fertilizer were unsuccessful at achieving high yields in artificial erosion plots where topsoil was lost or absent in an intermountain dryland region of Idaho. This study concluded that "adding N fertilizer each crop year was only a partial solution to inadequate topsoil." In contrast, there is evidence that using both N and P in different combinations was effective at increasing yield on eroded soil to equal to or greater than the level of the non-eroded check (Tanaka and Aase 1989; Dormaar et al. 1997)

There is evidence supporting and contradicting the benefits of adding fertilizer to eroded areas to improve yield. Even if fertilizer does successfully restore crop yield to non-eroded soil yield levels, there may not be an economic benefit to increasing fertilizer use (Smith et al. 2000). For example, Smith et al. (2000) evaluated the economics of N and P fertilization to restore wheat yields in the Brown and Dark Brown soil zones of the Canadian Prairies. They found that when economic optimum fertilizer levels were used crop yields declined as depth of erosion increased and, therefore, the net return over fertilizer cost also declined with increased erosion. They concluded that there was little to no economic benefit of applying additional inorganic fertilizer to eroded soils.

2.3.2 Use of Organic Amendments

Manure can be a good source of macro- and micronutrients while also providing long-term improved physical characteristics (Dormaar et al. 1988). Most research shows multiple benefits from adding manure to artificially eroded soils including increased yields, increased organic matter content and improved soil physical properties (Larney et al. 2000 a and b; Dormaar et al. 1988; Dormaar et al. 1997; Robbins et al. 1997; Izaurralde et al. 1997). Larney et al. (2000a) found manure (applied at a rate of 75 Mg ha^{-1} wet weight or 22 g kg^{-1} total N and 190 g kg^{-1} total C) was effective at restoring eroded soils over the two-year study period (or medium-term), however, the duration of these effects were uncertain and needed further study. Larney et al. (2000b) also reported manure addition significantly increased the organic C content of the soil (by 1.0%: from 10.7 in check to 11.9 in manure treatment) such that water holding capacity and yield was increased. This enhancement was linearly and inversely related to organic C concentrations of the recipient soil. Dormaar et al. (1988 and 1997) showed manure significantly increased soil organic matter (OM); however, the increase was not substantial. They (Dormaar et al. 1988) concluded that adding manure annually for several years may be required to rebuild the OM of eroded soil. Manure also added greater biological activity as indicated by measuring dehydrogenase activity (Dormaar et al. 1997). Robbins et al. (1997) showed adding manure benefited soil quality by increasing the organic carbon of the subsoil to the level of the topsoil (increased by 50% i.e. doubled the amount) after four study years. Izaurralde et al. (1997) also found a significant increase in OM (1.73 to 3.47%) with manure when soil was severely eroded (20 cm cut).

There are additional sources of organic matter that may also be used as ammendments; these include whey (cottage cheese by-product), sugar by products, crop biomass and green manures. Organic amendments in the form of whey and wheat straw did not benefit yield or OM of eroded soil (Robbins et al. 1997; Dormaar et al. 1997). Robbins et al. (1997) added two rates of whey and found it did not affect bean seed yields or OM content. Dormaar et al. (1997) repeated the study reported on in 1988 to include the addition of wheat straw plus commercial fertilizer. They found this treatment did not increase OM or total N of the soil over time and had little beneficial effect on wheat yield. Green manures may positively affect soil quality attributes essential to improving the productivity to eroded soils. Biederbeck et al. (1998) found an annual legume green manure had a strong influence on soil quality in the short-term including improved C and N mineralization, wet aggregate stability and light fraction organic matter.

Based on the literature reviewed here, manure appears to be a somewhat effective organic amendment for restoring crop yields; however, there are other important factors associated with manure application that must be considered. These include a) the availability of manure (not all producers cropping severely eroded topographically complex landscapes are also livestock producers); b) the cost of manure application increases as the distance from the facility increases therefore, manure application may not be a good option for all of the eroded areas of a producer's entire land base; c) eroded areas may be environmentally sensitive areas (e.g., nearby wetlands) that are not suitable for manure application; d) manure application to the same field year after year is not a common practice. For these reasons, alternatives to manure for improving eroded areas are still needed.

2.3.3 Cropping System

Crop rotation is known to play an important role in cropping systems by optimizing water and nutrient use, by breaking disease, insect, and weed growth cycles and thereby improving yields (Saskatchewan Agriculture and Food 1997; Stevenson et al. 1998; Stevenson and van Kessel, 1996). For these reasons, there is the potential for crop rotation to improve eroded soils. The literature regarding specific rotation effects on eroded soil is minimal. Robbins et al. (1997) included rotations in their study of improving exposed subsoils and concluded that the bean yield increase resulting from crop rotation was only minor when compared with the manure addition treatment. Although crop rotation is a beneficial tool in crop management, it may not be the ideal tool for restoring eroded soils.

2.3.4 Tillage System

The adoption of conservation tillage, specifically zero-till is increasing across the Canadian Prairies (Campbell et al. 2001). By reducing tillage practices, tillage erosion is reduced and the degraded soil is allowed to rebuild because a greater amount of organic matter from crop residues remains on and in the soil profile (Lal and Kimble 1997). However, conservation tillage takes years to rebuild topsoil to pre-erosion levels, and an alternative/additional management option that provides rapid results for improving topsoil levels, and ultimately soil productivity, is needed.

2.4 Soil Addition/Landscape Restoration

Landscape restoration as a soil management practice has not been studied, but there is some research documenting the effects of topsoil addition as a restorative amendment and in determining the impacts of soil erosion.

In 1986 in Nebraska, Mielke and Schepers (1986) monitored crop response to the replacement of lost topsoil (0, 10 and 20 cm additions). They found improved crop emergence as indicated by earlier emergence and greater total emergence, and overall greater corn yields were achieved. Interestingly, soil water content did not differ between added soil and control treatments. However, when below-normal precipitation occurred, the 20 cm topsoil addition treatment achieved 5 and 22% higher yields compared to the 10 cm and 0 cm soil addition treatments, respectively. The topsoil treatment consistently increased the dry-matter production of oats and the greater amount of added topsoil positively influenced total N uptake (however, grain N concentration did not differ among treatments). One important conclusion was that crop response to topsoil addition was more favorable in years where there was greater plant stress.

There were several studies that included a topsoil amendment treatment in their analysis of amending eroded soils using fertilizer and/or manure. The depth of the topsoil treatment was 5 cm for most studies. Dormaar et al. (1997) repeated the study reported on in 1988 this time including a topsoil addition treatment. Topsoil addition immediately increased the OM and total N content of the soil, however, these effects declined over time. This may have been the result of soil profile mixing because 5 cm of topsoil was not thick enough and easily became incorporated with the subsoil. Larney et al. (2000 a) explain that topsoil plays an important role beyond fertility and water storage as indicated by the fact that irrigation and fertilizer use did not offset the effects of lost topsoil. They also found greater organic carbon content resulted from adding topsoil compared with adding fertilizer, however, manure addition proved to add the greatest amount of OC (0.4 and 1.1 g kg^{-1} higher than the checks at the Lethbridge Dryland and Lethbridge Irrigated sites, respectively) (Larney et al. 2000b).

Massee and Waggoner (1985) studied the effect of topsoil depth on soil moisture regimes and on fertilizer response. Among the artificial erosion treatments, they included a topsoil addition treatment where 15 cm of topsoil was placed over the original profile. Compared with the untreated soil plot, the topsoil addition treatment showed a 40% yield increase when no nitrogen was added. Also, water-use efficiency increased with added soil. When adding 15 cm of topsoil to the original soil surface (15 cm Ap layer), Massee (1990) found the additional topsoil had a beneficial yield effect. Providing twice the active topsoil to maintain soil moisture favored nitrification of the added ammonium based fertilizer. They concluded that topsoil provides benefits to yield and water storage.

Verity and Anderson (1990) characterized soil erosion effects on soil quality and yield by adding incremental depths of topsoil to eroded knolls (5, 10, and 15 cm). Wheat grain yields resulting from the restored soil exceeded the control by 45 and 58% in the first year and 42 to 88% in the second. In this comparison, the 5 cm addition treatment resulted in yields that were similar to the 10 and 15 cm treatments. The straw yields from these treatments were also higher, ranging from 62 to 88% over the control. The 10 and 15 cm soil addition treatments yielded significantly greater straw yields in year two.

There are benefits to topsoil beyond nutrients alone (Tanaka and Aase 1989). It has been demonstrated that adding soil can improve some indicators of soil quality including productivity (in terms of yield), organic matter content (to varying degrees) and soil water holding capacity. Topsoil that is eroded by tillage moves down slope and accumulates in depressions but is not degraded, it can be a good source of organic matter. Using this accumulated soil and adding it to eroded hilltops to reverse the effects of tillage erosion is possible; however, landscape restoration as a soil management practice has not been researched. There are many potential environmental and agronomic factors that may be affected by moving soil within the landscape. Research is needed in the areas of environmental impacts, such as impacts on greenhouse gas emissions, and agronomic impacts beyond crop yield, such as impacts on weeds. Furthermore, research on soil removal from hill bottoms/depressions does not exist.

2.4.1 Soil Addition Effects on Greenhouse Gas Emissions

Currently there is pressure on the agriculture sector to reduce net GHG (mainly carbon dioxide, methane and nitrous oxide) emissions through the implementation of beneficial management practices, including those aimed at increasing carbon storage in soil (Janzen et al. 1998). The potential impact of landscape restoration on GHG is, therefore, important because it will affect soil carbon within the landscape. Changes in soil carbon may in turn induce changes in greenhouse gas emissions including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The literature regarding landscape restoration/application of topsoil effects on greenhouse gas (GHG) emissions does not exist. There is, however, a lot of research on GHG dynamics in agroecosystems as influenced by management system and/or soil parameters (Burton and Beauchamp 1985; Mahli et al. 1990; Lal and Kimble 1997; Pol-van Dasselaar et al 1998; Janzen et al. 1998). Soil erosion will likely influence C flux (and other GHG emissions) because of its effect on a number of processes including: 1) removal of soil organic carbon-rich soil, 2) burial of soil through deposition, 3) textural changes with subsoil exposure, 4) microbial activity due to soil moisture and temperature changes, and 5) plant growth and residue amounts (Bajracharya et al. 2000). Some of these processes are also influenced by landscape position (Pennock et al 1992; Corre et al.1996). Therefore, it is expected that landscape restoration will effect GHG emissions by influencing the same process affected by soil erosion and landscape factors. More research is needed to assess whether landscape restoration will positively or negatively affect GHG emissions from the landscape.

2.4.2 The Effects of Topsoil Addition on Weeds

The literature regarding landscape restoration/addition of topsoil effects on weeds does not exist; however there is some research that is applicable. One relevant topic in weed research is the weed seed bank. Much of the research looks at trying to characterize the seed bank on a horizontal plane (across level landscapes) with correlations to existing weed populations (Benoit et al. 1992) and few have looked at the relationship between seed bank and soil depth. It has been documented that most viable weed seeds exist within the top15 cm of soil, depending on the type of tillage system, crop rotation and weed management practices (Barberi and Lo Cascio 2001; Felix and Owen 2001; Buhler et al. 1997; Cavers 1995). This has implications for landscape restoration because it is the surface layer of soil that will be removed and applied to eroded hilltops. The composition of the seed bank within the soil profile, and the proportion of viable seed banks below the soil surface of accumulated soil are important for assessing the potential weed populations that might arise following landscape restoration in areas where soil is removed and where soil is applied.

While the weed seed bank relates to weed population variability in time, a second relevant topic is the variation of weed populations in space. Weed populations will vary within the landscape due to landscape variations in soil physical and chemical properties such as soil type, moisture, texture, and fertility (Dieleman et al. 2000). Therefore, it is expected that weed populations may be influenced by changes in soil properties within the landscape caused by landscape restoration.

3. IMPACTS OF LANDSCAPE RESTORATION ON GREENHOUSE GAS EMISSIONS

3.1 Abstract

Soil management can lead to increased or decreased greenhouse gas emissions; however, the variability of soil properties, and thus gas emissions, in space make it difficult to predict these effects. Landscape restoration is one soil management practice that can reduce the spatial variability of some soil properties in topographically complex landscapes, including soil organic matter. This study examined the effect of landscape restoration on greenhouse gas emissions (CO_2, CH_4, and N2O) from the soil. Landscape restoration did not affect greenhouse gas emissions in the upper slope area where soil was applied. Where soil was removed, soil CO_2 flux was decreased in the first year following landscape restoration. Changes in the soil environment including soil nitrate and soil microbial biomass carbon were also observed.

3.2 Introduction

Increase in the atmospheric concentration of greenhouse trace gases (e.g., CO_2, CH_4, N_2O) since pre-industrial times has led to climate change (Mosier 1998). Globally, agriculture contributes greenhouse gas emissions representing approximately one-fifth of the annual increase in global radiative forcing of climate change (Cole et al. 1997). In Canada, agriculture contributes 10% of anthropogenic greenhouse gas emissions (Enivronment Canada 2005). Soils act as a major source and potential sink for greenhouse gases (Janzen et al. 1998) and, therefore, managing the soil environment can lead to increased or decreased emissions. The influence of soil management on net emissions is difficult to predict due to the inherent variability of the soil environment in space and time (Mosier 1998; Corre et al. 1996). Soil properties and, as a result, greenhouse gas emissions, vary greatly within the landscape (Meixner and Eugster 1999).

Tillage can affect soil properties and thus greenhouse gas emissions from soil. Conservation tillage, specifically no-till, is a beneficial management practice (BMP) designed to reduce erosion processes, improve the overall quality of the soil environment and reduce landscape variability. Soil properties including soil organic matter content, soil moisture and soil nutrients all influence greenhouse gas emissions and, therefore, conservation tillage will also affect greenhouse gas emissions from the landscape. In fact, conservation tillage is known to increase soil organic carbon in the surface layer (Lal and Kimble 1997) resulting in reduced CO_2 emissions. Also, there is evidence of a strong positive correlation between organic carbon in the soil and nitrous oxide emissions (Malhi et al. 1990; Luo et al. 1998; Lemke et al. 1998).

Soil erosion can influence the spatial variability of soil properties in topographically complex landscapes. Soil erosion by wind, water and tillage results in the redistribution of soil within and often beyond the landscape. Tillage erosion is largely responsible for soil variability within the landscape by displacing organic rich topsoil from hilltops and moving it to lower slopes and depressions (Lobb 1999). Hilltops low in organic matter consequently have lower water and nutrient holding capacity and show low agricultural productivity; lower slopes and depressions tend to have an accumulation of organic rich topsoil with higher moisture and nutrient holding capacity and also greater productivity (Lobb 1999).

Landscape restoration is an innovative soil management practice that can be used in combination with conservation tillage to further reduce the variability of soil properties within the landscape. Landscape restoration is a practice whereby soil accumulated in lower slope and depressional areas is removed and added to eroded hilltops or upper slope areas. Adding soil to hilltops will likely increase soil organic matter of the surface soil; removing soil from lower slopes and depressions will also influence soil organic matter therein. By altering the organic matter within the landscape and soil properties influenced by soil organic matter, such as soil moisture and nutrients, there is the potential for landscape restoration to affect greenhouse gas emissions from the landscape. Landscape restoration is a practice with the potential for widespread adoption in areas where tillage erosion is prevalent and therefore, the impact of landscape restoration on greenhouse gas emissions from the landscape should be understood.

