The Economic, Agronomic and Environmental Impact of No-Till on the Canadian Prairies

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August 2009 – Version 1

Alberta Reduced Tillage LINKAGES

Funding provided by

Alberta

Alberta Agriculture and Rural Development
Alberta Environment
Climate Change Action Fund

This document is a work in progress
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Executive Summary

No-till or zero-till (ZT) *(planting of a crop into the untilled stubble of a previous crop with little or no soil disturbance)* is a conservation practice, that is economical (saving on fuel, farm machinery-life and reduced labor costs, while maintaining or improving crop yields); and it is environmentally friendly (increased soil-organic matter, improved soil tilth, improved moisture conservation and use efficiency, and reduced soil erosion). No-till seeding also has the potential to sequester atmospheric carbon dioxide, an important factor in the mitigation of green house gas emissions.

No-till adoption rate – The adoption of no-till in western Canada experienced a pronounced upward trend since 1991. The planted acres using no-till practices are estimated to be growing at an annual rate of 626,000 acres in Alberta. Since the mid 1980s, considerable research has been done on the characterization of no-tillage on the Canadian Prairies. The main objective of this report is to examine the value of no-till practices on the prairies.

Economic of no-till – Adoption of no-till on the farm depends on the assumption that it will maximize net farm income and/or reduce risk taking. Factors that contribute to the net farm income include yield, cost of inputs used in crop production (labor, fuel, fertilizer, pesticide, seed and machinery), and expected output (commodities) prices.

Grain yield – On average crop yields are generally higher in no-till systems (wheat: 3.5%; barley: 6.2%; flax: 7.9%; peas: 4.6% and lentils: 13%).

Labor cost – There is a lower cost for labor in no-till (ZT): 3.5 passes; minimum tillage (MT): 5.8 passes, and conventional tillage (CT): 7.5 passes).

Fertilizer use – There is no agreement in the literature on the effects of no-till on fertilizer needs and nutrient availability. Some researchers have suggested that, over the long haul, fertilizer use decreases under no-till because it is injected (side or mid-row banded) below the soil surface, resulting in more efficient use of nutrients, while others have suggested that the fertilizer requirement increases or stays the same for both no-till and conventional tillage systems. A study in southern Alberta has shown that no-till wheat tied up nitrogen in residue and soil organic matter, resulting in reduced yields. No-till, accompanied by appropriate nutrient management, increased net returns by 5% for canola, 30% for wheat, and 25% for peas, but in canola, it raised fertilizer costs by 14%.

Fuel consumption – There is a significant reduction in fuel consumption with reduced and no-till as compared to conventional tillage (peas – ZT: 18.8 L/ha; MT: 23.7 L/ha; CT 32.3 L/ha; flax – ZT: 18.6 L/ha; MT: 23.7 L/ha; CT: 30.3 L/ha; wheat on fallow – ZT: 23.5 L/ha; MT: 30.6 L/ha; CT: 47.1 L/ha; wheat on stubble: ZT: 19.9 L/ha; MT: 24.0 L/ha; CT: 30.2 L/ha).

Pesticide use – There are conflicting reports on the relative use and cost of herbicides across tillage systems in western Canada. An Alberta Agriculture study showed no difference in herbicide cost between no-till and conventional tillage systems. However, the cropping practices survey in Saskatchewan showed that herbicide cost for minimum – no-till was slightly higher than for conventional tillage.

Seed use – Studies in western Canada have shown that growers do not vary the seeding rate by tillage practices.

Machinery use – No-till and minimum tillage require fewer trips across the field, allow two or more activities to be combined into one, and permit the use of machines with greater capacity and lower draft.

Cost comparisons – generally, the production costs for no-till are lower as compared to those for conventional tillage. However, there is a considerable variability in the economics of no-till among various soil zones. In the dry Brown Soil of Alberta and Saskatchewan, conservation tillage (minimum and no-till) systems are less profitable, especially in continuous cereal and cereal-fallow rotations, whereas, in the Dark Brown soils, no-till is equal to or marginally more profitable than in conventional tillage. In the Black and Gray soils of western Canada, no-till and minimum tillage are superior to conventional tillage. This cost advantage in the Black and Gray soils is due to higher grain yields and better cost of production for no-till.

The economic analysis of the cereal-fallow rotations in no-till and conventional tillage systems in the Brown and Dark Brown soils zones was carried out in the early 1990s when glyphosate prices were high ($25.00 /L) and application of N was broadcast on the soil surface rather than side banded below the soil surface. Since then there has been a significant drop in glyphosate price (< $8.00/L), more efficient fertilizer placement, a substantial increase in fuel prices, and a majority of farmers in these soil zones are now practicing diversified cropping rotations. If the economic comparison were made now between no-till and conventional tillage, by taking current glyphosate, fuel and lack of fallow into the economic benefit equation, the profit picture for no-till would be either equal or superior to conventional tillage.

Soil Conservation – On the prairies, the on-farm cost of soil erosion in 1980 was estimated to be nearly $430 million in Alberta, Saskatchewan $560 million, and nearly $44 million in Manitoba. Studies on the prairies have shown that soil losses were greatest from conventional tillage and least from no-till management systems. Since the early 1990s, ZT and MT along with other soil conservation practices have resulted in a significant decline in soil losses, and, as a result, only a small proportion of agricultural land is now susceptible to soil erosion (water erosion: < 14%; wind erosion 30%).

No-till reduces run-off – No-till increases runoff infiltration by slowing the flow of rainwater or snowmelt from the field. In no-till fields, there is also more infiltration as compared to tilled fields; consequently this results in fewer pollutants entering the streams and open water bodies. Reduced runoff in no-tillage is also associated with decreased flooding and an increase in soil moisture. However, by not tilling the soil, there is a concern that it may increase leaching of water, nutrients and pesticide to the ground water. There are conflicting reports in the literature about the role of no-till in enhancing leaching. Some studies have found little or no difference in leaching of water and nutrients between no-till and tilled fields while others report greater leaching in no-till soils than in tilled soils

No-till reduces sediment loss – The most common pollutants in environmentally impaired waterways are sediment, nutrients, and bacteria. No-till practices reduce the amount of sediment by 60 – 90%.

No-till reduces phosphorus loss – No-till practices typically reduce soil erosion and sedimentation losses and may result in less phosphorus lost in runoff. Information on the effects of tillage systems on phosphorus loss is contradictory. Some studies have reported significantly lower dissolved phosphorus losses under no-till as compared to conventional tillage, while other studies have demonstrated that no-till reduced the loss of particulate and total phosphorus in surface runoff; however, it does increase the loss of soluble phosphorus to ground water.

No-till reduces nitrogen losses – No till may reduce runoff resulting in less nitrogen loss. Several studies have shown that no-till reduces sedimentation up to 97 % (relative to conventional tillage), and this results in a 75 to 90 % reduction in total nitrogen loss for soybeans planted following corn and 50 to 73 % reduction in nitrogen loss for corn following soybeans. No-till crop production also increases the amount of soil macropores and allows for greater water infiltration, increasing potential for nitrate leaching compared to conventional systems. However, more recent studies have shown no difference in nitrogen leaching between tillage types.

No-till reduces runoff of pesticides – No-till farming practices leave a large amount of crop residue on the soil surface rather than ploughing it under; these practices can reduce runoff of sediments, nutrients and chemicals into streams by more than 90%.

In western Canada, some of the residual herbicides (2,4-D, MCPA, trifluralin) have often been detected in surface and ground water. Transgenic crops such as glyphosate (Roundup Ready crops) and glufosinate-tolerant varieties (Liberty Link crops) have the potential to significantly reduce herbicide losses and concentration in runoff. Planting herbicide-tolerant varieties such as Roundup Ready crops and Liberty Link crops, and replacing some of the residual herbicides with glyphosate or glufosinate herbicides, can reduce herbicide losses and concentrations in runoff. Such herbicides are thought to be more environmentally benign.

No-till impact on weeds, diseases and insect population – Adoption of no-till has an impact on weeds, diseases, and insect species diversity and numbers. Many broad-leaf weeds decrease in no-till; however, some grassy weeds and perennial weeds increase. Studies in Alberta and Saskatchewan have shown that year-to-year variation in climatic conditions and crop rotations have a greater impact on weeds than tillage systems.

There are conflicting reports in the literature on the incidence and severity of plant diseases in minimum and no-till systems. Some of the earlier studies documented an increased incidence and severity of disease levels in conservation tillage as compared to cultivation, while others showed a decrease or no effect.

Similar to weeds and plant diseases, insect pests respond differently to tillage practices. Populations of some species increase under minimum and no-till while others decrease.

No-till sequesters atmospheric CO_2 – In Canada, conservation tillage practices on the farmland offer a large opportunity to sequester carbon and consequently enhance the soil carbon sink. Over the years, various models have been developed to estimate the national potential of CO_2 sequestration on the cultivated land.

- Agriculture and Agri-Food, Canada Sink Table model: a national potential to sequester 18.3 Mt CO_2 per year on cultivated land by 2012.
- McConkey (1999) the Prairie Provinces model: estimates 14,734,408 tonnes of carbon dioxide per year could be sequestrated on the cultivated land by 2008 – 2011.
- Goddard (2001) has estimated the Alberta potential to sequester 5.9 Mt CO_2 per year on cultivated land by 2011.

No-till enhances wildlife habitat – Studies in Canada and the United States have shown that no-till farming practices, especially fall-seeded winter cereals, have greater abundance and diversity of songbirds, ducks, small mammals and soil arthropods.

No-till enhances the physical, chemical and biological properties of the soils – Tillage practices affect soil quality indicators in a complex way. No-till, retains large qualities of residues**,** resulting in an increase in organic matter content, improved soil structure, buffered soil temperatures, and allows soil to hold more water. All these changes regulate plant growth processes and crop yields. Some of the important effects of no-till on soil qualities are:

- Increased soil organic matter: 2.9 ± 1.3 Mg ha^{-1} yr^{-1}

- Increased available plant nutrients: increase in mineralizable N. No-till also increases N immobilization. However, N – NO_3 or "available" nitrogen levels are not affected by no-till. P and K levels also increase under no-till
- No-till soils have higher microbial biomass and earthworm populations
- Improved physical qualities: no-till soils resulted in greater aggregate stability and/or aggregate size distribution, decreased soil compaction, improved soil tilth and structure, less run-off and increased water infiltration, and soil moisture content. No-till soils also have greater bulk density in the surface horizon (0-10 cm)
- No-till soils have moderate soil temperatures and significantly less heat stress as compared to tilled soils throughout the growing season.

