THE IMPACT OF LANDSCAPE RESTORATION ON CROP PRODUCTIVITY AND SOIL PROPERTIES IN SEVERELY ERODED HILLY LANDSCAPES IN SOUTHWESTERN MANITOBA

BY

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

MASTER OF SCIENCE

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THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES
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ABSTRACT

Smith, Diane M. M.Sc. The University of Manitoba, May, 2008. The impact of landscape restoration on crop productivity and soil properties in severely eroded hilly landscapes in southwestern Manitoba. Major Professor: Dr. David A. Lobb.

In many cultivated hilly landscapes, tillage erosion is the dominant soil erosion process. Organic-rich topsoil is removed from convex upper slope positions (i.e., hilltops, knolls, and ridges) and accumulates in concave lower slope positions (i.e., foot slopes and toe slopes/depressions) of the landscape. The loss of topsoil from hilltops results in low concentrations of organic matter, shallow soil profiles, increased stoniness and carbonates at the soil surface, reduced water holding capacity and nutrient retention, and ultimately a reduction in crop productivity. However, yield losses from eroded upper positions are not offset by equal crop yield increases in areas of soil accumulation within the landscape. Previous studies have examined the use of manures, commercial fertilizers, and conservation tillage practices to restore productivity to eroded upper slope positions, however, with limited success.

Landscape restoration is the practice of moving topsoil that has accumulated in the concave lower slope areas of the landscape and replacing it on the eroded convex upper slope positions from where it had originated. However, to date there is no known scientific literature on landscape restoration as a soil erosion and land management practice.

The overall goal of this research is to explore the practical application of landscape restoration as an alternative land management practice to restore crop productivity in eroded hilly landscapes.

A large field-scale study was conducted in the undulating and hummocky landscapes

of southwestern Manitoba. Four research sites, a primary site and three secondary sites were used in the study. Soil from each site was removed from lower slope positions at a depth of 10 cm (4 in) using a tractor equipped with a land scraper. The soil was then placed on eroded upper slope positions at a depth of 10 cm. The research plots were established as randomized complete block designs where each plot represented one replicate of a two treatment comparison. The upper slope pairs comprised a treatment plot (10 cm added topsoil) and a control plot (no topsoil added). Conversely, the lower slope positions comprised a treatment plot (10 cm removed topsoil) and a control plot (no removal of topsoil).

The objectives of Study 1 were (1) to determine the impact of landscape restoration on crop productivity in upper slope landscape positions where topsoil had been added and in lower slope landscape positions where topsoil had been removed and (2) to determine the net effect of landscape restoration on crop productivity within the landscape. Seedlings in topsoil addition plots were found to emerge faster and at a more consistent rate and had a 60 % greater plant population compared to the control plots. At the primary research site, the addition of topsoil significantly increased crop yields by 31 % in the first year post-restoration and continued to increase the following year by 64 %. Yield increases also occurred at each secondary site and ranged from 10 to 133 %. The effect of added topsoil on eroded hilltops was more evident during a year with below normal precipitation, as yield differences between control and addition plots were greater than yield differences in a year with above normal precipitation. At one secondary site, there was a 20 % reduction in crop yield in the lower slope positions where topsoil had been removed. However, the crop yield increase that occurred in the addition plots in the upper slope positions was slightly greater than the yield loss that occurred in the removal plots. Therefore, there was still a net benefit in crop production within the landscape. When crop yields were normalized across all research sites, yield differences between upper slope treatment plots were significantly greater than yield differences between lower slope treatment plots. Therefore, adding 10 cm of topsoil to severely eroded hilltops resulted in a net benefit in crop productivity within the landscape.

The objective of Study 2 was to determine the soil properties which contribute to increased crop production on severely eroded hilltops. Landscape restoration significantly increased nitrate nitrogen, Olsen phosphorus and, sulphate sulphur concentrations throughout the profile in topsoil addition plots. Soil organic matter concentrations were nearly 2.5 times greater in addition plots compared to control plots. Soil moisture retained at field capacity and plant available water was also significantly greater in addition and increased by 11 % and 21 %, respectively. Although the addition of topsoil improved the nutrient status on eroded upper slope positions, the significant increase in moisture retained at field capacity, attributed to the increased soil organic matter concentrations, likely played a major role in increasing field pea production on eroded hilltops, particularly during growing seasons with below normal precipitation.

In summary, the results from this study on landscape restoration illustrate that landscape restoration is an innovative, logical, and practical land management practice to restore crop productivity on severely eroded hilltops and requires further attention from researchers and from agricultural producers.

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FOREWARD

This thesis has been prepared in the manuscript format in adherence with the guidelines established by the Department of Soil Science at the University of Manitoba. This research was conducted as a part of the "Economic assessment of restoring eroded land" strategic project. This project is a joint effort between the University of Manitoba, South Dakota State University, and the United States Department of Agriculture. The Canadian Journal of Soil Science was the reference style used in this document. Chapters 2 and 3 will be submitted to Agriculture, Ecosystems and Environment journal. For all papers, I will be the lead author and co-authorship will be assigned accordingly.

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1. INTRODUCTON

The loss of crop productivity from agricultural landscapes as a result of soil degradation and redistribution from soil erosional processes is of economic and environmental importance worldwide (Wolman, 1985). In North America, globalization, world food shortages, technological advances, urbanization, and the search for alternative energy sources has put enormous demands and stresses on agricultural lands, and as a result, has magnified the need for soil conservation and land stewardship.

In hilly landscapes, topography and local hydrology play an important role in the spatial variability of soil properties, soil fertility, soil moisture, soil organic matter, and, consequently, crop productivity within the landscape. Studies have shown that tillage erosion is the dominant soil erosion process in cultivated hilly landscapes (Lindstrom et al., 1990; Lobb et al., 1995; Kachanoski and Carter, 1999; Papiernik et al., 2007). This soil erosion process causes the local redistribution of organic-rich topsoil within the landscape, with losses occurring from convex upper slope landscape positions (i.e., hilltops, knolls, and ridges) and accumulations occurring in concave lower slope landscape positions (i.e., foot slopes and toe slopes/depressions) (Govers et al., 1999), and as a result, the spatial variability within the landscape becomes exaggerated.

Cesium-137 (^{137}Cs) is used as an indicator of soil redistribution within a landscape and studies have estimated soil losses from upper slope positions range from 20 to 54 Mg ha^{-1} yr^{-1} (9 to 24 t ac^{-1} yr^{-1}) (Verity and Anderson, 1990; Lobb et al., 1995). The progressive downward movement of organic-rich topsoil results in eroded upper slope positions which can constitute between 18 to 30 % of the area in undulating and hummocky landscapes (Battiston et al., 1987; Pennock and de Jong, 1987). These areas can also be easily distinguished within the landscape by exposed subsoil, shallow soil profiles, reductions in soil organic matter, and increased stoniness and carbonates at the soil surface. The loss of topsoil also results in reduced crop yields by reducing nutrient supply, water infiltration, and soil water-holding capacity (Langdale and Shrader, 1982). Therefore, many agricultural landscapes have localized areas of poor crop growth (Larney et al., 1995). A study conducted by Battiston et al. (1987) in southwestern Ontario reported yield reductions of up to 50 % on eroded upper slope positions. However, yield losses from eroded upper slope positions are not offset by equal crop yield increases in areas of soil accumulation within the landscape (Carter et al., 1985). Therefore, it is essential that crop productivity is restored to these eroded areas.

Previous studies have examined the use of manures (Dormaar et al., 1988; Dormaar et al., 1997; Larney et al, 2000b), commercial fertilizer (Massee and Waggoner; 1985; Mielke and Schepers, 1986; Massee, 1990; Verity and Anderson, 1990; Larney et al., 1995; Larney et al., 2000a), and conservation tillage (Mueller et al., 1984; Grevers et al., 1986; McCarthy et al., 1993; Hussain et al., 1999) as ways to restore productivity to eroded soils once topsoil has been lost.

Applying livestock manure is another practice used to increase the productivity of eroded hilltops. A simulated erosion study found that the application of 30,000 kg ha^{-1} (26,710 lb ac^{-1}) of manure had significantly increased organic matter, total nitrogen, nitrate nitrogen, available phosphorus, and water holding capacity (Dormaar et al., 1988). However, these authors also stated, in order to restore the soil organic matter of previously eroded soils, it may be necessary to apply manure on an annual basis for many years.

Increasing the application rate of commercial fertilizers is one of the most common and quickest ways to increase crop productivity on eroded upper slope positions (Hamm, 1985). However, studies conducted by Massee and Waggoner (1985), Verity and Anderson (1990), Larney et al. (1995), Larney et al. (2000a) found that fertilizer application only partially remedied yield losses caused by increased soil erosion rates.

In the past two decades conservation tillage and other residue management practices have been widely adopted as a means of increasing soil water use efficiency and soil organic matter content as well as, reducing soil erosion processes (Grevers et al., 1986; McCarthy et al., 1993). However, there are several managerial disadvantages to these reduced tillage systems from a producer's standpoint. Cooler soil temperatures can delay germination and slow soil microbial breakdown of residues and increased soil water retention can also delay seeding, especially in poorly drained soils (McCarthy et al., 1993).

The above approaches used to increase productivity on eroded landscapes are only a means to cope with the problem of lost topsoil and mask the apparent long-term effects of tillage erosion. Manure and chemical fertilizer application become annual operations and the costs associated with these techniques must be investigated more thoroughly, especially with rising input costs. Conservation tillage, although it slows further soil loss, many years may be required to build up the soil organic matter levels to what they once were.

It has been stated that technology is not available to restore soil productivity to the level that would exist had there been no erosion, except for transporting topsoil from depositional areas within a field and returning it to eroded hilltops (Carter et al., 1985;

Massee and Waggoner, 1985; Frye et al., 1985; Hamm, 1985). Therefore, the shortcomings of traditional management practices have initiated a more innovative approach to restore crop productivity on eroded hilltops and reduce crop variability within cultivated hilly landscapes degraded by tillage erosion.

Landscape restoration is an innovative practice defined as removing topsoil that has accumulated in the concave lower slope positions within the landscape and replacing it on the eroded convex upper slope positions from where it had originated. Many agricultural producers in countries, including China and France, have recognized the impacts of soil erosion on crop productivity and have been implementing landscape restoration for centuries as a means of restoring the landscape and sustaining agricultural production. Several innovative agricultural producers in Canada and the United States have also undertaken this practice for similar reasons, but without technical, scientific, or financial support, or recognition. Although landscape restoration may be a common practice in other parts of the world, and more recently in North America, there is no known scientific documentation of this practice.

This landscape restoration study is part of the "Economic assessment of restoring eroded land" project. This study is part of a comprehensive research program which has included a study on the impacts of landscape restoration on greenhouse gas emissions (Erb, 2005) and an economic feasibility study on landscape restoration which involved the development of an economic model (Bosma, 2004).

The overall goal of this research is to fill the current information gap and to explore the practical application of landscape restoration as an alternative land management practice to restore crop productivity on eroded hilltops in cultivated hilly landscapes. The objectives of Study 1 were (1) to determine the impact of landscape restoration on crop productivity in upper slope landscape positions where topsoil had been added and in lower slope landscape positions where topsoil had been removed and (2) to determine the net effect of landscape restoration on crop productivity within the landscape. The objective of Study 2 was to determine which soil properties are affected during landscape restoration and contribute to increased crop productivity on eroded hilltops.

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2.0 IMPACTS OF LANDSCAPE RESTORATION ON CROP PRODUCTIVITY IN SEVERELY ERODED HILLY LANDSCAPES IN SOUTHWESTERN MANITOBA

2.1 Abstract

In many cultivated hilly landscapes, tillage erosion is the dominant soil erosion process and is responsible for local soil displacement and redistribution within the landscape. Topsoil is lost from convex upper slope landscape positions (i.e., hilltops, knolls, and ridges) and accumulates in concave lower slope positions (i.e., foot slopes and toe slopes/depressions), ultimately resulting in reduced crop yield on eroded hilltops. Landscape restoration is the practice of moving topsoil that has accumulated in the lower slope positions within the landscape and replacing it on the eroded upper slope positions (from where it had originated). A large-scale field study was conducted in the undulating and hummocky landscapes of southwestern Manitoba to examine the impact of landscape restoration on crop productivity. Four study sites (one primary and three secondary sites) were selected to compare crop emergence rates and yield differences on severely eroded upper slope positions that had been restored with the addition of 10 cm of topsoil with those that had not. Comparisons were also made between crop yields in lower slope positions where topsoil was removed with those areas where it was not. Crop emergence in addition plots was faster and more consistent than in control plots. Overall, there was a 60 % greater plant population in addition plots. At the primary site, crop yields in addition plots increased by 31 % in the first year post-restoration and continued to increase the following year by 64 %. Yield increases also occurred at each secondary site and ranged from 10 to 133 % in comparison with control plots. The effect of added topsoil on eroded hilltops was more evident during a year with below normal precipitation, as yield differences between control and addition plots were greater than yield differences in a year with above normal precipitation. At two of the three sites where lower slope positions were monitored, there were no significant reductions in crop yield where topsoil had been removed. However, there was a 20 % reduction in crop yield in removal plots at one secondary site, but, the crop yield increase that occurred in the addition plots in the upper slope positions was slightly greater than the yield loss that occurred in the removal plots. Therefore, there was still a net benefit in crop production between the two landscape positions. And when crop yields were normalized across all research sites, relative to regional crop yield averages, yield differences between upper slope treatment plots were significantly greater than yield differences between lower slope treatment plots. Therefore, adding 10 cm of topsoil to severely eroded hilltops resulted in a net benefit in crop productivity within the landscape.

The results from this study on landscape restoration demonstrate that landscape restoration is a logical and practical land management practice to restore crop productivity on severely eroded hilltops and requires further attention from researchers and agricultural producers.

Keywords: Landscape restoration; Tillage erosion; Crop productivity; Seedling emergence

2.2 Introduction

Tillage erosion, the progressive net downslope movement of soil by tillage operations, has been reported to be the dominant soil erosion process in many cultivated, topographically complex landscapes (Lindstrom et al., 1990; Govers et al., 1999; Lobb and Kachanoski, 1999; De Alba, 2003; Van Oost et al., 2003; Heckrath et al., 2005). For example, in eastern Canada, Lobb et al. (1995) determined that tillage erosion accounted for at least 70 % of the total soil loss on upper slope positions in the cultivated hilly landscapes of southeastern Ontario. Tillage erosion is characterized by the localized redistribution of soil within the landscape, with losses occurring from convex upper slope landscape positions (i.e., hilltops, knolls and ridges) and the accumulation of soil in concave lower slope landscape positions (i.e., foot slopes and toe slopes/depressions) (Govers et al., 1999). This progressive downward movement of organic-rich topsoil results in severely eroded upper slope positions. These eroded areas can be easily distinguished within the landscape by the reduction in soil organic matter, shallow soil profiles, and increased stoniness and carbonates at the surface. The loss of topsoil reduces nutrient supply, water infiltration, and soil water-holding capacity (Langdale and Shrader, 1982), eventually resulting in reduced crop yields of 43 to 85 % (Larney et al., 1995; Dormaar et al., 1997). As a result, many agricultural landscapes have localized areas of poor crop production (Larney et al., 1995).

Because the effect of tillage erosion is only evident after years of cultivation, several studies have used cesium-137 (^{137}Cs) as a means to estimate the amount of soil redistribution throughout the landscape (de Jong et al., 1983; Verity and Anderson, 1990; Moulin et al., 1994; Lobb et al., 1995; Lobb and Kachanoski, 1999; Kachanoski and

Carter, 1999; Heckrath et al., 2005). Heckrath et al. (2005) reported the average rate of tillage induced soil loss on shoulder slopes in cultivated topographically complex landscapes in Denmark was 27 t ha^{-1} yr^{-1} (12 t ac^{-1} yr^{-1}), conversely, soil deposition in foot- and toe-slopes was 12 t ha^{-} yr^{-1} (5.4 t ac^{-1} yr^{-1}). In a Canadian study, Lobb et al. (1995) calculated soil loss rates in excess of 54 t ha^{-1} yr^{-1} (24 t ac^{-1} yr^{-1}) from convex upper slopes in cultivated landscapes in southeastern Ontario.

The effect of topsoil depth on soil and crop productivity is well documented (Power et al., 1981; Frye et al., 1985; Carter, et al., 1985; Thompson, et al., 1991; Larney et al., 2000a). For instance, Carter et al. (1985) evaluated the effect of soil erosion on crop yield and demonstrated that topsoil depth has a considerable impact on crop growth and grain yield. These authors also concluded that yield losses on eroded upper slope positions of fields were not offset by equal crop yield increases in the deposition areas. Therefore, it is essential for agricultural producers to maintain and/or improve organic matter levels to achieve sustainable crop production.

Several studies have examined the use commercial fertilizers (Massee and Waggoner; 1985; Mielke and Schepers, 1986; Morrison-Ives and Shaykewich, 1987; Tanaka and Aase, 1989; Massee, 1990; Verity and Anderson, 1990; Larney et al., 1995; Larney et al., 2000a), manures (Dormaar et al., 1988; Dormaar et al., 1997; Robbins et al., 1997; Larney et al, 2000b), and conservation tillage practices (Mueller et al., 1984; Grevers et al., 1986; McCarthy et al., 1993; Hussain et al., 1999) as ways to restore productivity to eroded landscape once topsoil has been lost. Increasing the application rate of commercial fertilizers is one of the quickest ways to increase crop productivity on eroded knolls (Hamm, 1985). This is also the most common and widely used approach because of the ease of application and accessibility of fertilizers to producers. However, studies conducted by Massee and Waggoner (1985), Verity and Anderson (1990), Larney et al. (1995), and Larney et al. (2000a) found that fertilizer application only partially remedied yield losses caused by soil erosion. Applying livestock manure is another practice used to increase the productivity of eroded upper slope positions. A simulated erosion study found that the application of 30,000 kg ha^{-1} (26,710 lb ac^{-1}) of manure significantly increased organic matter, total nitrogen (N), nitrate nitrogen (NO_3-N), available phosphorus (P), and water holding capacity (Dormaar et al., 1988). However, Dormaar et al. (1988) also stated in order to restore the soil organic matter of previously eroded soils, it may be necessary to apply manure on an annual basis for several years. In the past two decades conservation tillage and other residue management practices have also been widely adopted as a means of increasing soil water use efficiency (WUE) and soil organic matter content, as well as, reducing soil erosion processes (Mueller et al., 1984; Grevers et al., 1986; McCarthy et al., 1993; Hussain et al., 1999). Grevers et al. (1986) reported that soil water recharge and WUE in zero-till fields were greater than in fields managed using conventional tillage practices in Saskatchewan soils. In addition, McCarthy et al. (1993) found a 50 % reduction in topsoil loss can occur from a 30 % surface residue cover using conservational tillage practices.

However, each of these three approaches used to increase productivity on eroded landscapes are only a means to cope with the problem of lost topsoil and mask the long-term effects of tillage erosion on crop production. Manure and chemical fertilizer application become annual operations and the costs associated with these practices must be investigated more thoroughly, especially with rising input costs. For example, Smith et al. (2000) reported that it was not economical to use commercial fertilizer on eroded hilltops to restore grain yields in Alberta, Canada. Conservation tillage practices, although slowing further soil loss, require many years to build up the soil organic matter levels to what they once were. In addition, upper slope landscape positions are typically slow in regenerating organic matter levels as a result of the inherent variability in soil moisture within complex landscapes. Furthermore, as the severity and extent of erosion increases, it becomes even more difficult to regain sufficient organic matter levels for crop production on upper slope positions.

It has been stated that technology is not available to restore soil productivity to the level that would exist had there been no erosion, except for returning topsoil to eroded areas (Carter et al., 1985; Hamm, 1985; Massee and Waggoner, 1985). However, several studies have used topsoil addition as a treatment to help explain the effects of soil erosion on crop yield. For example, Masse and Waggoner (1985) reported that yields increased from 1810 kg ha^{-1} (1611 lb ac^{-1}) on untreated topsoil to 3050 kg ha^{-1} (2715 lb ac^{-1}) when 15 cm (6 in) of topsoil was added to severely eroded knolls. Verity and Anderson (1990) reported increases in grain yields between 45 and 58 % by adding 5 cm (2 in) of topsoil, and Mielke and Schepers (1986) also reported greater crop yields where 10 cm (4 in) and 20 cm (8 in) of soil was added to eroded knolls. However, the high yields associated with added topsoil can not be duplicated by merely adding fertilizer (Olson, 1977) and transporting topsoil from depositional areas within a field to eroded areas is a means of restoring the productivity of eroded soils (Frye et al., 1985).