The objective of this study was to measure greenhouse gas emissions (carbon dioxide, methane and nitrous oxide) from the soil following landscape restoration, focusing on the hilltops where soil was added and on the lower slope and depressional areas from where soil was removed. A complementary growth chamber study was carried out using intact soil cores to determine if the depth of added and the depth of removed topsoil will influence gas flux. The findings from the growth chamber study were compared to the field experiment findings. The medium-term impacts of landscape restoration on greenhouse gas emissions are discussed.

3.3 Materials and Methods

Field and growth chamber experiments were conducted to address the thesis objectives which include the study of the impacts of landscape restoration on greenhouse gas (GHG) emissions and on plant species and abundance (Table 3.1). This section provides a description of the study site where the field experiments were carried out and from where soil was collected for the growth chamber experiments. The complete methodology for the field and growth chamber experiments designed to study greenhouse gas emissions is presented. The methodology for the study of plant species and abundance in the field and the complementary growth chamber experiment is included in Section 4.3.

Table 3.1 A summary of the field and growth chamber experiments

	Study A – Greenhouse gas emissions	**Study B** – Plant species and abundance
Field Experiment 1 – **FE1**	Sites identified fall 2002/experiment initiated spring 2003 and carried out through to fall 2004	
Field Experiment 2 – **FE2**	Sites identified fall 2003/experiment initiated fall 2003 and carried out through to fall 2004	
Growth Chamber Experiment 1 – **GC1**	Soil Column Experiment – Part 1 and Part 2 carried out winter/spring 2004	
Growth Chamber Experiment 2 – **GC2**		Weed Seed Bank Experiment carried out fall 2003

3.3.1 Site Selection and Description

The study area exists within the Aspen Parkland of the Prairies Eoregion of South-western Manitoba and is also considered to be a part of the Prairie Pothole Region of the province. Within this area, the Manitoba Zero Tillage Research Association (MZTRA) farm is located (Section 31-12-18) and was chosen as the study site. The landscape is topographically complex and contains numerous wetlands (or potholes) that are ephemeral to permanent in nature. The soils are predominantly Black Chernozems formed over calcareous glacial tills. Mean annual temperature for the area is 1.4°C and total precipitation is 460 mm with 340 mm mean annual rainfall (Podolsky and Schindler 1993). The land-use is largely agricultural with a focus on cereal, oilseed and livestock production.

The landscape of the MZTRA farm is characterized as undulating to hummocky with gently sloping (2-5%) topography (Podolsky and Schindler 1993). Soils are of the Newdale Association and are representative of the Newdale soils in the Parkland Region (Podolsky and Schindler 1993). The study site consists predominantly of Newdale Series soils with a small portion belonging to the Rufford, Cordova, Drokan and Angusville Series. Newdale soils (Orthic Black Chernozem) generally appear in the mid to upper slope positions while the Rufford (Rego Black Chernozem) and Cordova (Calcareous Black Chernozem) soils are found in upper slope positions and knolls. Drokan soils are typically found in depressional positions while the Angusville soils are found in the middle and lower slope positions of the undulating topography. In the lower slope areas, drainage ranges from poor in the depressions to well in the upper slopes. Twenty-two percent of the soils on the farm are considered weakly saline (Podolsky and Schindler 1993). Higher salinity levels occur in saturated soils or soils found adjacent two permanent sloughs and water bodies. The Drokan series found at the study site was characterized by Podolsky and Schindler (1993) as being weakly saline (4-8 mS cm^{-1}). Bulk density ranged from 0.99 and 1.08 g cm^{-3} in the top 12 cm of the Newdale and Rufford soils, respectively, and 1.24 g cm-3 in the top 17 cm of the Angusville soils. Bulk density measurements were not available for the Drokan and Cordova soil series.

The MZTRA farm has been under zero-till crop production since 1993 and was intensively tilled for decades prior to that. The farm is currently managed under a 5-year crop rotation under two different cropping systems: an annual rotation consisting of cereals and oilseeds as well as a livestock rotation consisting of cereals and oilseeds and alfalfa for hay production and for grazing cattle. The study site exists within the annual cropping system. The farm manager is responsible for all seeding, harvesting and herbicide application operations.

There is visual evidence of the tillage erosion that occurred prior to 1993 still present on many of the hilltops and upper slope areas of the MZTRA farm. This includes stoniness, high $CaCO_3$ content, low soil organic matter (SOM) at the surface, and a thin A horizon in soils occurring in upper slope areas; and a thick, organic-rich A horizon in soils in lower slope and depressional areas. The severity of past erosion on the hilltops was determined to be 20-40 t ha^{-1} yr^{-1} during the period of conventional tillage between 1960 and 1993 using the ^{137}Cs method described by Lobb and Kachanoski (1999).

Several severely eroded ridges and knolls were identified in the center of the west half of the MZTRA research farm in the fall of 2002 for the purpose of studying greenhouse gases and plants following landscape restoration. The first field experiment was established in the spring of 2003, while the second field experiment was established in the fall of 2003 (Table 3.1).

Two growth chamber experiments were conducted using soil collected at the MZTRA farm. A soil column experiment (Section 3.3.3) used intact soil cores sampled from a landscape on the NE quarter of the farm (GC 1). The landscape was similar in form, soil composition, and severity of erosion to that used in the field experiments. A weed seed bank experiment (Section 4.3.2) used soil collected from the same site as the field experiments (GC 2).

3.3.2 Field Experiments

Two field experiments were conducted with the same objectives but with slightly different experimental designs; one initiated in spring of 2003 and the other initiated in the fall of 2004.

3.3.2.1 Field Experiment 1 (FE1 2003-2004). A restoration experiment was initiated in May 2003 at the MZTRA research farm in a cropped landscape adjacent to a large permanent wetland and was conducted over two growing seasons (2003 and 2004). The edge of the wetland consisted of two distinct rings of riparian vegetation, the first containing hydrophilic plants (cattails and sedges) and the second, outermost ring, containing perennial grass (brome) and some perennial broadleaf plants (thistle; meadow arnica). For this experiment, soil was removed from the riparian area (the second, outermost riparian area) where soil had accumulated due to past erosion, and was added to the upper eroded ridge from where the soil was originally lost.

Approximately 20 cm of soil was removed from 3.2 m^2 plots in the riparian area and applied to 7.3 m^2 plots on the severely eroded upper slope area to give a final added depth of approximately 10 cm on May 5th, 2003. The soil was allowed to dry for several days and then disked with three passes to break up the sod and any large clods of soil (Figure 3.1 and 3.2). The depth of topsoil added was measured using a meter stick in nine places throughout the plots and averaged to characterize the final depth of addition (Appendix A.1). The depth of topsoil removed was also measured (Appendix A.2). The plots from where soil was removed contained large wheel tracks and soil debris. The wheel tracks were filled and the soil debris was removed in order to smooth and clean the surface of these plots. There are, therefore, two areas of interest in this experiment – the upper slope area to which soil was added (addition area) and the depressional area where soil that had accumulated from past erosion was removed (removal area).

Figure 3.1 Soil disking in the soil addition treatments of the upper slope area.

In the addition area, the treatments included 10 cm topsoil added plus disking (addition), 0 cm topsoil added plus disking (disturbed), and a control where 0 cm topsoil was added (control). The treatments were arranged as a paired treatment comparison with one pair consisting of an addition and disturbed treatment and the other pair consisting of an addition and control treatment (Table 3.2). The plot layout was such that each pair alternated across a ridge to give three replicates each. In the removal area, the treatments were: removal of 20 cm of soil plus removal of standing plant biomass (removal),

removal of standing plant biomass only (disturbed) and the control where nothing was removed (control). Standing plant biomass was removed from the plots by cutting the plants at the soil surface and taking them off the plots. The treatments were arranged in the same paired comparison as the addition area treatments. No attempt was made to pair plots of addition and removal. Both areas of interest were replicated in an adjacent field seeded to a different crop to give two blocks. Greenhouse gas emissions, soil temperature and moisture, soil chemistry and soil organic carbon (SOC), crop emergence and yield, and weed emergence were monitored over two growing seasons.

Table 3.2 Treatment descriptions for FE1 in (a) the upper and (b) the lower slope areas

Treatment	Pair	Treatment Description
(a) *Addition Area* – Upper slope		
Addition (U1A)	Pair 1	Addition of 10 cm of soil followed by disking (6 passes)
Disturbed (U1D)		Disking only (6 passes, no soil addition)
Addition (U2A)	Pair 2	Addition of 10 cm of soil followed by disking (6 passes)
Control (U2C)		No soil addition or disking
(b) *Removal Area* – Lower slope		
Removal (L1R)	Pair 1	Removal of standing plant biomass followed by 20 cm of soil removal
Disturbed (L1D)		Removal of standing plant biomass only
Removal (L2R)	Pair 2	Removal of standing plant biomass followed by 20 cm of soil removal
Control (L2C)		No plant biomass or soil removal

The restoration area plots were seeded by the MZTRA farm manager as a part of normal seeding operations for the farm in both years of the experiment. In 2003, Block A was seeded to flax (cv. "Bethune") on May 21 at 39 kg ha^{-1} and 2 cm deep with a Morris Maxim air drill seeder equipped with 2.5 cm knife-type openers on 25 cm spacing and metal packers. Nitrogen fertilizer (urea-ammonium nitrate 28-0-0) (67 kg N ha^{-1}) was side dribble banded at the time of seeding. Peas (cv. "Mozart") were seeded in Block B on May 15 at 202 kg ha^{-1} and 3 cm deep after being inoculated with a self-stick peat based inoculant. Weed control in both blocks followed normal weed control practices for the MZTRA farm. Both fields were treated with glyphosate (Block A and B received 648 and 432 g a.i. ha^{-1}, respectively) as a pre-seed burn off of winter annuals and volunteer cereals. The flax was sprayed with Flaxmax (660 g a.i. ha^{-1}) and Poast (211.5 g a.i. ha^{-1}) and the peas were sprayed with an Odyssey-Poast mix (31.5 g a.i. ha^{-1} and 90 g a.i. L ha^{-1}, respectively) for control of grassy and broadleaf weeds. Both crops also received a pre-harvest burn off of glyphosate (864 and 605 g a.i. ha^{-1}) in Blocks A and B, respectively) to help dry down the crop as well as control the Canada thistle (*Cirsium arvense*) in the pea field (Block B).

In 2004, Block A was seeded to canola (cv. "46A76") on May 28 at a rate of 5.6 kg ha^{-1} and 2 cm deep. Nitrogen (67 kg N ha^{-1} equivalent) and sulphur (22.5 kg ha^{-1}) was side dribble banded at the time of seeding. Block B was also seeded to canola (cv. "822 Nexera") on May 21 at the same rate. Nitrogen (74 kg N ha^{-1} equivalent) and sulphur (22.5 kg SO_4-S ha^{-1}) were side dribbled banded at the time of seeding and nitrogen (5.6 kg N ha^{-1} equivalent) and phosphorus (28 kg H_2PO_5 ha^{-1}) were placed with the seed. Both blocks received a pre-seed burn off with glyphosate at the same rates as the preceding year. Block A was treated with Odyssey (42 g ha^{-1}) on June 21 and Block B was first treated with Sevin XLR Plus (0.5 L ha^{-1}) on June 10 and 16 to control flea beetle, and on June 21 with Odyssey (42 g ha^{-1}).

3.3.2.2 Field Experiment 2 (FE2). The second field experiment also consisted of moving soil from the lower slope area to the severely eroded upper slope area, however, cropland depressions were the source of topsoil. The two areas of interest in this experiment are similar as in FE1 – the upper slope (addition area) and the depressional area where eroded soil has accumulated (removal area). This experiment was established in the late-fall of 2003 and only monitored over the growing season of 2004. Three adjacent cropland depressions occurring in the same field as Block B were selected as removal areas for this field experiment. The depressions are all similar in size and are surrounded by eroded ridges. Topsoil thickness in each depression was greater than 0.5 m. The depression was split in half with one side used as the removal area and the other as the control. Each depression was intended to represent one replication (rep) to give a total of three reps each of removal plots and controls. However, due to excess moisture (i.e. flooded conditions) in the spring and summer of 2004, the depression areas were not monitored.

The placement of the treatments was decided by the degree of erosion on the adjacent upper slopes and hilltops as indicated by the amount of and depth to carbonates at the surface as well as the degree of stoniness and the lack of soil organic matter. The upper slope treatments were the same as in FE1 (addition, disturbed, control) and applied in a randomized complete block design. One replicate, 12 m^2 in size, of each treatment was established in 9 different places along the eroded knolls to give 9 blocks and a total of 27 plots. The treatments were randomly assigned to three plots in each block. The treatments were prepared and applied using the same method as FE1. The depth of topsoil added was measured using a meter stick placed randomly in nine places throughout the plots and averaged to characterize the final depth of added soil (Appendix A.3). The same parameters were monitored as in FE1.

The addition area plots were seeded as a part of normal seeding operations for the MZTRA farm using the seeding equipment described for FE1; these operations were the same as for Block B in 2004. A problem occurred with the seeder in this field. It appeared that half of the seeder was plugged during seeding operations causing irregular emergence patterns throughout the FE2 plots. FE1 Block B plots did not appear to be affected in this way.

3.3.2.5 Gas Flux Measurement and Analysis. Greenhouse gas emissions (CO_2, CH_4 and N_2O) were measured throughout the growing season in the upper and lower slope areas to determine the effect of moving soil on soil gas flux. Greenhouse gases were sampled using vented static chambers (Hutchinson and Livingston 2002). The chambers consisted of a 20.3-cm-diameter x 10-cm-high collar and a 20.3-cm-diameter lid. The lid contained a vent tube (0.4-cm-internal-diameter, 7.5-cm-length) and second port fitted with a serum stopper to allow sampling (MacLeod et al. in preparation). Greenhouse gas chambers were installed 5 cm into the soil in each plot in both the removal and addition areas. After securing the lid in place, from the headspace at 30 and 60 minutes following closure. Samples consisted of 15 mL of atmosphere taken from the headspace of the chamber using a 20 mL disposable syringe (Becton-Dickinson), injected into a 10 mL exetainer (Labco, UK) and sealed with silicone sealant. The exetainers had been flushed with helium and evacuated to < 0.5 Torr prior to use. Five replications of fifteen mL samples of air were taken immediately after securing the lids to represent the headspace atmosphere at the start of the flux measurement. Three replications of fifteen mL samples of two standard gas mixtures were also injected into exetainers and handled in a similar manner as other gas samples. Exetainers were returned to the lab for analysis and gas was analyzed using a Varian Star Gas Chromatograph (Appendix B). The equations used for calculating gas flux from the sampling interval can be found in Appendix L.

Gases were sampled on nine dates between May 27 and September 17 in 2003 and on seven dates between April 21 and Aug 16 in 2004 for FE1; and on seven dates between April 27 and Aug 16 in 2004 for FE2. At each sampling date, soil temperature, and ambient air temperature were measured using a digital thermometer. Soil temperature was measured at two depths by inserting the thermometer into the surface soil and 5 cm below the soil surface. Ambient air temperature was measured by holding the thermometer 30 cm above the soil surface in the shade. Soil gravimetric moisture was also monitored for most sampling dates. Soil samples were collected to evaluate the size of the soil microbial biomass using the chloroform fumigation-direct extraction method (Vance et al. 1987; see Appendix C for a description of the method used). Microbial biomass C and N numbers were expressed simply as the amount of C and N released during fumigation and not corrected using published extraction coefficients (kc, kn). These parameters were measured to monitor change in soil biophysical characteristics following restoration as well as to help with the interpretation soil gas flux results.