SECTION 1

THE ECONOMIC, AGRONOMIC AND ENVIRONMENTAL IMPACT OF NO-TILL ON THE CANADIAN PRAIRIES

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Introduction

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The Economic, Agronomic and Environmental Impact of No-Till on the Canadian Prairies

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I. Introduction

The adoption of conservation tillage technology since the 1980s has been one of the most remarkable changes in the production of crops on the Canadian Prairies. Between 1991 and 2006, no-till farming acreages in Alberta rose from 0.6 million acres to 9.0 million acres, an increase of 1,358 % (Stats Canada, 2006). No-till farming systems are popular in Alberta, Saskatchewan, Manitoba, and the Peace River block of British Columbia because they improve the physical, chemical and biological properties of the soil, and provide substantial savings on fuel, farm machinery-life and labor costs. The most important benefits of no-till farming are:

- Protection of soil against wind and water erosion – no-till farming practices leave about 80 – 100% crop residues on the surface; this reduces erosion by protecting soil from the impact of raindrops and wind. With increased residues, water is more likely to infiltrate than to runoff, further protecting the soil against erosion
- Improvement in soil organic matter – by leaving the crop residues on the surface, soil organic matter on the surface is increased
- Preservation of soil structure – no-tillage reduces structural breakdown and increases macropores
- Improved aeration – improvement in soil organic matter, soil structure, macropores and earthworm populations, resulting in improved aeration over time
- Improved infiltration and percolation – improvements in soil organic matter, soil structure and retention of crop residues, slows runoff, and results in improved long-term infiltration and percolation
- Soil moisture conservation – tillage leaves the soil exposed to drying, while no-tillage and increased residues greatly reduce drying, resulting in better water use efficiency by the crop and higher grain yields; this feature is especially important under drought condition
- Moderates soil temperatures – crop residue insulates the soil and slows the rate at which thermal energy is exchanged between the soil and the atmosphere, and it results in higher soil moisture and slightly cooler soil temperatures in the early growing season. Cooler soil temperatures may persist till mid-season or throughout the whole season, resulting in reduced root heat stress and higher grain yields in cereals
- Reduction in non-point source pollution – retention of residues in no-tillage systems slows down runoff; this results in reduced sedimentation of rivers, reservoirs, lakes, wetland and micro catchments. Reduced sedimentation also has the potential to reduce the loading of fertilizer/manure (nitrates and phosphorus) and pesticides in environment.
- Enhancement of soil bio-diversity – no tillage systems encourage the multiplication of earthworms and other soil fauna
- Improvement of habitats for wildlife – residues in zero tillage provide improved conditions for ground nesting birds. Increased surface cover and reduced field disturbance provide direct benefits by increasing the amount of land area, which can be used as nesting habitat for some species
- Fuel conservation – no-tillage farming operations use up to 80% less fuel as compared to conventional tillage. This saving becomes even more important with the current high fuel prices

- Time conservation – no-tillage seeding generally requires 1 trip over fields compared with 5-6 trips with conventional tillage; this represents a huge saving in time, farm machinery-life and labor costs
- Time flexibility – no tillage allows later decisions to be made about growing crops in a field; for instance grain prices may vary and farmers may then make more economically sound decisions
- Reduces germination of some weeds -- the absence of soil disturbance under no-tillage reduces the germination of certain problem weeds.
- Suppresses certain plant diseases – studies in Western Canada have shown that zero tillage suppresses root rot and net blotch of barley, take-all of wheat, and seedling blight of canola
- Reduces greenhouse gas emissions – no-tillage farming also plays a major role in sequestering atmospheric carbon dioxide; this is an important factor in the mitigation of greenhouse gases emissions.

II. Rationale of the Study

In recent years on the Canadian Prairies considerable research has been done on the characterization of no-tillage advantages. Despite the fact that the findings sometimes seem to be contradictory, it is important to synthesize the research results and present the arguments and the supporting data as objectively as possible to allow growers to develop appropriate techniques for their situations.

Why are there sometimes-contradictory research findings?

- Academic studies, both in the field and in greenhouse studies tend to have a narrow focus, be small scale, and look at individual issues rather than integrate the research findings with other data
- Similarly, longer term research is needed so trends can be discerned rather that having findings that are field specific, dependent on growing conditions in one or two years and in small geographical areas
- There are regional differences that affect no-till systems; as a result, it is clear that different soil zones require different approaches.

What are the benefits of quantifying the no-till system?

- Growers and the general public can better appreciate what no-till does for the environment when they see quantitative proof of the difference it can make, and be more open to further no-till developments
- No-tillage stakeholders (boards, governments, NGOs) benefit from the positive PR and react favorably to positive environmental news
- Growers become aware that there are multiple environmental, and agronomic benefits of no-till to society; it's not just private economic benefit
- Proof of a "green" advantage can make any business more attractive and competitive in the current environmentally aware market.

What will happen if no-till is not promoted?

- Other conservation initiatives will develop to show what their value is. No-till may lose ground compared to other conservation practices or environmental issues that can show what they are worth

- No till risks being singled out in a negative sense and losing public support if it is unable to prove it benefits
- Growers and the public will not understand the value of no-till practices, and current use may actually decrease
- Further long-term, larger scale research initiatives that could better quantify the benefits of no-till and develop improved no-till systems will not be supported.

III. Goals of the Study

In recent years on the Canadian prairie, considerable research has been done on the characterization of no-tillage advantages. Therefore it is the primary objective of this report is to summarize all the economic, agronomic and environmental benefits of no-till in western Canada with especial emphasis on Alberta. A secondary objective is to identify gaps in our current knowledge about no-till in Alberta and apply information from elsewhere in North America to fill these gaps.

IV. Terms and Definitions

The following terms, defined below, are used in this report:

No-till (Zero tillage-ZT) — involves the planting of a crop into the untilled stubble of a previous crop with almost no soil disturbance. Seeding is accomplished in a one-pass operation that places seed and fertilizer in a relatively undisturbed seedbed; it packs the furrow while retaining surface residue to prevent soil erosion. In general, less than 10 % of the soil surface is disturbed for seed and fertilizer placement. Some of the advantages of this system are reduced soil erosion, soil moisture conservation and water use efficiency, savings in fuel, reduced wear and tear on machinery, and, under some situations, reduced weed pressure as weed seeds are on the soil surface where they are unlikely to germinate and are subject to predation by insects, rodents and birds. Fertilizer, seed placement and weed control practice in this system involves:

No-till practices on the Canadian Prairies
• Crop harvest and residue management in August – September • Pre-harvest or post-harvest glyphosate application ▪ Systemic annual or biannual application of glyphosate (if perennial weeds such as quackgrass, and Canada thistle are present) ▪ Pre-seeding or pre-emergence weed burn-down with glyphosate (0.5 L/acre) • Seed placement and fertilizer banding (late April – May) with little or no soil disturbance • In-crop herbicides for grasses and broad-leaves weeds

Modified from Li et al (2005): Agriculture and Agri-Food Canada

Direct Seed System — involves the planting of crops where no tillage occurs prior to seeding. In contrast, to no-till, direct seeding allows some disturbance to soil and crop residues to deal with special situations, such as some tillage with the seeding operation for immediate weed problems, harrowing to deal with excessive crop residues or a fall fertilizer injection. Any fall soil disturbance must leave the soil surface level, minimize stubble knock-down and keep most of the crop residue on the surface in order to conserve soil moisture and increase snow trapping. Depending on the amount of soil disturbance and type of opener used, direct seed systems can be further divided into:

- *High Soil Disturbance Seeding (HDS)* — seeding is done with high disturbance equipment such as shovels, sweeps, discers and harrow packing. High soil disturbance planters disturb more than 40% of the soil surface. Openers wide enough to overlap disturb the entire soil surface. Sweep openers produced high disturbance. They give varying degrees of weed control and sometime pre-seeding weed burndown treatment may not be necessary. HDS generally creates a good environment for weed and volunteer seeds from previous crop to germinate. High disturbance openers may require additional seedbed finishing to cover the seed and to improve weed control

- *Low Soil Disturbance Seeding (LDS)* — planting is done with low disturbance equipment, such as no-till drills or air drills with narrow openers. *LDS* disturbs less than 40% of the soil surface and retains nearly the entire crop residue on the soil surface. Some soil from the opener action may be deposited between furrows. Soil firmness, moisture conditions and planter speed may affect the amount of soil disturbance. *LDS* are very much like zero-till systems except that some tillage options remains available in direct seeding

Minimum-Tillage or Reduced Tillage — involves at least one tillage operation either in the fall or spring prior to seeding. In this system, at least 15 – 30% crop residue is left on the soil surface after planting. This system generally maintains 560 – 1,100 kg ha^{-1} (500 lbs – 1000 lbs ac^{-1}) residue on soil surface during the critical erosion period. Typically, tillage, fertilizer and seed placement and weed control consist of:

Minimum-tillage or reduced tillage practice on the Canadian Prairies
• Crop harvest and residue management in August – September • Pre-harvest or post-harvest glyphosate application (if perennial weeds are present) • Fall fertilizer banding (anhydrous ammonia/urea), with medium depth tillage (10 – 15 cm) • Pre-seeding weed burndown with glyphosate and/or shallow spring tillage, 7 – 8 cm deep with sweeps and mounted harrows (April to May) ▪ Possibly second tillage at right angle to the first, if there is too much residue ▪ The first or second tillage could be the seeding operation • In-crop herbicides for grasses and broad-leaf weed control

Modified from Li et al (2005): Agriculture and Agri-Food Canada

Conservation Tillage — an umbrella term encompassing several tillage systems including direct seed (*HDS, LDS*), minimum/reduced tillage, and no-till or zero tillage systems. This system retains at least 30% of the crop residue on the surface.

Conventional Tillage systems use multiple-tillage passes for weed control, fertilizer application, seedbed preparation and seeding. This system buries most of the crop residue. With this system the moldboard plow or heavy-duty cultivator is often used first, followed by other implements. Since this method plows under much of the crop stubble, it leaves the surface relatively bare and prone to erosion. The main disadvantages of this system are

- Increasing the rate of organic matter decomposition
- Drying out the soil
- Reducing the size and stability of soil aggregates, which increases the risk of compaction, crusting and erosion.