The shortcomings of traditional management practices have initiated a more innovative approach to prevent and mediate soil erosion. Landscape restoration is the practice of moving topsoil that has accumulated in concave lower slope positions of the landscape and replacing it on the eroded convex upper slope positions from where it had originated. The overall goal of this research project was to explore the practical application of landscape restoration as an alternative land management practice to restore crop productivity on eroded hilltops in cultivated hilly landscapes. The objectives of this study were (1) to quantify the impact of landscape restoration by examining crop productivity on convex upper slope positions, where topsoil had been added, and concave lower slope positions, where topsoil had been removed and (2) to determine the net impact of landscape restoration on crop productivity within the landscape.

2.3 Materials and Methods

2.3.1 Site Description

Four research sites, one primary field site and three secondary field sites, were selected to study the net effect of landscape restoration on crop productivity in undulating and hummocky landscapes common to the Canadian Prairies. The primary research site was located near the town of Treherne, Manitoba, approximately 150 km (93 mi) southwest of Winnipeg. The secondary research sites were located near the towns of Bruxelles, Swan Lake, and Brookdale, Manitoba.

Crop yield was collected at the primary site for two consecutive years, 2005 and 2006. Seedling emergence was also monitored at this site in 2006. Two of the secondary sites, Bruxelles and Swan Lake, have a single year of crop yield data during the 2006 field season. However, the third secondary site has three years of data collection; 2004 through to 2006.

The research sites were selected because they appeared to be severely degraded by past soil erosion. The initial selection process was based on visual observations of organic matter and carbonates exposed at the soil surface, as well as the amount of soil accumulation in the lower slope landscape positions.

2.3.1.1 Primary Research Site: Treherne. The primary research site was located in Treherne (TRE), Manitoba in the northeast and northwest quarter-sections of 15-07-10W (Appendix B: Figure B.1a). The site is dominated by a hummocky landscape with slopes ranging from 5 to 9 %, and is situated in the Pembina Hills Upland subdivision of the Saskatchewan Plain physiographic region of Manitoba. This field site was established in the early 1950's for grain production. Conventional, high intensity tillage practices were used to farm the land which caused the downward movement of topsoil from convex upper slope positions and the resultant accumulation of topsoil in concave lower slope positions within the landscape. It wasn't until the early 1980's that the land owners began implementing conservation tillage practices. This typically included one tillage pass in the fall to facilitate water drainage and seedbed preparation and one pass in the spring for seeding and fertilizing.

Due to the complex local topography of the research site, several soils occur within each landscape position. Soils found on the upper slope positions are eroded phases of Orthic Dark Grey Chernozems (Typic Argiudoll) of the Dezwood and Fifere Associations. The soils of the Dezwood Association are developed on strongly calcareous mixed shale, limestone, and granite glacial till deposits, whereas soils of the Fifere Association are developed on weakly calcareous, shale glacial till deposits (Langman, 1989). Imperfectly drained Gleyed Rego Black Chernozems (Aeric

Calciaquoll) of the Carroll Association and Gleyed Black Chermozems (Typic Edoaquall) of the Knudson Association are found in the concave lower slope positions of the landscape (Langman, 1989). The Gleyed Rego Black Chernozem of the Carroll Association is characteristic of high carbonate levels due to the deep lacustrine sediments from which they are derived. The Gleyed Black Chernozem of the Knudson Association is a calcareous lacustrine veneer overlying calcareous mixed glacial till deposits.

2.3.1.2 Secondary Research Sites.

2.3.1.2.1 Bruxelles. One secondary site was located in the southwest quarter-section of legal land description 27-06-11W near Bruxelles (BRX), Manitoba (Appendix B: Figure B.2a). The BRX site is dominated by a hummocky landscape and is situated in the same physiographic region as the TRE site. The BRX field site is managed using conservation tillage practices and has been under zero-till management since 1966.

Similar to the TRE site, soils in the upper slope positions are eroded phases of Orthic Dark Grey Chernozems (Typic Argiudoll) of the Dezwood Association. Soils in the lower slope positions are also of the Dezwood Association and are dominated by imperfectly drained Gleyed Rego Black Chernozems (Aeric Calciaquoll) derived from calcareous mixed glacial till deposits.

2.3.1.2.2 Swan Lake. A second secondary site was located near Swan Lake (SWL), Manitoba in the northwest quarter-section of 07-06-10W (Appendix B: Figure B.3a). Similar to the TRE and BRX sites, this site is also dominated by a hummocky landscape and is located in the same physiographic region. The SWL site is managed using conservation tillage practices and was converted to minimum tillage in 1993.

The soils that occur in the upper slope positions are eroded phases of Orthic Dark

Grey Chernozems (Typic Argiudoll) of the Fifere Association which also occur at the TRE site. Similar to the BRX site, imperfectly drained Gleyed Rego Black Chernozems also occur in lower slope positions. However, they are of the Altamont Association and are developed on calcareous lacustrine veneers overlying calcareous mixed glacial till deposits (Langman, 1986).

2.3.1.2.3 Brookdale. A third secondary site was located at the Manitoba Zero Tillage Research Association' farm in Brookdale (BKL), Manitoba (31-12-18W) (Appendix B: Figure B.4a). The farm lies in the undulating to hummocky landscape of the Newdale Plain physiographic subdivision of the Assiniboine River Plain where slopes range from level (0-2%) to gently sloping (2-5%) (Podolsky and Schindler, 1994). The farm at the BKL site has been practicing zero-till since 1993. However for decades prior, the farm incorporated intensive conventional tillage practices resulting in the severe soil erosion. The soils at the BKL site were developed on calcareous mixed glacial till of limestone, granite, and shale and are of the Newdale Association (Podolsky and Schindler, 1994). An eroded phase of a Rego Black Chernozem (Udic Haplustoll) dominates the upper slope positions and a Gleyed Rego Black Chernozem occurs in the depressional areas.

2.3.2 Experimental Design

As mentioned previously, the primary objective of the study was to quantify the net effects of landscape restoration by examining crop yield on restored upper slope positions and in lower slope positions where topsoil had been removed. However, it was not possible to monitor the lower slope plots at all locations. Nevertheless, the overall objective remained the same. A randomized complete block design was used at all four field sites, with each plot representing one replicate of a two treatment comparison. The upper slope pairs comprised a treatment plot (10 cm (4 in) added topsoil), and a control plot (no topsoil added). At the three sites where lower landscape positions were monitored (TRE, BRX, SWL), there was a treatment plot (10 cm (4 in) removed topsoil) and a control plot (no removal of topsoil). However, it should be noted that at the BKL site the soil was removed from three cropland depressions (as opposed to the foot slope) at a depth of 20 cm (8 in). The plots at the BKL site were previously established for a graduate thesis project to examine the effects of landscape restoration on greenhouse gas emissions and plant species and abundance (Erb, 2005).

A topsoil depth of 10 cm was chosen for this study based on other research that has investigated incremental depths of topsoil addition on eroded hilltops (Mielke and Schepers, 1986; Verity and Anderson, 1990). However, it should be noted that during the course of this landscape restoration study, a supplementary study was also carried out. The objective of the study was to determine the optimum depth of topsoil addition and removal based on crop response using incremental depths of topsoil addition on eroded upper slope positions and corresponding incremental depths of topsoil removal from lower slope positions. The study site was located near the town of Deerwood, Manitoba (06-05-07W) in a hummocky landscape with slopes ranging from 5 to 9 %. The field site was established in the spring of 2005 and was monitored during the 2005 and 2006 growing seasons. Four eroded ridges and four adjacent cropland depressions (i.e., toe slopes) were monitored for crop yield. Each ridge included a four treatment comparison: a control with no topsoil added, 5 cm (2.5 in), 10 cm (4 in), and 15 cm (6 in) of topsoil added. Each adjacent cropland depression contained the four corresponding incremental topsoil removal treatments: a control with no topsoil removed, 5 cm, 10 cm, and 15 cm of topsoil removal. The field site was set up as a randomized complete block design where each ridge or depression represented one block and each treatment was randomly assigned to each plot. Wooden frames were constructed along the length of each ridge and bottom of each depression and the soil was added or removed to the appropriate depth (Verity and Anderson, 1990). Unfortunately, due to uncontrollable circumstances, severe crop damage occurred both years, and as a result, no crop data was collected. Although the attempt to determine the optimum depth of topsoil addition and removal was unsuccessful, the topsoil depth used in this study was appropriate based on other literature (Mielke and Schepers, 1986; Verity and Anderson, 1990).

An important component of this study was to accurately represent how producers would execute landscape restoration in their fields. Therefore, for the TRE, BRX, and SWL sites, it was important to not compromise the surface drainage of the field when removing topsoil from each lower slope position. Therefore, the removal pattern at these sites was long strips with a small grade (Figure 2.1). At the BKL site, the soil removal areas were smaller in size (compared to the other three sites) and deeper cuts were made to remove the soil.

Figure 2.1 Removing topsoil from lower slope positions using a land scraper.

The restoration of each site took place in the fall, allowing time for the soil to settle to create a suitable seedbed in the following spring. Depending on the capacity of the land scraper and the volume of topsoil removed during each pass, an average of 3 to 6 loads of topsoil were required to achieve the desired topsoil depth of each addition plot at each research site. The initial depth of topsoil added to the eroded hilltops exceeded the desired final depth of 10 cm by 2 to 5 cm (Appendix A). The purpose of exceeding the 10 cm depth was to compensate for any volume changes that would occur (as the added topsoil settled) during the fall, winter, and early spring months before seeding. Once the soil was added to the upper slope positions, it was left to dry for several days and then disced to help break up large clods to facilitate seeding. A meter stick was used to measure the thickness of topsoil added to each addition plot and the depth of topsoil removed from the removal plots. Topsoil depth measurements were taken during the initial restoration in the fall and again the following spring at each research site (Appendix A).

2.3.2.1 Primary Research Site: Treherne. The TRE site was restored on October 28, 2004. On the upper slope positions, four plots were selected; two knolls and two ridges based on similar degrees of erosion and slope gradient. Three adjacent foot slopes were chosen for topsoil removal. At this site, each plot represents one replicate of the two-treatment comparison and each treatment was randomly assigned to each replicate (Appendix B: Figure B.1b). To facilitate seeding and fertilizer application in the spring, each plot was 12 m (40 ft) wide, the width of one pass of the seeding equipment and approximately 15 m (50 ft) long. Soil was taken from the foot slope positions using a 165 kW (225 hp) front wheel assist Versatile 800 tractor equipped with a 4.5 m^3 (212 ft^3) hydraulic Leon land scraper.

2.3.2.2 Secondary Research Sites

2.3.2.2.1 Bruxelles. The BRX was established on October 27, 2005 and reflects the same experimental design at the TRE site where each plot represents one replicate of a randomly assigned two-treatment comparison. Five eroded upper slope positions were chosen for the addition of topsoil (Appendix B: Figure B.2b). Upper slope plots were 9 m (20 ft) wide and 3 m (10 ft) in length to accommodate for seeding equipment. Soil was removed in one strip, approximately 30 m (100 ft) long and 4 m (13 ft) wide from a single centralized foot slope position using a 88 kW (120 hp), 4430 John Deere tractor equipped with a 4.4 m^3 (155 ft^3) 850 Leon land scraper. Three locations along the lower slope position were randomly selected for treatment pairs of a control plot and removal plot.

2.3.2.2.2 Swan Lake. The SWL site was also established on October 27, 2005 as a randomized complete block design. The site had one knoll and a large ridge restored.

The ridge was large enough to contain two treatment pairs. The size of the plots were 12 m wide (40 ft) and 9 m (30 ft) in length to accommodate for the size of the seeding equipment. Similar to the BRX site, only one centralized foot slope position was used as the source of topsoil. However, due to the large size of the removal area, three locations were randomly selected to represent each treatment pair (Appendix B: Figure B.3b). Soil was removed using a four wheel drive, 239 kW (325 hp) 946 Ford tractor equipped with a 7.6 m^3 (268 ft^3) Leon land scraper.

2.3.2.2.3 Brookdale. The plots at the BKL site were established in the northwest quarter section of the farm in the fall of 2003 (Appendix B: Figure B.4b). These plots were set up as a randomized complete block design. Each block contained a control plot and a topsoil addition plot and measured 12 m^2 (40 ft^2). Each treatment was randomly assigned to each block. As previously mentioned, three cropland depressions were the source of topsoil for the addition plots on the eroded upper slopes. The soil was removed using a 70 kW (95 hp) 4020 John Deere tractor equipped with a front end loader. However, due to position of each removal plot within the landscape, extensive and persistent surface ponding occurred during each spring. As a result, it was not impossible to seed these areas in the spring and, therefore, they were not monitored for yield.

2.3.3 Crop Management

Due to the large scale of this study and the long-term cropping rotations of each farm, the same crop type at each site in each year was not possible.

2.3.3.1 Primary Research Site: Treherne. The TRE site was seeded to barley (*Hordeum vulgare*) (cv. "Robust") on May 25, 2005 a rate of 134 kg ha^{-1} (120 lbs ac^{-1})

using a 12 m (40 ft) hoe drill, on 19 cm (7 in) row spacing. A custom blended liquid fertilizer was applied with the seed and at a rate of 78 kg ha^{-1} (70 lb ac^{-1}) nitrogen (N), 39 kg ha^{-1} (35 lb ac^{-1}) phosphorus (P), and 6 kg ha^{-1} (5 lb ac^{-1}) sulphur (S). Upper slope plots were harvested on August 29, 2005, however the plots in lower slope positions were not harvested this year because of extensive ponding in the lower slope positions and as a result, there was severe crop loss.

In 2006, inoculated field peas (*Pisum sativum*) (cv. "Topeka") were sown on May 18, 2006 at a rate of 202 kg ha^{-1} (180 lbs ac^{-1}). No additional fertilizer was applied. After seeding, one pass with at set of harrows (25 cm (10 in) spacing) was used to smooth out any furrows left by the seeder. A land roller was used to smooth out the surface to ensure good soil-to-seed contact and to punch in any small stones as to avoid problems during harvest. Plots were hand-harvested on August 03, 2006.

2.3.3.2 Secondary Research Sites.

2.3.3.2.1 Bruxelles. The BRX site was sown to Canadian Red Spring Wheat (*Triticum aestivum*) (cv. "AC Cadillac") on May 12, 2006 at a rate of 85 kg ha^{-1} (75 lbs ac^{-1}) using a Versatile Nobel 2200 Zero-Till seeder with 20 cm (8 in) row spacing. Fertilizer was applied at seeding; 37 kg ha^{-1} (30 lb ac^{-1}) N, 17 kg ha^{-1} (15 lb ac^{-1}) P, 6 kg ha^{-1} (5 lb ac^{-1}) potassium (K), and 6 kg ha^{-1} (5 lb ac^{-1}) S. Harvesting took place on August 09, 2006.

2.3.3.2.2 Swan Lake. At the SWL site, flax (*Linum usitatissimum*) (cv. "Bethune") was sown on May 17, 2006 at a rate of 50 kg ha^{-1} (45 lbs ac^{-1}) using an air drill with 25 cm (10 in) row spacing. Liquid urea ammonium nitrate (UAN) fertilizer was side-dribble banded at the time of seeding and applied at a rate of 67 kg ha^{-1} (60 lb ac^{-1}) N. Plots at this secondary site were the last to ripen and were harvested on September 29, 2006.

2.3.3.2.3 Brookdale. At the BKL site, Argentine canola (*Brassica napus*) (cv. "Nex 822") was seeded at a depth of 2 cm (0.8 in) and at a rate of 5.6 kg ha^{-1} (5.1 lb ac^{-1}) on May 21 2004. Nitrogen was applied as UAN at a rate of 74 kg ha^{-1} (66 lb ac^{-1}). Sulphur was applied as liquid ammonium thiosulphate (15-0-0-20) at a rate of 22.5 kg ha^{-1} (20 lb ac^{-1}) and was side-dribble banded with UAN at the time of seeding. Granular monoammonium phosphate (MAP) was used as a P source and was applied at a rate of 28 kg ha^{-1} (25 lb ac^{-1}) and an additional 5.6 lb ac^{-1} (5.0 lb ac^{-1}) of N was placed with the seed. Plots were harvested on September 07, 2004. In 2005, BKL was seeded to Canadian Spring Wheat (*Triticum aestivum*) (cv. "5701") on May 5, 2005 at a rate of 134 kg ha^{-1} (120 lb ac^{-1}). UAN was side-dribble banded and applied at a rate of 79 kg ha^{-1} (70 lb ac^{-1}) N and MAP was applied at a rate of 34 kg ha^{-1} (30 lb ac^{-1}) P. Plots were harvested on August 24, 2005. Flax (cv. "Bethune") was sown on May 16, 2006 at a rate of 8 kg ha^{-1} (45 lb ac^{-1}). UAN fertilizer was side-dribble banded at the time of seeding and applied at a rate of 67 kg ha^{-1} (60 lb ac^{-1}) N. Plots were harvested on August 29, 2006.

2.3.4 Crop Measurements

2.3.4.1 Seedling Emergence. Seedling emergence was monitored at the TRE site in 2006. Immediately after seeding, the total number of seeds were counted within each plot in three randomly placed 0.5 m^2 (4.6 ft^2) quadrats. Seedlings were counted in the same quadrats on six separate occasions over a two week period until emergence ceased.

2.3.4.2 Crop Yield. Crop yield was the primary agronomic parameter measured to assess the effectiveness of landscape restoration. At each site, plots were hand-harvested with a serrated sickle and stocks were cut 5 cm (2 in) above the ground. A meter stick was thrown randomly in each plot and the row in which it landed was cut the length of the meter stick. This was repeated four times to obtain a representative sample. The harvested samples were placed in rice bags and dried at 45°C (113°F). The samples were threshed using a stationary threshing machine to separate the chaff and grain. The grain was then cleaned and weighed.

2.3.5 Statistical Analyses

SAS 8.0® was the statistical software used to analyze the crop data in this study (SAS Institute Inc., 2000). The plots were analyzed as replicated pairs, therefore, the T-TEST procedure was used to compare the difference between treatment means within each landscape position (Frye et al., 1982). The T-TEST procedure was also used to compare the differences in crop yield between landscape positions to determine the net effect of landscape restoration on crop productivity within the landscape. In addition to a t-test, regression analysis (R^2) was determined using PROC REG to test relationships between seedling emergence and sampling date within each treatment of each landscape position. An analysis of covariance (ANCOVA) was used to compare the means and slopes of the linear regression between treatments within each landscape position using PROC GLM. The level of significance used was $\alpha = 0.10$ due to the high variability inherent in uncontrolled, field-based landscape experiments (Pennock et al., 1994; Steele et al., 1997; Lal et al., 2000; Manning et al., 2001). A higher probability level is justified to detect treatment differences and employing a probability threshold (α) of 0.05 or lower in landscape studies increases the chances of making a Type II error (β), and, therefore, failing to detect treatment differences when, in fact, these differences do occur (Steele et al., 1997).

2.4 Results

2.4.1 Primary Research Site: Treherne

2.4.1.1 Seedling Emergence. Gan et al. (1992) reported that the rate at which a crop is established is directly related to crop yield. Therefore, seedling emergence was monitored in both upper slope and lower slope position plots for five weeks after planting in 2006. In upper slope plots, the regression analysis determined a significant relationship between seedling emergence and sampling date in both control and addition plots, R^2 values 0.93 and 0.96, respectively (Figure 2.2).

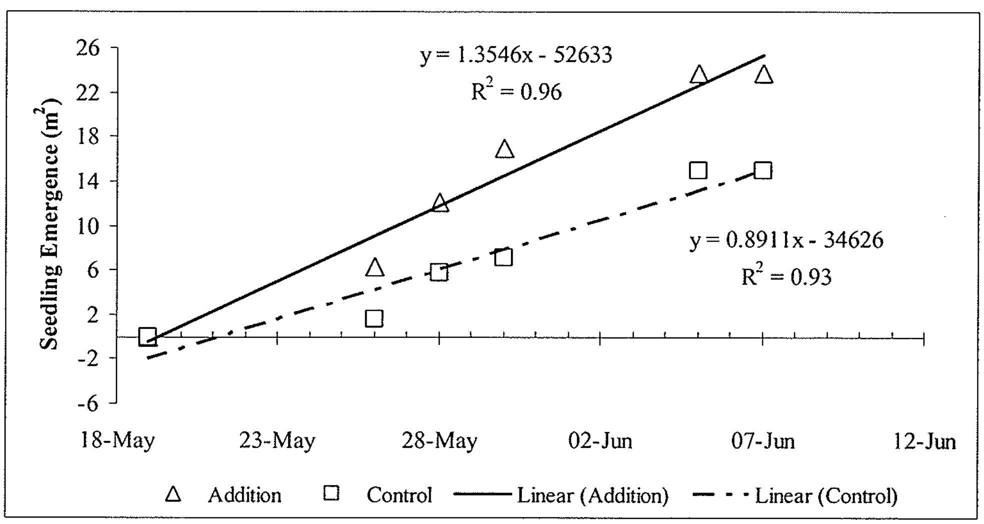

Figure 2.2 Relationship between field pea (*Pisum sativum*) seedling emergence and sampling date in upper slope positions at Treherne in 2006.