3.3.2.6 Soil Sampling and Analysis. Soil was sampled from the 0-15 and 15-60 cm depth increments in the fall of 2003 in FE1 and in the spring of 2004 in FE2 for soil nutirent status. Soil samples from FE1 were sent to Agvise Laboratories and analyzed for nutrient status (N, P, K, and S), total carbon including organic carbon and carbonate content and salinity (Appendix D.1). Soil samples from FE2 were sent to South Dakota

State University and analyzed for the same parameters using the same methodologies. The soil nutrient status was monitored to reflect any changes in nutrients, total carbon, carbonates and salinity following landscape restoration. These parameters have important implications for the overall productivity of the soil (although this is not the focus of this study) and soil gas flux.

Soil bulk density was measured once during the duration of the study on July 15, 2004 in both FE1 and FE2. The core method was used to sample bulk density (Appendix K); however, the data for the upper slope area are not consistent with findings by Podolsky and Schindler (1993) and the lower slope area data are very low (Appendix M.2) implying the data is suspect and cannot be referred to with confidence.

3.3.2.7 Rainfall. In year 2003, rainfall was monitored on site using a tipping bucket rain gauge. In 2004, the data was obtained from MZTRA farm records.

3.3.3 Soil Column Experiment

This experiment consisted of a two-part landscape restoration experiment using intact soil columns taken from an eroded upper slope landscape position (Part 1) and from the accumulation area of a cropland depression (Part 2). Greenhouse gas flux from the columns was measured in a growth chamber after treatments were applied.

3.3.3.1 Part 1 – Addition Experiment. In the fall of 2003, intact soil columns were taken from an eroded ridge in the NE quarter section of the MZTRA farm using PVC pipe 20.3 cm in diameter (1.25 cm wall thickness) and equipped with apparatus to secure a gas chamber lid as described in Section 3.3.2.5. The columns were taken to a depth of 30 cm with enough length remaining to add the restoration treatments and allow for the headspace necessary for greenhouse gas flux measurement. This depth was chosen based on the assumption that gases produced in the upper 30 cm provide the major contribution to surface emissions. The soil columns were frozen, thawed and incubated at 25°Cfor one week prior to adding the treatments. Incubation allowed the microbial populations to re-stabilize after being frozen and thawed. At the time of taking the soil columns from the field, bulk density samples were taken at four places along the ridge at three depths (0-10 cm, 10-20 cm and 20-30 cm) to provide an estimate of the bulk density. The bulk density method used was the core method (Appendix K). This information was used to determine the volumetric water content of the columns at the start of the experiment.

Soil addition treatments were 0, 10 and 20 cm of added soil using soil that had accumulated in the depression (D) to give treatments 0, 10D and 20D, respectively. A fourth treatment was included where 10 cm of soil was added using soil from the upper (U) eroded ridge named treatment 10U. The 0 cm increment served as a control. Each treatment was replicated three times. Soil was added to the columns at a bulk density of 1.0 g cm^{-3}. Soil columns were stored in a growth chamber at 25 °C, 80% RH. Soil moisture was maintained at 70% of water filled pore space by adding 600 mL of water to the surface of the column at the end of each gas sampling. Columns were open ended and excess water was allowed to drain out of the column. The surface flux was taken on 12 days during a one-month period using the same apparatus and method as described in Section 3.3.2.5. The interval between measurements varied as the experiment proceeded with samples taken frequently following the treatment additions and less frequently towards the end of the one-month period.

3.3.3.2 Part 2 – Removal Experiment. In the spring of 2004, intact soil columns were taken from the depositional area of a depression associated with the eroded ridge used in

Part 1 of the experiment. A depth of 30 cm of intact soil was taken using the same PVC conduit as in the previous experiment. The treatments consisted of 0, 20, and 40 cm of removal and were each replicated three times. For this experiment, the treatments were applied in the field before taking the columns. That is, 20 or 40 cm of soil was removed and then the 30-cm-deep intact column was taken from the new surface and the same assumption was made that only gases produced in the upper 30 cm contribute to surface emissions. The control columns were taken from the original soil surface. Therefore, each treatment consisted of soil from a different part of the soil profile. After removing the columns, bulk density samples were taken from each column sample location at two depths (5 and 20 cm from the surface) to provide an estimate of the bulk density of the soil columns. This information was used to determine the volumetric water content of the columns at the start of the experiment.

Soil columns were stored in a growth chamber at 25 °C, 80% RH. Soil moisture was maintained at 70% of water filled pore space based on soil volumetric moisture prior to starting the experiment by adding 600 mL of water to the surface of the column at the end of each gas sampling. Columns were open ended and excess water was allowed to drain out of the column. The surface flux was sampled on 12 days over a one-month period using the same apparatus and method as described in Section 3.3.3.

3.3.4 Data Analyses

All statistical analyses were performed using SAS version 8 software (SAS Institute Inc. 2000).

3.3.4.1 Field Data. A paired t-test was used to determine treatment differences for FE1. FE2 data were analyzed using a mixed linear model in SAS to test for treatment and rep effects. The rep*treatment interaction was specified as the random statement. The level of significance used for these experiments was $\alpha = 0.10$ based on the high degree of variability characteristic of uncontrolled, field-based experiments (Corre et al. 1996). In both experiments, the upper slope data was treated and analyzed separately from the lower slope data. The gas flux was calculated as the change in the amount of gas contained in the headspace as a function of time and expressed per unit area based on the area enclosed by the chamber (MacLeod et al. in preparation). Rates of CO_2, CH_4 and N_2O flux were compared on an individual date basis after log(X+1) transformation of the data was made to improve the normality of the distribution of the error variances. LSMEANS were also calculated to compare mean significance groupings of treatments.

3.3.4.2 Column Experiment Data. Gas flux was calculated as the change in the amount of gas contained in the headspace as a function of time and expressed per unit area based on the area enclosed by the chamber (Appendix I). A general linear model analysis of variance tested for treatment effects using SAS version 8. Daily greenhouse gas emission data was log-transformation based on the Kolmogrov-Smirnov test for homogeneity of error variance. On dates where significant treatment effects were observed, Tukey's test determined the minimum significant difference groupings at $\alpha = 0.05$.

3.4 Results

3.4.1. Soil Environment

Soil temperature, gravimetric moisture content, soil nutrient status, and soil microbial biomass were all monitored throughout the sampling periods to document changes in the soil environment following landscape restoration. Soil temperature and gravimetric moisture were monitored on each greenhouse gas sampling date while soil microbial biomass was sampled once per month in year one and in the spring of year two; soil nutrients were measured in the fall of 2003 for FE1 and in the spring of 2004 for FE2 prior to seeding and fertilization. These characteristics directly affect greenhouse gas production and emission (Corre et al. 1996; Smith et al. 2003) and therefore, understanding the change in the soil environment may also help with the interpretation of gas flux results.

3.4.1.1 Soil Temperature and Moisture. In FE1, soil temperature measurements followed a seasonal trend in the upper slope position in both blocks with lowest temperatures occurring in the spring and fall in 2003 and in the spring and late-summer in 2004 (Figure 3.2). In general, the control treatment (U2C) showed consistently lower temperatures compared with all other treatments. In the lower slope, similar seasonal trends were observed for soil temperature. The removal treatments (U1A and U2A) showed consistently significantly ($P<0.10$) higher temperatures compared with the control and disturbed treatments for most dates in both years except in Block B in 2004 where the removal treatments were consistently cooler.

Mean soil gravimetric moisture was 24 % in 2003 and 27% in 2004 across Blocks A and B. The pattern in soil moisture is consistent with that of rainfall for both years (Figure 3.3). Significant ($P<0.10$) moisture differences were most common in Block B where the addition treatment maintained higher soil moisture than the disturbed and control treatments on three dates in both 2003 and 2004 (Figure 3.4). In the lower slope, mean gravimetric moisture was 36% and 40% across both blocks in 2003 and 2004, respectively. In Block B, soil moisture was significantly ($P<0.10$) higher in the removal treatments in 2003 (Appendix F.2). However, the removal treatments showed consistently lower soil moisture in all other comparisons.

In FE2, soil temperatures followed a similar seasonal trend as in FE1. The addition and disturbed treatment soils were warmer than the control soil on the first three sampling dates, but all soils maintained similar temperatures throughout the rest of the sampling period.

The range in soil gravimetric moisture was similar to that found in FE1 in 2004. Significant treatment effects were found on April 21 and June 9 where the addition treatment soils showed the highest soil moisture (Figure 3.5).

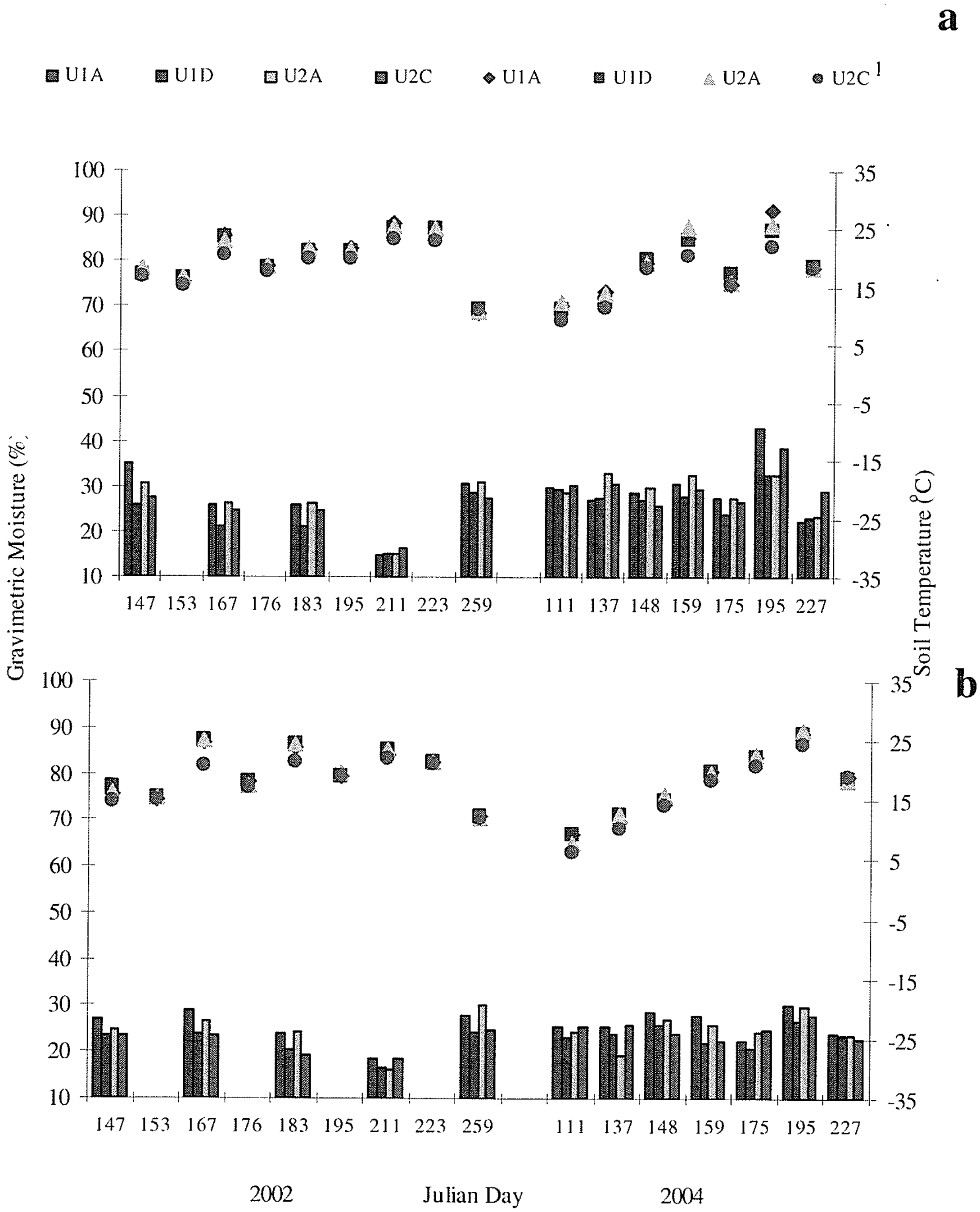

Figure 3.2 Soil gravimetric moisture (bars) and soil temperature (symbols) (5 cm below the soil surface) in the upper slope area for (a) Block A and (b) Block B in 2003 and 2004 (see Appendix E.2 and F.1 for numeric values and statistical significance).

[1] U1A = Addition treatment pair 1; U1D = Disturbed treatment pair 1; U2A = Addition treatment pair 2; U2C = Control treatment pair 2

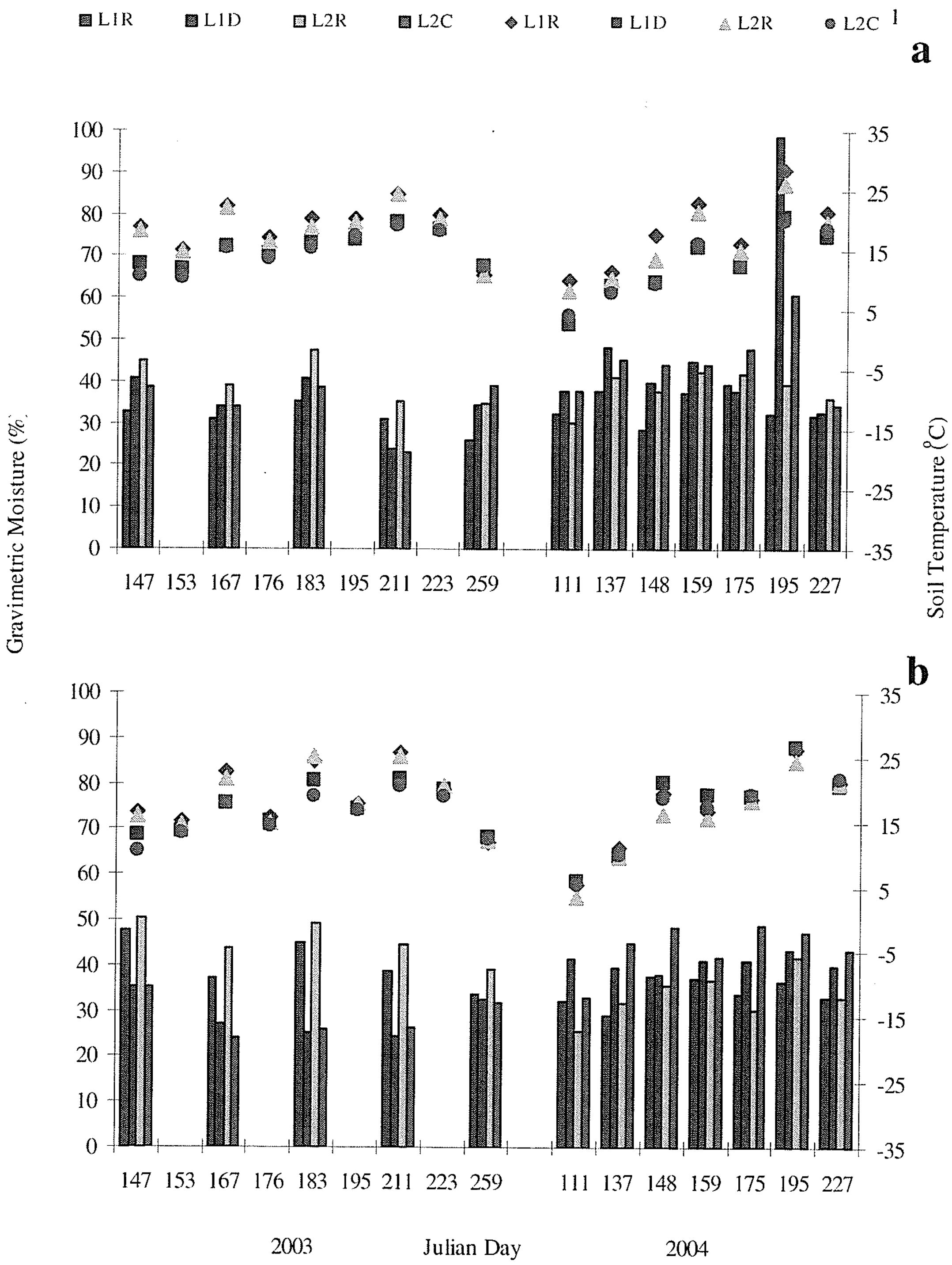

Figure 3.3 Soil gravimetric moisture (bars) and soil temperature (symbols) (5 cm below the soil surface) in the lower slope area for (a) Block A and (b) Block B in 2003 and 2004 (see Appendix E.4 and F.2 for numeric values and statistical significance).