Summer-fallow – involves keeping normally cultivated land free of vegetation throughout one growing season by cultivating and/or applying chemicals to destroy weeds, insects and soil-borne diseases; it allows a buildup of soil moisture reserves for the next crop year. Summer-fallow includes chemical-fallow, tillage, and/or a combination of chemical and tillage weed control on the same land. It is a part of crop rotation systems in the Brown and Dark Brown soil zones of western Canada.

Chemfallow (Chemical-fallow) – is a type of summerfallow; it is the practice of leaving cultivated land free of vegetation for one growing season and using only herbicides such as glyphosate to control weeds.

Conservation Agriculture (CA) – Conservation agriculture is the integration of ecological management with modern, scientific, agricultural production. The Food and Agricultural Organization of United Nations defines **"***CA is a concept for resource-saving agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment*" (FAO 2007). The main aim of *CA* is to achieve sustainable and profitable agriculture and to improve upon soil building processes that effect soil health via soil qualities.

Conservation agriculture is based on implementing the following integrated practices (Dumanski et al 2006)

- Maintaining permanent soil cover and promoting minimal mechanical disturbance of soil through zero tillage systems, to ensure sufficient living and/or residual biomass to enhance soil and water conservation and control soil erosion
- Promoting diverse crop rotations with reduced fallow and cover crops and the use of integrated pest management technologies
- Promoting application of fertilizers, pesticides, herbicides, and fungicides in balance with crop requirements
- Promoting precision placement of inputs to reduce costs, optimize efficiency of operations, and prevent environmental damage
- Promoting legume fallows (including herbaceous and tree fallows where suitable), composting and the use of manures and other organic soil amendments.

V. Adoption of No-till on the Canadian Prairies

According to the 2006 Census of Agriculture, there are 105,007 farms on the western Canadian prairies. 41,624 are located in Alberta, 44,329 are in Saskatchewan, and 19,054 are in Manitoba

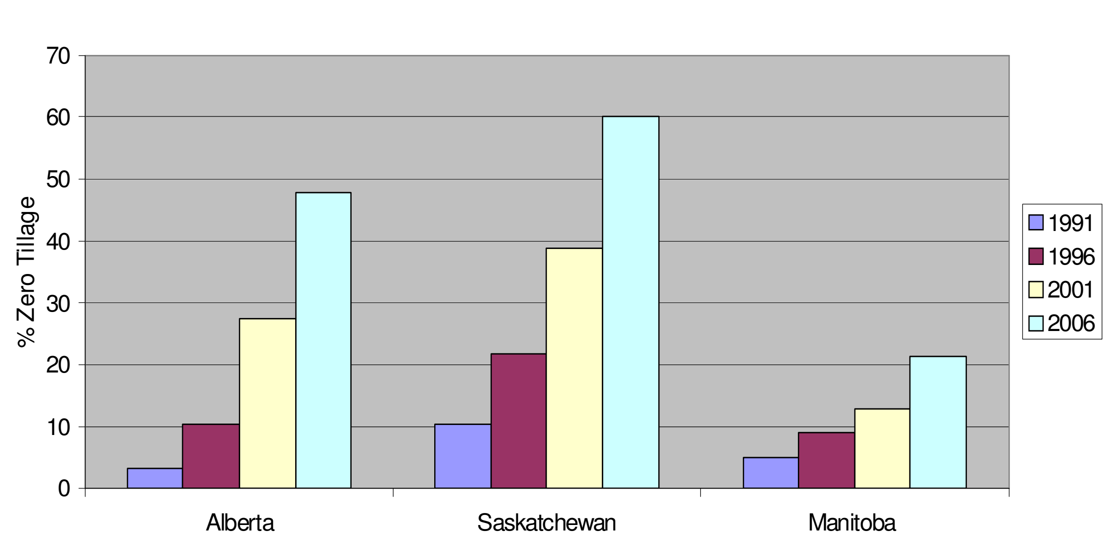
The adoption of no-till technology since the 1990s has been one of the most remarkable changes that have revolutionized the crop production system in Canada, especially on the Canadian Prairies. Nationally, in 1991, only 6.7% of producers used no-till to prepared land for seeding. Between 1991 and 1996, the use of no-till more than doubled with about 16.0% of producers using no-till for seedbed preparation. By 2001, the use of no-till jumped by 14 percentage points; approximately 30% of the farmers were practicing no-till in Canada. By 2006, the use of no-till technology increased by another 18 percentage points to 47% (Table 1 and Figure 1).

Table 1. Tillage practices used to prepare land for seeding: 1991 - 2006

Tillage practice	1991	1996	2001	2006
	(Acres)			
Canada				
Total planted acres	71,731,650	70,901,537	73,472,899	71,781,032
Conventional tillage*	49,387,997	37,891,867	29,750,778	20,114,443
Reduced tillage**	17,522,247	21,663,137	21,918,819	18,354,767
No-till***	4,821,406	11,346,533	21,803,302	33,311,822
% zero till planted acres	6.7	16.0	29.7	46.4
Alberta				
Total planted acres	19,685,588	18,761,116	18,465,784	18,726,144
Conventional tillage*	14,291,324	10,657,824	6,847,096	4,589,714
Reduced tillage**	4,779,955	6,166,922	6,550,489	5,185,594
No-till***	614,109	1,936,370	5,068,199	8,950,836
% zero till planted acres	3.1	10.3	27.4	47.8
Saskatchewan				
Total planted acres	32,210,142	33,202,335	34,827,771	32,984,104
Conventional tillage*	20,592,996	15,036,366	11,300,237	6,036,996
Reduced tillage**	8,274,250	10,915,424	10,036,457	7,107,149
No-till***	3,342,896	7,250,545	13,491,077	19,839,959
% zero till planted acres	10.4	21.8	38.7	60.1
Manitoba				
Total planted acres	10,425,498	9,781,661	9,693,885	9,613,927
Conventional tillage*	6,912,686	6,196,544	5,280,248	4,174,437
Reduced tillage**	2,988,719	2,691,876	3,163,890	3,388,755
No-till***	524,093	893,241	1,249,717	2,050,735
% zero till planted acres	5.0	9.1	12.9	21.3

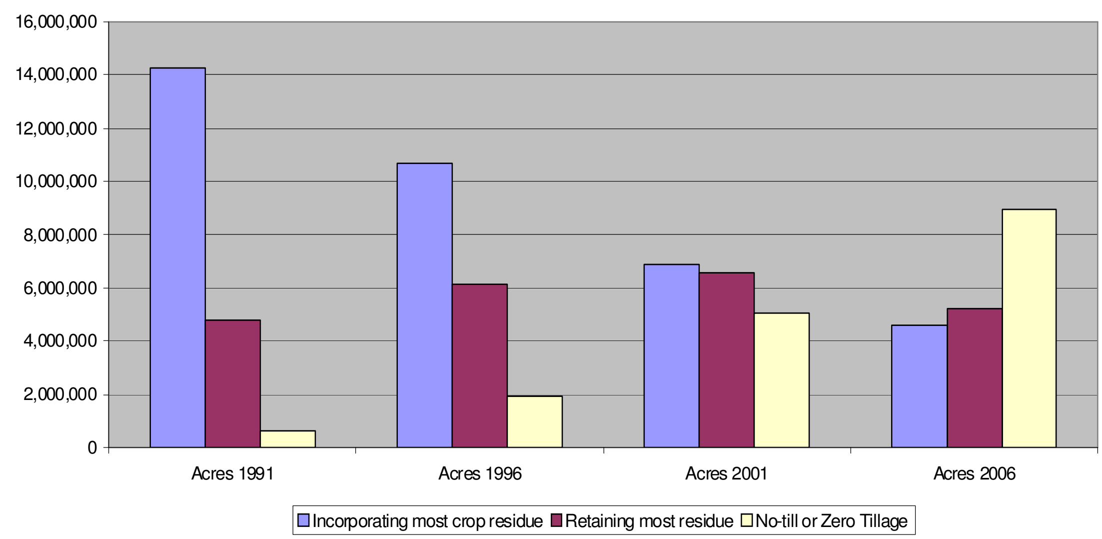
*Incorporating most of the crop residue into the soil; ** Retaining most of the crop residue on the surface; *** No-till or zero-till seeding
Source: Statistics Canada, 2007

Figure 1. Adoption of Zero Tillage on the Canadian Prairie:1991 - 2006



More growers in Alberta and Saskatchewan have adopted the use of zero-tillage technology as compared to growers in Manitoba. In Alberta, the number of farms using no-tillage seeding practices increased substantially while the number using reduced and conventional tillage practices decreased. Between 2001 and 2006, the number of farms using no-till and reduced tillage pre-seeding practices increased (61.8%) while the number using conventional tillage practices decreased (33.0%). In 2006, no-till was used on 9.0 million acres, representing 48% of the seeded acres. While reduced tillage was used on 5.1 million acres (28.0%) of the seeded acres, conventional tillage was used on 4.6 million acres (24.5%) of the land prepared for seeding (Figure 2).

Figure 2. Conservation Tillage Practices in Alberta 1991-2006



VI. Adoption Rate of No-Till in Alberta

No-tillage, no-till and direct seeding are terms that are often used interchangeably on the Canadian Prairies. However, Statistics Canada Census of Agriculture has a definition it has used for no-tillage since 1991 i.e. *planting of a crop into the untilled stubble of a previous crop with almost no soil disturbance*. As a result, there is a good picture of adoption in Canada since then. In 1991, there were just over 614,000 acres of no-till, and by 2006, no-till had increased to 8.95 million acres.

A regression analysis on the adoption curve has revealed that adoption of no-till in Alberta experienced a pronounced upward trend till 1996 (Philips 2008, personal communication). Since that time, the rate of adoption has declined slightly, but the actual number of acres adopted each year remained constant, approximately 626,000 acres per year (Figure 3).

A regression analysis on the adoption curve for no-till is a nearly perfect fit (Phillips 2008). Using this curve for future projection, Alberta will have approximately 10.8 million acres of no-till in 2009 or about 58% of the annually seeded acres, and adoption will continue to increase at a similar rate of (Figure 4).