However, the analysis of covariance (ANCOVA) found significant differences between the regression lines of the control and addition plots as well as, in the date*treatment interaction (Table 2.1).

Table 2.1 Analysis of covariance (ANCOVA) of field pea (*Pisum sativum*) seedling emergence for upper slope and lower slope plots at Treherne in 2006.

	Upper Slope Position			
	Sampling Date	Treatment	Date*Treatment	
F value	<.0001***	0.023**	0.013**	
R^2				0.83
	Lower Slope Position			
	Sampling Date	Treatment	Date*Treatment	
F value	<.0001***	0.14	0.12	
R^2				0.89

*Significant at $F<0.10$, **Significant at $F<0.05$, ***Significant at $F<0.01$.

Therefore, pea seedlings emerged faster and at a more consistent rate in the addition plots compared to the control plots. In addition, the number of seedlings in control plots were 33 %, 50 %, 41 %, and 60 % of addition plots 8, 10, 12 and 18 days post-seeding, respectively (Appendix C: Figure C.1). In lower slope positions, a significant relationship also existed between seedling emergence and sampling date in both control and removal plots (Figure 2.3).

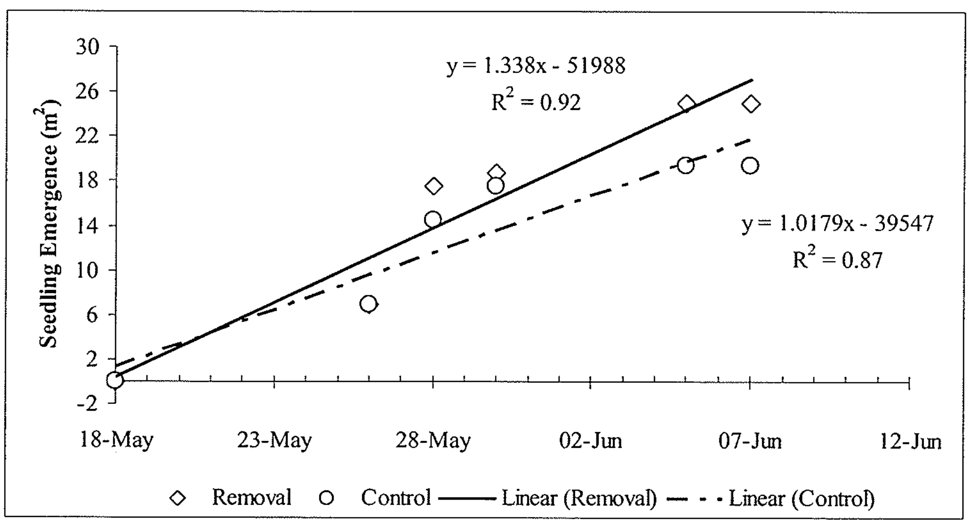

Figure 2.3 Relationship between field pea (Pisum sativum) seedling emergence and sampling date in lower slope positions at Treherne in 2006.

However, the ANCOVA analysis determined that there were no significant differences between regression lines of the control and removal plots or in the date*treatment interaction (Table 2.1). Therefore, emergence trends were similar between the control and removal plots. At the end of the 5 week monitoring period, there was a significant difference in the total number of emerged seedlings between treatments in the lower slope positions, with 25 % more seedlings observed in the removal plots, compared to the control plots (Appendix C: Figure C.2).

2.4.1.2 Crop Yield. In 2005, the first year post-restoration, barley yields were 31 % higher in addition plots, compared to the control (Table 2.2). In general, this was the largest yield increase that occurred in addition plots when compared to the BKL site of the same year (Table 2.5). In year-two (2006), even larger yield differences occurred in addition plots. Pea yield was significantly greater than control plots with an average yield difference of 800 kg ha^{-1} (713 lb ac^{-1}). Although a significant difference in crop yield occurred between plots in the upper slope positions, this trend was not seen in the control and removal plots in the lower slope positions (Table 2.2).

Table 2.2 Crop yield results in upper slope and lower slope plots at Treherne in 2005 and 2006.

	Upper Slope[1]			Lower Slope		
	Control	Addition	Δ	Control	Removal	Δ
	(kg ha^{-1})					
a) 2005 Grain Yield[a]	1810	2365	555*	-	-	-
b) 2006 Grain Yield[b]	1249	2049	800***	3330	2740	590

[a]Barley yield.
[b]Pea yield.
[1]Values represent the means for 4 replicates.
[2]Values represent the means for 3 replicates.
Δ = Treatment - Control
*Significant at $P<0.10$, **Significant at $P<0.05$, ***Significant at $P<0.01$ using a paired t-test.

2.4.2 Secondary Research Sites

The purpose of the secondary sites was to provide further information on the effects of landscape restoration on crop yield. Therefore, only crop yield was collected at these sites.

2.4.2.1 Bruxelles. Among site in 2006, the largest yield difference between addition and control plots occurred at the BRX site. Wheat yields increased significantly by 1077 kg ha^{-1} (961 lb ac^{-1}), translating to a 133 % increase in crop yield between addition and control plots (Table 2.3). There were no significant differences in crop yield between removal and control plots in lower slope positions.

Table 2.3 Crop yield results in upper slope and lower slope plots at Bruxelles in 2006.

Upper Slope[1]				Lower Slope[2]		
Control	Addition	Δ		Control	Removal	Δ
			($kg\ ha^{-1}$)			
796	1856	1060***		2609	2654	-45

[1]Values represent the means of 5 replicates.
[2]Values represent the means of 3 replicates.
Δ = Treatment - Control
*Significant at $P<0.10$, **Significant at $P<0.05$, ***Significant at $P<0.01$ using a paired t-test.
Note: Crop yield values are wheat yields.

2.4.2.2 Swan Lake. Similar to the BRX site, a significantly higher yield difference occurred between addition and control plots at the SWL site. The flax yield in the addition plots increased by 380 kg ha^{-1} (339 lb ac^{-1}) and was 94 % higher than the control (Table 2.4). In the lower slope positions, a yield reduction of 360 kg ha^{-1} (321 lb ha^{-1}) occurred in the removal plots, compared to the control plots (Table 2.4). However, yields in lower slope positions were more than three times larger than non-restored upper slope positions and double those of upper slope addition plots. Although there was a reduction in crop yield where topsoil was removed, the yield increase that occurred in the addition plots in upper slope positions was slightly greater. Therefore, there was still a net benefit in crop production within the landscape.

Table 2.4 Crop yield results in upper slope and lower slope plots at Swan Lake in 2006.

Upper Slope[1]				Lower Slope[1]		
Control	Addition	Δ		Control	Removal	Δ
			($kg\ ha^{-1}$)			
404	784	380*		1767	1407	360*

[1]Values represent the means of 3 replicates.
*Significant at $P<0.10$, **Significant at $P<0.05$, ***Significant at $P<0.01$ using a paired t-test.
Δ = Treatment - Control
Note: Crop yield values are flax yields.

2.4.2.3 Brookdale. During the 2004 field season, a problem occurred with the seeding equipment causing an irregular seeding pattern which went undetected until long after the crop had been seeded. As a result, most of the plots were not evenly seeded and in some cases missed all together. The uneven crop emergence resulted in noticeable differences in crop yields as well as high populations of weed species (Erb, 2005). Therefore, the 2004 data collected during this particular field season is not representative of the landscape restoration practice, and as a result, will not be considered in the research study. However in 2005, a significant difference in wheat yield was observed in addition plots with an average yield increase of 290 kg ha^{-1} (259 lb ac^{-1}), representing a 10 % increase in overall yield (Table 2.5). During the 2006 field season, three years after the initial landscape restoration, yield increases were still significantly higher in upper slope positions where topsoil had been added compared to control plots. Flax yield in addition plots was 2679 kg ha^{-1} (2392 lb ac^{-1}) and 1907 kg ha^{-1} (1703 lb ac^{-1}) in control plots, an increase in yield by 40 % (Table 2.5).

Table 2.5 Crop yield results in upper slope plots at Brookdale in 2005 and 2006.

2005 Grain Yield[a]				2006 Grain Yield[b]		
Control	Addition	Δ		Control	Addition	Δ
			($kg\ ha^{-1}$)			
2831	3121	290*		1907	2679	772***

[a] Wheat yield.

[b] Flax yield.

Δ = Treatment - Control

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

Note: Values represent the means of 9 replicates.

2.5 Discussion

2.5.1 Seedling Emergence

The addition of topsoil on eroded hilltops accelerated the rate at which seedlings emerged and significantly increased plant populations, demonstrating more favourable growing conditions in addition plots. These results are similar to those found in Mielke and Schepers (1986), who reported that only 40 % of seedlings emerged in control plots 13 days after seeding in a Nebraska study, compared to 90 % emergence in plots that received 10 cm (4 in) and 20 cm (8 in) of topsoil. In addition, emergence ceased 20 days after seeding and plant populations were nearly equal in control and topsoil addition treatments. This contrasts with the 60 % difference in final plant populations between control and addition plots in this study. Mielke and Schepers (1986) attributed the delayed emergence in control plots to lower soil temperatures early in the growing season. It was speculated that the delayed emergence was due to higher surface albedo in the control plots than the topsoil addition plots. Black and Greb (1968) also reported lower soil temperatures associated with exposed subsoil delayed crop maturity by 5 to 7 days and continued to delay crops up to 3 to 5 days even with N and P fertilizer application. The application of dark organic-rich topsoil to eroded upper slope positions would have likely raised the temperature in the addition plots and in effect, stimulated faster emergence than in the control plots. Therefore, this may explain the faster emergence rates in addition plots reported in this study.

Another explanation for higher plant populations and accelerated emergence in addition plots is the possibility of improved moisture status in the rooting zone. The loss of topsoil results in reduced water holding capacity and poor water infiltration (Langdale and Shrader, 1982). Several other studies have shown that soil organic matter has a dominant influence on improving crop yields (Mielke and Schepers, 1986; Tanaka and Aase, 1989; Verity and Anderson, 1990; Bauer and Black, 1994) and influences the amount of soil moisture available to plants (Hudson, 1994; Olness and Archer, 2005). A study conducted by Hudson (1994) found that for every percent increase in soil organic matter, available water holding capacity increased by 2.2 % to 3.7 % across a range of textural groups. Recently, Olness and Archer (2005) used a prediction model to illustrate that soil organic carbon strongly influenced available soil moisture; for every 1 % increase in organic carbon, available water holding capacity increased by 2 % to > 5 %, depending on the soil texture. Therefore, adding organic-rich topsoil on severely eroded hilltops may improve the moisture status and stimulate earlier and faster emergence.

In upper slope positions, the 60 % higher plant population in the addition plots corresponded with an equally significant final crop yield increase of 64 %. This is similar to the study by Gan et al. (1992), who reported a significant correlation between date of seedling emergence and grain yield. Plants that emerged earlier had 1.4 and 3.2 times greater wheat yields than plants that had emerged 4 to 6 days later and 7 to 9 days later, respectively. In South Dakota, a simulated erosion study also reported a 3-day delay in plant emergence where 30 and 45 cm (15 and 18 in) of topsoil had been removed. This delay resulted in a corresponding delay in plant development during the reproductive stage (silking) in corn plants and significant yield reductions of 20 and 25% where 30 and 45 cm of topsoil was removed, respectively. However, in this landscape restoration study, the removal plots in the lower slope positions had 25 % more seedlings emerge, but this did not translate into an increase in crop yield. This may be due to the lack of moisture stress, associated with increased levels of soil organic matter during, critical periods of plant growth and development in this particular landscape position.

2.5.2 Crop Yield

Despite the different crop types and variations in cropping systems at each study site, the addition plots consistently yielded significantly higher than the control plots. As well, addition pots continued to experience significantly greater yields two years (TRE) and three years (BKL) post-restoration. In general, study sites where lower slope plots were monitored (TRE, BRX, and SWL), yield was not significantly compromised in two of the three sites, TRE and BRX. Although, there was a reduction in yield in the removal plots at the SWL site, there was still a slight overall net increase in crop yield between the two landscape positions.

The yield increases in addition plots can be explained by the treatment effect of adding 10 cm of topsoil on severely eroded upper slope positions. Our results are similar to those found in Eck (1969), Massee and Waggoner (1985), Mielke and Schepers (1986), Massee (1990), Verity and Anderson (1990), and Larney et al. (2000b). For example, Verity and Anderson (1990) conducted a two-year study in Saskatchewan, Canada and determined that as little as 5 cm of added topsoil increased grain yields on eroded hilltops and additional increments only marginally increased yields. Yields increased from 914 kg ha^{-1} (816 lb ac^{-1}) in control plots to 1343, 1443, and 1327 kg ha^{-1} (1199, 1288, 1185 lb ac^{-1}) with the addition of 5, 10, and 15 cm, respectively. In year two, grain yields continued to increase from 42 % with 5 cm of topsoil to 88 and 72 % with 10 and 15 cm topsoil addition, respectively. The authors speculated that the lower yields on eroded hilltops were due to limitations in soil fertility as lower yields also occurred in year-two when there was adequate precipitation during the growing season, suggesting soil moisture was not limiting.

Results from a study by Larney et al. (2000b) which included irrigated and non-irrigated fields, also attributed increases in yield from the addition of 5 cm of topsoil to increases in soil fertility as irrigation eliminated any moisture stress during the growing season. In a simulated erosion study, Massee and Waggoner (1985) and Massee (1990) illustrated that the addition of 15 cm topsoil resulted in a 69 % higher grain yield than fertilized plots alone. They also reported that higher yielding plots had less soil moisture at the time of harvest and concluded that the relationship between greater volumes of available soil moisture at harvest and crop yield was negatively correlated. However, due to unknown sources of variation they concluded yield differences were a result of N deficiencies. Mielke and Schepers (1986) also reported significantly higher yields associated with the addition of 10 and 15 cm of topsoil on eroded soils. Although results did not reveal any significant differences in stored soil moisture, the authors recognized that topsoil had beneficial properties and yield increases may be influenced by properties other than soil fertility. In an earlier simulated erosion study, Eck (1969) used stored soil moisture, water use, and water-use efficiency to explain higher yields in 15 and 30 cm (12 in) added topsoil. Eck (1969) found that added topsoil supplied adequate plant nutrients to support higher yields and as a result, crops extracted more soil moisture and water was used more efficiently than those grown on eroded soils.

A comparison between crop years was made when considering the two sites with multiple years of data, TRE and BKL. During a dry growing season, when less water is available, poor crop growth on eroded upper slope positions is more evident. However, during growing seasons where there is adequate water available for plant uptake, the effects of soil loss are suppressed (Mielke and Schepers, 1986; Henning and Khalaf, 1984). Therefore, it was speculated that during wet years eroded upper slope positions could be left unrestored and still experience high yields. However, during the growing season in 2005, both the TRE and BKL sites experienced excess moisture (Appendix D). In 2005, from the month of April through to the end of August, the TRE and BKL sites received 185.3 mm (73.0 in) and 128.5 mm (45.6 in), respectively, above normal precipitation levels. Nevertheless, addition plots produced significantly higher yields by 31 and 10 % over unrestored upper slope positions at the TRE and BKL sites, respectively. In contrast, the 2006 field season was considered a dry year, as sites experienced less than average rainfall (Appendix D). As expected, crop yields in both control and addition plots were lower than those of the previous year. However, the yield difference between control and addition plots was much greater; 64 % at TRE and 40 % at BKL. Mielke and Schepers (1986) also reported similar effects and confirmed that the effect of topsoil addition on crop response was greater in years that received less rainfall during the growing season. Therefore, the results from this landscape restoration study illustrate the positive impact that the addition of topsoil on eroded hilltops can have on yield regardless of moisture availability during the growing season.

In the case of yields in the lower slope positions, topsoil removal did not significantly compromise yields in two of the three research sites (TRE and BKL) where these areas were monitored. However, the loss of crop yield in removal plots at the SWL site may be partly be explained by the possibility of soil compaction and a poor seedbed. During the restoration process, soil in the lower slope positions had high soil moisture contents as a result of several rainfall events which occurred prior to the removal of soil. Therefore, due to the use of larger and heavier machinery at this site (Section 2.3.2.2.2), the soil may have become compacted in areas where topsoil was removed. Therefore, during seeding operations the following spring, there was a less favourable seedbed in removal areas, and as result, fewer plants emerged in removal plots compared to the control plots (Appendix E) and may explain the subsequent reduction in final crop yield.

Although there was a significant yield loss in the removal plots at the SWL site, the yield variability between upper slope and lower slope landscape positions was reduced. As well, yields in lower slope positions were consistently higher than upper slope positions at the TRE, BRX, and SWL sites. This can be explained by the variability in organic matter, available moisture, and fertility within the landscape (Hamm, 1985; Kachanoski et al., 1985; Battiston et al, 1987; Verity and Anderson, 1990). Hamm (1985) explained yield losses on eroded upper slope positions resulted in early ripening and shattering of seed heads. This was especially evident in the BRX site. Verity and Anderson (1990) demonstrated crop yields in a toposequence were consistently lower in upper slope positions than positions lower the landscape. Organic carbon also followed the same trend, whereas available water was higher in lower landscape positions than eroded upper slope positions. Battiston et al. (1987) also attributed higher yields in lower landscape positions to greater available water holding capacity.

Regional crop yield averages from the Manitoba Agriculture Services Corporation (MASC) were used to normalize the 2006 TRE, BRX, and SWL crop yields in order to determine the net effect of landscape restoration on crop productivity within the landscape. Yields from each research site were normalized based on crop type and variety, as well as the corresponding crop insurance risk area of each research site (Manitoba Agriculture Services Corporation, 2008). The yield differences between upper slope treatment plots were significantly greater than yield differences between lower slope treatment plots (Appendix F). Therefore, in general, the addition of 10 cm of topsoil to severely eroded hilltops resulted in a net benefit in crop productivity within the landscape.

2.5 Conclusion

This study of the impact of landscape restoration on crop productivity demonstrates that as little as 10 cm of added topsoil to severely eroded upper slope positions can increase crop yields by as much as 133 % in years with below normal precipitation during the growing season. During years when precipitation is not limited and moisture stress is less evident in upper landscape positions, greater yields are still present in addition plots. We suspect this is attributed to a more favourable growing environment associated with increased organic matter content, water holding capacity, and nutrient availability provided to the crop. These improved soil properties can help reduce further soil erosion from wind and water by improving the water infiltration and increasing residue on hilltops. Improving nutrient-use efficiency decreases the risk of fertilizer toxicity and nutrient losses to the environment.

Crop response was still evident two and three years post-restoration demonstrating that, unlike manure and commercial fertilizer application, landscape restoration does not become an annual operation. This suggests that landscape restoration may be a more cost-effective practice to restoring eroded hilltops.

Although a reduction in crop yield occurred in the lower slope positions after topsoil was removed at one site, this trend was not observed in any of the other two research sites where the effect of topsoil removal on crop yield was monitored. However, regardless of the yield loss in the removal plots at that particular site, there was still an overall net increase in crop yield within the landscape. It should also be noted that lower landscape positions, particularly depressions, commonly experience yield losses due to excess moisture. For example, the BKL site experienced complete yield losses in lower slope positions (i.e., both control and removal plots) each year crop yields were monitored (2004 to 2006) and the TRE site also experienced losses in lower slope positions in 2005. The producers of each study site estimated that the lower slope positions within their fields experience complete crop failure at least 1 out of every 5 years. Therefore, the removal of 10 cm topsoil from lower slope positions is unlikely to contribute to severe yield losses.

In general, upper slope landscape positions have pedological and hydrological attributes that inherently produce lower yields than lower landscape positions. The difference in crop yield between these two landscape positions is magnified when upper slope positions become severely eroded. However, when crop yields from each site were normalized, the yield increases observed in the upper slope positions were significantly greater than the yield losses observed in the lower slope treatment plots. Therefore, this study demonstrates that the addition of 10 cm of topsoil on severely eroded hilltops results in a net benefit in crop productivity within the landscape and can reduce crop variability within a hilly landscape. This study provides significant evidence of the positive impact of landscape restoration on crop productivity, as well as, the foundation and framework to develop additional studies on landscape restoration. There is a need for agronomically, environmentally, and economically sound management practices available for producers. It is these benefits that make landscape restoration an attractive practice and a promising new approach for producers to adopt in order to manage the negative influences of tillage erosion in cultivated hilly landscapes.

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3.0 IMPACTS OF LANDSCAPE RESTORATION ON SOIL PROPERTIES AFFECTING CROP PRODUCTIVITY

3.1 Abstract

In topographically complex landscapes, soil moisture, nutrient status and, consequently, crop production are inherently spatially variable. Generally, concave lower slope landscape positions (i.e., foot slopes and toe slopes/depressions) have greater concentrations of nutrients, higher levels of soil moisture, and as a result are generally more productive than convex upper slope landscape positions (i.e., hilltops, knolls, and ridges). However, in cultivated hilly landscapes, tillage erosion further magnifies this variability by removing organic-rich topsoil from convex upper slope positions and locally redistributing it in convex lower slope positions.