[1] U1A = Addition treatment pair 1; U1D = Disturbed treatment pair 1; U2A = Addition treatment pair 2; U2C = Control treatment pair 2

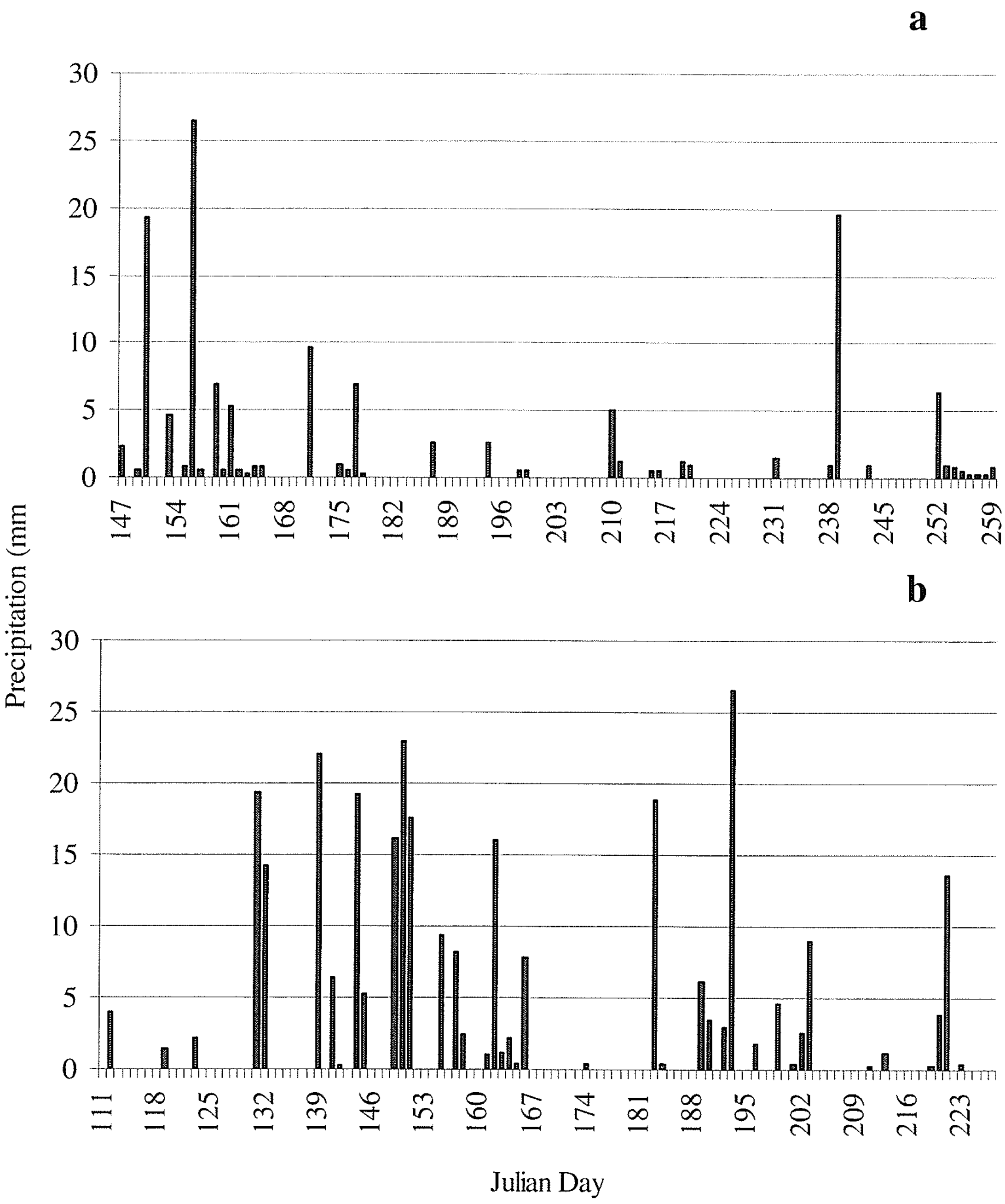

Figure 3.4 Precipitation at the MZTRA research farm over the (a) 2003 and (b) 2004 sampling periods.

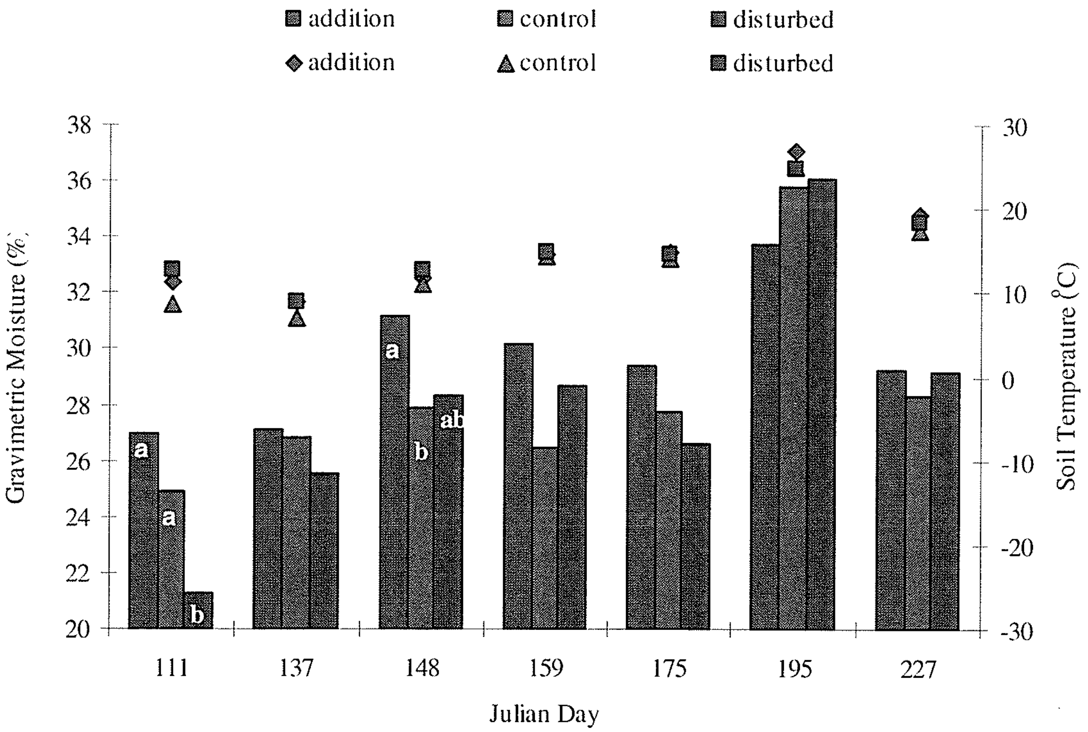

Figure 3.5 Soil gravimetric moisture (bars) and soil temperature (symbols) (5 cm below the soil surface) in FE2, 2004. a-b Mean bar values followed by the same letter (within sampling dates) are not significantly different. LSMeans groupings are associated with significant treatment effects found using linear mixed ANOVA and P < 0.10; values indicate the means of 3 replicates (see Appendix E.5 and F.3 numeric values and statistical significance).

3.4.1.2 Soil Nutrients

In the upper slope area of FE1 soil addition significantly increased soil nitrate-nitrogen (NO_3^--N) in the 0-15 cm depth by 80% over the control in Block A and by 50% over the control in Block B (Table 3.3). Although phosphorus appears to have increased as well, this difference was only significant in Pair 2 of Block A. Sulphate-sulphur (SO_4-S) increases in the addition treatment followed a similar pattern as nitrogen. Soil calcium carbonates in the surface soil were reduced by adding soil, with a significant reduction of 50% occurring in Block B. Soil addition did not significantly affect the percent total carbon (TC), although a small but statistically significant ($p<0.10$) increase in total organic carbon (TOC) occurred in both comparisons of Block B. Soil addition also increased the salt concentration of the soil at the 0-15 cm depth from 0.5 in the control to 0.8 mS cm^{-1} in the U2A treatment in Block A, and from 0.6 to 1.1 mS cm^{-1}, and 0.6 to 1.4 (mS/cm) in U1A and U2A, respectively, in Block B. At depth (15-60 cm) the percent TC and TOC were found to be significantly higher in U1A of Block B compared with the disturbed treatment, however the difference is small.

In the lower slope area, removal of soil had the greatest effect on soil NO_3-N, P, K, TC and TOC at both sampling depths, with the effects being more pronounced in Block A (Table 3.4). Significant increases in SO_4-S were found in Block B in the 0-15 cm sampling depth. TC and TOC contents were each significantly reduced by an average of 65% in Block A. In Block B, the reduction was small with significant reductions occurring only for TOC contents. At the 15-60 cm sampling depth, similar reductions were found; however, the magnitude of the decrease was slightly less.

In FE2, the addition of soil significantly increased soil nutrients in the surface layer (0-15 cm) (Table 3.5a). Soil nitrate, phosphorus, potassium and sulphate levels were 40, 50, 30 and 90% higher, respectively, in the addition treatment compared with the disturbed and control treatments. No significant treatment effect was observed for total carbon; however, inorganic carbon was significantly lower in the addition treatment compared with both the disturbed and control treatments. Organic carbon can be calculated by subtracting inorganic carbon (%) from total carbon (%). Based on this calculation and the spring soil fertility results, organic carbon was 3.9% in the addition treatment compared with 2.7% in the disturbed treatment and 2.8% in the control. The addition of soil did not alter the pH to any great degree; however salts were increased following soil addition from 0.5 mS cm^{-1} in the control to 0.7 mS cm^{-1}.

It should be noted that the removal area soils of FE1 (Drokan series) were characterized as being being weakly saline (Podolsky and Schindler 1993) and commonly showed gypsum crystals ($CaSO_4$) in the surface and subsurface soil horizons. The sulphate measurements provided here represent total sulphate-sulphur (including sulphate associated with gypsum) and therefore high levels of gypsum in the removal area soil may falsely inflate the sulphate-sulphur results of the addition treatments.

Table 3.3 Fall soil fertility results in the upper slope area of FE1 in 2003

	Block A[b]						Block B					
Nutrient	U1A[c]	U1D	Δ	U2A	U2C	Δ	U1A	U1D	Δ	U2A	U2C	Δ
a) 0-15 cm Upper Slope Area												
NO_3^--N (kg ha^{-1})	102	56	46	134	29	105**	64	31	25*	66	27	39*
P-Olsen (kg ha^{-1})	36	20	16	40	36	16**	27	18	9	25	20	5
K (kg ha^{-1})	1104	782	322	1185	853	332	820	652	168	889	681	208
SO_4-S (kg ha^{-1})	84	60	24	122	21	100**	134	46	87***	124	69	65**
$CaCO_3$ (%)	0.4	4.4	-4.0	1.0	2.7	-1.6	4.4	9.7	-5.3***	4.3	8.7	-4.4*
Total Carbon (%)	5.1	5.2	0.0	5.2	4.1	1.1**	4.1	3.8	0.3	4.3	3.9	0.4
Total Organic Carbon (%)	5.1	4.6	0.7	5.1	3.8	1.3	3.5	2.6	0.9*	3.8	2.9	0.9*
EC[a] (mS cm^{-1})	0.7	0.6	0.1	0.9	0.5	0.3*	1.1	0.6	0.5*	1.4	0.6	0.8*
b) 15-60 cm Upper Slope Area												
NO_3^--N (kg ha^{-1})	84	56	29	71	48	23	38	28	9	38	22	16
SO_4-S (kg ha^{-1})	68	89	-21	78	36	43*	203	202	1	182	252	-69
$CaCO_3$ (%)	10.9	13.2	-2.3	13.4	10.8	2.6	12.1	12.7	-0.6	12.2	12.2	0.0
Total Carbon (%)	4.0	3.9	0.1	3.9	4.0	-0.1	3.4	3.1	0.3**	3.5	3.1	0.4
Total Organic Carbon (%)	2.7	2.4	0.3	2.3	2.7	-0.4	2.0	1.5	0.5*	2.1	1.6	0.5

[a] Electrical Conductivity based on a 1:1 soil:water extraction

[b] Flax in Block A and Peas in Block B

[c]U1A = Addition treatment pair 1; U1D = Disturbed treatment pair 1; U2A = Addition treatment pair 2; U2C = Control treatment pair 2

*Significant at *P<0.10*; ** Significant at *P<0.05*; ***Significant at *P<0.01* using a paired t-test

Note: Values indicate the means of 3 replicates

Table 3.4 Fall soil fertility results for the lower slope area of FE1 in 2003

	Block A						Block B					
Nutrient	L1R[b]	L1D	Δ	L2R	L2C	Δ	L1R	L1D	Δ	L2R	L2C	Δ
a) 0-15 cm Lower Slope Area												
NO_3^--N (kg ha^{-1})	2	6	-4***	3	8	-5	12	19	-7*	28	15	13*
P-Olsen (kg ha^{-1})	11	49	-38***	9	34	-25**	11	31	-20	20	38	18
K (kg ha^{-1})	585	1510	-925***	564	1149	-584***	587	1192	-605	703	1174	-471
SO_4-S (kg ha^{-1})	134	134	0	134	134	0	134	134	0	134	134	0
$CaCO_3$ (%)	0.2	0.2	0.0	1.4	0.2	1.2	8.6	2.8	5.8***	5.6	3.2	2.4*
Total Carbon (%)	2.4	8.3	-5.9**	2.6	6.9	-4.3**	5.3	5.4	-0.1	6.4	6.0	0.4
Total Organic Carbon (%)	2.3	8.2	-5.9**	2.4	6.9	-4.5**	4.2	5.1	-0.9*	5.8	5.6	0.1*
EC[a] (mS/cm)	1.5	1.1	0.34	1.4	1.1	0.2	2.4	2.3	0.1**	3.4	2.4	1.03*
b) *15-60 cm* Lower Slope Area												
NO_3^--N (kg ha^{-1})	8	16	-8**	8	23	-15	15	36	-22	35	37	-2
P-Olsen (kg ha^{-1})	11	31	-20**	13	25	-12**	16	27	-11	25	31	-6
K (kg ha^{-1})	1042	1369	-327**	883	1236	-353**	1205	1427	-222	1263	1243	-20
SO_4-S (kg ha^{-1})	403	403	0	403	403	0	403	403	0	403	403	0
$CaCO_3$ (%)	11.2	5.9	5.3*	13.0	5.2	7.8*	12.8	6.3	6.5	12.8	8.9	3.9
Total Carbon (%)	2.9	4.1	-1.2**	3.3	3.6	-0.3	3.9	4.9	-1.0***	4.7	4.7	0
Total Organic Carbon (%)	1.6	3.4	-1.8***	1.8	3.0	-1.2	2.4	4.2	-1.8*	3.1	3.7	-0.6

[a] Electrical Conductivity based on a 1:1 soil:water extraction

[b] U1A = Addition treatment pair 1; U1D = Disturbed treatment pair 1; U2A = Addition treatment pair 2; U2C = Control treatment pair 2

*Significant at *P<0.10*; ** Significant at *P<0.05*; ***Significant at *P<0.01* using a paired t-test

Note: Values indicate the means of 3 replicates

Table 3.5 Spring soil fertility results for the upper slope area of FE2 in 2004

	NO_3^--N [2] (kg ha^{-1})	P-Olsen (kg ha^{-1})	K (kg ha^{-1})	SO_4-S (kg ha^{-1})	Total Carbon (%)	Inorganic Carbon (%)	Total Nitrogen (%)	pH	EC[1] (mS cm-^{1})
a) 0-15 cm Upper Slope Area									
Addition	34a	54a	965a	43a	4.8	0.9b	0.3a	7.7c	0.7a
Control	19b	25b	701b	4b	4.2	1.4a	0.3b	7.8b	0.5b
Disturbed	21b	25b	668b	4b	4.5	1.8a	0.3b	7.8a	0.5b
b) 15-30 cm Upper Slope Area									
Addition	24a	-	-	6.9	4.5a	0.2	-	-	-
Control	12b	-	-	10.5	4.0b	0.1	-	-	-
Disturbed	11b	-	-	14.6	4.5a	0.1	-	-	-

[1] Electrical Conductivity based on a 1:1 soil:water extraction

a-c Mean values followed by the same letter (within columns) are not significantly different based on an LSMeans comparison at $P<0.01$

Note: Values indicate the means of 9 replicates

3.4.1.3 Microbial Biomass Carbon (MBC). The soil microbial biomass carbon data is referring to the organic carbon released upon chloroform fumigation and not the corrected biomass (Jenkinson et al. 2003). These numbers provide an estimation of the microbial pool indicative of changes in soil organic matter and they might be useful for interpreting soil gas flux results.