Figure 3. Conservation Tillage Practices in Alberta 1991-2011
Projected from Statistics Canada Data

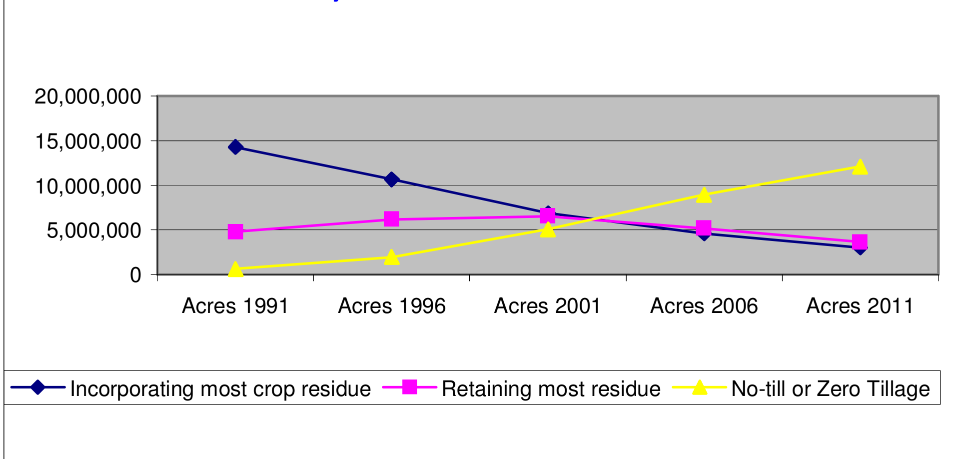
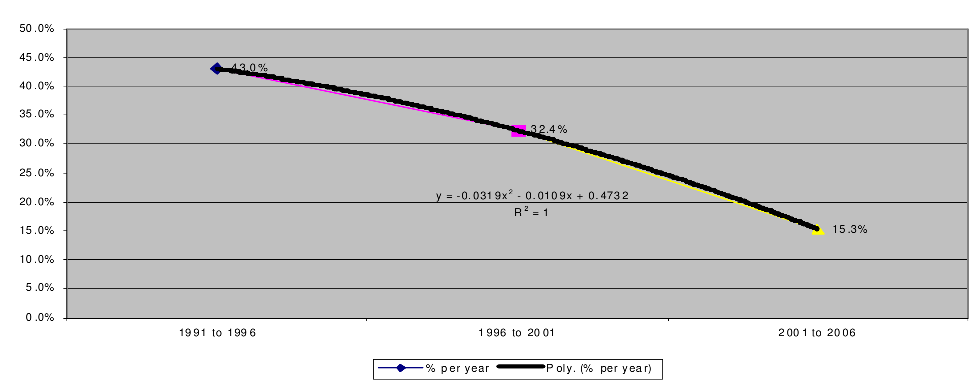


Fig 4. Rate of Adoption of No-till per Year



In Saskatchewan, between 2001 and 2006, the numbers of farms using no tillage practices increased substantially while the number using reduced and conventional tillage practices decreased. No tillage technology was used on 19.8 million acres (60%), reduced tillage was utilized on 7.1 million acres (22%) of the seeded acres, and conventional tillage was used on 6.0 million acres (18%) of the land prepared for seeding.

Manitoba also experienced a significant growth in no-till technology. Between 2001 and 2006, no-till was used on 2.0 million acres (21.3%), reduced tillage was employed on 3.4 million acres (34.4%), and conventional tillage was used on 4.1 million acres (43.4%) of the land prepared for seeding.

VII. Factors Influencing the Adoption of No-Till on the Canadian Prairies

There are several factors that increase the likelihood of Prairie framers adopting no-till technology. According to the 2006 Census of Agricultural data, farmer age and socio-economic factors play an important role in determining whether zero-tillage will be adopted. Davey et al (2008) using 1991, 1996 and 2002 Census of Agricultural data together with other data sources estimated a probit model on the adoption decision. They found the most important variable includes socio-economic factors, farm size, total gross farm sales, age, proximity to a research station, type of soil, and weather conditions.

VIII. Others Trends in Conservation Tillage Practices on the Canadian Prairies

Reduction in Tillage Intensive Fallow

Summerfallow is largely a western Canadian farming practice. It has been used through out the history of Prairie agriculture as a means of conserving soil moisture and weed control. Many farms, particularly in the driest part of the Brown and Dark Brown soil zones, traditionally followed a 50/50 rotation, which meant 50 percent of annual cropland was summerfallow each year.

Conventional summerfallow involves several light tillage treatments throughout the growing season to control weeds and conserve subsurface moisture. With the introduction of glyphosate, more producers have switched to a technique of chemical fallow (Chemfallow), which means crop residue and stubble are usually left undisturbed on the soil surface during the fallow year, and weed control is accomplished by the use of non-selective broad-spectrum herbicides such as glyphosate or paraquat.

Western Canada

According to the 2006 Census of Agriculture data, there are 6 million acres of summerfallow on the Canadian Prairies. Between 2001 and 2006, fallow acres declined by about 22%, and Chemfallow acres increased by 37.7% (Table 2)

- Chemical control was used on 2.6 million acres (37.7% of total summerfallow)
- A combination of chemical fallow and tillage was used on 1.9 million acres (30.9% of total summerfallow)
- Intensive tillage was used on 1.8 million acres (31.4% of the total summerfallow).

Table 2. Summer-fallow practices on the Canadian Prairies: Alberta, Saskatchewan, and Manitoba

Summerfallow practices	2006	2001	Absolute change	% change
	Acres		Acres	
Total summerfallow land	6,001,296	7,738,453	- 1,737,157	- 22.4
Tillage only	1,884,615	3,747,327	- 1,862,712	- 49.7
Chemicals and tillage	1,855,339	2,747,865	- 892,526	- 32.5
Chemfallow only	2,261,342	1,243,261	1,018,063	54.9
% Chemfallow acres	37.7	16.1		
Farms Reporting				
Total summerfallow land	18,779	28,114	- 9,335	- 33.2
Tillage only	8,026	15,791	- 7765	- 49.2
Chemicals and tillage	6,433	11,369	- 4936	- 43.4
Chemfallow only	5,562	4,994	568	11.4

Alberta

Relative to 2001, the number of acres where chemical fallow was used for weed control has increased and the use of tillage or combination of chemical fallow and tillage for control has decreased (Table 3).

- Chemical control was used on 1.1 million acres (44.8% of total summerfallow)
- Tillage only was used on 0.6 million acres (27.3%)
- A combination of chemical fallow and tillage was used on 0.62 million acres (27.8%)

Table 3. Summerfallow practices in Alberta: Census years 2001 to 2006

Summerfallow practices	2006	2001	Absolute change	% change
	Acres		Acres	
Total summerfallow land	2,239,633	3,053,214	- 813,581	- 26.6
Tillage only	611,550	1,186,260	- 574,710	- 48.4
Chemicals and tillage	623,710	1,145,908	- 522,198	- 45.6
Chemfallow only	1,004,373	721,046	283,327	39.3
% Chemfallow	44.8	23.6		
Farms Reporting				
Total summerfallow land	8,390	13,268	- 4,878	- 36.8
Tillage only	4,020	6,677	- 2,657	- 39.8
Chemicals and tillage	2,759	5,252	- 2,493	- 47.5
Chemfallow only	2,068	2,625	- 557	- 21.2

Saskatchewan

Relative to 2001, the number of acres where chemical fallow was used for weed control has increased while tillage only and a combination of tillage and chemical practices have declined (Table 4).

- Chemical control was used on 2.3 million acres (38% of total summerfallow)
- Tillage only was used on 1.9 million acres (31%)
- A combination of chemical fallow and tillage was used on 1.9 million acres (31%)

Table 4. Summerfallow practices in Saskatchewan: Census years 2001 to 2006

Summerfallow practices	2006	2001	Absolute change	% change
	Acres		Acres	
Total summerfallow land	6,001,296	7,738,453	- 1,737,157	- 22.4
Tillage only	1,884,615	3,747,327	- 1,862,712	- 49.7
Chemicals and tillage	1,855,339	2,747,865	- 892,526	- 32.5
Chemfallow only	2,261,342	1,243,261	1,018,063	54.9
% Chemfallow acres	37.7	16.1		
Farms Reporting				
Total summerfallow land	18,779	28,114	- 9,335	- 33.2
Tillage only	8,026	15,791	- 7765	- 49.2
Chemicals and tillage	6,433	11,369	- 4936	- 43.4
Chemfallow only	5,562	4,994	568	11.4

Manitoba

Relative to 2001, the number of acres where chemical fallow tillage only or the combination of tillage and chemical practices was used for weed control has decreased (Table 5)

- Chemical control was used on 41,308 K acres (13.2% of total summerfallow).
- Tillage only was used on 144,929 K acres (46.3%)
- A combination of chemical and tillage was used on 126,558 K acres (40.5%)

Table 5. Summerfallow practices in Manitoba: Census years 2001 to 2006

Summerfallow practices	2006	2001	absolute change	% change
	Acres		Acres	
Chemfallow only	41,308	76,454	- 35,146	- 46.0
Tillage only	144,929	318,196	- 173,267	- 54.5
Chemicals and tillage	126,558	237,280	- 110,722	- 46.7
Total summerfallow land	312,795	631,930	- 319,135	- 50.5
Farms Reporting				
Chemfallow only	2,792	5,902	- 3,110	- 52.7
Tillage only	300	850	- 550	- 64.7
Chemicals and tillage	1,001	2,133	- 1,132	- 53.1
Total summerfallow land	4,092	8,885	- 4,793	- 53.9

Additional Soil Conservation Practices

On the western Prairies, the absolute number of farms practicing crop rotation declined, however, the percentage of the total farms using crop rotations increased. Relative to 2001, the numbers of farms using winter cover crops, plowing down of green manure crops, and the use of windbreaks and shelterbelts as conservation practice have also increased (Table 6).