Landscape restoration is an innovative practice used to restore crop productivity on eroded hilltops by removing accumulated topsoil from lower slope positions within the landscape and replacing it on severely eroded hilltops where it had originated. A previous study on landscape restoration demonstrated that the addition of 10 cm (4 in) of topsoil on severely eroded hilltops increased wheat yields by as much as 133 %.

The purpose of this landscape restoration study was to determine the soil properties that are affected and contribute to increased crop production on eroded hilltops. The addition of 10 cm of topsoil significantly increased nitrate nitrogen (NO_3^--N), Olsen phosphorus (Olsen-P), and sulphate sulphur (SO_4-S) concentrations. Soil organic matter concentrations were nearly 2.5 times greater in addition plots compared to control plots. Soil moisture retained at field capacity and plant available water was also significantly greater in addition and increased by 11 % and 21 %, respectively. Although landscape restoration improved the nutrient status of eroded upper slope positions, spring and fall fertility analysis revealed adequate concentrations of plant available N, P, and S for field pea production in control plots. Therefore, improved soil fertility in addition plots did not likely have a direct impact on improved crop productivity in the 2006 field season. However, the significant increase in moisture retained at field capacity, associated with the increase in soil organic matter concentrations, likely played a major role in increasing field pea yields on eroded hilltops in 2006. Therefore, this study has demonstrated that by replacing organic-rich topsoil on severely eroded hilltops, landscape restoration has the potential to be used as an alterative land management practice in order to restore crop productivity on eroded upper slope positions within cultivated hilly landscapes.

Keywords: Landscape restoration; Soil properties; Erosion; Organic matter

3.2 Introduction

Topography plays an important role in the spatial variability of soil fertility, soil moisture, soil organic matter, and consequently, crop productivity within the landscape. However, in cultivated hilly landscapes, tillage erosion magnifies this variability by redistributing organic-rich topsoil from convex upper slope positions (i.e., hilltops, knolls, and ridges) to concave lower slope positions (i.e., foot slopes and toe slope/depressions) within the landscape (Lobb et al., 1995; Lobb and Kachanoski, 1999; Kachanoski and Carter, 1999; Heckrath et al., 2005) and thus altering soil physical and chemical properties associated with crop productivity (Gregorich and Anderson, 1985; Pennock et al., 1994; Campbell et al., 1996; Kravchenko and Bullock, 2000; Papiernik et al., 2005; Papiernik et al., 2007).

Assessing the effects of soil erosion on soil productivity is difficult. In cultivated fields eroded sites tend to occupy different topographic and hydrologic positions than un-eroded sites (Morrison-Ives and Shaykewich, 1987). For example, a study conducted by Gregorich and Anderson (1985) compared soil profiles of native and cultivated toposequences in Saskatchewan, Canada. They discovered that A horizons of natural, uncultivated toposequences were thickest at the lowest point (toe-slope or depression) of the toposequence and thinnest at the highest point (crest). In cultivated toposequences, the trend was similar with the thinnest A horizons occurring at the crest of the hill and thickest A horizons near the bottom of the hill (i.e., the foot-slope). In addition, the native toposequence had thicker A horizons and deeper sola (depth to carbonates) throughout the entire toposequence compared to cultivated landscapes. However, in both toposequences, soil carbon, total nitrogen, and total phosphorus levels increased downslope from the crest to positions lower in the landscape, but were predominantly higher in a native toposequences than cultivated ones. These finding are also consistent with other studies that have characterized cultivated eroded landscapes (Verity and Anderson, 1990; Pennock et al., 1994; Papiernik et al., 2005; Papiernik et al., 2007). In addition to soil properties, hydrology is also closely associated with topography and is therefore variable, as well as predictable within the landscape. For example, depressions and lower slope positions within the landscape are wetter and have greater water holding capacities than upper slope positions (Battiston et al., 1987; Verity and Anderson, 1990).

Due to soil moisture, organic matter, and fertility variability within a landscape, it is not surprising that crop production also varies across the landscape. In both native and cultivated landscapes, lower slope and depressional areas generally experience greater biomass production than upper slope positions (Battiston et al., 1987; Verity and Anderson, 1990; Pennock et al., 1994; Papiernik et al., 2005). However, when yield and/or quality losses in lower slope positions do occur, they are generally a result of: (1) excess nitrogen causing lodging, (2) late ripening increasing the risk of disease and pest infestations and frost damage, and (3) because these areas are prone to excess moisture, they are more commonly affected by severe water logging resulting in complete crop failure in these landscape positions (Hamm, 1985). In contrast, eroded upper slope positions generally experience losses in productivity due to: (1) severe fertility deficiencies, (2) decreased water holding capacity, (3) poor soil structure, (4) high bulk densities, and (5) early ripening and shattering at harvest (Hamm, 1985).

It is well documented that tillage erosion has a negative impact on crop production (Schumacher et al., 1999; Van Oost et al., 2000; Kosmos et al.; 2001). Several erosion simulation studies have attempted to regain crop yields with the use of various forms of amendments such as manure (Dormaar et al., 1997; Larney et al., 2000) and commercial fertilizers (Morrison-Ives and Shaykewich, 1987; Tanaka and Aase, 1989). Many of these studies have been unsuccessful and have concluded that organic-rich topsoil should be considered as a means to restore severely eroded hilltops (Eck, 1969; Olson, 1977; Massee and Waggoner, 1985; Mielke and Schepers, 1986; Massee, 1990).

The results in Study 1 (Chapter 2) demonstrated that the application of 10 cm (4 in) of topsoil to severely eroded hilltops significantly increased crop productivity without significantly compromising yields in areas where topsoil was removed. The objective of this study was to determine which soil physical (texture, bulk density, organic matter, soil moisture) and chemical properties (soil fertility, electrical conductivity, pH) are improved during landscape restoration and contribute to increased crop productivity on severely eroded upper slope positions.

3.3 Materials and Methods

3.3.1 Site Description and Experimental Design

This study was designed to examine the soil properties or combination of properties, that are improved by restoring eroded hilltops and, as a result, contribute to increased crop productivity.

The location of the study took place in Treherne (TRE), Manitoba (15-07-10W) on eroded phases of Dark Gray Chernozems (Typic Argiudoll) of the Dezwood and Fifere Associations in the upper slope positions. Lower slope positions are dominated by imperfectly drained Gleyed Rego Black Chernozems (Aeric Calciaquall) of the Carroll Association and Gleyed Black Cherrnozems (Typic Edoaquall) of the Knudson Association (Langman 1989). The landscape is described as having hummocky topography, with slopes ranging from 5 to 9 %. The site is further described in greater detail in Section 2.3.1 of Chapter 2.

The site was restored on October 28, 2004. Four eroded upper slope positions (two knolls and two ridges) where chosen for topsoil addition and three lower slope positions were selected as sources of topsoil. The study used a randomized complete block design where each plot represents one replication of the two-treatment comparison and each treatment was randomly assigned to each replicate (Appendix B: Figure B.1). The four upper slope pairs were comprised of a treatment plot (10 cm (4 in) added topsoil), and a control plot (no topsoil added), whereas three lower slope positions were comprised of a treatment plot (10 cm removed topsoil) and a control plot (no removal of topsoil). Each plot was 12 m (40 ft), the width of one pass of the seeding equipment and approximately 15 m (50 ft) long. Soil was removed from foot slope positions using a 165 kW (225 hp) front wheel assist Versatile 800 tractor equipped with a 4.5 m^3 (212 ft^3) hydraulic Leon land scraper. It was important not to compromise the surface drainage of the field when removing topsoil from each lower slope position, therefore, the removal pattern from these areas was one long strip with a small grade. The restoration took place in the fall prior to seeding the following spring; this allowed time for the added soil to settle creating a suitable seedbed. Depending on the capacity of the land scraper and the volume of topsoil removed during each pass, an average of 3 to 6 loads of topsoil were required to achieve the desired topsoil depth of each addition plot at each research site. The initial depth of topsoil added to the eroded hilltops exceeded the desired final depth of 10 cm by 2 to 5 cm (Appendix A). The purpose of exceeding the 10 cm depth was to compensate for any volume changes that would occur (as the added topsoil settled) during the fall, winter, and early spring months before seeding. Once the soil was added to the upper slope positions, it was left to dry for several days and then disced to help break up large clods to facilitate seeding. A meter stick was used to measure the added topsoil thickness of each addition plot, as well as the depth of topsoil removed in the removal plots to ensure an average thickness/removal of 10 cm. Soil depth measurements were taken during the restoration in the fall and again the following spring.

On May 15, 2006, six CS616 water content reflectometers (Campbell Scientific, Inc.) and a tipping-bucket rain gauge (Texas Electronics, Inc.), connected to a 23X micrologger (Campbell Scientific, Inc.), were installed at the site for the purpose of collecting continuous soil moisture data and precipitation events during the entire length of the field season. In order to capture the variability in soil moisture between landscape positions, the CS616s were installed in the upper and lower slope position of the toposequence located near the upper slope Treatment Pair 2 (Appendix A.1). Three CS616s were installed at each landscape position (upper and lower slope) at a depth of 15, 30, and 45 cm (6, 12, and 18 in).

3.3.2 Soil Properties

3.3.2.1 Soil Fertility, Carbon, and Organic Matter. Soil samples for fertility analysis were taken in the spring (pre-seeding) and fall (post-harvest) on May 12 and August 16, 2006, respectively. Triplicate samples were taken from each control and addition plot at two depths; 0 to 15 cm (0 to 6 in) and 15 to 60 cm (6 to 24 in). Samples were air dried at 29 °C (85 °F) and a composite sample from each depth was pulverized using a Thomas Wiley Model 4 soil grinding mill and sent to AgVise Laboratories in Northwood, North Dakota, USA for analysis.

Samples were analysed for pH, electrical conductivity (EC), nitrate nitrogen (NO_3^--N), phosphorus (P), potassium (K), sulphate sulphur (SO_4^--S), total carbon (TC), total organic carbon (TOC), calcium carbonate equivalent (CCE), and organic matter (OM) (Appendix H). The 15 to 60 cm samples were not analyzed for K.

3.3.2.2 Soil Texture. Three replicate samples were collected from each soil horizon of each plot on November 23, 2007. Samples were air dried and sieved through a 2 mm (0.08 in) mesh screen to separate coarse fragments. A composite sample from the remaining soil was used for analysis. Soil texture was determined using the pipette method as described in McKeague (1978). Carbonates and organic matter were removed using a 30 % hydrogen peroxide pre-treatment digestion and sodium metaphosphate sodium bicarbonate was used as a dispersing agent. Sand, silt, and clay fractions were determined based on recovered weight and the soil textural classes were determined using the soil textural triangle. A check soil (i.e., a soil of known particle size fraction) was included in the analysis for quality control.

3.3.2.3 Bulk Density. Soil samples to determine bulk density (ρ_b) were taken on May 19 and August 16, 2006 using a copper cylinder corer of constant volume (5 cm (2.5 in) high and 5 cm diameter). Three samples were taken at each plot.

3.3.2.4 Soil Moisture Retention. Soil moisture retained at field capacity (FC) (0.33 bar; 33 kPa), permanent wilting point (PWP) (15 bar; 1500 kPa), and plant available water (PAW) was estimated on upper slope plots using a pressure membrane apparatus (Soil Moisture Equipment Co.). Triplicate samples were collected at two depths; 0 to 5 cm (0 to 2.5 in) and 10 to 15 cm (4 to 6 in), on April 26, 2007 from each addition and control plot. When determining the water retention at FC, it is extremely important that the soil structure, bulk density, and pore size, space and distribution are representative of the field conditions. Therefore, soil samples taken for FC were sampled using a stainless steel core of constant volume (5 cm high and 5 cm diameter) and remained undisturbed. At higher matric suction, pore size and distribution becomes unimportant, therefore samples used to determine the water retained at PWP were taken with a small hand trowel and placed in a sealed plastic bag.

To prepare the 0.33 bar samples for the membrane apparatus, rubber rings (1 cm (0.4 in) high and 5 cm diameter) with cloth bottoms were placed on the bottom of each core.

Soil for the 15 bar samples was placed in the rubber rings and filled ¾ full to allow for soil expansion (Wilson, 2002). The samples were then placed on a shallow tray with distilled water and allowed to saturate for 24 hours prior to being placed on the appropriate retention plates (Figure 3.1).

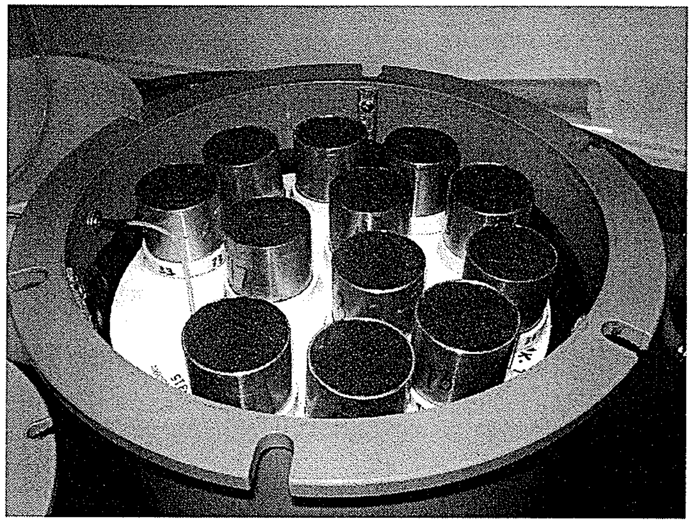

Figure 3.1 Using a pressure membrane apparatus to measure soil moisture retained at 0.33 bar (1300 kPa) on undisturbed samples.

A mercury barometer was used to measure the pressure of the FC samples that were placed under a constant pressure of 0.33 bar using atmospheric air. The samples used to determine the PWP were subjected to15 bar pressure using compressed nitrogen gas. Each layer of retention plates in the pressure membrane apparatus was connected to a burette to monitor the water outflow from the samples. When the water outflow ceased, it was assumed the samples had reached equilibrium. Once this occurred the average gravimetric moisture content was determined from each sample. The PAW of each sample was determined by the difference between moisture retained at FC and PWP expressed on a weight basis using Eq. 1.

$$PAW = FC - PWP \qquad (1)$$

3.3.2.5 Volumetric Water Content. A 50 MHz Stevens Water HydraProbe capacitance probe, in combination with a hand held digital data recorder, was used to collect volumetric water content (θ_v) data in the field. The data was collected on eleven occasions during the 2006 growing season and three moisture readings were taken in each upper and lower slope plot using the 'one time' installation procedure (Stevens Vitel, Inc, 1994). The digital data recorder converts the raw analog voltages into the appropriate moisture content without any post-processing algorithms. The Hydra Probe has an accuracy of ± 0.015 % volumetric moisture content, provided that a general estimate of soil texture is known (Stevens Vitel, Inc, 1994).

3.3.2.6 Soil Temperature. Soil temperature was monitored during the 2006 field season at the TRE site. Soil temperature measurements were taken using a Traceable® Long-Stem Thermometer (Control Company) to monitor soil temperatures during seedling emergence. Triplicate temperature readings were taken at the soil surface and 5 cm (2.5 in) below the soil surface in each plot at each landscape position.

3.3.3 Statistical Analyses

SAS 8.0® was the statistical software used to analyze the soil properties data collected in this study (SAS Institute Inc., 2000). The plots were established as replicated pairs, therefore the T-TEST procedure was used to compare the difference between treatment means (Frye et al., 1982). The level of significance used was $\alpha = 0.10$ due to the high variability inherent in uncontrolled, field-based landscape experiments (Pennock et al., 1994; Steele et al., 1997; Lal et al., 2000; Manning et al., 2000). A higher probability level is justified to detect treatment differences and employing a probability threshold (α)

of 0.05 or lower in landscape studies increases the chances of making a Type II error (β), and, therefore, failing to detect treatment differences when, in fact, these differences do occur (Steele et al., 1997). Due to the lack of treatment comparisons of each soil property, correlation analysis was not possible.

3.4 Results

3.4.1 Soil Fertility, Carbon, and Organic Matter

Spring fertility results in upper slope positions indicated that at the 0-15 cm depth (surface), the addition of topsoil more than doubled nitrate nitrogen (NO_3^--N) concentrations in addition plots compared to the control (Table 3.1). Phosphorus (Olsen-P) and sulphate sulphur (SO_4-S) concentrations were also significantly higher in addition plots by 88 % and 53 %, respectively. A small but significant increase in the salt concentration also occurred when topsoil was added to the eroded hilltops. Although potassium (K) concentrations increased by 79 ppm in the addition plots, this did not result in a significant difference. There was also no difference in total carbon (TC) between treatments, however the total organic carbon (TOC) increased from 0.7 % in the control to 2.4 % in addition plots. Adding topsoil also significantly diluted the calcium carbonate equivalent (CCE) by 7.3 % at the surface in addition plots and subsequently lowered the pH level to 7.8 from 8.0 in control plots. The organic matter (OM) content was nearly 2.5 times greater in addition plots and significantly increased from 1.5 % to 3.6 % in control plots and addition plots, respectively. At depth (15-60 cm), NO_3^--N, SO_4-S, OM, and electrical conductivity (EC) where significantly higher in the addition plots compared to the control plots. When comparing the spring fertility data in control and removal plots in the lower slope positions, the only significant difference in nutrient status that occurred was at the 15-60 cm depth with a reduction in NO_3^--N in the removal plots (Table 3.1). No differences in pH, EC, OM, and carbon levels occurred between treatments at either depth.

Fall fertility results showed similar trends in nutrient and carbon levels at the surface (0 to 15 cm) in the upper slope positions, where NO_3^--N, Olsen-P, and SO_4-S were significantly higher in the addition plots over the control plots (Table 3.2). K concentrations were 25 % higher in the addition plots than in the control plots, but these differences were not significant. There was also no significant difference in TC concentrations between control and addition plots. However, TOC concentrations were significantly higher in addition plots and CCE concentrations were still significantly lower compared to control plots. Although there was a slight reduction in OM content in addition plots from spring to fall, the OM in the addition plots was greater than in control plots. As well, the salt concentration also remained higher in addition plots. At depth (15-60 cm), significantly higher NO_3^--N, Olsen-P, and SO_4-S concentrations were found in the addition plots over the control, and CCE and OM was also slightly higher in addition plots. There were no significant differences in pH, TOC, and TC .

In lower slope positions, there was a significant reduction in NO_3^--N observed at the 15-60 cm depth in the removal plots (Table 3.2). Olsen-P at both depths, 0-15 cm and 15-60 cm, was significantly higher in control plots; 35 ppm and 11 ppm, respectively. The removal of topsoil also resulted in significant reductions in TC in the 0-15 cm depth and OM at both depths. Conversely, removal plots had significantly higher CCE levels deeper in the profile.

Table 3.1 Spring fertility results in upper slope and lower slope positions at Treherne in 2006.

	Upper Slope Positions†									
	NO_3^--N (kg ha^{-1})	P-Olsen (ppm)	K (ppm)	S-SO_4^- (kg ha^{-1})	TC (%)	TOC (%)	CCE (%)	OM (%)	pH	EC[1] mmhos cm^{-1}
a) 0-15 cm										
Control	22	17	136	17	2.5	0.7	16.5	1.5	8.0	0.68
Addition	46	32	215	26	3.5	2.4	9.2	3.6	7.8	0.81
Δ	24***	15**	79	9**	1.0	1.7***	-7.3*	2.1***	-0.2*	0.13**
P value	0.002	0.049	0.147	0.017	0.155	0.009	0.073	0.008	0.059	0.034
b) 15-60 cm										
Control	35	9	-	44	2.1	0.5	16.0	1.1	8.1	0.50
Addition	57	10	-	59	2.4	0.4	16.2	1.5	8.0	0.58
Δ	22**	1	-	15**	0.2	-0.1	0.2	0.4***	-0.1	0.08**
P value	0.020	0.424	-	0.019	0.345	0.393	0.430	0.005	0.123	0.040

	Lower Slope Positions‡									
	NO_3^--N (kg ha^{-1})	P-Olsen (ppm)	K (ppm)	S-SO_4^- (kg ha^{-1})	TC (%)	TOC (%)	CCE (%)	OM (%)	pH	EC[1] mmhos cm^{-1}
a) 0-15 cm										
Control	48	47	147	134	6.6	5.9	4.1	8.4	7.9	1.47
Removal	40	52	210	134	5.2	4.9	2.6	6.5	7.8	1.26
Δ	-8	5	63	0	1.4	-1.0	-1.5	-1.83	-0.1	-0.20
P value	0.208	0.451	0.151	-	0.103	0.190	0.176	0.159	0.289	0.170
b) 15-60 cm										
Control	101	13	-	324	3.5	2.4	10.2	3.5	7.9	1.49
Removal	53	37	-	282	3.5	2.3	18.5	3.5	7.9	1.06
Δ	-48**	24	-	42	0.0	-0.1	8.3	0.0	0.0	-0.43
P value	0.042	0.103	-	0.265	0.500	0.451	0.206	0.391	0.500	0.174

[1]Electrical conductivity values based on a 1:1 soil:water extraction.