In FE1, the addition treatment soil contained 60% more MBC on average than the disturbed or control treatments (Table 3.6). In year two, only two dates were sampled early in the sampling period. No clear trend was observed for microbial biomass C.

In the lower slope position in 2003 of FE1, significant reductions in microbial biomass C in the removal treatment occurred on all dates in Block A (Table 3.7). In 2004, a similar pattern was observed.

Microbial biomass was analyzed from two sampling dates for FE2. Soil addition or soil disturbance did not significantly affect soil MBC (Table 3.8).

Table 3.6 Microbial biomass carbon results in the upper slope area of FE1

Date	Block A						Block B					
	U1A	U1D	Δ	U2A	U2C	Δ	U1A	U1D	Δ	U2A	U2C	Δ
			$\mu g\ g\ soil^{-1}$						$\mu g\ g\ soil^{-1}$			
a) 2003												
27-May	338.6	180.2	158.5	357.9	193.2	164.7**	323.0	183.9	139.0**	297.3	196.6	100.7**
17-Jun	242.7	212.8	29.9	342.6	216.2	126.4**	309.8	174.0	135.9***	255.9	165.1	90.9*
3-Jul	178.3	174.2	4.1	230.5	169.0	61.5*	266.2	199.1	67.1**	344.2	197.0	147.2**
31-Jul	236.4	205.6	30.8	223.6	209.6	14.0	281.4	207.2	74.2	260.4	301.3	-40.9
17-Sep	237.4	247.3	-9.9	270.2	240.0	30.2	272.4	232.3	40.1	272.9	192.2	80.7**
CV %	32	21		25	20		16	21		16	24	
b) 2004												
27-May	311.2	286.5	24.7	283.9	296.4	-12.6	337.6	232.6	105.0	357.6	204.6	153.0*
9-Jun	236.7	272.4	-35.7	247.0	240.3	6.7	271.9	204.4	67.4**	297.5	289.0	8.4
CV %	20	10		24	23		18	14		15	33	

*Significant at *$P<0.10$*; ** Significant at *$P<0.05$*; ***Significant at *$P<0.01$* using a paired t-test

Note: Values indicate the means of 3 replicates

Table 3.7 Microbial biomass carbon results in the lower slope area of FE1

	Block A						Block B					
Date	L1R	L1D	Δ	L2R	L2C	Δ	L1R	L1D	Δ	L2R	L2C	Δ
			μg g soil^{-1}						μg g soil^{-1}			
a) 2003												
27-May	92.4	578.4	-485.9*	217.9	329.9	-112.0**	360.7	371.8	-11.1	343.9	504.7	-160.8
17-Jun	127.1	314.1	-187.0***	182.8	307.2	-124.4**	222.7	336.5	-113.8	275.4	314.1	-38.7
3-Jul	121.5	492.1	-370.6**	177.8	454.6	-276.8**	266.9	362.1	-95.3	298.9	327.1	-28.2
31-Jul	130.4	460.9	-330.5**	161.5	432.3	-270.9**	278.4	342.0	-63.6	319.7	452.5	-132.8
17-Sep	72.4	436.3	-363.8**	162.5	536.9	-374.4**	227.3	414.4	-187.1*	256.4	517.5	-261.2
CV %	30	28		22	25		24	23		20	35	
b) 2004												
27-May	165.4	581.3	-415.9**	344.4	603.6	-259.2	426.1	438.0	-11.9	235.9	515.4	-279.4
9-Jun	126.9	594.3	-467.4**	164.8	491.9	-327.1	333.7	370.4	-36.7	278.4	465.7	-187.3
CV %	28	16			74	27	39	52		66	46	

*Significant at *P<0.10*; ** Significant at *P<0.05*; ***Significant at *P<0.01* using a paired t-test

Note: Values indicate the means of 3 replicates

Table 3.8 Microbial biomass carbon results (μg g soil^{-1}) for two sampling dates in the upper slope area of FE2 in 2004

Treatment	27-May	9-Jun	CV %
	Carbon		
Addition	243.7	241.0	27
Control	562.4	274.3	195
Disturbed	294.5	259.8	39

CV% for each treatment was calculated by dividing the standard deviation units by the mean using all reps and all dates

3.4.2 Gas Flux

Soil addition did not have a consistent positive or negative effect on gas flux in the field. The gas flux results were variable and few significant treatment differences occurred. This may be the result of having limited data for individual dates in FE1 because only a small number of replications of each pair were used. Also, because gas emissions are highly variable in space and time (Corre et al. 1996; Bremner 1997; Smith et al. 2003), sampling a small number of replications made it difficult to capture any treatment effects. Coefficients of variation (calculated for each treatment by dividing the standard deviation units by the mean using all reps and dates) were on average 100%, 250%, and 500% for CO_2, CH_4 and N_2O, respectively.

3.4.2.1 Carbon Dioxide. Soil respiration rates (CO_2 flux) increased as the growing season progressed and soil temperatures rose; all treatments followed the same general pattern. In the upper slope area in 2003 of FE1, significant differences in soil respiration rates occurred on four of the nine sampling dates where the control treatment (U2C) emitted higher levels of CO_2 than the addition treatment (U2A) (Figure 3.6). In 2004, the opposite was found; significantly higher respiration rates were observed from the addition treatment on two sampling dates in both blocks. A sharp peak in CO_2 flux was observed on July 15 (Day 195) for all treatments which corresponds with a rainfall event and an increase in soil moisture and temperature. When the soil CO_2 flux was calculated as a cumulative rate over each sampling period, treatment effects were not found to be statistically significant in either Block A or B; however, the data suggests the control treatment soil may have emitted greater cumulative soil CO_2 flux than the addition treatments (Appendix N.1).

In the lower slope area, soil respiration rates varied greatly between dates in 2003 and in Block A in 2004. Respiration generally increased as the growing season progressed with a peak also occurring on July 15 (Day 195) as was observed in the upper slope. In Block A, the disturbed (L1D) and control (L2C) treatments showed higher soil CO_2 flux throughout both sampling periods with significantly higher rates occurring on three dates in 2003 and on five dates in 2004 (Figure 3.7). In Block B, similar flux rates were observed for all treatments in both years except for on two dates in 2003 where the removal (L1R) treatment showed significantly greater soil CO_2 flux than the disturbed treatment. Cumulative CO_2 flux results indicate the removal treatment soil emitted significantly lower emissions than the control soil in 2003 and the disturbed soil in 2004 in Block A. In Block B the opposite was found where the data suggests that the removal treatment emitted greater cumulative soil CO_2 flux than the disturbed and control treatments; however, the comparison was only statistically significant when compared to the control soil in 2004 (Appendix N.2).

On June 25 (Day 176), 2003, the mean rate of soil respiration for the removal treatment (L2R) (399 mg CO_2-C m^{-2} hr^{-1}) was three times higher than the average rate across all treatments. This value appears to be anomalous, and in reviewing the literature pertaining to CO_2 evolution from soils, this number does exceed the expected range of emission (Bajracharya et al. 2000). This high value is attributed to the 60 min sample vial showing CO_2 concentration higher by a factor of 10.

In FE2, soil respiration remained below 20 mg CO_2-C m^{-2} hr^{-1} for the early part of the growing season with a large rise in respiration rates on July 15 (Day 195) and August 16 (Day 227) (Figure 3.8). The addition and disturbed treatment soils of FE2 emitted greater rates of CO_2 compared with the control on April 21 (Day 111) and May 17 (Day 137). On July 15 (Day 195), soil respiration in the control significantly exceeded the other treatments by a factor of three. The control soil emitted significantly higher cumulative flux over the 118-day sampling period in 2004 compared with both the addition and disturbed treatments (Appendix N.3).

3.4.2.2 Methane. When both years and both blocks are considered, methane emissions generally remained below or near zero for the majority of sampling dates in 2003 and 2004 in the upper slope area. In 2003 a positive emission occurred for most treatments early in the growing season on May 27 (Julian Day 147) and in the fall (September 17 – Day 259). Significant treatment effects were observed on three sampling dates in both 2003 and 2004 (Figure 3.9). In most cases, methane consumption was lower in the addition treatment compared with the disturbed or control treatments. When the methane flux was calculated as a cumulative rate over the each sampling period, significant treatment effects were found in Block A in 2003 and 2004 and in Block B in 2003; however, the treatment effect is variable (Appendix N.1).

In the lower slope area, methane emissions remained near zero for most sampling dates. The removal treatments showed lower methane consumption rates compared with the disturbed and control treatments with significant differences occurring on two sampling dates in 2003 and one sampling date in 2004 (Figure 3.12).

In FE2, methane emissions also remained near or below zero for most dates. Early in the growing season, the addition and disturbed treatment soils consumed higher rates of methane compared with the control on April 21 (Day 111) and May 17 (Day 137) (Figure 3.11). However, on Aug 16 (Day 227), the addition treatment emitted 3.59 μg CH_4-C m^{-2} hr^{-1} while the disturbed and control treatment soils consumed methane.

3.4.2.3 Nitrous Oxide. When looking at nitrous oxide flux across both sampling periods, the flux for all treatments generally remained below 20 μg N_2O-N m^{-2} hr^{-1} in year one but greatly exceeded this level in year two. In the upper slope area, no clear and consistent significant treatment effects were observed for soil N_2O emissions in either 2003 or 2004. However, when looking at individual dates, significant differences were found on two dates in 2003 and on three dates in 2004 (Figure 3.12). Although some significant difference was found, there was no consistent treatment effect. A slight burst in soil N_2O flux was observed on June 9, 2004 in both blocks. This corresponded with a rainfall event during that time (Figure 3.4) as well as canola seeding and fertilization which occurred on May 21 and May 28, 2004 in Block B and Block A, respectively. Cumulative soil N_2O emission rates were significantly greater in the addition treatment compared with the disturbed treatment in 2003 (Appendix N.1).

The effect of removing soil on soil N_2O emissions was also variable (Figure 3.13). No significant treatment differences were found in Block B. On April 21, 2004 the disturbed treatment emitted a slightly higher rate of soil N_2O in Block A. In Block B, the removal treatment showed significantly higher rates of soil N_2O emission on two of the seven sampling dates. When cumulative soil N_2O emission rates are considered, the removal treatment showed significantly higher emission rates than the disturbed treatment in 2003 in Block A and in 2004 in Block B. Cumulative soil N_2O emission rates were higher in the removal treatment compared with the control treatment in Block B in 2004 (Appendix N.2).

Soil nitrous oxide emissions were quite low in the upper slope area of FE2 in the early part of the sampling period. A burst of activity on June 9 (Figure 3.14) was also observed for this experiment where the addition and control treatments showed much higher emissions than the disturbed treatment; however, no significant differences between treatments were found for this or any other date.

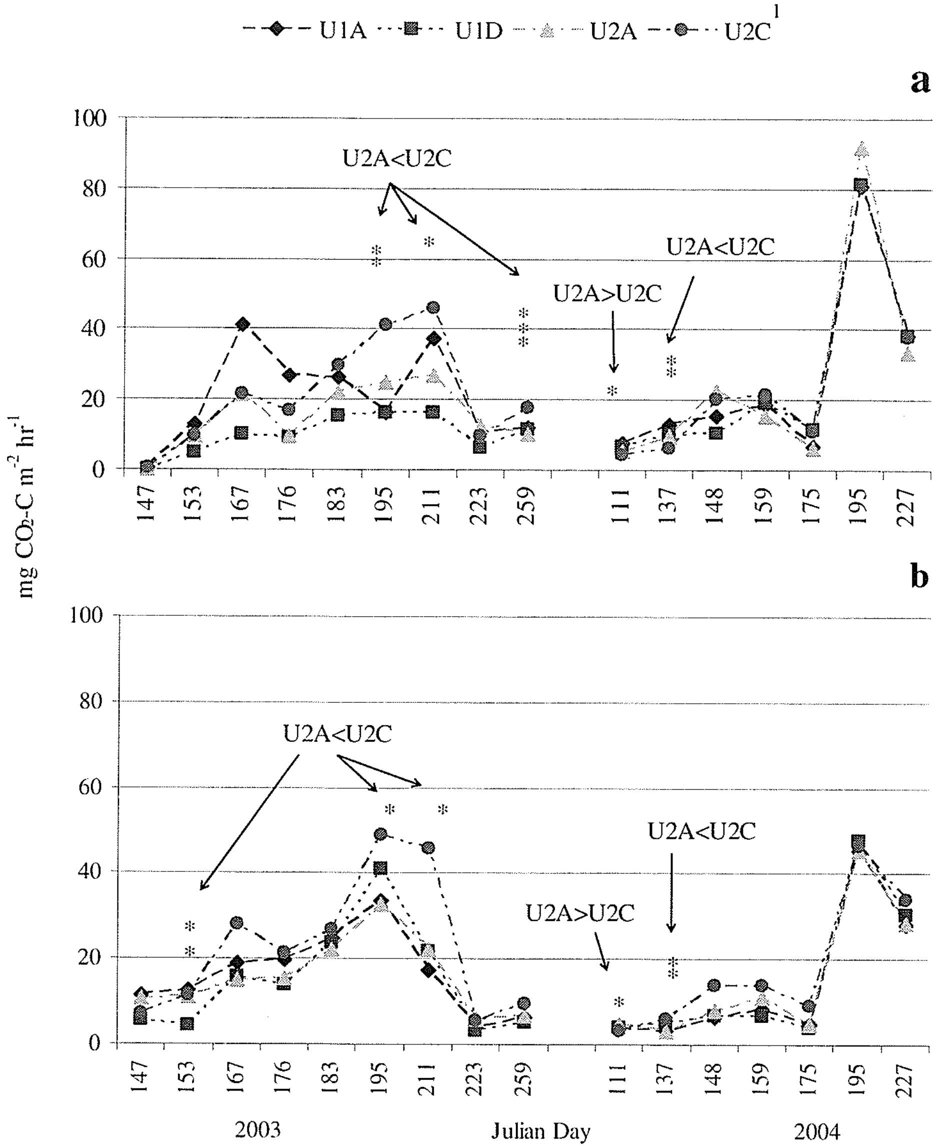

Figure 3.6 Soil respiration (CO_2 flux) in the upper slope area for (a) Block A and (b) Block B in FE1 in 2003 and 2004. *Significant at $P<0.10$; ** Significant at $P<0.05$; ***Significant at $P<0.01$; Values indicate the means of 3 replicates; significance symbols following differences are based on an analysis of log-transformed data but non-transformed means are presented (see Appendix G.1 for numeric values and statistical significance).