Table 6. Soil conservation practices on the Canadian Prairies: 2001 – 2004

Soil conservation practices	Number of farms reporting		
	2006	2001	% Change
Alberta			
Farms practicing crop rotation	29,332	31,206	- 6.0
Plowing-down of green crops (green manure)	1,943	1,243	56.3
Winter cover crops	2803	1,557	80.0
Wind-breaks or shelter-belts	24,810	9,784	153.5
Rotational grazing	21,609	N/A	
Buffer zones around water bodies	9,147	N/A	
Saskatchewan			
Farms practicing crop rotation	34,827	39,229	- 11.2
Winter cover crops	1,769	1,181	49.8
Plowing-down of green crops (green manure)	1,886	1,197	57.6
Wind-breaks or shelter-belts	18,104	7,282	148.6
Rotational grazing	11,240	N/A	
Buffer zones around water bodies	2,593	N/A	
Manitoba			
Farms practicing crop rotation	12,043	13,344	- 9.75
Winter cover crops	1,943	1,243	56.3
Plowing-down of green crops (green manure)	2,803	1,557	80.0
Wind-breaks or shelter-belts	9,451	4,072	132.1
Rotational grazing	6,041	N/A	
Buffer zones around water bodies	2,591	N/A	

IX. Concluding Remarks

No-till *(planting of a crop into the untilled stubble of a previous crop with little no soil disturbance)* is a conservation practice and it is economical (saving on fuel, farm machinery-life and reduced labor costs), while maintaining or improving crop yields) and is well known to be environmentally friendly (increased soil-organic matter, improved soil tilth, improved moisture conservation and use efficiency, and reduced soil erosion). No-till seeding also has the potential to sequester atmospheric carbon dioxide – an important factor in the mitigation of green house gas emissions.

The adoption of no-till in western Canada experienced a pronounced upward trend until 1996. Since that time, the percentage of planted acres using zero-tillage practices has exhibited a slight upward trend, growing at annual rate of 626,000 acres and this growth will continue until 2011.

Between 1991 and 2006, no-till seeded acres on the Prairies rose from 4.4 million acres to 30.8 million acres, an increase of 700% or 46.6% growth per annum. Similar to zero-tillage, the trend in other soil conservation practices have also increased substantially. In 2006, number of farms practicing other soil conservation practices was as follows:

- Reduction in summerfallow (26.4%)
- Increase in chemfallow (38%)
- Farms practicing crop rotation (39%)
- Farms using plowing-down of green crops (green manure) (4%)
- Farms using winter cover crops (5%)
- Farms with wind-breaks or shelter-belts (19%)
- Farms practicing rotational grazing (27%)
- Farms using grasses waterway or buffer-zone around water bodies (7%).

X. References

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SECTION 2

THE ECONOMIC, AGRONOMIC AND ENVIRONMENTAL IMPACT OF NO-TILL ON THE CANADIAN PRAIRIES.

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The Economics of No-Till

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The Economics of No-Till

In recent years, no-till has gained popularity among Canadian growers because this practice effectively reduces wind and water erosion, reduces fuel, labor, machinery wear and tear, and saves time. No-till also improves soil tilth, increases organic matter, traps soil moisture, improves water availability, enhances water and air quality, and increases wildlife. At the present time, no-till is practiced on more than 56% of the planted acres in western Canada. In order for this practice to be widely adopted on the remaining planted acres in western Canada, it is important to emphasize both the economic and environmental benefits and costs to farmers of using conservation tillage. Over the last ten years, considerable research has been carried out in western Canada comparing the economic and environmental performance of conventional, minimum and no-till systems. Following is a brief review of this research.

I. Background Information

Studies carried out in the late 1980s and early 1990s in western Canada have shown that reduced tillage systems were less economical than conventional tillage systems (Zentner and Lindwall 1978; 1982; Malhi et al 1988; Smith et al 1996; Zentner et al 1996, and Miller et al 1997). There were several main reasons for this poor economic performance in conservation tillage in the past:

- Monoculture cereal and cereal-fallow rotations in the Brown and Dark Brown soil zones
- Expensive glyphosate –the price of glyphosate in the mid to late 1980s was over $25.00/L as compared to the current price of less than $ 8.00/L
- Lack of glyphosate rate refinement and lack of familiarity with low water volume technology for weed control
- Broadcast application of N on the soil surface rather than side banding below the soil surface.

For example, in Alberta, the barley yield grown under zero-tillage achieved 79 – 93% of the yields under conventional tillage. The mean reduction in crop value (NPV) was also $34.47 lower than for conservation tillage. In this study, nitrogen fertilizer was surface applied, and the cost of Roundup was $25.00/L (Table 1).

Table 1. Difference in costs and value of sales on net present value (NPV) from barley production for no-till versus conventional tillage systems at four locations in central Alberta (Average 5 years – Experiment 1)

Location	Difference in numbers of operations		Net savings of field operations for zero-till	Extra cost of herbicide on no-till[b]				Reduction in crop value		
				Roundup		Other herbicides ($ ha-1)	Total ($ ha^{-1})	Yield (t ha^{-1})	Value of sales ($ ha^{-1})[d]	NPV loss ($ ha^{-1})[c]
	Cultivation	Spraying		Rate (L ha^{-1})	Cost ($ ha-1)					
Lacombe	-3.2	1.8	19.51	0.70	- 7.67	- 3.40	- 11.07	- 0.29	- 23.57	- 15.53
Joffre	-2.6	2.0	9.25	1.44	- 16.32	- 4.83	- 21.15	- 0.418	- 33.97	- 45.87
Crestomere	-3.4	1.8	18.20	1.72	- 18.85	- 6.58	- 25.43	- 0203	- 16.50	- 23.3
Blackfelds	-3.6	2.2	20.70	1.44	- 15.77	- 4.20	- 19.97	- 0.662	- 53.80	- 50.07
Mean	-3.2	2.0	16.91	1.34	- 14.67	- 4.75	- 19.42	- 0.393	- 31.96	- 34.47

[b] Cost and price data: harrowing = $4.24 ha^{-1}; cultivation = $10.43 ha^{-1}; spraying = $ 3.41 ha^{-1}; no-till seeding = $ 27.51 ha^{-1}; conventional tillage seeding = 16.09 ha^{-1}; barley price = $ 81.26 t^{-1}; Roundup (356 g/L) = $10.95. Sowing of barley was done by zero till drill on no-till plots and conventional tillage drill on conventional tillage plots.
[C] NPV loss is sum of savings from field operations, extra herbicide cost and reduction in crop value for no-till
[d] Number of field operations with no-till minus the number of field operations for conventional tillage
Source: Malhi et al (1993)

Studies carried out in the mid 1990s and early 2000s included diversified and extended crop rotations, inexpensive glyphosate, customized herbicide rates using the low water volume spray technology, and side banding of nitrogen fertilizer below the soil surface. The net returns in these studies are generally higher for no-till systems compared to conventional tillage systems (Zentner et al 1992; Lafond et al

1993; Malhi et al 1993; Nagy and Johnson 1997; Sonntag et al 1997 and Zentner et al 1999). For example, in a long-term study in central Alberta, barley yields and the net returns under no-till were equal to or greater to those obtained under conventional tillage at nitrogen rates of 67 and 101 kg N^{-ha} [(Table 2) (Malhi et al 1992)]. In this study, the price of Roundup was 10.95 per L, and nitrogen fertilizer was side banded into the soil at the time of sowing into zero-till plots (Malhi et al 1993). Band placement of fertilizer reduced losses of fertilizer nitrogen and possibly enhances nitrogen use efficiency more with no-till than conventional tillage (Brandt 1992). Surface application of N reduces the availability of N and increases the potential of N loss due to ammonia volatilization; these problems may contribute to yield difference found between no-till and conventional tillage (Malhi et al 1992).

Table 2 Grain yields and net present value of grain above fertilizer cost under various tillage and straw disposal treatments at four levels of Urea N side banded at the time of sowing at 2 locations in central Alberta (Average of 5 years – 2 experiments).

Location	Treatment		Grain yields (t^{-ha}) at N rates (kg N $^{ha-1}$)				NPV ($\$^{ha-1}$) at N rates (kg N $^{ha-1}$)			
	Straw	Tillage	0	34	67	110	0	34	67	110
Rimbey	Removed	ZT	1.491	2.071	2.912	3.294	121	151	204	219
	Retained	CT	1.600	2.281	2.961	3.015	130	169	208	196
	Removed	ZT	1.350	2.086	3.016	3.424	110	153	212	229
	Retained	CT	1.613	2.264	3.006	3.180	131	168	212	209
Innisfail	Removed	ZT	2.727	3.170	3.575	3.832	221	241	258	262
	Retained	CT	3.123	3.318	3.683	3.790	254	253	267	259
	Removed	ZT	2.505	2.940	3.664	3.878	204	223	265	266
	Retained	CT	2.656	3.196	3.627	3.917	216	243	262	269

Fertilizer price at 6 times the barley price (historical mean); discounted barley price \$86.21 t^{-1} of grain
ZT and CT refers to no-till and conventional tillage, respectively.
Source: Malhi et al (1993)

II. Economic Evaluation of No-till

No-till systems have many short, and long-term agronomic and environmental benefits, however, the long-term sustainability of no-till cropping system depends upon its profitability (i.e., grain yield must be equal to or greater than that of conventional tillage), agronomic feasibility and economic viability (Campbell et al 1995). Farmers who adopt conservation tillage practices do so with the hope that it will maximize net farm income and/or reduce risk taking. Factors that contribute to the net farm income include yield, cost of input used in crop production (labor, fuel, fertilizer, pesticide, seed and machinery), and expected output (commodities) prices (Uri 1999).

1. Grain Yield – Small Scale Research Plots

Grain and straw yield are determined by site-specific factors such as soil characteristics, local climatic conditions, cropping patterns, and overall farm management practices. Over the long haul, no-till affects soil structure, organic matter content, and soil microbial populations, moisture availability, affecting grain and straw yield. Yield benefits associated with conservation tillage practice takes a relatively long time to materialize. In the present paper, an attempt was made to summarize all the available yield response studies to different tillage systems under a wide variety of soil and climatic conditions in western Canada.

A. Wheat and Barley

Grain yields of spring and winter wheat are presented in Table 3. Based on 23 studies, wheat grain yield was on average 3.5 % higher with no-till compared with all other tillage systems. In 7 studies, no-till had a significantly higher (9 – 26%) yield compared to conventional tillage. In 13 studies, there were no significant differences in yield between zero and conventional tillage. In contrast, in 3 studies, conventional tillage had a significantly higher yield compared with no-till.