†Values indicated the means of 4 replicates; ‡Values indicated the means of 3 replicates.

Δ = Treatment - Control

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

Table 3.2 Fall fertility results in upper slope and lower slope positions at Treherne in 2006.

	NO_3^--N (kg ha^{-1})	P-Olsen (ppm)	K (ppm)	S-SO_4^- (kg ha^{-1})	TC (%)	TOC (%)	CCE (%)	OM (%)	pH	EC¹ mmhos cm^{-1}
Upper Slope Positions†										
a) 0-15 cm										
Control	24	18	273	16	3.0	1.3	14.3	1.8	7.9	0.52
Addition	45	37	340	31	3.8	2.7	9.3	3.3	7.9	0.84
Δ	21***	19**	67	15**	0.8	1.4**	-5.0*	1.5***	0.0	0.32**
P value	0.009	0.050	0.102	0.014	0.148	0.039	0.056	0.007	0.427	0.041
b) 15-60 cm										
Control	21	5	-	44	3.0	0.8	19.1	1.1	8.2	0.52
Addition	50	15	-	60	2.7	1.2	9.3	1.7	8.1	0.58
Δ	29**	10*	-	16**	-0.3	0.4	-9.8**	0.6**	-0.1	0.06
P value	0.034	0.084	-	0.048	0.298	0.128	0.033	0.017	0.177	0.262
Lower Slope Positions‡										
a) 0-15 cm										
Control	36	35	235	73	4.1	3.0	1.2	4.9	7.8	0.78
Removal	29	17	163	75	3.8	2.8	8.1	3.8	7.8	1.30
Δ	-7	-18**	-72	2	-0.3*	-0.1	6.9	-1.1*	0.0	0.52
P value	0.129	0.014	0.101	0.408	0.094	0.387	0.127	0.076	0.500	0.227
b) 15-60 cm										
Control	48	11	-	152	2.2	1.8	3.0	2.8	8.0	0.57
Removal	30	6	-	190	3.3	2.3	13.2	2.1	8.1	1.39
Δ	-18*	-5***	-	38	1.2	0.5	10.2*	-0.7**	0.1	0.82
P value	0.089	0.007	-	0.294	0.216	0.322	0.070	0.027	0.135	0.215

¹Electrical conductivity values based on a 1:1 soil:water extraction.

†Values indicated the means of 4 replicates; ‡Values indicated the means of 3 replicates.

Δ = Treatment - Control

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

3.4.2 Soil Texture

It is important to note that the erosion which has occurred on the upper slope positions is so severe that the original A horizon has been entirely removed and tillage implements have began ploughing into the parent material (Figure 3.2).

Figure 3.2 Exposed parent material at the soil surface. As the result of severe soil erosion the A horizon has been completely removed from an upper slope position, tillage implements are now tilling into parent material at Treherne in 2006.

Therefore, based on the lack of organic matter and increased carbonates at the surface (Table 3.1 and 3.2), the surface horizon of each hilltop is more accurately described as a Cp horizon, However, for simplicity, surface horizons of each control plot on upper slope positions will be identified as Ap horizons.

In upper slope positions, the A horizon of control Plots I through III are classified as loam textured and Plot IV as sandy clay loam (Table 3.3). These textures are consistent with the textural descriptions of the soil series described in Langman (1989). In Plots I and IV, the addition of topsoil altered the texture of the surface horizon in the addition plots from loam to silty loam and silty clay loam, respectively. The surface texture of the addition treatment in Plots II and III remained unchanged from that of the texture of the control. However, two years post-restoration, the surface texture of the addition treatment in Plot I remained the only modified A horizon to correspond with the soil texture from the lower slope area from which it was taken (Table 3.3). The textures of each 'buried' Ap horizon (the former surface horizon) of the addition plots were consistent with the textures of the corresponding surface horizon of the control plots. In the lower slope position, the surface texture of the control and removal plots of Plots I and II remained the same; silty loam. However, the clay loam A horizon of the removal treatment of Plot III was a slightly finer texture, containing approximately 9% more clay, compared to the silt loam in the control plot (Table 3.3).

Table 3.3 Soil particle size analysis and soil texture of horizons in upper slope and lower slope plots at Treherne.

		Horizon	Depth (cm)	S (%)	Si (%)	C (%)	Texture
a) Upper slope							
Plot I	Control	Apk*	0-10	43.06	32.48	24.46	L
		Ck	12-90	44.02	32.23	23.75	L
	Addition[1]	A**	0-9	27.23	60.21	12.56	SiL
		Apk*	9-21	44.92	29.78	25.30	L
		Ck	21-90	43.56	32.99	23.46	L
Plot II	Control	Apk*	0-12	33.58	44.13	22.29	L
		Ck	12-90	54.15	27.49	18.36	SL
	Addition[2]	A**	0-10	40.31	42.59	17.10	L
		Ap	10-22	40.97	38.11	20.92	L
		Ck	22-90	37.93	40.17	21.90	L
Plot III	Control	Apk*	0-12	48.57	34.83	16.60	L
		Ck	12-90	39.38	45.53	15.08	L
	Addition[2]	A**	0-9.5	35.65	41.58	22.77	L
		Apk*	9.5-23	35.56	44.71	19.73	L
		Ck	23-90	21.95	55.56	22.49	SiL
Plot IV	Control	Ap*	0-12	54.75	17.63	27.61	SCL
		Ck	12-90	57.48	21.28	21.24	SCL
	Addition[3]	A**	0-10	28.26	57.69	14.05	SiCL
		Ap	10-20	54.67	24.45	20.88	SCL
		Ck	20-90	47.87	28.24	23.89	L
b) Lower Slope							
Plot I	Control	Apk	0-20	22.29	71.44	6.27	SiL
		Cca	20-53	26.71	41.29	32.00	CL
		Ckg	53-90	36.95	39.86	23.18	CL
	Removal	Apk	0-13	26.60	54.76	18.64	SiL
		Ccag	13-23	27.91	54.39	17.70	SiL
		Ckg	23-90	42.31	46.13	11.56	L
Plot II	Control	Apk	0-18	29.42	61.10	9.48	SiL
		Ahk	18-30	-	-	-	-
		Ccag	30-70	34.19	31.18	34.62	CL
		Ckg	70-90	76.54	11.59	11.87	SL
	Removal	Apk	0-14	26.47	67.10	6.43	SiL
		AC	14-34	24.75	42.04	33.21	CL
		Ccag	34-60	-	-	-	-
		Ckg	60-90	62.28	22.03	15.70	SL
Plot III	Control	Ap	0-22	32.01	51.89	16.10	SiL
		Bm	22-35	30.17	41.13	28.70	CL
		BC	35-41	-	-	-	-
		Ccagj	41-59	36.97	42.15	20.89	L
		Ckgj	59-90	67.59	22.68	9.73	SL
	Removal	Ap	0-18	35.03	40.03	24.94	CL
		Bm	18-22	33.09	35.37	31.54	CL
		BC	22-29	-	-	-	-
		Ccagj	29-50	37.73	37.01	25.26	L
		Ckgj	50-90	56.23	28.11	15.66	SL

*A horizon was severely eroded and tillage implements were plowing into parent material.

A** = modified A horizon with the addition of topsoil.

S= sand; Si= silt; C= clay; L= loam.

[1]Topsoil for the addition plot originated from lower slope Plot I.

[2]Topsoil for the addition plot originated from lower slope Plot III.

[3]Topsoil for the addition plot originated from lower slope Plot II.

3.4.3 Bulk Density

Bulk density samples were taken immediately prior to seeding and harvest, May 16 and August 19, 2006, respectively (Table 3.4). In both cases, a slight reduction in bulk density occurred with the addition of topsoil. However, a significant improvement was only observed in samples taken after harvest.

Table 3.4 Surface bulk density (ρ_b) in upper slope positions at Treherne in 2006.

	May	August
	(cm^3 cm^{-3})	
Control	1.14	1.21
Addition	1.03	1.05
Δ	0.11	0.16*

*Significant at $P<0.10$ using a paired t-test.

Δ = Addition - Control

Values indicate means of 4 replicates.

3.4.4 Soil Moisture Retention

Field capacity (FC), permanent wilting point (PWP), and plant available water (PAW) was determined on the upper slope plots to distinguish any changes in the soils' moisture retention capacity. Results indicated that at the soil surface (0-5 cm) the addition of topsoil significantly increased soil moisture retained at FC and PAW by 18 % and 21 %, respectively (Table 3.5). However, water held at 15 bar pressure at the same depth was not significantly different. The addition of topsoil did not influence any changes in FC, PWP, and PAW at the 10-15 cm depth (Table 3.5).

Table 3.5 Water retained at 0.33 bar, 15 bar, and plant available water (PAW) in percent (%) by mass (g) at 0-5 cm and 10-15 cm depths in upper slope plots at Treherne.

	0.33 bar	15 bar	PAW
		(%)	
a) 0-5 cm depth			
Control	22.59	13.42	9.17
Addition	26.66	15.54	11.12
Δ	4.07*	2.12	1.95*
P value	0.085	0.254	0.094
	0.33 bar	15 bar	PAW
b) 10-15 cm depth			
Control	21.93	13.65	8.28
Addition	22.23	15.07	7.17
Δ	0.30	1.42	□.11
P value	0.437	0.137	0.329

*Significant at $P<0.10$ using a paired t-test.
Δ = Addition - Control
Values indicate means of 4replicates.

3.4.5 Volumetric Water Content

In general, a seasonal trend in volumetric water content (θ_v) can be seen when comparing landscape positions. The lower slope positions have a consistently greater amount of soil moisture at the surface throughout the growing season compared to the upper slope positions (Figure 3.3).

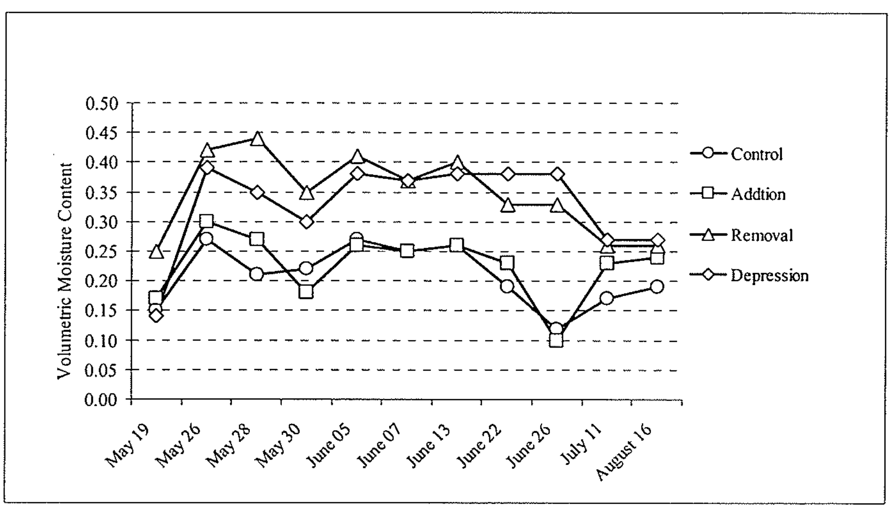

Figure 3.3 Surface volumetric water content on upper slope and lower slope plots using a 50 MHz capacitance probe at Treherne.

However, there is no apparent influence of the addition or removal of topsoil on surface volumetric moisture as there were no significant differences when comparing the individual dates of each treatment within each landscape position (Table 3.6).

Table 3.6 Surface (0-5 cm) volumetric soil moisture in upper and lower slope plots using a 50 MHz capacitance probe at Treherene in 2006.

Date	Upper slope				Lower slope		
	Control	Addition	P value		Control	Removal	P value
				(cm cm^{-3})			
May-19	0.15	0.17	0.351		0.14	0.25	0.110
May-26	0.27	0.30	0.198		0.39	0.42	0.116
May-28	0.21	0.27	0.126		0.35	0.44	0.266
May-30	0.22	0.18	0.130		0.30	0.35	0.139
Jun-05	0.27	0.26	0.465		0.38	0.41	0.081
Jun-07	0.25	0.25	0.147		0.37	0.37	0.287
Jun-13	0.26	0.26	0.492		0.38	0.40	0.079
Jun-22	0.19	0.23	0.480		0.38	0.33	0.264
Jun-26	0.12	0.10	0.280		0.38	0.33	0.175
Jul-11	0.17	0.23	0.416		0.27	0.26	0.225
Aug-16	0.19	0.24	0.108		0.27	0.26	0.206

Values indicate means of 4 replicates.

3.4.6 Soil Temperature

Soil temperatures at the surface were significantly higher in addition plots than control plots throughout the sampling period (Table 3.7). The largest difference in soil temperature between treatments occurred the day of seeding with addition plots 3.9 °C (7.0 °F) warmer than control plots. Significant differences between addition and control plots also occurred at the 5 cm depth. However, the trend was not as clear as lower soil temperatures in addition plots were also detected. In the lower slope position, the removal of topsoil had no significant effect on soil temperatures either at the surface or 5 cm below the surface, except at the 5 cm depth the last day temperatures were monitored (Table 2.1). In general, surface temperatures were greater than at the 5 cm depth in both landscape positions (Appendix H).

Table 3.7 Soil surface and subsurface (5 cm) temperatures (°C) in upper slope and lower slope positions at Treherne in 2006.

		Upper Slope Position†				
		May-18	May-26	May-28	May-30	Jun-05
a) Surface						
	Control	20.0	18.3	18.5	15.2	29.8
	Addition	23.9	18.9	19.2	15.3	31.8
	Δ	3.9**	0.5*	0.7*	0.1**	2.0***
	P value	0.032	0.083	0.056	0.048	0.004
b) 5 cm depth						
	Control	13.7	17.1	18.5	13.3	23.9
	Addition	14.1	16.5	17.7	14.0	24.5
	Δ	0.4**	□0.5	□0.8**	0.7*	0.6
	P value	0.043	0.156	0.017	0.074	0.103
		Lower Slope Position‡				
		May-18	May-26	May-28	May-30	Jun-05
a) Surface						
	Control	21.50	19.40	19.00	14.50	29.50
	Removal	20.40	18.67	18.65	14.22	29.85
	Δ	-1.10	-0.73	-0.35	-0.28	0.35
	P value	0.198	0.176	0.318	0.163	0.250
b) 5 cm depth						
	Control	12.17	16.90	17.25	12.88	22.65
	Removal	12.32	16.67	17.82	12.65	23.40
	Δ	0.15	-0.23	0.57	-0.23	0.75*
	P value	0.345	0.250	0.345	0.129	0.063

†Values represent the means for 4 replicates.
‡Values represent the means for 3 replicates.
Δ = Treatment - Control
*Significant at $P<0.10$, **Significant at $P<0.05$, ***Significant at $P<0.01$ using a paired t-test.

3.5 Discussion

3.5.1 Soil Fertility, Carbon, and Organic Matter

3.5.1.1 Nitrogen. The addition of topsoil to eroded hilltops more than doubled NO_3^--N concentrations at the surface depth and significantly increased NO_3^--N concentrations deeper in the profile. Consequently, replacing topsoil on severely eroded hilltops also dramatically increased the available nitrogen concentrations in eroded upper slope profiles from a rating of Moderate to Very High$^+$ (Manitoba Soil Fertility Advisory Committee, 1990a). This is a result of removing topsoil from an area within the landscape that is inherently more fertile than eroded upper slope positions and has likely contributed to improved crop productivity in these formerly non-productive areas of the landscape. The increase in NO_3^--N deeper in the profile may be evidence of nitrate-leaching and improved water infiltration and percolation. Our results are consistent with results found in studies by Mielke and Schepers (1986), Massee and Waggoner (1985), and Eck (1969). Mielke and Schepers (1986) found that the addition of 20 cm (8 in) of topsoil on a soil with an exposed C horizon had a significant effect on dry matter production and nitrogen uptake, especially early in the season, contributing to higher yields. Moreover, each study included additional inorganic fertilizer treatments applied to eroded and topsoil addition plots and determined that the additional fertilizer did not have any additive effect on crop production where topsoil was added.

In lower landscape positions, although there is evidence of a reduction in NO_3^--N concentrations at depth in removal plots, there remained adequate (Very High$^+$) NO_3^--N concentrations throughout the profile for crop growth (Manitoba Soil Fertility Advisory Committee, 1990a).

Fall fertility results follow trends similar to spring results when comparing plots within landscape positions. This demonstrates that landscape restoration has an ongoing and lasting improvement on the soil fertility even two years post-restoration.

Although adding NO_3^--N rich topsoil soil on severely eroded hilltops dramatically improved NO_3^--N concentrations in addition plots, given that the field peas were inoculated prior to seeding (Section 2.3.3.1) to ensure nitrogen fixation (Manitoba Soil Fertility Advisory Committee, 2007), it is unlikely that there was a crop response to the additional nitrogen in the addition plots (Chapter 2).

3.5.1.2 Phosphorus. Similar to NO_3^--N concentrations, landscape restoration significantly increased Olsen-P concentrations at the surface of addition plots by adding fertile, organic-rich topsoil, with higher Olsen-P concentrations. Although Olsen-P concentrations in control plots were adequate for crop growth (Manitoba Soil Advisory Committee, 1990b), adding organic-rich topsoil to eroded areas increases plant available P and may be associated with corresponding dilution of CCE at the surface (Table 3.1 and 3.2). In general, plant available phosphorus binds very strongly to calcium carbonates, which are abundant in Manitoba soils, and as a result is difficult for plants to utilize (Lewis and Racz, 1969). In a simulated erosion study using inorganic fertilizers to restore eroded soils, Larney et al. (1995) reported yield reductions associated with P deficiencies and inability of P uptake by plants. They concluded that the availability of P was limited by high calcium carbonate concentrations by the precipitation of insoluble calcium-phosphate (Ca-P). In west central Minnesota, Papiernik et al. (2007) also reported a negative correlation between Olsen-P and inorganic carbon content in the eroded Ap horizon of an upper slope landscape position in a tilled landscape. Olsen-P levels at the 15 to 60 cm depth are very similar in both treatments and are lower than levels found at the surface. This can also be explained by high carbonate levels deeper in the profile in both control and addition plots which are interestingly similar to those of the surface carbonate levels of the control plots.

Because Olsen-P concentrations in control plots were adequate for crop production, the significantly higher concentrations in addition plots would have unlikely directly contributed to the higher yields (Chapter 2).

3.5.1.3 Potassium. Landscape restoration had no significant affect in K concentrations between treatments at either landscape position. As well, K concentrations were comparable in both spring and fall fertility analysis between landscape positions and ranged between High and Very High$^+$ by the Manitoba Soil Fertility Advisory Committee (1990c). As a result, K concentrations would have been an unlikely limiting factor in crop production. This theory is consistent with results reported by Kravchenko and Bullock (2000) in a study conducted in Illinois. The authors examined the spatial variability of grain yields and soil properties within a topographically complex landscape and determined that based on high soil concentrations, K would not have played a major role in yield variability between control and addition plots (Chapter 2).

3.5.1.4 Sulphur. As expected, addition plots also had higher SO_4-S concentrations throughout the soil profile. Similar to NO_3^--N levels, the higher SO_4-S concentrations at the surface are attributed to the addition of topsoil with higher soil fertility and the elevated levels deeper in the profile are attributed to the downward movement and leaching of soluble SO_4-S. However, according to the Manitoba Soil Fertility Advisory Committee (1990d), SO_4-S concentration is control plots were adequate for crop production. Therefore, SO_4-S probably was not a limiting factor in crop growth in control plots (Chapter 2). Our results are similar to Mielke and Schepers (1986) where they reported that there was no additional benefit in crop yields from the application of S fertilizer. There was no consequential reduction of SO_4-S in removal plots at the surface as levels in these plots remained the same as those in control plots of the lower slope positions.

3.5.1.5 Total Carbon, Total Organic Carbon, and Calcium Carbonate Equivalent. The addition of topsoil did not significantly change TC concentrations in addition plots. However, there was a significant increase in the TOC fraction which can be explained by an accompanied increase in OM. In addition, adding topsoil significantly diluted the

CCE at the soil surface. The rather large reduction in CCE concentration in addition plots may play a role in increasing crop yields by improving P bioavailability. Papiernik et al. (2007) found a significant negative correlation between available P and inorganic carbon (IC) content and a positive correlation between P and organic carbon.

In addition, there were slight increases in surface CCE concentrations in control and addition plots from spring to fall; this can be explained by tillage and seeding implements continuing to till further into the carbonate-rich parent material.