[1] U1A = Addition treatment pair 1; U1D = Disturbed treatment pair 1; U2A = Addition treatment pair 2; U2C = Control treatment pair 2

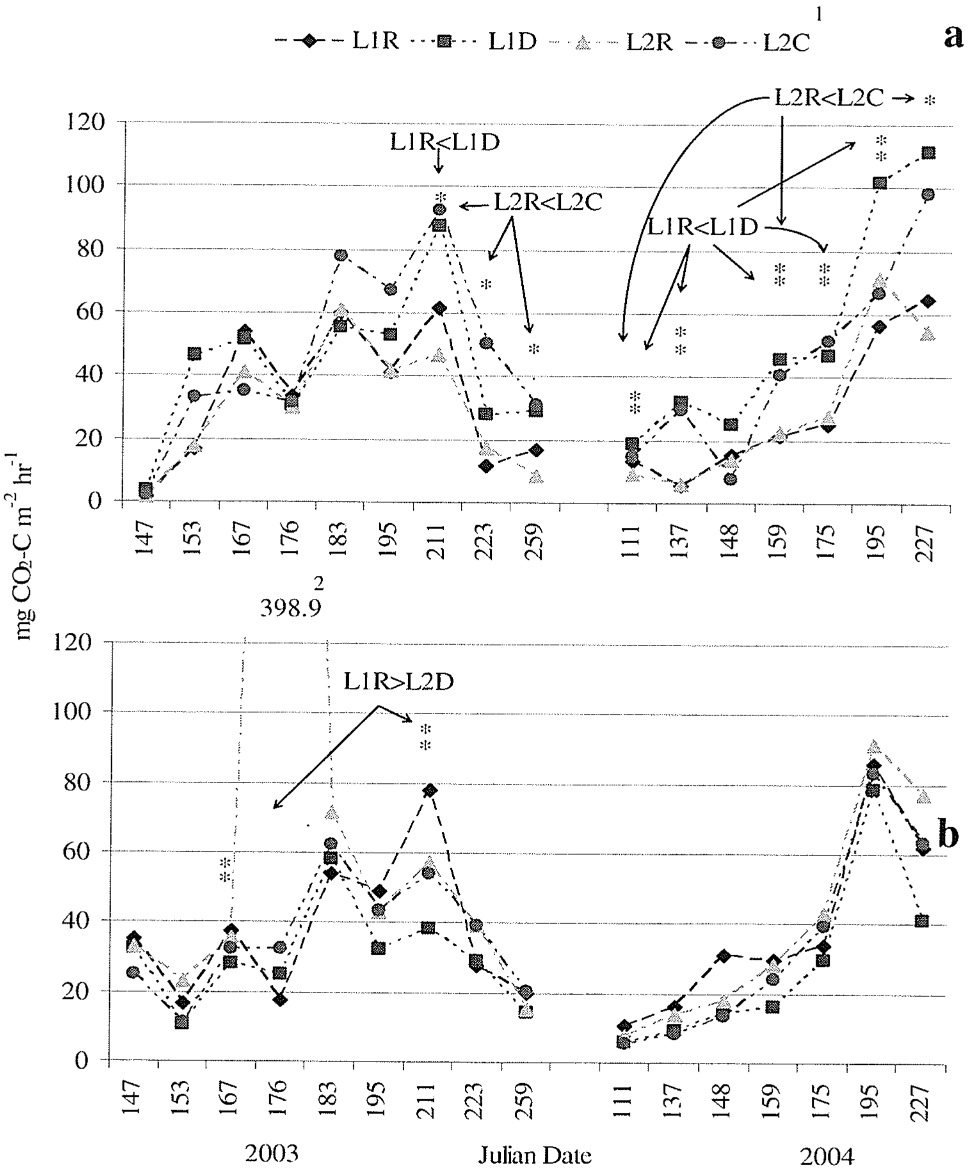

Figure 3.7 Soil respiration (CO_2 flux) in the lower slope area for (a) Block A and (b) Block B in FE1 in 2003 and 2004. *Significant at $P<0.10$; ** Significant at $P<0.05$; ***Significant at $P<0.01$; Values indicate the means of 3 replicates; significance symbols following differences are based on an analysis of log-transformed data but non-transformed means are presented (see Appendix G.2 for numeric values and statistical significance).

[1] U1A = Addition treatment pair 1; U1D = Disturbed treatment pair 1; U2A = Addition treatment pair 2; U2C = Control treatment pair 2

[2] This value exceeds the scale of the CO_2 flux for all other treatments and dates.

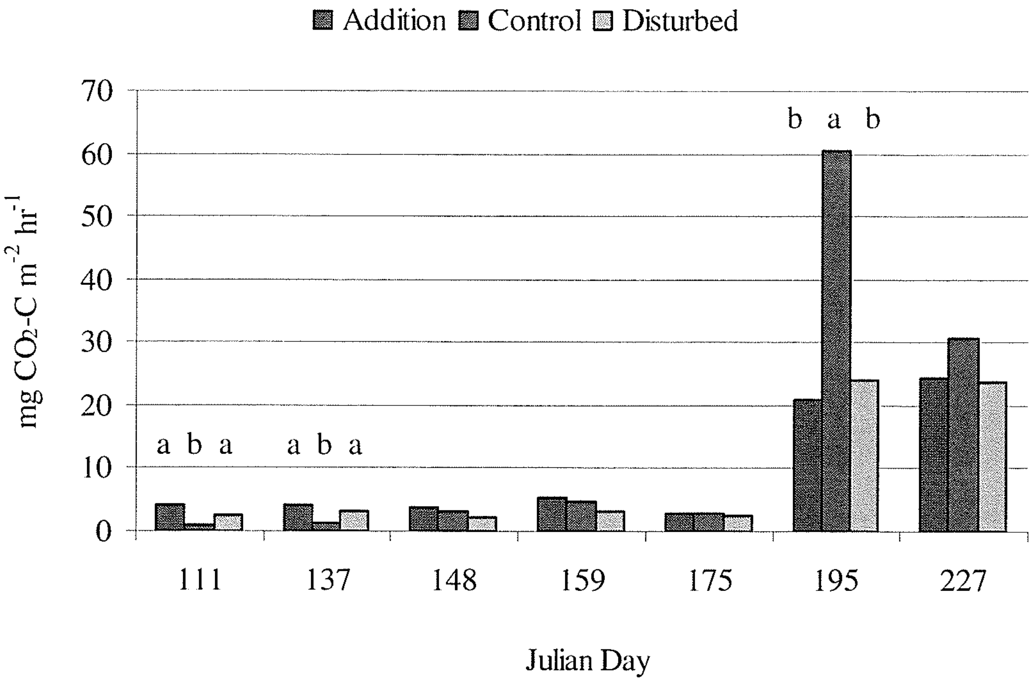

Figure 3.8 Soil respiration (CO_2 flux) in the upper slope area for FE2 in 2004. a-b Mean values followed by the same letter (within sampling dates) are not significantly different. LSMeans groupings are associated with significant treatment effects found using linear mixed ANOVA at $P < 0.10$; values indicate the means of 3 replicates (see Appendix G.7 for numeric values and statistical significance).

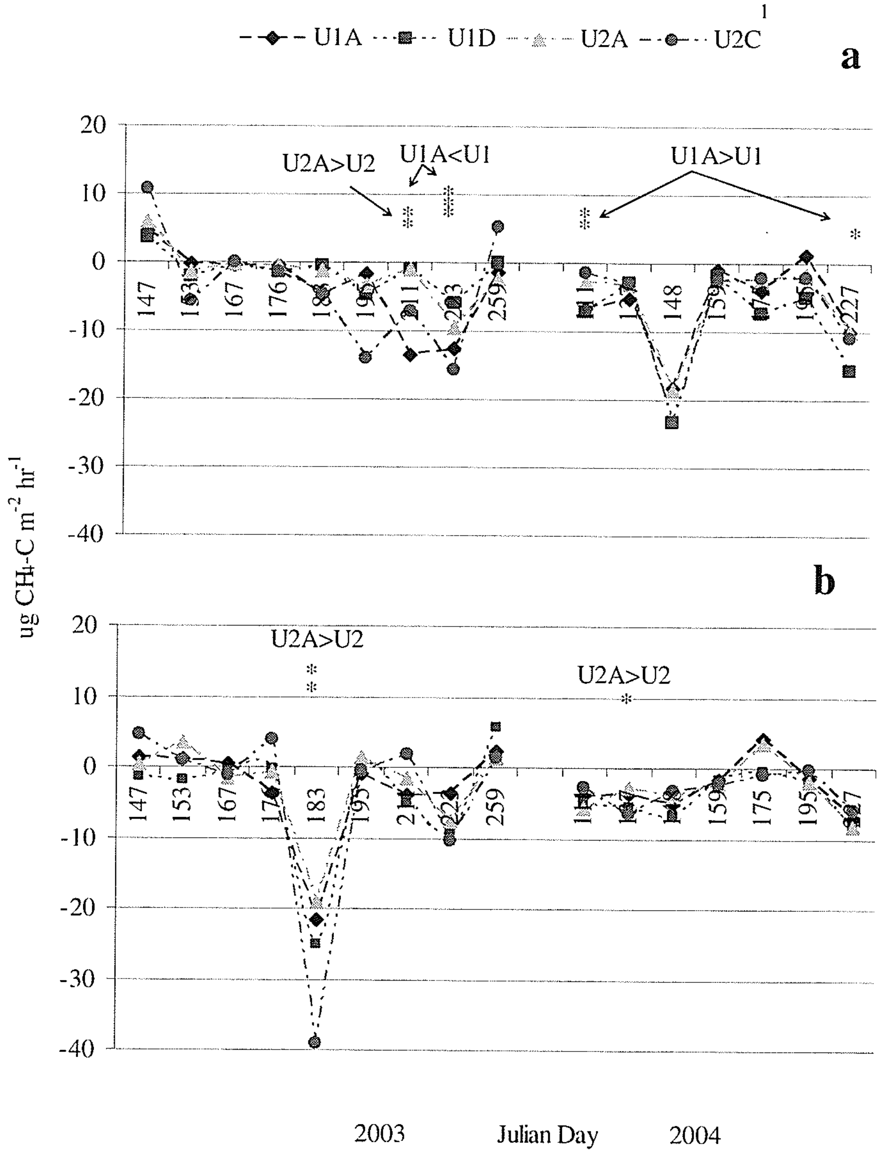

Figure 3.9 Soil methane flux in the upper slope area for (a) Block A and (b) Block B in FE1 in 2003 and 2004.*Significant at $P<0.10$; ** Significant at $P<0.05$; ***Significant at $P<0.01$; Values indicate the means of 3 replicates; significance symbols following differences are based on an analysis of log-transformed data but non-transformed means are presented (see Appendix G.3 for numeric values and statistical significance).

[1] U1A = Addition treatment pair 1; U1D = Disturbed treatment pair 1; U2A = Addition treatment pair 2; U2C = Control treatment pair 2

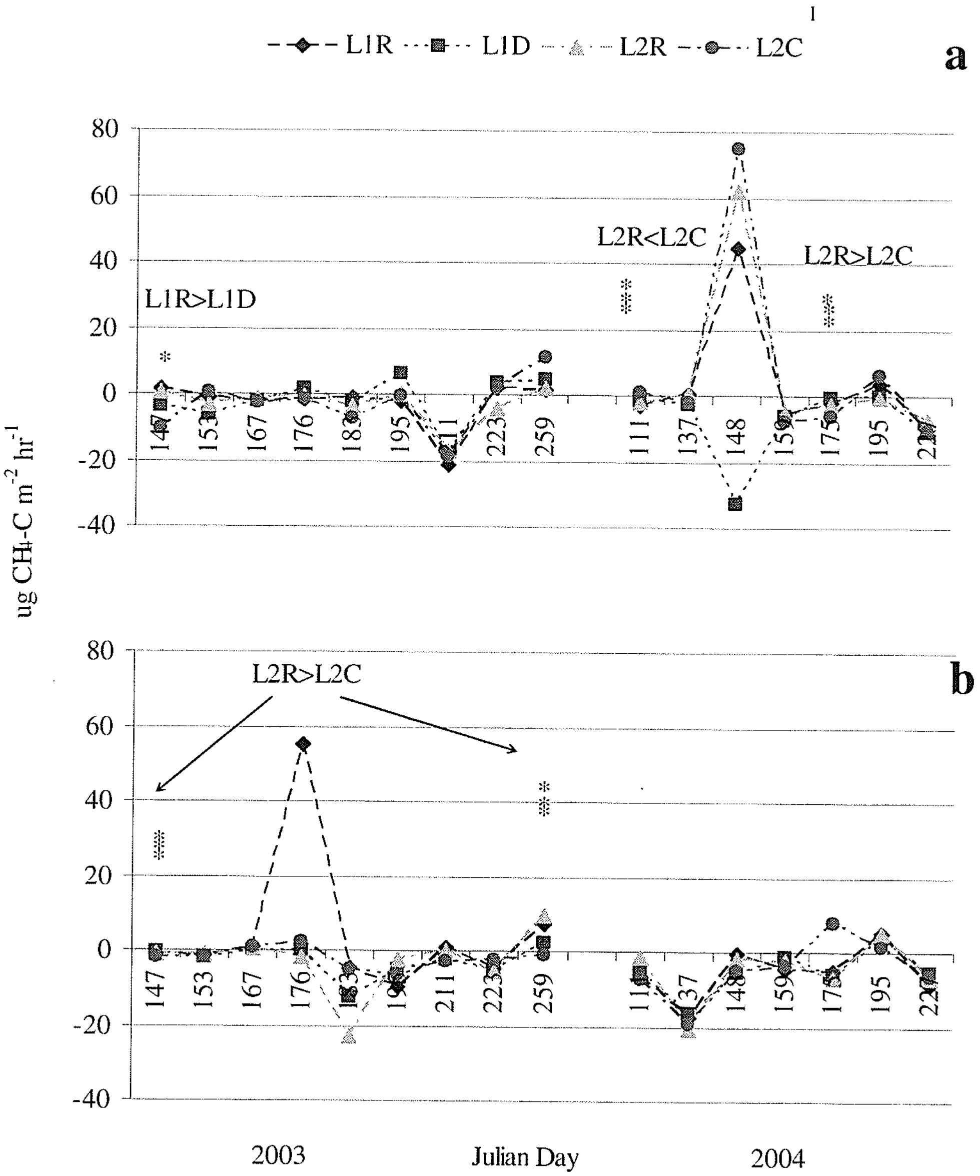

Figure 3.10 Soil methane flux in the lower slope area for (a) Block A and (b) Block B in FE1 in 2003 and 2004. *Significant at P<0.10; ** Significant at P<0.05; ***Significant at P<0.01; Values indicate the means of 3 replicates; significance symbols following differences are based on an analysis of log-transformed data but non-transformed means are presented (see Appendix G.4 for numeric values and statistical significance).