Table 3. Spring wheat and winter wheat grain yield in western Canada by tillage system and soil types

Location	Soil Zone	Year	Tillage System			No-till yield advantage (%)	Reference
			Conventional	Minimum	No-till		
			-------------- Yield (kg ha^{-1}) --------------				
Wheat, spring							
Melfort, SK	Black	1994 –97	4487	4482	4469 ^{NS}	- 0.4	Nagy and Johnson 2000
Melfort, SK	Black	1986 – 89	2058	—	2300 *	+ 11.8	Wright 1990
Melfort, SK	Black	1986 – 89	2038	—	2231 *	+ 9.4	Wright 1990
Carman, MB	Black	1989	2051	—	1816 ^{NS}	- 11.5	Borstlap and Entz 1994
Portage, MB	Black	1990	4223	—	4055 ^{NS}	- 3.9	Borstlap and Entz 1994
Carman, MB	Black	1989	2051	—	1809 ^{NS}	- 11.8	Borstlap and Entz 1994
Portage. MB	Black	1990	3544	—	3887 ^{NS}	+ 9.6	Borstlap and Entz 1994
Univ-Manitoba, MB	Black	1969 – 89	2448	—	2575 *	+ 5.2	Lafond et al. 1990
Three Hills, AB	Thin Black	2001 –03	1647	—	2078	+ 26.2	Wang et al. 2004
Indian Head, SK	Thin Black	1987 – 90	2549	2636	2549 ^{NS}	0	Lafond et al. 1992
Indian Head, SK	Thin Black	1987- 90	1560	1896 *	1883 *	+ 20.1	Lafond et al. 1992
Indian Head, SK	Thin Black	1987-98	2431	2497	2434 ^{NS}	+ 0.12	Zentner et al 1999
Coronation, AB	Dark Brown	1986 – 90	1714	1836 *	2112 *	+ 23.2	Jans et al. 1991
Coronation, AB	Dark Brown	1987 – 90	2374	—	2401 ^{NS}	+ 1.1	Jans et al. 1991
Scott, SK	Dark Brown	1979 – 90	1883	—	2098 *	+ 11.4	Grevers et al. 1992
Swift Current, SK	Brown	1993-97	2234	—	2326 ^{NS}	+ 4.1	Miller and Zentner 2000
Swift Current, SK	Brown	1992-96	2303	—	2337 ^{NS}	+ 1.5	Miller and Zentner 2000
Ft.Vermilion, AB	Gray	1985 – 87	2683	2622	2542 *	- 5.2	Clayton, 1999
Star City, SK.	Gray	2004	2896	—	2694 *	- 7.0	Melhi et al 2006
Tisdale, SK	Gray	1994-97	3439	3171	2956 *	- 14.0	Nagy and Johnson 2000
						Mean: + 3.5%	
Wheat, winter							
Indian Head, SK	Thin Black	1992	2037	2152	2084 ^{NS}	+ 2.5	Lafond et al 1992
Indian Head, SK	Thin Black	1987-98	2613	2548	2532 ^{NS}	- 3.1	Zentner et al 1999
Melfort, SK	Black		2037	—	2287 *	+ 12.3	Wright 1990
						Mean: + 4.1%	

* Denotes significant at 0.05 level of significance, NS = non-significant, — = system not included in the experiment.

Grain yield of barley from 15 studies is presented in Table 4. Barley grain yield on average was 6.2 % higher with no-till compared with all other tillage systems. In 6 studies, no-till had a significantly higher (2 – 51%) yield compared to conventional tillage. In 8 studies, there were no significant differences in yield between zero and conventional tillage.

Table 4. Barley grain yield in western Canada by tillage system and soil type

Location	Soil Zone	Year	Tillage System			No-till yield advantage (%)	Reference
			Conventional	Minimum	No-till		
			-------------- Yield (kg ha^{-1}) --------------				
Hairy Hill, AB	Black	1989 – 92	3389	3395	3507 [NS]	+ 3.5	McAndrew et al 1994
Melfort, SK	Black	1986 – 89	3292	—	3465 [NS]	+ 5.1	Wright 1990
Melfort, SK	Black	1986 – 89	3212	—	3621 [*]	+ 12.7	Wright 1990
Melfort, SK	Black	1994 – 97	3249	3379	3193 [NS]	- 1.7	Nagy and Johnson 2000
Univ-Manitoba, MB	Black	1969 – 89	3911	—	4013 [NS]	+ 2.6	Lafond et al. 1990
Wainwright, AB	Thin Black	1989 – 92	4035	3927	4250 [*]	+ 5.3	McAndrew et al 1994
Indian Head, SK	Thin Black	1985 – 87	2260	2330	2389 [*]	+ 5.7	Lafond et al. 1992
Indian Head, SK	Thin Black	1987- 98	2954	2846	2841 [*]	- 3.8	Zentner et al 1999
Alliance, AB	Dark Brown	1989 – 92	3663	3868	4245 [*]	+ 15.9	McAndrew et al 1994
Ft. Vermilion, AB.	Gray	1985 – 87	2577	2613	2450 [NS]	- 4.9	Clayton, 1999
Rycroft, AB	Gray	1989 – 90	1350	1560	1399 [NS]	+ 3.6	Arshad et al 1995
Elk Point, AB	Gray	1989 – 92	2566	2609	2550 [NS]	- 0.6	McAndrew et al 1994
Plamondon, AB	Gray	1989 – 92	3362	3045	3427 [*]	+ 1.9	McAndrew et al 1994
Star City, SK	Gray	2002-05	670	—	1014 [*]	+ 51.4	Melhi et al 2006
Tisdale, SK	Gray	1994-97	2954	2846	2841 [NS]	- 3.8	Nagy and Johnson 2000
						Mean: + 6.2%	

[*] Denotes significant at 0.05 level of significance, NS = non-significant, — = system not included in the experiment.

B. Canola and Flax

Grain yield of canola is presented in Table 5. Based on 12 studies, canola yield, on average, was 2.0% lower in no-till treatments as compared to conventionally tilled treatments. In 2 studies, zero tilled plots had 5 - 14% higher yield as compared to conventionally tilled plots, whereas, in 3 studies the opposite was true. In another 7 studies, there were no significant differences in yield between zero and conventionally tilled plots. Information on flax yield is presented in Table 5. On average, flax yields were 7.9% higher in zero tilled plots as compared with conventionally tilled plots.

Table 5. Canola and flax grain yield in western Canada by tillage system and soil types

Location	Soil Zone	Year	Tillage System			Zero-till yield advantage (%)	Reference
			Conventional	Minimum	Zero		
			-------------- Yield (kg ha^{-1}) --------------				
Canola							
Carman, MB	Black	1989	1995	—	1832 [NS]	- 8.2	Borstlap and Entz 1994
Carman, MB	Black	1990	2269	—	2180 [NS]	- 3.9	Borstlap and Entz 1994
Portage, MB	Black	1989	2001	—	1928 [NS]	- 3.6	Borstlap and Entz 1994
Portage, MB	Black	1990	2253	—	2247 [NS]	- 0.3	Borstlap and Entz 1994
Univ- Manitoba	Black	1969 - 89	1395	—	1592 [*]	+ 14.1	Lafond et al 1990
Melfort, SK	Black	194-97	1815	1777	1842 [NS]	+ 1.5	Nagy and Johnson 2000
Indian Head, SK	Thin Black	1985 - 87	1250	1121	1132 [*]	- 9.4	Lafond 1992
Ft. Vermilion, AB.	Gray	1985 - 87	1200	1143	1180 [NS]	- 1.7	Clayton, 1999
Rycroft, AB	Gray	1989 -90	588	869	622 [*]	+ 5.8	Arshad et al 1995
Star City, SK	Gray	2002	2082	—	1909 [NS]	- 4.6	Melhi, 2005 et al
Tisdale, SK	Gray	1994-97	1752	1759	1637 [*]	- 8.3	Nagy and Johnson 2000
Scott, SK	Dark Brown	1979 - 90	1292		1217 [*]	- 5.8	Grevers et al. 1992
						Mean: - 2%	
Flax							
Univ - Manitoba	Black	1969 - 71	728	—	791 [*]	+ 8.7	Lafond et al. 1990
Melfort, SK	Black	1986 - 89	1306	—	1394 [*]	+ 6.7	Wright 1990
Melfort, SK	Black	1994 - 97	1867	1717	1820 [NS]	- 2.5	Nagy and Johnson 2000
Indian Head, SK	Thin Black	1987 - 91	1232	—	1401 [*]	+ 13.7	Lafond et al 1992
Indian Head, SK	Thin Black	1987 - 91	1440	1612	1629 [*]	+ 13.1	Zentner et al 1999
						Mean: + 7.9 %	

* Denotes significant at 0.05 level of significance, NS = non-significant, — = system not included in the experiment.

C. Field Peas and Lentils

Field peas and lentils yield is presented in Table 6. On average, field peas and lentils yields were 5 and 13% higher respectively, in zero tilled plots as compared with conventionally tilled plots.

Table 6. Field peas and lentils grain yield in western Canada by tillage system and soil types

Location	Soil Zone	Year	Tillage System			Zero-till yield advantage (%)	Reference
			Conventional	Minimum	Zero		
			-------------- Yield (kg ha^{-1}) --------------				
Field peas							
Carman, MB	Black	1989	1957	—	2010 ^{NS}	+ 2.7	Borstlap and Entz 1994
Carman, MB	Black	1990	3779	—	4129 ^{NS}	+ 8.4	Borstlap and Entz 1994
Portage, MB	Black	1989	3739	—	3369 ^{NS}	- 9.9	Borstlap and Entz 1994
Portage, MB	Black	1990	3403	—	3470 ^{NS}	+ 1.9	Borstlap and Entz 1994
Melfort, SK	Black	1986 - 89	1910	—	2219 *	+ 16.2	Wright 1990
Melfort, SK.	Black	1994 - 97	2260	2125	2362 ^{NS}	+ 4.5	Nagy and Johnson 2000
Indian Head, SK	Thin Black	1987 - 90	1950	1903	2152*	+ 10.2	Lafond et al 1992
Indian Head, SK	Thin Black	1987 - 98	2272	2407	2450 *	+ 7.8	Zentner et al 1999
Star City, SK	Gray	2003	1992	—	1997 ^{NS}	+ 0.1	Melhi et al 2006
						Mean: + 4.6%	
Lentils							
Melfort, SK	Black	1986 -89	1210	—	1527 *	+ 26.2	Wright 1990
Swift Current, SK	Brown	1992 – 96	1551	—	1547 ^{NS}	- 0. 3	Miller and Zentner 2000
						Mean: + 13.0%	

* Denotes significant at 0.05 level of significance, NS = non-significant, — = system not included in the experiment.