3.5.1.6 Organic Matter. Due to the deeper A horizons in the lower slope areas of the landscape (Table 3.3), there was no significant reduction in OM concentrations in removal plots and no adverse effect on crop yields in this landscape position. As expected, replacing organic-rich topsoil on severely eroded hilltops more than doubled OM concentrations and likely played a large role in significantly increasing yields in addition plots (Chapter 2). These results are consistent with a study conducted by Kravchenko and Bullock (2000) where they examined grain yield, topography, and soil property relationships. They demonstrated that the OM levels were greater in lower slope positions of the landscape and concluded that "*OM was the source of the most consistent positive influence on yield among the soil properties studied*". They also determined that OM content was a more significant "yield-affecting factor" in soils that were deficient in OM than soils that were abundant in OM. Bauer and Black (1994) and Volk and Leoppert (1982) also reported significant correlations between soil OM and crop productivity. In the study conducted by Bauer and Black, soil nitrogen and available water holding capacity were held constant and demonstrated that 1 Mg ha^{-1} (892 lb ac^{-1}) of OM in the upper 30.5 cm (12 in) of the soil profile increased grain yields by 15.6 kg ha^{-1} (13.9 lb ac^{-1}). Volk and Leoppert (1982) reported that crop yields increased by an average of 21 % for each 1 % increase in soil organic carbon.

3.5.1.7 pH. The spring fertility results show a significant decrease in pH in addition plots. However, the reduction is very small and the overall soil pH remains largely unchanged between treatments and landscape positions. This is due to the fact that the soils in Manitoba are generally developed from limestone parent material rich in calcium and magnesium carbonates. As a result, soils range in pH from neutral to alkaline. Therefore, under these growing conditions, it is unlikely that pH had a direct effect on increased crop production in addition plots (Chapter 2).

3.5.1.8 Electrical Conductivity. One of the concerns land owners had with adopting landscape restoration was the potentially adverse affect of using topsoil with undesirable soil properties to restore eroded hilltops and, in turn, creating undesirable soil quality in the areas where topsoil was removed. In some cases, removing topsoil can alter the normal field drainage and cause increases in soluble salt concentrations at the surface due to changes in the local hydrology. Therefore, EC was analyzed in this study to address this concern.

Salt concentrations at the soil surface in addition plots were significantly higher than in control plots in both spring and fall fertility results. These increases reflect the higher salt concentrations that normally occur in lower slope positions of the landscape where the topsoil was taken. However, the EC levels at each landscape position are in the range 0-2 mmhos cm^{-1} which is classified as non-saline (Agriculture and Agri-Food Canada, 2006). Therefore, there were no adverse changes in soil salinity by removing topsoil from lower slope positions and replacing it on eroded hilltops (Chapter 2).

3.5.2 Soil Texture

Soil texture influences a wide range of other soil physical and chemical properties such as; porosity, pore size distribution, bulk density, water holding capacity, thermal regime, and nutrient retention. Studies have shown that tillage induced soil erosion can alter the surface texture of the soil by exposing subsoil with higher clay contents restricting water infiltration, decreasing water holding capacity (Frye et al., 1982; Heckrath et al., 2005), and providing an inadequate foundation for a proper seedbed (Henning and Khalaf, 1984; Mielke and Schepers, 1986). As well, a concern of producers was the potential to create a similar condition in areas where topsoil was removed by exposing finer textured surface material. However, particle size analysis indicated that the clay content at the surface in control plots did contain higher amounts of clay but was not statistically significant (Appendix I). Overall, surface texture did not change when topsoil was added to eroded hilltops, nor did it alter the surface texture in removal plots when topsoil was removed. However, it is important to note that particle size analysis was performed on samples taken two years post-restoration and there was evidence of mixing subsoil with the added topsoil because three of the addition plots do not correspond to surface textures from depressional areas where the topsoil derived. However, our data suggests that soil texture unlikely directly contributed to increased yields in addition plots (Chapter 2).

3.5.3 Bulk Density

Bulk density (ρ_b) was monitored because of the correlation with other soil physical properties such as; pore space and pore size distribution, thermal regime, water infiltration and percolation, soil strength, as well as the effect on root penetration and growth (Brady and Weil, 2002). Therefore, although the soil in the addition plots was slightly less compact than the control, the ρ_b in both treatments was relatively low and similar; as a result, did not likely contribute to any adverse effects on rooting growth or water infiltration in control plots. These results are similar to those of Mielke and Schepers (1985) who reported little difference in bulk densities between soil addition and control plots. They also concluded that bulk density did not directly impact yield differences between treatments (Chapter 2).

3.5.4 Field Capacity, Permanent Wilting Point, and Plant Available Water

As expected, there was an increase in the moisture held at FC and PAW at the surface (0-5 cm) in addition plots. These results are consistent with an earlier study by Eck (1969) using topsoil as an amendment to restore eroded soils. Results showed 5.5 % more water (by volume) was held in the soil profile where 30 cm (12 in) of topsoil had been replaced on eroded soil. The author stated that although the difference in water holding capacity was small between treatments, it contributed to significantly reduced yields on severely eroded soils.

The increase in soil moisture retained at FC and PAW in addition plots is likely a result of the significant increase in soil OM content. Research has shown that the loss of organic-rich topsoil from convex upper slope positions corresponds to a lack of PAW and is directly related to the reduction in crop productivity, commonly observed in these areas of the landscape (Battiston et al., 1987; Verity and Anderson, 1990). Researchers have also attributed increases in PAW to increases in soil organic matter (Hudson, 1994; Olness and Archer, 2005). Hudson (1994) found that for every percent increase in soil OM, available water holding capacity (AWC) increased by 2.2 % to 3.7 % across a range of textural groups. Hudson also concluded that OM content was found to have contributed more than 60 % of the AWC when OM content is increased from 1 % to 4 % in all textural groups. Using a prediction model, Olness and Archer (2005) also illustrated that soil organic carbon strongly influenced AWC; for every 1 % increase in organic carbon, AWC increased by 2 % to > 5 %, depending on the soil texture.

In addition, by improving the soil's water-holding capacity the possibility of improving the water infiltration also exists. As more water is able to move down through the soil profile there is less potential for water to runoff and less risk of soil loss due to water erosion. The soil fertility results show evidence of nutrient leaching as a result of improved infiltration in the addition plots as higher soluble NO_3^--N and SO_4-S concentration were found deeper in the profile (15 to 60 cm) (Section 3.5.1).

Although the volumetric soil moisture data determined by the HydraProbe did not indicate any significant differences between upper slope treatment plots (Table 3.6), the data obtained from the water reflectometers does indicate that FC was reached on several sampling dates early in the growing season during critical periods of growth (Figure 3.4). Therefore, considering that soil moisture is the most limiting factor in crop productivity in the semi-arid Canadian prairies (Kachanoski et al., 1985; Grevers et al., 1986) and the 2006 growing season received below normal precipitation (Appendix D), the significant increase in soil moisture retained at FC is likely to have contributed to the significant yield increases in the addition plots (Chapter 2).

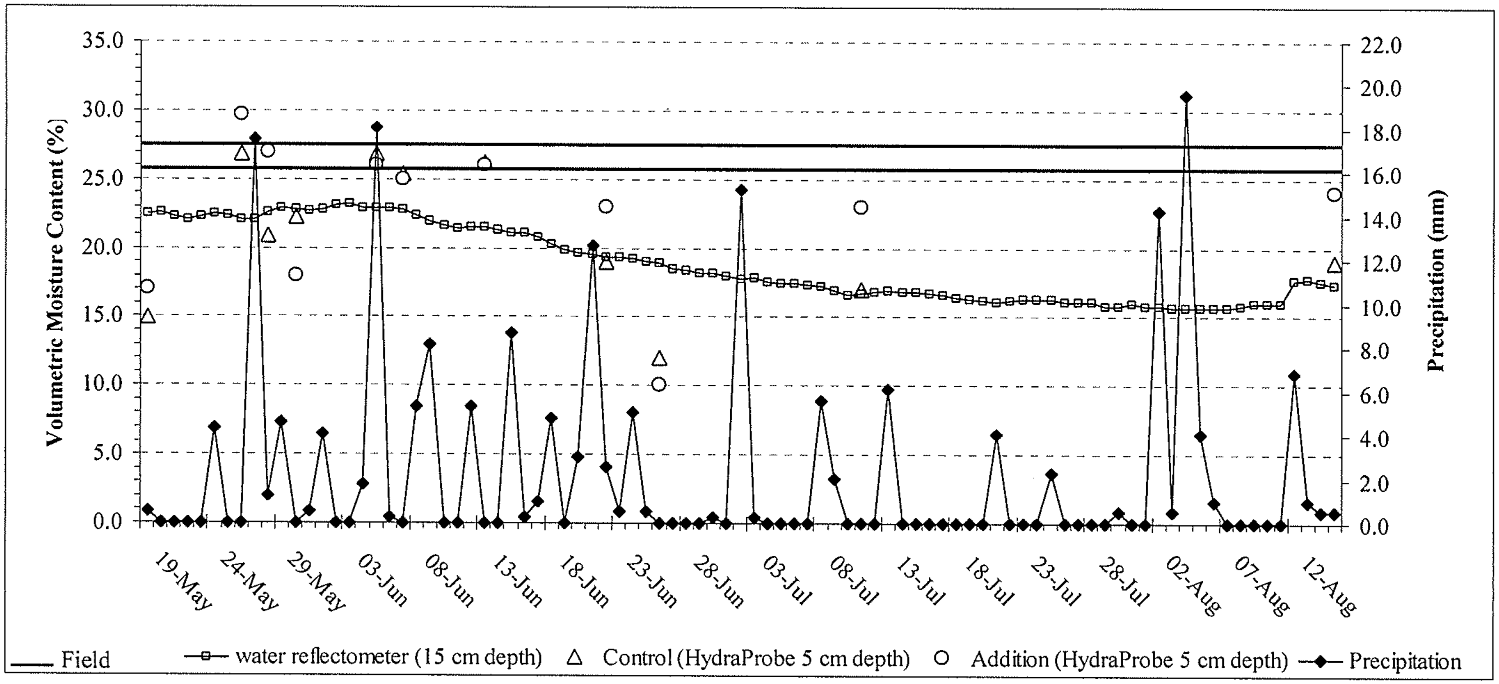

Figure 3.4 Comparison of volumetric soil moisture content at 5 cm (using a 50MHz HydraProbe) and soil moisture retained at field capacity between control and addition plots in upper slope plots in 2006 at Treherne. Solid lines indicate field capacity in addition (top) and control plots (bottom). Continuous volumetric soil moisture content (using a water reflectometer installed at a depth of 15 cm) in an upper slope landscape position and precipitation over the entire field season are also shown.

3.5.5 Volumetric Water Content

There were no obvious trends in VWC between treatments at either landscape position (Figure 3.3). However, the results do suggest that local moisture regimes exist within the landscape as large moisture gradients are evident between upper slope and lower slope positions. This is consistent with other studies examining moisture variability with landscapes (Verity and Anderson, 1990; Manning et al., 2001). In addition, a concern of agriculture producers was whether or not removing topsoil in lower areas of the landscape would affect the drainage of their fields. Our results illustrate that the removal of topsoil from lower slope positions and the subsequent addition of topsoil on upper slope positions did not change the local hydrology or drainage of the landscape.

However, with a closer examination of emergence rates (Appendix C) and volumetric moisture content (Table 3.6), there is a trend regarding moisture usage between treatments. Both the addition plots in upper slope positions and the removal plots in lower slope positions had accelerated emergence and greater numbers of seedlings. As a result of a larger plant population, there is greater demand and a more rapid decline in soil moisture in these plots which is reflected in the data. Although the removal plots had a larger plant population than the control, because these lower landscape positions had more moisture, crops are generally less stressed during critical growth stages, and, as a result, there were no differences in crop yield between these treatments at this landscape position (Chapter 2). However, upper slope positions and to a greater extent, eroded upper slope positions, experience greater levels of moisture stress. Therefore, early in the growing season soil moisture becomes critical in crop establishment and may impact final crops yields. A similar trend was seen in a simulated erosion study conducted by Massee and Waggoner (1985) where the addition of 15 cm of topsoil produced higher yields and in turn extracted the greatest quantity of moisture from the soil profile than crops grown where 15 and 30 cm of topsoil was removed.

3.5.6 Soil Temperature

The addition of topsoil significantly increased surface soil temperatures on eroded hilltops. The warmer soil surface temperatures in the addition plots are attributed to the addition of dark coloured soil organic matter resulting in a difference in surface albedo between control and addition plots. For example, an earlier study using simulated soil erosion in Akron, Colorado showed that exposed subsoil is lighter in colour than non-eroded soil surfaces and corresponds to a higher reflectance of solar energy (Black and Greb, 1968). As a result, cooler soil temperatures were associated with the removal of topsoil and found a 1.5 °C (2.7 °F) difference between a 7.6 cm (3 in) and 38.1 cm (15 in) cut. In this study, the surface colour (moist) of the four addition plots was 10YR 2/1 (black) compared to three control plots with 2.5Y 4/4 (olive brown) colour and one with 2.5Y 4/2 (dark grey), due to the shale deposits of the Fifre Association (Figure 3.5).

Figure 3.5 Comparison of soil surface colour on hilltops. Addition plots have a darker soil colour at the surface from the application of organic-rich topsoil (bottom) compared to the lighter soil colour of the exposed subsoil in control plots (top).

The darker colour of the organic matter in the addition plots would have directly contributed to the amount of radiation that is adsorbed and consequently raised the surface soil temperatures. These results are consistent with those of Lindstrom et al. (1986) who found that higher organic matter concentrations at the surface corresponded to darker soil colours in a simulated erosion study in South Dakota. As well, the warmer surface temperatures in the addition plots would have also contributed to the accelerated seedling emergence as seen in Chapter 2 (Section 2.4.1.1). These findings are similar to those of Black and Greb (1968) and Lindstrom et al. (1986) who reported cooler temperatures in exposed subsoils delayed seedling emergence. In addition, the relationship between warmer soil temperatures and accelerated emergence rates may have indirectly played a role in the increased crop yields of the addition plots (Chapter 2). For instance, Gan et al. (1992) reported a significant correlation between date of seedling emergence and grain yield. They determined that plants that emerged earlier had 1.4 and 3.2 times greater wheat yields than plants that had emerged 4 to 6 days later and 7 to 9 days later, respectively. Lindstrom et al. (1986) also concluded that lighter surface colour resulted in delayed plant emergence, poor plant development, and reduced stover and corn grain yields.

3.6. Conclusion

This study has demonstrated that landscape restoration improves several soil physical and chemical properties that contribute to increased crop productivity on severely eroded hilltops. A soil's nutrient status is generally a good indicator of crop productivity. For instance, soil fertility in addition plots was significantly greater throughout the soil profile and the nutrient status in control plots was adequate for sustaining field pea production. Therefore, considering nutrient status alone, control plots should have had comparable yields to addition plots, as weather conditions were the same in both treatments. However, the control plots consistently produced significantly lower yields (Chapter 2). Therefore, these results indicate that there are other conditions which affect crop yields on eroded hilltops. For example, considering that soil moisture is the most limiting factor in crop productivity in the semi-arid Canadian prairies (Kachanoski et al., 1985; Grevers et al., 1986) and the 2006 growing season received below normal precipitation, the improved soil moisture status at FC in the addition plots has likely contributed to greater field pea yields. However, although it appears that FC may be the determining factor in crop productivity on restored hilltops during dry years, the significant improvements in soil fertility should not overlooked. It may be that under certain field conditions soil moisture retained at FC is the dominant soil property influencing crop productivity and under different field conditions and/or crop species, soil fertility plays a more dominant role.

Nevertheless, increasing OM levels will have also played a large role in yield improvements, considering it provides a chemical, physical, and biological environment essential for crop productivity. However, because OM affects a range of soil properties that are strongly correlated such as; bulk density, porosity, aggregate stability, soil structure and texture, cation exchange capacity, nutrient holding ability, infiltration rate, and water holding capacity, it becomes difficult to isolate a single soil property and determine its impact on crop production. However, linking the relationships between soil OM, PAW, and nutrient status to crop productivity, it can be concluded that increasing the soil OM content is one of the most effective and practical ways to help restore crop productivity to eroded hilltops in cultivated hilly landscapes. Further research is needed to fully characterize the optimum quantity of soil OM required to restore crop productivity in eroded landscapes.

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4. OVERALL SYNTHESIS

This study was conducted as part of the "Economic assessment of restoring eroded land" project funded by the Agri-Food Research Initiative (ARDI). The overall goal of the research program was to fully explore landscape restoration as an alternative and sustainable land management practice in eroded topographically complex landscapes. The research program comprised three fundamental components which examined the agronomic, economic, and environmental implications of landscape restoration. This has been accomplished by the development of an economic model in a preliminary economical feasibility study (Bosma, 2004) and a study on the environmental impacts of landscape restoration on greenhouse gas emissions and weed populations (Erb, 2005). This study has contributed to the research program by providing valuable agronomic data and detailed information on the soil properties which contribute to improved crop yields on eroded hilltops. This research study also demonstrated that the overall impact of landscape restoration on crop productivity was positive.

The results in Study 1 demonstrated the addition of topsoil on eroded hilltops significantly increased crop production regardless of crop type or conservation tillage practice. As well, benefits of added topsoil were evident within the first year eroded hilltops were restored and crop productivity continued to increase three years post-restoration. Although the removal of topsoil reduced crop yields at one site, there remained a slight net increase in crop yield within the landscape. This study illustrates the potential for landscape restoration to be a widely adopted practice, given that as productivity increases profitability is also likely to increase.

However, new production technologies are adopted when the technologies are perceived as being in the farmer's best interest (Nowak, 1992; Smith and Shaykewich, 1990), which in many cases implies financial gains. Therefore, when considering the adoption of landscape restoration, the question that is likely to weigh more heavily on producers is whether or not the benefits offset the costs. Previous studies have expressed the importance of reducing the costs of restoring crop production on eroded landscapes to an economically competitive level (Langdale and Shrader, 1982). Massee and Waggoner (1985) have also stated that the greatest recovery from erosion can be achieved when it is economical to return deposited topsoil from lower slope positions to eroded upper slope areas. Therefore, the economic feasibility of landscape restoration ultimately depends on whether or not the improvements in crop yields on restored hilltops out-weigh the costs of the operation (Frye et al., 1985).

In order to address this matter, one of the fundamental components of the overall project included an economic feasibility study. The purpose of the study was to develop a tool to assist agricultural producers in making sound economic business decisions. Therefore, an economic model was developed to assess the cost-benefit analysis of landscape restoration and determine whether or not landscape restoration was an economically feasible practice in restoring crop productivity to eroded landscapes (Bosma, 2004). This user-friendly model incorporates many aspects associated with landscape restoration such as; rental fees or depreciation costs for restoration equipment, labour, input costs (fertilizer and seed), and the size of the area being restored (areas of topsoil accumulation and eroded upper slope positions). Although rudimentary, this study has shown landscape restoration to be an economically viable management practice. Bosma and Lobb (2004) reported that although the estimated costs associated with the practice are incurred in the initial year of restoration and the benefits are highly dependant on market prices, the practice could easily pay for itself within a few years. It was also reported that planting high-value crops and changing to zero-till systems (as time between successive restoration events would be extended) would further improve the economic benefit. Nevertheless, one of the major limiting factors of the model is the lack of good agronomic data as the feasibility of the model is greatly dependant on the yield and topsoil depth relationship. A positive non-linear relationship between the two parameters has been assumed based on erosion simulation studies which compared yield and the loss of topsoil rather than the application of topsoil. Therefore, the agronomic and soils data gathered from this study will be incorporated into the model to provide more accurate predictions and create a more robust model.

Landscape restoration has economic implications that extend to a broader scale. For instance, in Manitoba there are 11.6 million acres (4.7 million hectares) of cultivated cropland (Statistics Canada, 2007a) of which 36 % are considered at risk for tillage erosion (Lobb, 2005). In cultivated undulating and hummocky landscapes eroded upper slope positions represent approximately 18 to 30 % of the area (Battiston et al., 1987; Pennock and de Jong, 1987). If eroded hilltops experience average yield losses of 50 %, based on the data generated from this study, this would result in annual yield losses of 9 to 15 %. Furthermore, it is estimated that the crop production in Manitoba is valued at $2 billion annually. Therefore, losses in crop yields due to tillage induced soil erosion can lead to $180 to 300 million in lost revenues each year. Taking into consideration that more than 75 % of cultivated agricultural land in the northern North American Great

Plains is classified as rolling, undulating, and hummocky (Li et al., 2007b), it becomes clear that the potential economic benefits of landscape restoration at the on-farm and regional levels are significant.