[1] U1A = Addition treatment pair 1; U1D = Disturbed treatment pair 1; U2A = Addition treatment pair 2; U2C = Control treatment pair 2

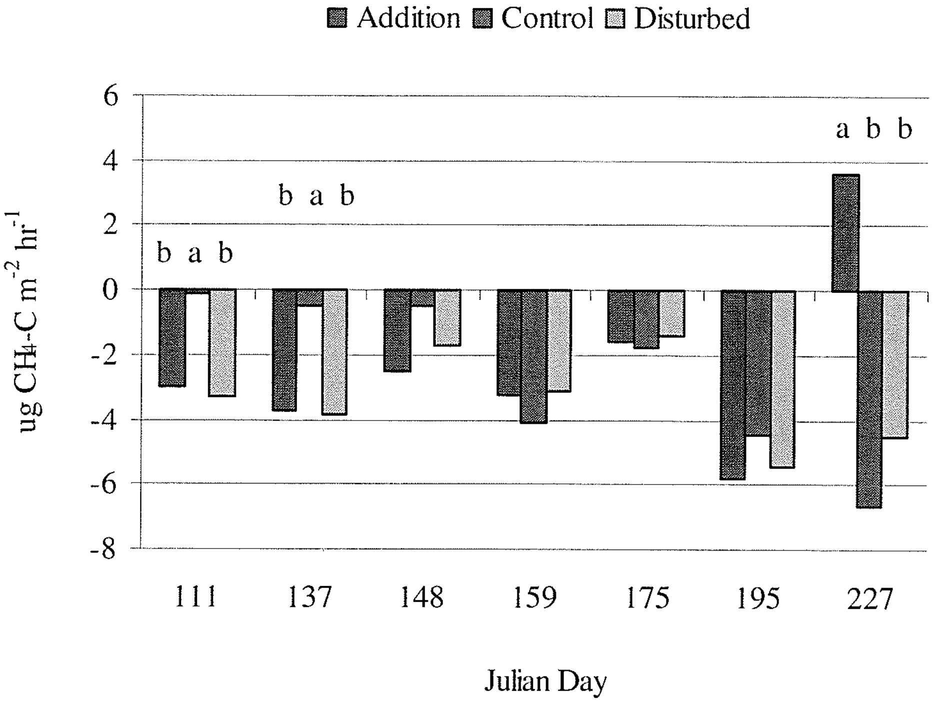

Figure 3.11 Soil methane flux in the upper slope area for FE2 in 2004. a-b Mean values followed by the same letter (within sampling dates) are not significantly different. LSMeans groupings are associated with significant treatment effects found using linear mixed ANOVA at $P < 0.10$; values indicate the means of 3 replicates (see Appendix G.7 for numeric values and statistical significance).

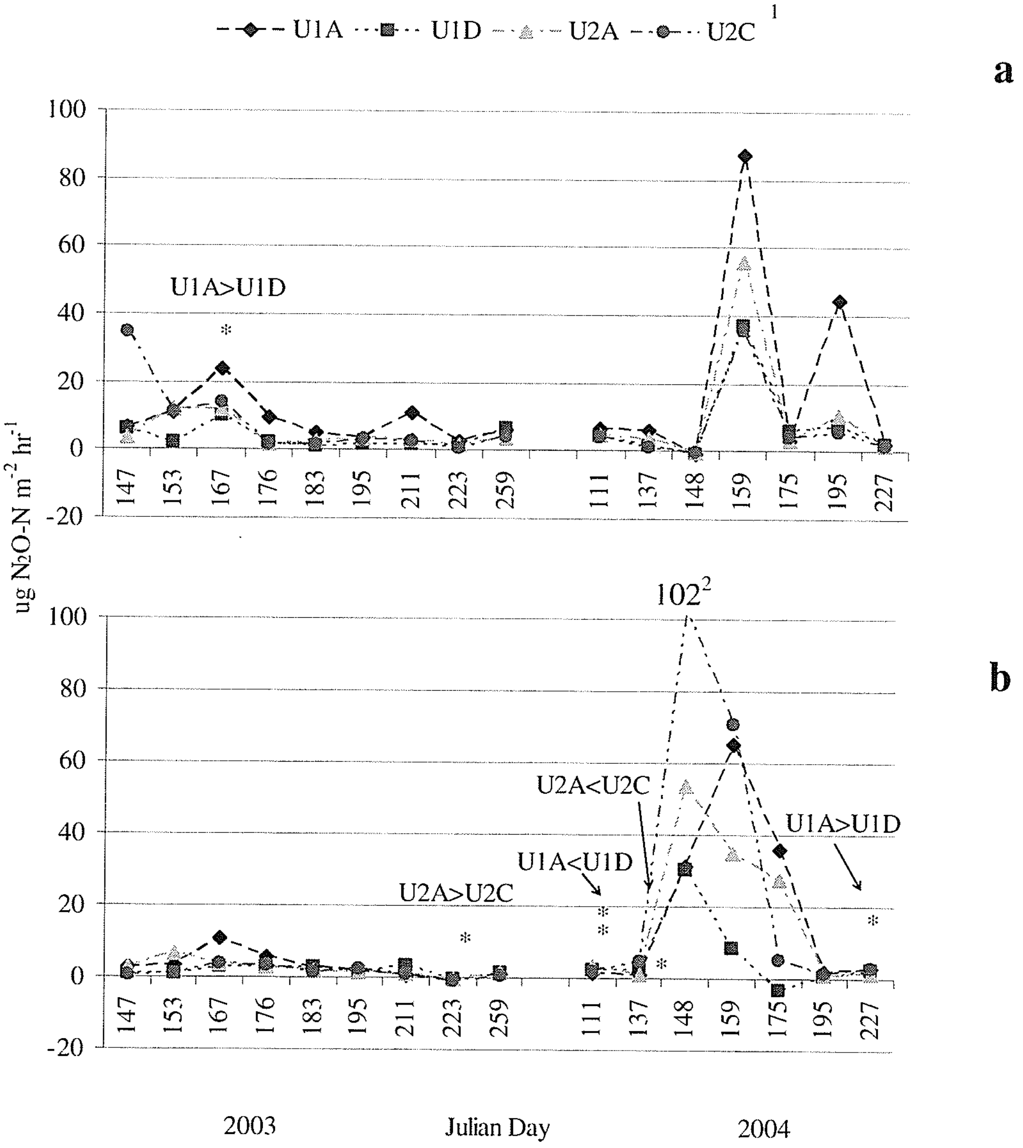

Figure 3.12 Soil nitrous oxide flux in the upper slope area for (a) Block A and (b) Block B in FE1 in 2003 and 2004. *Significant at P<0.10; ** Significant at P<0.05; ***Significant at P<0.01; Values indicate the means of 3 replicates; significance symbols following differences are based on an analysis of log-transformed data but non-transformed means are presented (see Appendix G.5 for numeric values and statistical significance).

[1] U1A = Addition treatment pair 1; U1D = Disturbed treatment pair 1; U2A = Addition treatment pair 2; U2C = Control treatment pair 2

[2] This value exceeds the scale of the N_2O flux for all other treatments and dates.

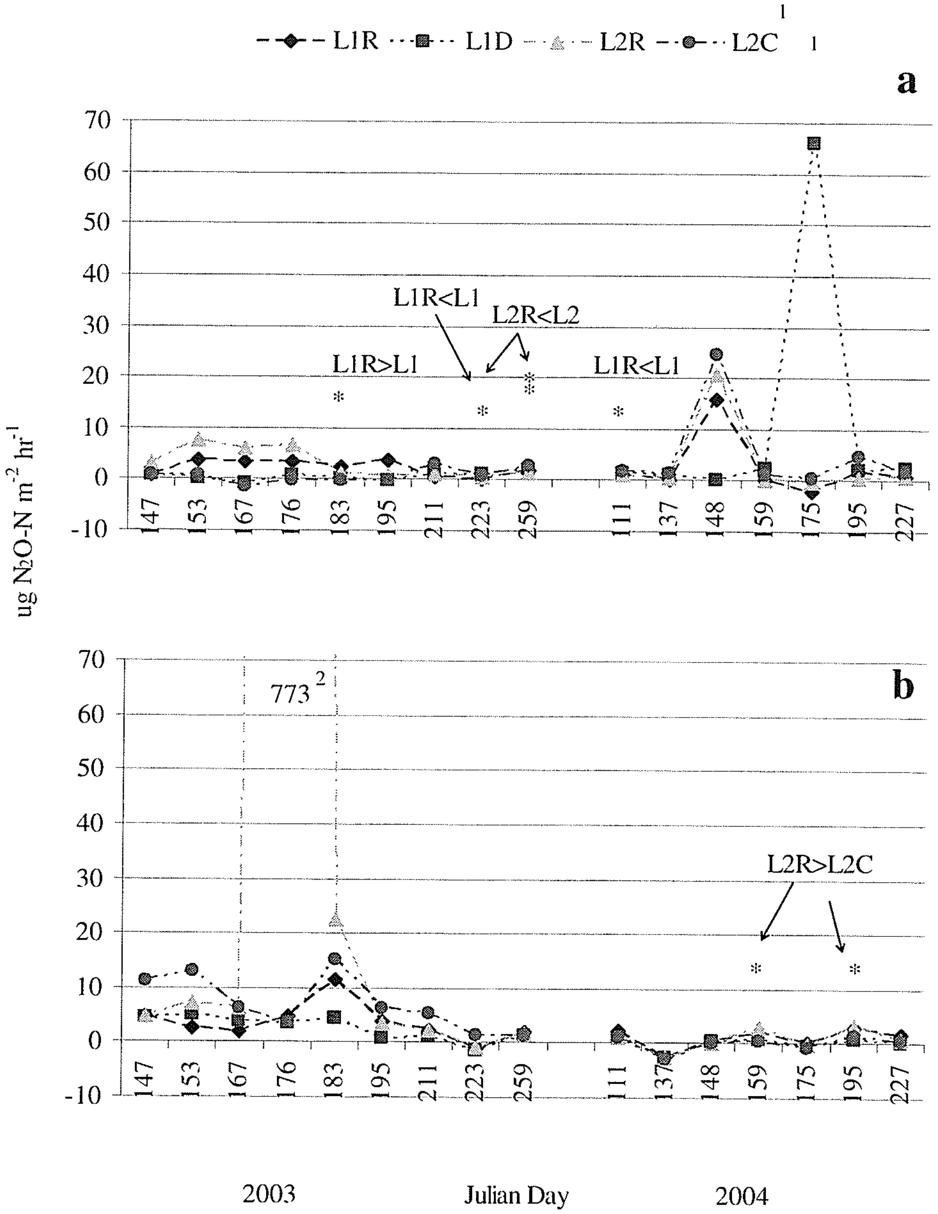

Figure 3.13 Soil nitrous oxide flux in the lower slope area for (a) Block A and (b) Block B in FE1 in 2003 and 2004. *Significant at P<0.10; ** Significant at P<0.05; ***Significant at P<0.01; Values indicate the means of 3 replicates; significance symbols following differences are based on an analysis of log-transformed data but non-transformed means are presented (see Appendix G.6 for numeric values and statistical significance).

[1] U1A = Addition treatment pair 1; U1D = Disturbed treatment pair 1; U2A = Addition treatment pair 2; U2C = Control treatment pair 2

[2] This value exceeds the scale of the N_2O flux for all other treatments and dates.

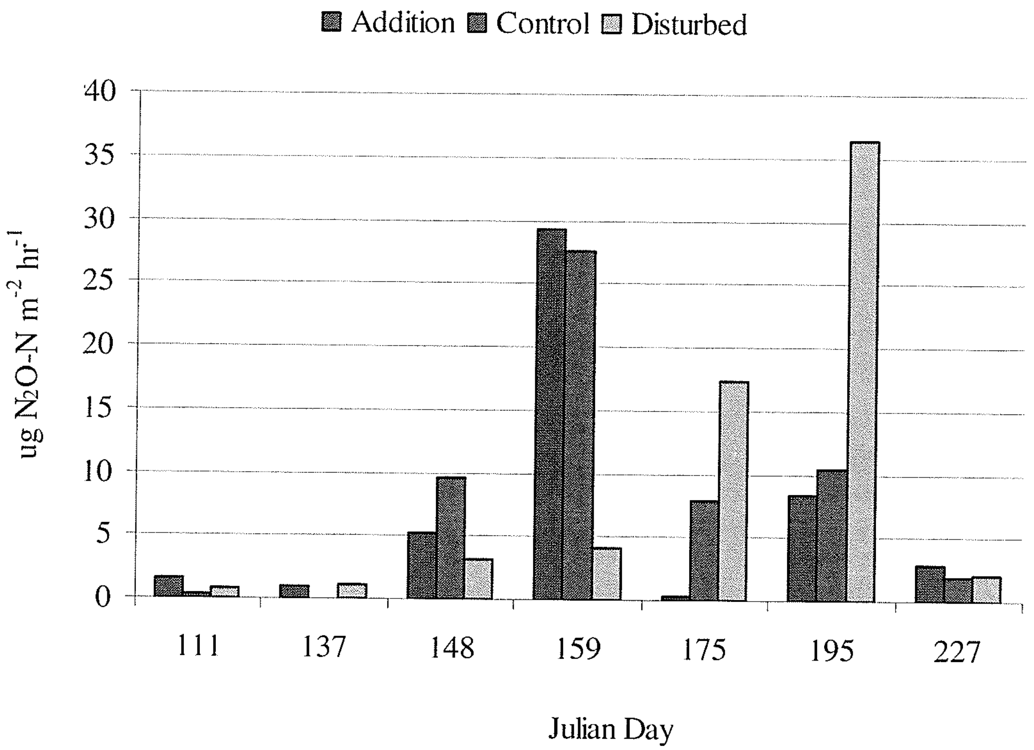

Figure 3.14 Soil nitrous oxide flux in the upper slope area for FE2 in 2004. No significant treatment effects were observed based on LSmeans comparison using a linear mixed ANOVA at $P < 0.10$; values indicate the means of 3 replicates (see Appendix G.7 for numeric values and statistical significance).

3.4.3 Relationship between Flux and Depth of Added Soil/Depth of Removed Soil

3.4.3.1 Column Experiment Part 1. On average, the daily CO_2 flux results indicate the depth of soil addition does not affect soil respiration (Table 3.9 a). Significant treatment effects were observed on three of the twelve sampling days; however, no trend in treatment effect was found. Mean respiration rates for the 12 sampling days were 22.2, 30.5, 27.3 and 21.4 mg CO_2-C m^{-2} hr^{-2} for the control, 10U, 10D and 20D treatments, respectively.

The data suggests that soil CH_4 flux was consistently higher for the control treatment compared to the 20 cm addition treatment; however, this was only statistically significant on one of the twelve sampling days (Table 3.9 b). The addition treatments showed significantly higher soil N_2O flux on three of the twelve sampling days; the depth of soil added did not consistently affect soil N_2O flux (Table 3.9 c). The quality of the soil did not influence soil greenhouse gas flux where the 10U and 10D treatments acted the same on all dates where significant treatment effects were found. Data was also analyzed on a flux per kg of soil basis and the same results were found. When the daily soil greenhouse gas flux measurements were calculated as a cumulative rate over the 30-day sampling period, significant treatment effects were found for cumulative soil CO_2 flux where the 10U treatment emitted the greatest soil CO_2 flux compared with all other treatments. The 10D, 20D and control treatments emitted similar rates based on Tukey's Least Significant Difference comparison ($P<0.05$) (Appendix O.1a).