2. Grain Yield – Field Scale Plots

A 5-year field scale study in western Manitoba compared the economics of zero, minimum tillage, and conventional tillage (Manitoba Department of Agriculture 1990). In this study a 90-acre field was divided into thirds: one third farm conventionally (one to two cultivations in the fall plus fertilizer application, cultivation, harrow and seeding in spring), another third was farmed using minimum tillage (fall banding of fertilizer, cultivation, harrow and seeding in spring), and the remaining third was farmed with no-till practice (fall banding, spring seeding). Similar to small-scale research plots, the grain yield for conservation tilled wheat; yields for barley and canola were either equal to or higher than for the conventional tilled areas. (Table 7)

Table 7. Wheat barley and canola grain yield in a 5-Year Manitoba study by tillage systems

Location	Crop	Year	Tillage System			No-till yield advantage (%)
			Conventional	Minimum	No-till	
			-------------- Yield (kg ha^{-1}) -------------			
Manitoba	Wheat	1985	3632	3766	3766	3.4
	Barley	1986	3562	3938	4159	16.7
	Barley	1987	3400	3744	4148	22.0
	Canola	1988	367	460	622	69.5
	Wheat	1989	3692	4122	4317	16.9

In summary, for conservation tilled (minimum and zero) wheat, barley, canola, flax, peas and lentils, grain yields were either higher or equal to conventional tillage. Yield increases with no-till management are usually associated with improved soil water conditions. At some locations there was a decreased yield with no-till relative to conventional tillage. This often occurs in environments with abundant precipitation and on poorly drained soils (Unger and McCalla 1980). Lower yields under reduced tillage systems may also be related to changes in physical properties of the soil, and residue management that influences the survival and activity of plant pathogens, resulting in the potential buildup of disease in these systems (Rothrock 1992).

III. Production Costs

Production costs are an important component in the net return equation of no-till relative to conventional tillage. Production cost involves cost of labor, fertilizer, fuel, pesticides, seed and machinery. Grain handling and drying costs also come into play in the equation if there are significant differences in yield. Land cost is usually the same as with the conventional tillage systems

1. Labor Use and Cost

In zero and minimum tillage systems there is a significant reduction in the intensity and number of tillage operations as compared to conventional tillage. This lowers the cost for labor and machinery, especially if machinery is used optimally. Appleby (1988 –1992) calculated the typical field operation for various tillage systems in Alberta. Conventional tillage systems have the greatest labor requirement for tilling, fertilization and planting crops (7.5 field operations). Reduced tillage systems require 5.8 field operations for tilling and planting, while no-till systems require the fewest field operations (Table 8). Weersink et al (1992) also found that by adopting no-till practices, corn and soybean farmers in southern Ontario realized a significant amount of savings in labor costs. They showed that the omission of pre-plant spring tillage alone reduces the labor requirement by 60%, thus freeing up the extra time for other operations on the farm.

The number of hours devoted to tillage operations is different for conventional, reduced and no-till systems. A cropping survey study in Alberta in 1992 has shown that conventional tillage operations took one-hour and 23 minutes per hectare while no-till required only 0.5 hours per hectare [(Appleby 1988 – 1992) (Table 9)]. Similarly, the USDA, Economic Research Service, Cropping Pracice Survey (1990-1995) also showed that conventional tillage operations for wheat took 116 minutes per hectare, while conservation tillage required only 54 minutes per hectare (Uri 1999).

Table 8. Field operations by tillage systems

	Conventional tillage	Reduced tillage	No-till
Fall tillage	0.90	0.36	0.00
Fall spray	0.00	0.17	0.00
Fall fertilization	0.20	0.49	0.00
Pre-seed tillage	1.70	0.57	0.00
Pre-seed harrow	0.80	0.00	0.00
Pre-seed weed burndown	0.00	0.25	0.50
Seeding	1.0	1.0	1.0
Harrowing	0.40	0.45	0.00
Post-seed spray	1.10	1.00	1.20
Swathing	0.40	0.53	0.10
Combining	1.0	1.00	1.00
Total passes	**7.50**	**5.82**	**3.80**

Source: Appleby 1988 – 1992: Alberta Agriculture Farm Survey

Table 9. Field operation hours by tillage systems: Alberta Agriculture Farm Survey 1988 – 1992

Tillage System	Average Size of Farm	Number of hours labour	Minutes per hactare
Conventional	127 acres	63.15	73.7
Reduced	93 acres	29.22	46.8
Zero	160 acres	37.70	34.9

Source: Appleby 1988 – 1992: Alberta Agriculture Farm Survey

2. Fertilizer Use and Cost

Conservation tillage systems retain a large amount of crop residues on the soil surface and keep the soils cooler and wetter. Soils in conservation tillage systems also have increased organic matter, improved moisture retention and permeability, and reduced mineralization of nutrients due to less mixing of soils. All these characteristics can have an impact on the fertilizer needs of the crop and nutrient availability (Schoenau and Campbell 1996).

There is no agreement in the literature on the effects of no-till on fertilizer needs and nutrient availability. Some researchers have suggested that, over the long haul, fertilizer use will decrease under no-till because it is injected (side or mid-row banded) below the soil surface, resulting in more efficient use of nutrients, while others have suggested that the fertilizer requirement will increase or stay the same for both no-till and conventional tillage systems.

Cropping Practice Survey data by USDA have shown that the use and cost of both nitrogen and phosphate is about the same for both reduced tilled and conventionally tilled crops (Table 10). A 12-year tillage and crop rotation study in Iowa has shown a lower nitrogen and phosphate requirement in corn following soybeans. In contrast, Lindwall et al. (2000) found that no-till wheat tied up nitrogen in residue and soil organic matter. They concluded that no-till decreased yields unless accompanied by better nutrient management. No-till, accompanied by appropriate nutrient management, increased net returns by 5% for canola, 30% for wheat, and 25% for peas, but in canola, it only raised fertilizer costs (14%).

Table 10. Average fertilizer use by tillage practices – 1995

Commodity	Conventional tillage	Conservation tillage
	Pounds per acre	
Spring wheat		
Nitrogen	58.0 ± 2.91	47.4 ± 4.93
Phosphate	26.2 ± 1.42	29.9 ± 1.52
Potash	6.23 ± 0.91	1.37 ± 0.62
Durum wheat		
Nitrogen	59. 9 ± 4.55	65.1 ± 5.88
Phosphate	17.6 ± 1.55	19.0 ± 2.09
Potash	1.3 ± 0.49	1.5 ± 1.49
Winter wheat		
Nitrogen	61.7 ± 1.61	55.6 ± 2.84
Phosphate	20.9 ± 0.87	23.5 ± 1.84
Potash	9.3 ± 0.87	17.0 ± 2.08

± Denotes standard errors.
Source: USDA, Economic Research Service, Cropping Practices Survey: 1990 – 1995

3. Fuel Use and Cost

The major components of conventional tillage systems are tillage (fall and spring), fertilization, harrowing, seeding, in-crop spraying and harvesting (swathing and combining). All these are major users of diesel. It is estimated that conventional tillage with a heavy-duty cultivator uses about 5.4 L/ha (2.2 L/acre) of diesel fuel for every tillage operation. No-till replaces tillage with a glyphosate application for weed control, thus significantly reducing trips across the field. Fuel use for spraying is about 1 L/ha (0.4 L/acre) of diesel, less than 20% of that required for tillage. Depending on the size of seed and fertilizer tank, direct seeding equipment (air seedier or air drills) uses more fuel (3.0 – 3.5 L/acre) as compared to conventional seeding with a hoe-drill. During harvest operations, there are no difference in fuel consumption between zero till and conventional tillage. Fuel used for combine during the harvesting operation can be as high as 12.4 L/ha or 5.0 L/acre. In direct seeding operations, seeding, harvesting, and two weed control passes uses about 8.8 L/acre of diesel (Table 11).

In a long-term study on the effects of tillage, Lafond et al (1999) have shown a significant reduction in fuel consumption with reduced and zero-tillage as compared to conventional tillage (Table 12).

Table 11. Estimate of fuel consumption by tillage systems.

Field operations	Tillage systems		
	Conventional tillage	Reduced tillage	No-till
	Fuel consumption L/acre		
Fall tillage	1.98	0.8	0.00
Fall spray	0.00	0.09	0.00
Fall fertilization	0.44	1.1	0.00
Pre-seed tillage	3.75	1.25	0.00
Pre-seed harrow	0.4	0.00	0.00
Pre-seed weed burndown	0.00	0.80 (2-passes)	0.80 (2-passes)
Seeding	2.5	2.50	3.00
Harrowing	0.16	0.18	0.00
Post-seed spray	0.44	0.40	0.50
Swathing	0.44	0.58	0.11
Combining	5.0	5.0	5.0
Oil and Grease	2.66	1.8	1.3
Total fuel used:	17.8	13.7	9.9

Source: Appleby 1988 – 1992: Alberta Agriculture Farm Survey

Table 12. The effects of tillage systems and crops on fuel use at Indian Head, SK. (1987-97).

Tillage system	Field peas	Flax	Winter wheat	Spring wheat	
				Fallow	Stubble
	Fuel Use $L.ha^{-1}$				
Zero-tillage	18.8	18.6	19.4	23.5	19.1
Minimum tillage	23.3	23.7	19.3	30.6	24.0
Conventional till	32.3	30.3	19.2	47.1	30.2
	Contrast				
ZT + MT vs. CT	**	**	NS	**	**
ZT vs. MT	**	**	NS	**	**

** Denotes significant at 0.05 level of significance, NS = non-significant,
Source: Lindwall et al (2000).

4. Pesticide use and Cost

Chemical weed control in any tillage system depends on catching the right stage of plant growth, pre- and post-spraying environmental conditions, plant stress, weed species diversity and number. For these reasons, the management strategy varies with location and tillage system and requires site-specific management strategies. In minimimu and zero-tillage systems, most of the weed seeds are at or near the soil surface (0 – 5 cm) where they have lower seed dormancy and high seedling mortality due to drought, and by predation by insects and other animals. Thus, adequate above ground weed control in the first few years of no-till can greatly reduce the weed seed bank in the upper layer of soils (O'Donovan and McAndrew 2000). In contrast, in conventional tillage systems, seeds are buried in the soil, resulting in conditions that are conducive to seed dormancy and perpetual weed problems.