The objective of Study 2 was aimed at answering how landscape restoration improves crop productivity on eroded hilltops by examining several soil properties. The study concluded that improving the moisture retained at field capacity, associated with the increase in organic matter concentration, was likely the factor contributing to the yield response in 2006. This finding is of significant importance, especially in the Canadian Prairies where moisture is the yield-limiting factor (Kachanoski et al, 1985; Grevers et al., 1986). When considering the impacts of global warming and climate change on crop production, studies have reported trends of significantly less snowfall on the Prairies (Akinremi and McGinn, 1999). This is detrimental because "*crop production depends primarily on the moisture stored in the soil at seeding time, as precipitation during the growing season is seldom sufficient*" (Grevers et al., 1986). Therefore, studies that have focused on improving the nutrient status of eroded hilltops with commercial fertilizers (Massee and Waggoner; 1985; Mielke and Schepers, 1986; Massee, 1990; Verity and Anderson, 1990; Larney et al., 1995; Larney et al., 2000a) and manures (Dormaar et al., 1988; Dormaar et al., 1997; Larney et al, 2000b) have had limited success. As a result, if soil moisture is indeed the yield-limiting factor, there is no other alternative in restoring crop productivity to eroded hilltops other than landscape restoration.

Aside from the economic benefits of adding organic-rich topsoil on eroded hilltops, landscape restoration has environmental implications as well. As society becomes increasingly concerned for the environment and aware of its link to agriculture, producers find themselves at the forefront of this issue and are often encouraged to modify their management practices. Reducing greenhouse gas (GHG) emissions, specifically carbon dioxide (CO_2), is quickly becoming a priority and carbon sequestration is an important process in reducing CO_2 emissions. The environmental component of the overall project was designed to address this issue. Canadian croplands can sequester as much as 22 million tonnes (24 million tons) of atmospheric CO_2 per year by using conservation- and zero-till practices (Soil Conservation Council of Canada, 2004). Erb (2005) examined the environmental impacts of landscape restoration and reported that the addition or removal of topsoil had no significant effect on CO_2 emissions from the landscape during the growing season. This suggests that producers can adopt this management practice without significantly contributing to increased levels of atmospheric carbon. However, the loss of greenhouse gases may occur during the restoration event. For example, a recent study in Winnipeg, Manitoba found that the short-term CO_2 flux (up to5 days) following a soil disturbance event is characterized by an immediate increase in CO_2 flux that quickly dissipates within 24 hours and that nitrous oxide (NO_2) flux may have a similar response (Koiter, 2008). The agricultural industry has also been continually targeted and criticized for the negative impact on the environment because of the wide spread use of chemical pesticides and commercial fertilizers. Many Manitoban producers rely heavily on these chemicals to increase crop production. For instance, in 2002 Manitoba producers used 859,300 tonnes (947,216 tons) of commercial fertilizer and spent an estimated $201.4 million on pesticides (Manitoba Agriculture, Food and Rural Initiatives, 2003). Soil organic matter plays a large role in the degradation of pesticides. Studies have shown that in topographically complex landscapes, pesticide sorption increases progressively down slope and coincides with the variability of soil organic carbon concentrations (Farenhorst et al., 2003; Gaultier et al., 2006), soil moisture, and microbial populations (Cattaneo et al., 1997; Soulas and Lagacherie, 2001) across these landscapes. However, due to the low organic matter levels and poor water holding capacity of eroded upper slope positions the efficiency and efficacy of these chemicals is reduced. Therefore, landscape restoration can potentially reduce the levels of pesticides and fertilizers that are lost to the environment by returning organic-rich topsoil to eroded hilltops.

Soil erosion continues to remain one of the most damaging and detrimental processes affecting crop production in agricultural lands in western (Izaurralde et al., 2006) and eastern (Tiessen et al., 2007a,b) Canada. If little is done to restore eroded landscapes and prevent further soil erosion, the current state of these landscapes will only worsen as productivity will continue to decline and more importantly, the ability of these landscapes to provide food, fibre, and fuel to a rapidly growing global population will become increasingly more difficult. For instance, the maximum tolerable rate of soil loss is estimated at 5 t ha^{-1} yr^{-1} (2.2 t ac^{-1} yr^{-1}) (Manitoba Agriculture, Food and Rural Initiatives, 2006.). On the Canadian Prairies, between 18 to 43 % of land is seeded using conventional tillage practices (Statistics Canada, 2007b) and is subjected to unsustainable levels of tillage erosion. Further removal and continued downward movement of soil from eroded upper slope positions will result in advanced stages of tillage erosion, burying once productive A horizons in lower slope positions with poor quality soil (de Alba et al., 2004). The logical outcome of this situation is that the entire landscape will become eroded to a degree that reductions in crop productivity will occur throughout the entire landscape and will no longer be isolated to hilltops.

If adopted, the agronomic, economic, and environmental benefits of landscape restoration may have significant and positive impacts in agricultural regions worldwide. However, to date there is no known scientific literature on landscape restoration as a land management practice. This study of landscape restoration provides significant evidence of the positive impact on crop productivity and soil properties in eroded topographically complex landscapes as well as, the foundation and framework to develop additional studies on landscape restoration. In order to 'fine-tune' this practice, future research should be focused on the practical aspects associated with landscape restoration. For instance, although the degree of erosion will ultimately determine the depth at which topsoil is added to eroded hilltops, determining the optimal depth of topsoil addition and removal will optimize the efficiency, productivity, and profitability of the practice. A long-term study should also be considered to determine the length of time that is required between successive restoration events. Dormaar et al. (1997) reported that the application of 5 cm of topsoil on an eroded Alberta soil had 'lost its effect' after four years of continuous cultivation as a result of tillage implements mixing in subsoil. A comparison between alternative tillage practices should also be included in this study, as the erosivity differs between tillage systems (Li et al., 2007a). Future studies should also consider the potential for landscape restoration to reduce further soil loss from water and wind erosion. Therefore, research should include measuring water infiltration rates, aggregate stability, and crop residue levels on eroded hilltops. By improving water infiltration there is less risk for soil loss by water erosion as runoff rates are also reduced and, hilltops with higher levels of residue are at less risk for wind erosion than hilltops that have less residue. Future research should also focus on conducting landscape restoration within a range of climatic regions, landscapes, soil types, and cropping systems. This will be helpful in understanding how landscape restoration can be applied under various conditions and is relevant to many agricultural regions.

"*While soil loss prevention is important in maintaining soil productivity, once erosion has occurred producers need to know how best to restore productivity*" (Smith et al., 2000). This research has shown that landscape restoration is a logical and practical approach to restore eroded landscapes and has the potential to be widely adopted, at both the farm scale and international level. There is a need for agronomically, environmentally, and economically sound management practices available for producers. Landscape restoration could prove to be one of the most influential land management practices in farming of the twenty first century (Bosma and Lobb, 2004) because yield loss cannot be overcome by any method presently known, except possibly the returning of topsoil to eroded areas (Carter et al., 1985). In addition, landscape restoration provides agricultural producers with an alternative land management practice they can incorporate with other beneficial management practices allowing them to optimize productivity and maximize profitability.

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5.0 APPENDICES

Appendix A

Topsoil Addition and Removal Depth Measurements

Table A.1 Topsoil addition and removal depth measurements within each addition and removal plot following restoration in the spring of 2005 at Treherne.

	Upper Slope Positions									
	Depth Measurement (cm)									
a) Addition Plot	1	2	3	4	5	6	7	8	9	**Mean**
1	10	10	10	10	10	9	10	9	10	**9.7**
2	10	9	10	10	10	10	8	9	10	**9.6**
3	10	10	10	9	10	9	10	10	10	**9.9**
4	9	9	9	10	10	10	10	10	10	**9.8**
	Lower Slope Positions									
	Depth Measurement (cm)									
b) Removal Plot	1	2	3	4	5	6	7	8	9	**Mean**
1	10	11	10	11	11	11	11	10	11	**10.7**
2	11	10	10	10	10	12	11	10	10	**10.5**
3	10	11	10	11	11	11	10	10	10	**10.4**

*Topsoil depth measurements taken on May 25, 2006.

Table A.2 Initial topsoil addition and removal depth measurements within each addition and removal plot during landscape restoration in 2005 at Bruxelles*.

	Upper Slope Positions									
	Soil Depth Measurement (cm)									
a) Addition Plot	1	2	3	4	5	6	7	8	9	**Mean**
1	13	13	11	11	10	11	12	12	10	**11.5**
2	11	11	12	13	17	14	15	14	15	**13.3**
3	15	15	12	11	14	15	11	12	15	**13.3**
4	15	13	15	12	14	13	16	12	11	**13.5**
5	13	14	16	15	15	13	14	12	16	**14.0**
	Lower Slope Positions									
	Soil Depth Measurement (cm)									
b) Removal Plot	1	2	3	4	5	6	7	8	9	**Mean**
1	11	12	11	9	11	9	11	11	10	**10.5**
2	11	9	10	11	11	11	10	10	11	**10.5**
3	10	11	10	9	10	11	11	10	11	**10.4**

*Topsoil depth measurements taken on October 27, 2005.

Table A.3 Topsoil addition and removal depth measurements within each addition and removal plot following landscape restoration in 2006 at Bruxelles*.

	Upper Slope Positions									
	Soil Depth Measurement (cm)									
a) Addition Plot	1	2	3	4	5	6	7	8	9	**Mean**
1	9	8	9	8	7	8	9	9	8	**8.2**
2	10	10	9	9	9	10	10	10	10	**9.6**
3	11	9	10	10	11	9	10	10	9	**9.8**
4	9	11	10	10	10	10	11	10	9	**10.1**
5	9	9	10	12	11	11	10	11	10	**10.2**
	Lower Slope Positions									
	Soil Depth Measurement (cm)									
b) Removal Plot	1	2	3	4	5	6	7	8	9	**Mean**
1	11	11	9	12	9	11	9	11	9	**10.2**
2	11	10	10	11	10	9	11	11	10	**10.4**
3	9	11	9	10	9	11	10	10	11	**10.0**

*Topsoil depth measurements taken on May 12, 2006.

Table A.4 Initial topsoil addition and removal depth measurements within each addition and removal plot during landscape restoration in 2005 at Swan Lake*.

	Upper Slope Positions									
	Soil Depth Measurement (cm)									
a) Addition Plot	1	2	3	4	5	6	7	8	9	**Mean**
1	15	14	15	15	14	13	14	16	15	**14.5**
2	16	16	15	14	14	14	14	14	13	**14.5**
3	16	15	15	15	15	15	15	14	15	**15.1**

	Lower Slope Positions									
	Soil Depth Measurement (cm)									
b) Removal Plot	1	2	3	4	5	6	7	8	9	**Mean**
1	11	11	12	12	10	10	11	11	10	**11.0**
2	11	10	11	11	12	10	10	10	10	**10.6**
3	9	11	10	11	12	12	10	10	12	**10.8**

*Topsoil depth measurements taken on October 27, 2005.

Table A.5 Topsoil addition and removal depth measurements within each addition and removal plot following landscape restoration in 2006 at Swan Lake*.

	Upper Slope Positions									
	Soil Depth Measurement (cm)									
a) Addition Plot	1	2	3	4	5	6	7	8	9	**Mean**
1	11	11	11	10	10	11	11	10	10	**10.7**
2	10	10	12	11	11	12	10	10	11	**10.8**
3	11	12	11	10	11	11	10	10	10	**10.6**

	Lower Slope Positions									
	Soil Depth Measurement (cm)									
b) Removal Plot	1	2	3	4	5	6	7	8	9	**Mean**
1	11	10	12	12	11	12	11	10	11	**11.1**
2	10	12	11	12	11	11	11	10	10	**10.8**
3	11	10	10	11	10	11	10	10	10	**10.4**

*Topsoil depth measurements taken on May 17, 2006.

Table A.6 Topsoil addition and removal depth measurements within each addition and removal plot following landscape restoration in 2004 at Brookdale*.

	Upper Slope Positions									
	Soil Depth Measurement (cm)									
a) Addition Plot	1	2	3	4	5	6	7	8	9	**Mean**
1	10	12	13	11	6	13	13	11	9	**10.9**
2	17	13	11	11	11	16	6	10	16	**12.3**
3	13	12	13	15	15	20	7	18	10	**13.7**
4	11	14	13	14	9	18	14	10	9	**12.4**
5	8	18	11	12	18	18	14	18	13	**14.4**
6	9	13	17	18	12	15	16	16	14	**14.4**
7	13	10	10	14	14	12	13	12	15	**12.6**
8	12	15	10	15	13	10	14	15	10	**12.7**
9	10	17	13	16	14	14	13	15	9	**13.4**

	Lower Slope Positions									
	Soil Depth Measurement (cm)									
b) Removal Plot	1	2	3	4	5	6	7	8	9	**Mean**
1	20	19	35	26	31	30	34	19	19	**25.9**
2	26	18	27	30	33	22	24	15	15	**23.3**
3	30	26	22	22	16	22	29	21	20	**23.1**

*Topsoil depth measurements taken on June 07, 2004 (Erb, 2005).

Appendix B

Field Plans and Plot Layouts

(a)

(b)

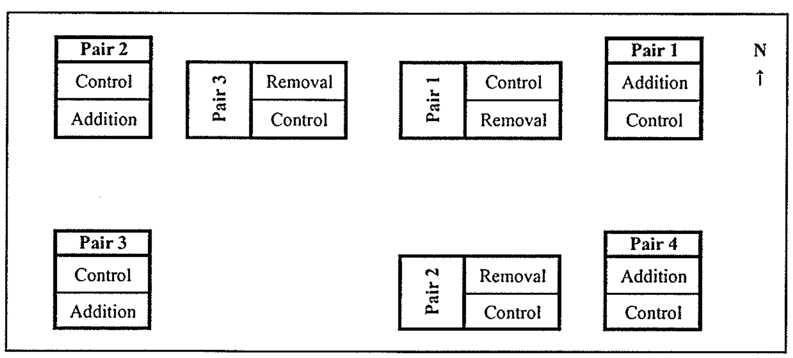


Figure B.1 Field plan and plot layout of primary research site at Treherne (15-07-10W) (a) Field plan. Circles represent plots located on eroded upper slope positions and squares represent plots in lower landscape positions were topsoil was removed (Image from Agri-Maps Map Gallery, Government of Manitoba, Manitoba Agriculture, Food and Rural Initiatives, 2001 [Online] http://geoapp2.gov.mb.ca/website/mafri/index3.html). **(b) Plot layout.**

(a)

(b)

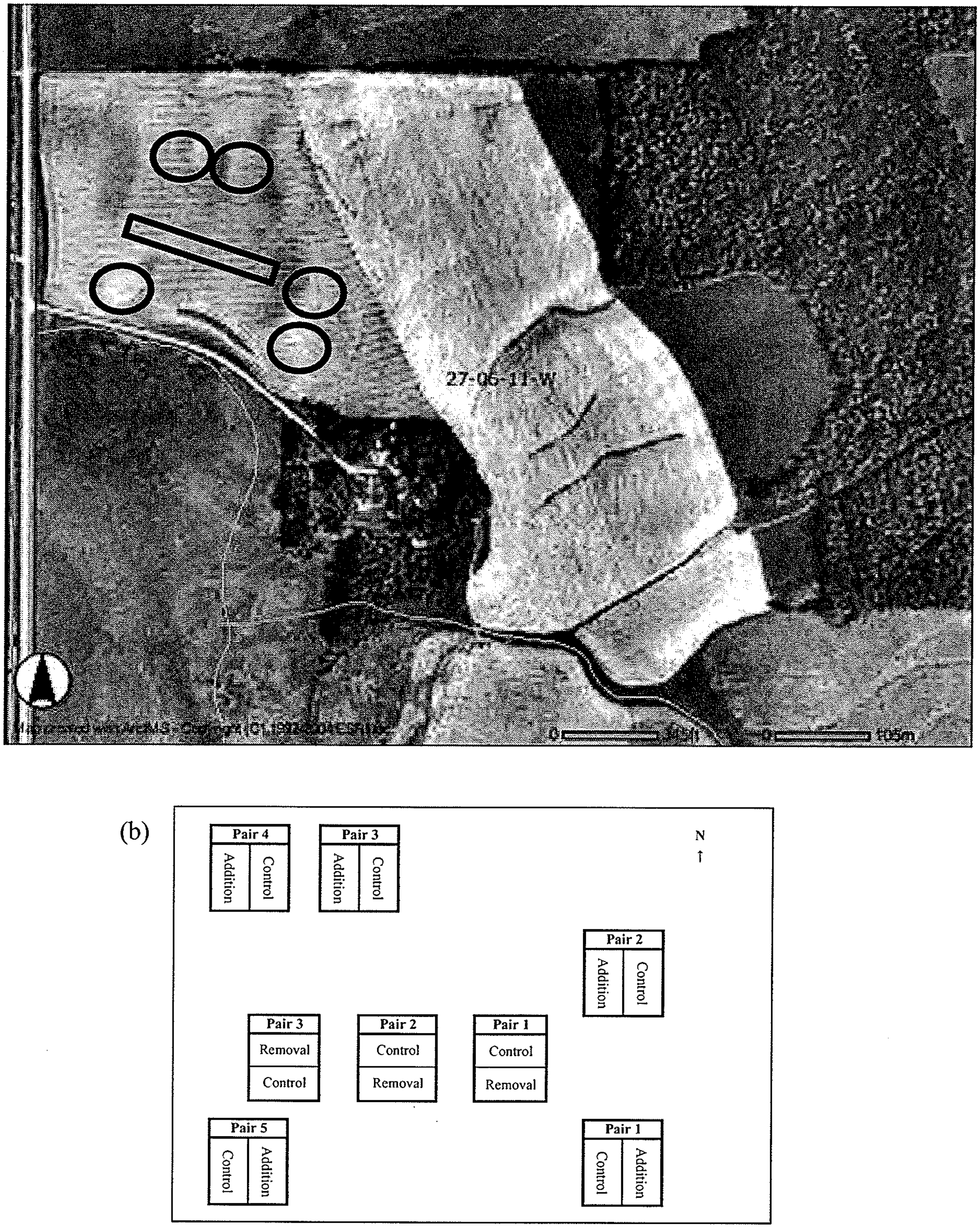
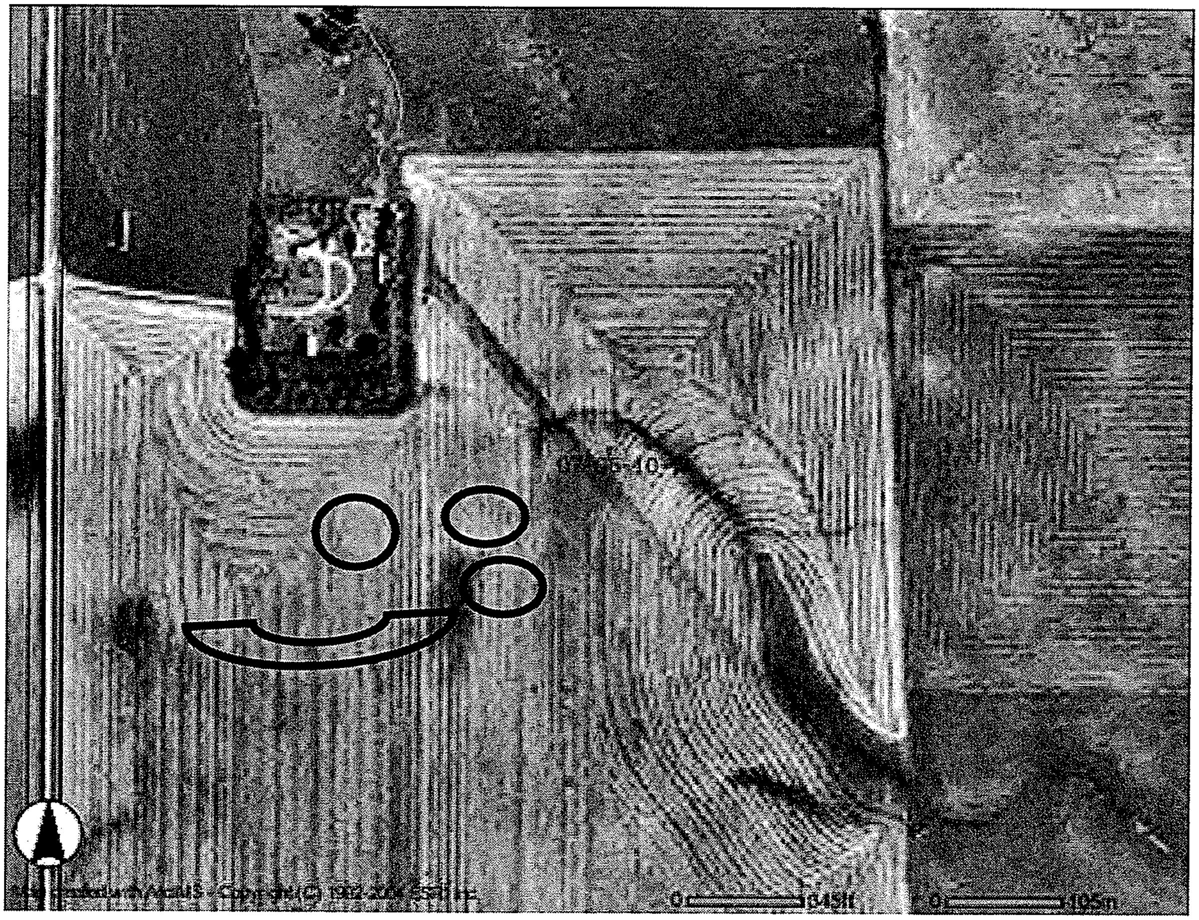