3.4.3.2 Column Experiment Part 2. Mean daily soil CO_2 flux was five times higher in the surface treatment (control) than in either of the removal treatments (Table 3.10 a). The control treatment showed significantly higher ($P<0.5$) soil CO_2 flux compared with both removal treatments on the first nine sampling days but all treatments emitted similar rates thereafter. No significant differences between treatments were observed for cumulative soil CH_4 flux. The surface treatment (control treatment) also showed significantly higher ($P<0.05$) nitrous oxide flux compared with the removal treatments, with 33.1, 4.5, an d 4.6 μg N_2O-N m^{-2} h^{-1} emitted from the surface on average for the control, -20 and -40 cm treatments, respectively (Table 3.10 c). When the daily soil greenhouse gas flux measurements were calculated as a cumulative rate over the 36-day sampling period, significant treatment effects were found for cumulative soil CO_2 and N_2O flux. The removal treatments emitted significantly lower soil CO_2 and N_2O flux compared with the control treatment. (Appendix O.3). The depth of soil removal did not affect daily or cumulative gas flux.

Table 3.9 Soil gas flux for the soil addition growth chamber experiment (Column Experiment 1)

	Sampling Day											
Treatment[1]	1	2	3	4	5	6	7	8	9	10	11	12
a) CO_2 (mg CO_2-C m^{-2} hr^{-1})												
Control	40.3a	26.8	28.9	45.5	23.8b	30.5	24.3	4.3	9.4	14.5	16.9	19.3b
10U	9.5b	44.6	47.2	1.8	64.7a	41.9	35.5	15.1	19.9	24.8	25.4	25.9a
10D	12.2b	13.7	46.5	30.7	62.3a	31.2	31.2	12.7	20.4	28.1	27.9	27.6ab
20D	12.8b	11.1	25.7	7.2	22.0b	37.5	28.4	20.4	21.2	22.0	22.7	23.4ab
b) CH_4 (µg CH_4-C m^{-2} hr^{-1})												
Control	3.0	3.7	-28.8	4.6	8.6	-0.4	2.5	5.3	5.4a	5.5	1.5	-2.6
10U	4.3	3.8	-23.4	8.8	0.9	2.0	2.7	9.5	4.8ab	0.2	0.1	0.0
10D	2.5	2.4	-24.6	0.2	1.8	5.0	2.4	7.9	4.0ab	0.2	-3.0	-6.1
20D	1.8	0.5	-20.8	2.9	6.4	-0.9	1.3	1.6	0.2b	-1.2	-1.4	-1.5
c) N_2O (µg N_2O-N m^{-2} hr^{-1})												
Control	12.1	16.9b	-4.2	15.7	5.0	7.8	8.0	2.7	4.2	5.7b	5.8	5.8b
10U	21.4	65.5ab	24.4	1.3	34.6	23.1	17.5	12.4	36.3	60.2a	59.6	59.0a
10D	24.0	20.1b	30.3	69.9	32.7	28.4	26.7	17.5	31.7	46.0a	54.0	61.9a
20D	11.3	140.9a	72.5	2.6	30.3	41.9	28.8	16.2	36.0	55.9a	54.6	53.2a

a-b Mean values followed by the same letter (within columns) are not significantly different based on a Tukey's student minimum significant difference comparison at *$P<0.05$* based on log-transformed data but non-transformed means are presented

Note: values indicate the mean of three replicates

[1] Control: upper slope soil only, no soil added; 10U: 10 cm upper slope soil added to the upper slope soil; 10D: 10 cm depression soil added to the upper slope soil; 20D: 20 cm depression soil added to the upper slope soil

Table 3.10 Soil gas flux for the soil removal growth chamber experiment (Column Experiment 2)

	Sampling Day												
Treatment[1]	1	2	3	4	5	6	7	8	9	10	11	12	13
a) CO_2 (mg CO_2-C m^{-2} hr^{-1})													
Control	28.6a	52.3a	54.3a	51.6a	63.8a	48.8a	56.3a	43.9a	42.4a	15.3	19.2	15.0	12.8
-20	8.8b	6.1b	6.4b	5.b9	8.1b	5.4b	14.1b	12.5b	12.8b	6.0	6.1	1.3	4.1
-40	3.5b	5.3b	8.9b	2.0b	4.3bb	6.8b	6.1b	3.9b	3.0b	13.9	17.1	11.6	20.5
b) CH_4 (μg CH_4-C m^{-2} hr^{-1})													
Control	-1.8	-0.4	3.3	11.8	10.0	7.0	20.2	6.7	6.4	1.1	2.1	-4.1	4.6
-20	-8.0	-1.9	0.5	-3.2	-0.5	-0.7	2.1	3.3	0.8	-4.0	3.0	-0.4	4.4
-40	-9.7	-4.0	-5.2	-3.4	1.1	-6.2	-1.0	-1.2	-3.6	1.8	16.2	11.4	7.8
c) N_2O (μg N_2O-N m^{-2} hr^{-1})													
Control	18.4a	71.5a	62.0a	38.8a	27.6a	42.4a	40.2a	39.5a	32.3	15.9	18.0	12.1	11.5
-20	8.4b	2.7b	4.0b	7.3b	5.0b	4.7b	9.3ab	8.6ab	2.3	0.5	1.6	0.7	3.3
-40	5.0b	2.0b	2.1b	2.4b	2.0b	1.5b	0.4b	1.2b	4.7	5.8	5.8	6.1	21.2

a-b Mean values followed by the same letter (within columns) are not significantly different based on a Tukey's student minimum significant difference comparison at $P<0.05$ based on log-transformed data but non-transformed means are presented

Note: values indicate the mean of three replicates

[1] Control: depression soil only, no soil removed; -20: 20 cm soil removed from the depression; -40: 40 cm soil removed from the depression

3.5 Discussion

3.5.1 The Effects of Landscape Restoration on the Soil Environment

3.5.1.1 Soil Temperature and Moisture. In the upper slope area, landscape restoration was expected to increase soil temperature and moisture due to increased organic matter content and reduced plant residue cover resulting in decreased albedo and higher water holding capacity. Warm and moist soil conditions are favorable for microbial activity which in turn may affect gas flux from soil.

In the first year of the field experiments, a slight increase in soil temperature in the addition treatments compared with the control treatment was observed. The dark color of the added soil absorbed more solar radiation causing it to warm sooner in the season and reach warmer temperatures at depth. The eroded soils that comprised the disturbed and control treatments were much lighter in color and, therefore, would have reflected more radiation and stayed cooler longer. In addition to light colored surface soil, the control was a zero-till soil and the light colored plant residue on the soil surface increased the proportion of reflected radiation (Figure 3.1). These results are consistent with Malhi et al. (2001) who found that during the spring, soil temperatures at the same depths were lower for no-till versus conventional tillage systems. In year two, little differences in temperature were found between treatments in FE1. This is likely the result of all treatments being under zero-till cropping and, therefore, all treatments having a layer of standing stubble which increased the albedo in the addition and disturbed treatments.

The added topsoil increased the moisture holding potential of the soil in general. The results show that moisture content is greater in the spring following restoration compared to the disturbed treatment; the magnitude of the difference is smaller when compared to the control treatment. This is especially important considering 2003 was a dry year at the MZTRA farm and any added moisture could be beneficial to crop growth. In year two when higher rainfall was observed over the growing season (Figure 3.4), there were more variable and less consistent moisture results when comparing the addition of soil to the control and disturbed treatments. In FE2, moisture was also greater on the upper slope after the addition of soil and this effect was most evident in the spring.

In the lower slope area, the effects of landscape restoration, specifically soil removal, on soil temperature were much more obvious. Lower slope temperatures were significantly higher for the removal treatments compared with the controls, most likely due to the dark soil surface absorbing more radiation. The grass residues on the controls may have reflected radiation and may act as insulation causing the soil to stay cooler longer. The same results are observed at depth. In the fall, the opposite is true; the removal treatments were cooler in September compared with the controls. Again, the layer of plant material on the soil surface may have acted like an insulating layer, causing the soil below to stay warmer longer.

When soil is removed from a riparian area, there are a few factors influencing the effect of soil removal on soil moisture. One factor is the physical effect of removing soil. Removing 20 cm of soil results in a new surface that is closer to the water table thereby increasing soil moisture (increase H_2O per volume of soil). Also, the area of removal might act as a catchment for runoff water and snow concentrating the total volume of water for a given area. A second factor includes the biologic effects of soil removal. In the control plots, drier soil conditions over summer and fall may be caused by greater plant respiration and evapotranspiration. In the spring, there is little plant growth and little evapotranspiration resulting in little difference in soil moisture in the removal area compared with non-removal areas. As plants begin to take up water and transpire, the difference grows where the removal plots are expected to maintain higher moisture levels. Higher moisture was observed in the removal plots of Block B in 2003; however, there was no clear trend in Block A.

3.5.1.2 Soil Nutrients. Landscape restoration positively influenced soil fertility and $CaCO_3$ content in the surface soil based on fertility results from 2003. Increased fertility has important implications for crop and weed growth and also for soil gas flux.

It was hypothesized that restoration would increase the organic carbon of the topsoil; however, the increase that was found was only minor. Based on calculations using the measured TOC (%).in the uppper slope and lower slopea area treatments in FE1, and based on the assumption that 10 cm of soil was in fact added to the upper slope area addition plots, a 1.6% increase in TOC should have been observed (Appendix H). In FE1, the addition treatments showed 1.3% greater TOC in Block A compared with the control, and 0.8% greater TOC compared with the control in Block B. In FE2, the increase was also minor at 1.1%. The minor increase in TOC in Block B may be attributed by the fact that the actual depth of soil may not have been 10 cm once the soil had settled and been seeded. Also, some of the organic carbon may have been mineralized resulting from a "flush" of microbial CO_2 in response to heavy disking (Reicosky 1997b); however this was not observed statistically in the field or in the growth chamber. Finally, it is difficult to measure changes in soil organic matter over time and space due to the inherent variability of this soil property (Izaurralde et al. 1997).

There was a significant increase in salt content in the addition treatments over the control in both field experiments; however, the increase was small and remained within tolerable levels (less than 3 mS cm^{-1}) for crop growth (Bower and Wilcox 1965). There was a concern with the potential for causing salinity in the upper slope area where soil was added because salinity had been indicated (Podolsky and Schindler 1993) in the areas from where soil was removed. The higher salinity level where soil was applied is likely only a short-term concern as salts are easily leached lower in the soil profile with the downward movement of water.

Landscape restoration reduced fertility in the removal areas. Since soil was removed from an area of accumulation of up to 0.75 m, it was expected that there would have been a large quantity of nutrients remaining after removing 20 cm of surface soil. The perennial vegetation and the adjacent wetland may influence the low reserve of nutrients at depth. An examination of soil fertility is necessary prior to removing the soil to ensure enough nutrients remain to achieve sustainable crop production (this is relevant to soil removal from cropland depressions).

3.5.1.3 Microbial Biomass Carbon. Adding organic rich topsoil was expected to increase the organic matter content, specifically organic carbon, of the soil and even though the fertility results show little increase in TOC, the soil microbial biomass carbon results better support this hypothesis. In the upper slope area, the addition treatments showed significantly greater soil microbial biomass carbon levels. The increase is somewhat short-lived, however, based on year two biomass numbers. There were too few sampling points from year two to make any strong conclusions.

In the lower slope area of FE1, it was expected that soil removal would remove much of the active organic fraction (i.e. the microbial population). The buried material exposed by soil removal would likely contain a smaller amount of active soil microbial biomass carbon because soil oxygen is reduced at depth and soil moisture and temperature are below optimum conditions for microbial activity (Lobb et al. 2002). This effect was observed in the removal treatments where the soil microbial biomass carbon levels were significantly lower. This helps explain the reduced gas flux from the removal treatment soil in the short-term but this result may only occur until microbial populations build up.

3.5.2 The Effects of Landscape Restoration on Soil Gas Flux

3.5.2.1 Carbon Dioxide. Soils with higher organic matter content generally show larger microbial populations that in turn can cause greater mineralization rates of organic nutrients such as carbon and nitrogen (Lobb et al. 2002; Pekrun et al. 2003). For this reason, adding organic rich topsoil to the previously eroded hilltop should have resulted in higher CO_2 flux. Tillage also affects the amount of carbon and nitrogen being cycled and stored in the soil system (Eghball et al. 1994; Reicosky 1997b) and therefore disking the addition plots should have caused a greater CO_2 flux to be observed. Tillage creates favorable conditions for microbial decomposition to take place. It improves aeration and temperature in cool, wet soils, or where soils are dry, it mixes drier surface soils with moister subsurface soils (Campbell et al. 1996). Increasing organic matter decomposition and microbial activity will increase the amount of carbon being mineralized and released as CO_2 (Pekrun et al. 2003; Reicosky 1997a). However, this was found only in FE2 and only in the spring; in contrast, the control treatments showed greater flux in the later part of the growing season.

There is evidence that a large loss of soil CO_2 gas occurs immediately (less than 1 hour) following tillage with smaller differences observed 19 days after the tillage operation (Reicosky 1997b). Considering that gas flux was not sampled for four weeks following soil addition and disking in FE1 the treatment effect may have been missed. This implies that the effect of adding soil on soil respiration is possibly short-lived and may only occur in the first spring season following restoration or shortly after the restoration event. The objective of this study was to identify medium-term impacts of landscape restoration on greenhouse gas emissions and, therefore, CO_2 lost immediately following landscape restoration (i.e. in the short-term) may be overlooked.

The greater CO_2 flux exhibited in the control treatments of both experiments may be explained by the fact that zero-till soils can show higher respiration rates compared with conventional tillage soils (Reicosky 1997b); however, this is more common in regions experiencing higher annual precipitation and temperature. A second possible explanation is that the source of soil CO_2 gas emissions may be inorganic in nature resulting from the dissolution of $CaCO_3$ (Burton and Beauchamp 1994) in the control soils which contained higher $CaCO_3$ levels. A third possible explanation is the greater proportion of roots that exist below the surface of the zero-till control soils compared with the addition and disturbed treatments (that had been recently tilled) may be contributing to CO_2 flux because carbon dioxide is released by autotrophic root respiration (Smith et al. 2003).

The removal of soil does not appear to increase soil respiration but it either remains the same as non-removal treatments or is significantly reduced. Soil moisture and temperature are two key factors influencing soil respiration. The trend in these two parameters is generally opposite to that observed in the respiration data i.e. where soil moisture and temperature are higher for removal treatments, the respiration is lower. Therefore, there may be other factors influencing respiration such as substrate and/or root activity. The removal plots had lower soil organic C (this is true based on soil microbial biomass carbon results and soil fertility TOC results) and lacked the root system and organic residues found in the non-removal treatments. Carbon dioxide is released from soil organic matter both by heterotrophic respiration and by autotrophic root respiration (Smith et al. 2003). It has also been noted that 'spatial variations in N and C dynamics have been related to differences in vegetation' (Corre et al. 1996) where the vegetation influences N and C availability.

3.5.2.2 Methane. Soil methane emission and oxidation (or absorption) is influenced by soil redox potential, depth to water table, the vegetation present and soil texture (Smith et al. 2003) as well as the nitrogen dynamics in soil (Paul and Clark 1996). In the upper slope area where soils are generally drier, methane oxidation, carried out by methanotrophs, is more likely. This process requires the presence of NO_3^- and NO_2^- and it is inhibited by high levels of NH_4^+ (Paul and Clark 1996). In FE1 higher NO_3^- levels were observed, however, methane emissions were quite variable with the majority of the values lying near 0 (positive or negative 1). In FE2, significantly greater absorption of methane occurred in the addition and disturbed treatments on the first two sampling