Figure B.2 Field plan and plot layout of secondary research site at Bruxelles (27-06-11W). (a) Field plan. Circles represent plots located on eroded upper slope positions and the rectangle represents plots in the lower slope position where topsoil was removed (Image from Agri-Maps Map Gallery, Government of Manitoba, Manitoba Agriculture, Food and Rural Initiatives, 2001 [Online] http://geoapp2.gov.mb.ca/website/mafri/index3.html). **(b) Plot layout.**

(a)



(b)

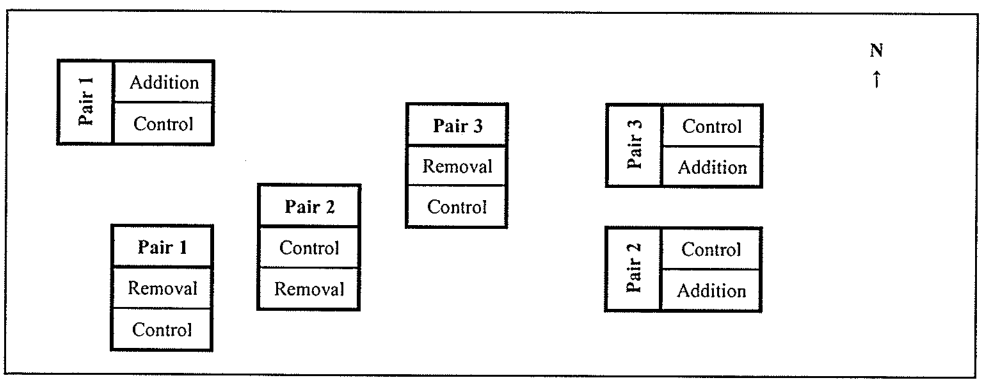


Figure B.3 Field plan and plot layout of secondary research site at Swan Lake (07-06-10W). (a) Field plan. Circles represent plots located on eroded upper slope positions and the crescent shape represents the plots in the lower slope position where topsoil was removed (Image from Agri-Maps Map Gallery, Government of Manitoba, Manitoba Agriculture, Food and Rural Initiatives, 2001 [Online] http://geoapp2.gov.mb.ca/website/mafri/index3.html). **(b) Plot layout.**

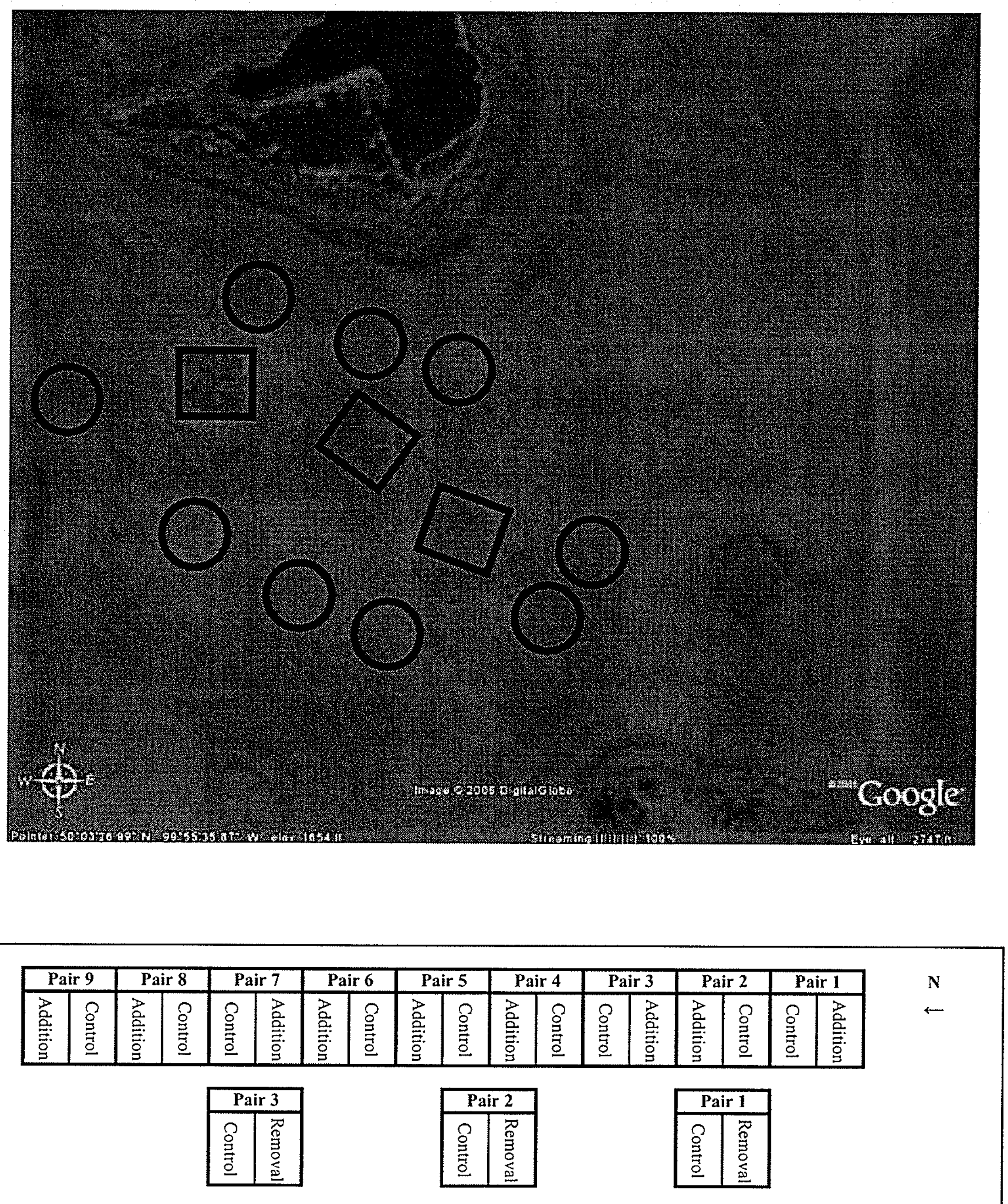


Figure B.4 Field plan and plot layout of secondary research site at Brookdale (31-12-18W). (a) Field plan. Circles represents plots on eroded upper slope positions and the squares represent the depressions where topsoil was removed (Image from Google Earth, Google Inc., 2005). **(b) Plot layout. Pairs are not adjacent to one another, they are arranged in nine different areas along the eroded ridge.**

Appendix C

Seedling Emergence at Primary Research Site: Treherne

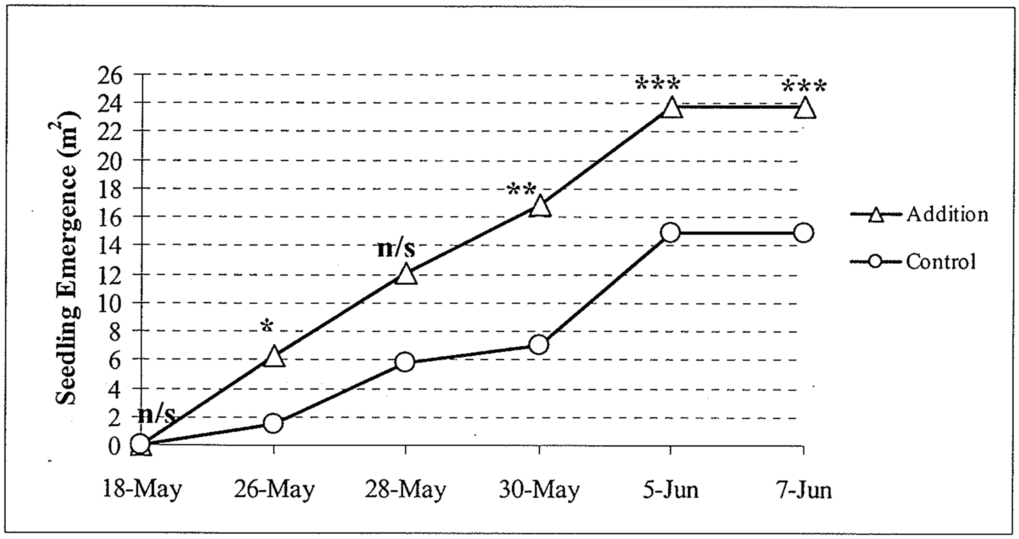


Figure C.1 Comparison of field pea (*Pisum sativum*) seedling emergence (m^2) in upper slope positions between control and addition plots at Treherne in 2006. Values represent the means of 3 measures of 4 replicates. *Significant at *P<0.10*; ** Significant at *P<0.05*; ***Significant at *P<0.01*; n/s = not significant using a paired t-test.

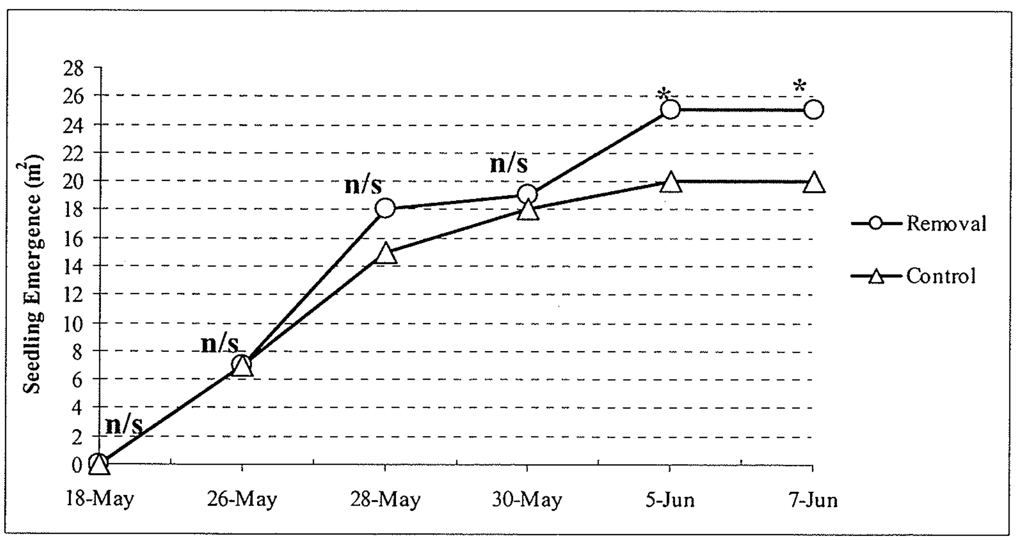


Figure C.2 Comparison of field pea (*Pisum sativum*) seedling emergence in lower slope positions between control and removal plots at Treherne in 2006. Values represent the means of 3 measures of 4 replicates. *Significant at *P<0.10*; ** Significant at *P<0.05*; ***Significant at *P<0.01*; n/s = not significant using a paired t-test.

Appendix D

Monthly Mean Precipitation Data for Research Sites at Treherne and Brookdale

Table D.1 Monthy mean precipition data for reseach sites located at Treherne and Brookdale in 2005 and 2006.

Month	Treherne 2005[a]	Treherne 2006[a]	Treherne Normal[b]	Brookdale 2005[c]	Brookdale 2006[c]	Brookdale Normal[d]
	(mm water equivalent)					
January	27.0	19.0	21.7	30.0	12.2	18.0
February	9.4	38.0	18.8	3.2	13.2	14.1
March	16.6	33.6	29	29.6	33.4	22.2
April	20.2	26.4	34.2	10.0	46.2	31.0
May	109.0	27.4	56.1	56.8	41.0	52.7
June	221.4	28.6	88.2	216.2	81.6	74.4
July	118.4	16.4	82.6	130.2	7.8	75.8
August	47.8	35.0	70.4	18.4	76.4	69.2
September	19.6	28.2	58.2	10.4	74.6	50.1
October	21.6	22.0	45.2	21.4	15.0	27.7
November	30.2	30.4	32.6	34.1	38.8	17.7
December	14.0	30.0	25.9	27.6	22.0	19.2
Sum	**655.2**	**335.0**	**562.9**	**587.9**	**462.2**	**472.0**

[a]Values based on data for weather station located at Holland,Manitoba, 49°36.600'N, 98°5.800'W, elevation 374.90 m, 9.4 km northwest of site (Envrionment Canada, 2002a, http://www.climate.weatheroffice.ec.gc.ca/climateData/monthlydata_e.html).

[b]Values based on data for weather station located at Somerset, Manitoba, 49°27.000'N, 98°37.200'W, elevation 487.8 m, 30.5 km southeast of site (Envrionment Canada, 2002b, http://www.climate.weatheroffice.ec.gc.ca/climate_normals/results_e.html).

[c]Values based on data for weather station located at Brandon, Manitoba Airport, 49°55.200'N, 99°57.000'W, elevation 409.40 m, 15.4 km from site (Envrionment Canada, 2002a, http://www.climate.weatheroffice.ec.gc.ca/climateData/monthlydata_e.html).

[d]Values based on data for weather station located at Brandon, Manitoba Airport, 49°55.200'N, 99°57.000'W, elevation 409.40 m, 15.4 km from site (Envrionment Canada, 2002b, http://www.climate.weatheroffice.ec.gc.ca/climate_normals/results_e.html).

Appendix E

Crop Emergence at Secondary Research Site: Swan Lake

Table E.1 Final crop emergence counts in lower slope position at Swan Lake in 2006.

Control	Removal	Δ
	(m^2)	
129	85	44*

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

Appendix F

2006 Crop Yield Differences on Upper and Lower Slope Positions

Table F.1 Normalized 2006 crop yield differences on upper and lower slope positions.

	TRE[a]	BRX[b]	SWL[c]	Mean
	-------------	% of Regional	Crop Average	-------------
a) Upper Slope [1]	25.3	39.4	31.9	32.2
b) Lower Slope [2]	18.7	1.7	30.2	16.9
Net	-	-	-	**15.3***

[a] Risk area 5, regional field pea yield average 3161 kg ha^{-1} (2822 lb ac^{-1}).

[b] Risk area 5, regional wheat yield average 2690 kg ha^{-1} (2402 lb ac^{-1}).

[c] Risk area 5, regional flax yield average 1632 kg ha^{-1} (1457 lb ac^{-1}).

[1] 2006 yield difference between addition and control plots in upper slope position.

[2] 2006 yield difference between removal and control plots in lower slope position.

*Significant at $P<0.10$ using a t-test.

Note: Risk areas and 2006 average regional crop yield values obtained from Manitoba Agriculure Services Corporation (2008).

Appendix G

Soil Test Analysis Methodologies

Table G.1 Soil test analysis methodologies for analysis performed by Agvise Laboratories, Northwood, ND, USA.

Nutrient	Symbol	Quantity	Method
Nitrate	NO_3^-	lb ac$^-$	Extraction in 0.12 N KCl, detection by Cd reduction.
Phosphorus	P	ppm	Extraction using sodium bicarbonate (Olsen), detection by ammonium molybdate-ascorbic acid colour developer.
Potassium	K	ppm	Exctration with 1.0 N ammomium acetate method, detection by AA (Atomic Absorption spectrophotometer).
Sulphate	SO_4^-	lb ac$^-$	Extraction in 0.12 N KCl, detection by Barium Chloride Precipitate method.
Total Carbon	TC	%	Determined using carbon analyzer (Leco instrumatation).
Total Organic Carbon	TOC	%	Determined with a carbon analyzer (Leco instrumentation) with the inorgainc carbon fraction subtracted out.
Calcium Carbonate Equivalent	CCE	%	Determined by addition of HCl to soil and measuring CO_2 by transducer.
Organic Matter	OM	%	Determined by loss of weight on ignition at 360 °C.
Electrical Conductivity	EC	mmhos cm^{-1}	1:1 soil water extraction.
pH			1:1 soil water extraction.

Soil test analysis methodologies followed the NRCS Soil Survey Laboratory Methods Manual.

Appendix H

Soil Temperature Data at Primary Research Site: Treherne

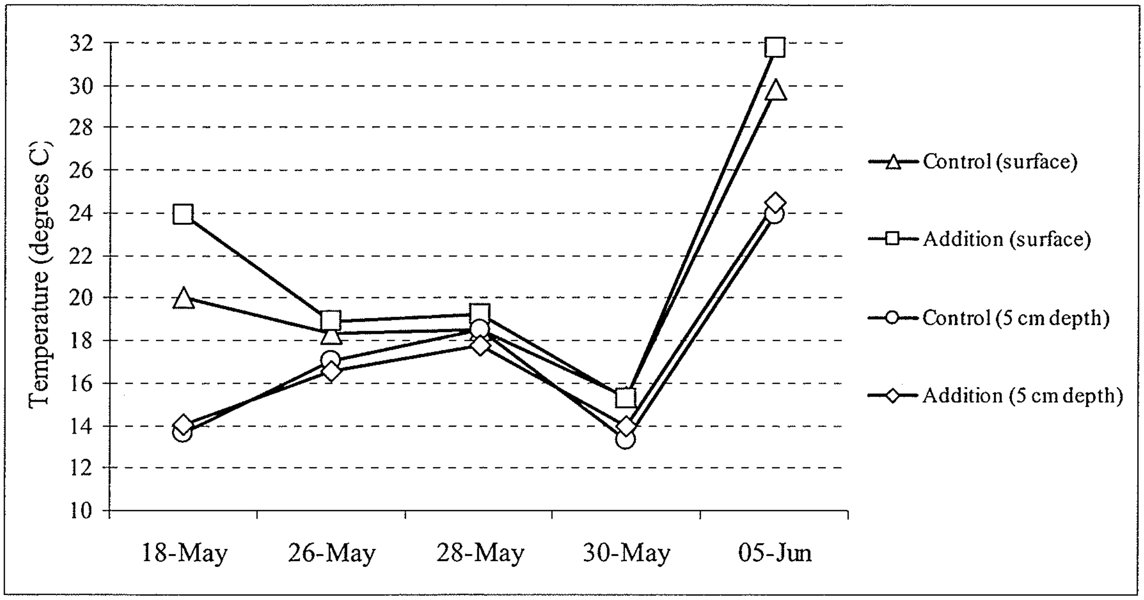


Figure H.1 Soil temperatures at surface and 5 cm depths in addition and control plots in upper slope landscape position at Treherne in 2006.

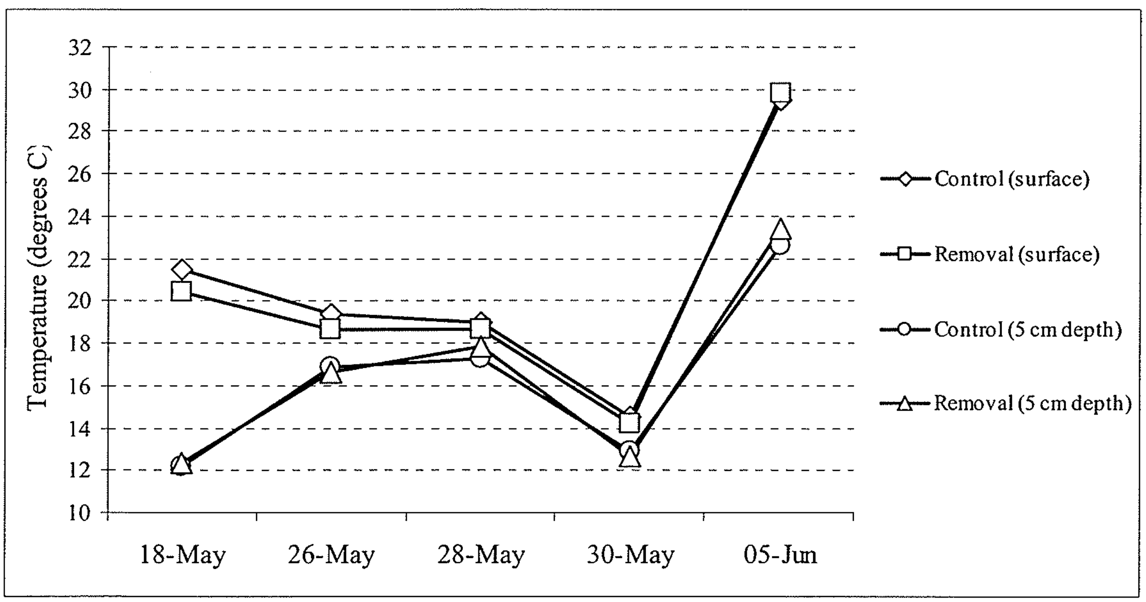


Figure H.2 Soil temperatures at surface and 5 cm depths in removal and control plots in lower slope landscape position at Treherne in 2006.

Appendix I

Mean Clay Content in Soil Surface at Primary Research Site: Treherne

Table I.1 Mean clay content (%) at soil surface in upper slope plots.

Control	Addition	Δ
	(%)	
22.74	16.62	6.12

Δ = Addition - Control

Values indicate means of 4 replicates.