There are conflicting reports on the relative use of herbicides across the tillage systems in western Canada. An Alberta Agriculture study showed no difference in herbicide cost between minimum – zero-tillage and conventional tillage systems (Lewis 2000). However, the cropping practices survey in Saskatchewan showed that herbicide cost for minimum – no-till was slightly higher than conventional tillage (Table 13). Lindwall et al (2000) also showed that herbicide application costs for minimum – zero-tillage were greater than for conventional tillage over the period 1987 to 1997 for wheat on fallow, wheat on pea stubble, and for wheat on cereal stubble (Table 14). Appleby (1988 – 1992) also showed slightly higher herbicide cost for minimum – zero-tillage as compared to conventioanal tillage.

In western Canada, there is no information available on insecticide use in minimum – zero-tillage versus conventional tillage. However, according to the USDA, Economic Research Service, Cropping Practice Survey (1990-1995) in the U.S., less insecticde is used in conservation tillage than in conventional tillage. For example, in corn, the insecticide use on conservation tilled acreage was 0.68 kg ai/ha and 0.87 kg ai/ha for conventional tilled acreage (Uri 1999).

Table 13. Estimated herbicide costs for minimum – zero and conventional seeded stubble crops

Crop Type	Conventional seeded stubble crops $/ha			Direct Seeded Stubble Crops $/ha		
	Brown Soil Zone	Dark Brown Soil Zone	Black Soil Zone	Brown Soil Zone	Dark Brown Soil Zone	Black Soil Zone
Wheat	25.95	35.77	35.77	34.34	44.14	44.14
Barley	26.71	37.18	37.18	35.10	45.55	45.55
Canola	-	48.81	48.81	-	58.63	58.63
Mustard	39.58	-	-	41.36	-	-
Flax	51.06	52.05	52.05	59.43	60.41	60.41
Field peas	-	46.96	50.22	-	55.34	55.34
Lentils	82.11	82.11	82.11	90.49	90.49	90.49

Source: Saskatchewan Agriculture and Food and Rural Revitalization, 2002

Table 14. The effects of tillage systems and crops on herbicide and fuel use at Indian Head, SK. (1987-97).

Tillage system	Field peas	Flax	Winter wheat	Spring wheat	
				Fallow	Stubble
	Herbicide Use g a.i.ha^{-1}				
No-till (NT)	1726	1721	1164	3536	1966
Minimum tillage (MT)	1410	1528	1157	2816	1719
Conventional till (CT)	1565	1034	1155	1430	1284
	Contrast				
ZT + MT vs. CT	NS	**	NS	**	**
ZT vs. MT	NS	**	NS	**	**

Source: Lindwall et al (2000)
** Denotes significant at 0.05 level of significance, NS = non-significant,

5. Seed Use and Cost

Most of the studies in western Canada have shown no difference in seeding rates between conservation tillage and conventional tillage. Results of the Cropping Practices Survey by USDA also indicate that growers do not vary the seeding rate by tillage practices.

6. Machinery Use and Cost

Conservation tillage requires fewer trips across the field, allows two or more activities to be combined into one, or permits the use of machines with greater capacity and lower draft (Table 15). However, producers who switch to conservation tillage may see an increase in capital cost expenditures. The amount of investment depends on the existing machinery complement

Table 15. Cost of tillage, seeding and spraying operation in zero, minimum and conventional tillage: Operation for 2000-acre farm

Machinery	Size	Value ($)	Use (ac yr^{-1})	Use (hrs $^{-1}$)	Total cost ($ Yr$^{-1)}$
No-till					
Air drill (new)	33 ft	75,000	2,000	125	13,650
Sprayer (used)	80 ft	15,000	4,000	85	7,070
Cultivator (used)	42 ft	12,000	200	10	2,590
Harrow (used)	70 ft	4,000	400	10	980
4 WD Tractor (used)	300 hp	100,000		185	18,280
2 WD Tractor (used)	150 hp	50,000		247	5,560
					Total: 48,130
Minimum tillage					
Air drill (new)	33 ft	75,000	2,000	250	18,510
Sprayer (used)	80 ft	15,000	2,500	53	5,540
Cultivator (used)	42 ft	12,000	200	12	2,940
Harrow (used)	70 ft	4,000	1,000	23	1,090
4 WD Tractor (used)	300 hp	100,000		335	23,770
2 WD Tractor (used)	150 hp	50,000		203	3,570
					Total: 55,420
Conventional tillage					
Press drill (new)	40 ft	56,000	2,000	90	9,790
Sprayer (used)	80 ft	15,000	2,500	53	5,540
HD Cultivator (used)	42 ft	15,000	5,000	250	6,930
Disc (used)	30 ft	15,000	1,000	61	4,870
Harrow (used)	70 ft	8,000	4,000	90	2,540
4 WD Tractor (used)	300 hp	100,000		452	2,6870
2 WD Tractor (used)	150 hp	50,000		294	7,180
					Total: 63,720

A = water supply tank $ 35.00/hr
B = other farm activities @ $50/hr
Source: Appleby 1988 – 1992: Alberta Agriculture Farm Survey

IV. Cost Comparison for Different Tillage Systems

Crop production profits are a function of soil characteristics, climatic conditions, cropping sequences, and other farm management practices. Conservation tillage provides savings in cost for labor, fuel, machinery repairs and overheads. In most years, crop yield is either higher or equal to conventional tillage. Along with machinery cost, herbicide use is major input affected by tillage systems. Conservation and conventional tillage system relay on herbicides for weed control. Depending on the weed problem in a given year herbicide cost in conservation system can be greater than, equal to or smaller than conventional tillage

1. Brown and Dark Brown Soil Zones

Considerable research has been conducted on the economic benefits of reduced tillage systems in the Brown and Dark Brown soil zone in western Canada. Zentner et al (1996) reported that use of minimum and no-till practices in wheat fallow rotation generated saving in machinery and labor cost averaged $141 ha$^{–1}$ for F–W and $224 ha$^{–1}$ (or 59% more) for continuous wheat. The use of conservation tillage practices produced savings in labor, machinery operation, and ownership costs of $3 to $7 ha-1 for minimum tillage and $6 to $9 for no-till managed fallow – wheat, but saving was only $2 ha-1 for continuous wheat system. In contract, to these saving in labor and machinery related cost with conservation tillage practices, the expenditure for herbicide increased by $11 ha^{-1} with minimum tillage and by $31 ha^{-1} with no-till-managed fallow – wheat. The net effect was that total costs for the fallow–wheat systems averaged 6% higher ($7 ha^{-1} more) when using minimum tillage versus conventional tillage practices.

In another 4–yr (1992 –1996) study of diversified cropping systems conducted at Swift Current SK., total cost averaged $222 ha^{-1} for fallow–crop–crop rotations compared with $303 ha^{-1} (or 36% more) for continuously cropped systems (Table 16). In this study production costs were higher for no-till than for conventional management in both the 3-yr ($18 ha^{-1}) higher, or 9% more) and continuous crop rotations ($15 ha^{-1} higher, or 5%more).

Table 16. Production costs and economic return for complete cropping systems in the Brown soil zone, Swift Current, SK

Cropping system	Tillage method	Variable cost	Total cost	Gross return*	Net return
		--		$ha^{-1}	-------------------------------
Fallow–Wheat–Wheat	Conventional	169	197	227	30±23
	No-till	195	214	228	14±20
Wheat–Wheat	Conventional	221	272	280	8±24
	No-till	234	286	285	– 1±17
Fallow–Mustard–Wheat	Conventional	177	205	257	53±42
	No-till	203	223	258	36±29
Mustard–Wheat	Conventional	235	286	306	20±45
	No-till	250	302	325	23±40
Fallow–Sunflower–Wheat	Conventional	171	198	208	10±43
	No-till	197	216	204	– 11±29
Sunflower–Wheat	Conventional	229	280	273	– 7±47
	No-till	243	295	278	– 17±44
Fallow–Lentil–Wheat	Conventional	220	249	348	99±36
	No-till	246	267	348	81±38
Lentil – Wheat	Conventional	291	345	466	121±81
	No-till	305	359	460	100±73
Fallow–Field pea–Wheat	Conventional	184	213	241	28±23
	No-till	212	233	257	24±24
Field pea–Wheat	Conventional	238	291	340	50±43
	No-till	252	306	347	41±38
Fallow–Chickpea–Wheat	Conventional	188	214	283	68±45
	No-till	215	233	286	53±47
Chickpea–Wheat	Conventional	246	296	407	111±73
	No-till	260	312	415	103±69

* $138 t^{-1} for wheat (12% protein), $287 t^{-1} for mustard, $243 t^{-1} for sunflower, $441 t^{-1} for lentil, $132 t^{-1} for field pea, and $375 t^{-1} for chickpea. Inputs were valued at 1999 cost levels.
± mean follow by standard error
Source: Zentner et al 2002 Agron. J. 94:216–230.

In the Dark Brown soil zone at Scott, SK, results from a 12-yr study of fallow–oilseed–wheat and oilseed–wheat–wheat rotations in which conventional tillage and no-till practices were compared showed that production costs (based on 1991 input cost levels) averaged $166 ha^{-1} for fallow – oilseed – wheat and $217 ha^{-1} for oilseed–wheat–wheat. Costs were also higher for no-till than conventional tillage. In this study the use of no-till practices generated labor and machinery cost savings of $7 to $10 ha^{-1}, however, these savings were more than offset by higher herbicide expenditure (Zentner 1992).

Smith et al. (1996) also reported that total cost were highest for no-till, less for minimum tillage and least for conventional tillage for wheat and barley production in the Dark brown soil zone at Lethbridge, AB.

The high relative cost for minimum – no-till is mainly due to higher cost of controlling weeds on summerfallow with glyphosate (1994 price level) compared to conventional tillage. It should be noted that recently the price of glyphosate has fallen substantially and taking this price reduction into account, the cost production would be in favor of no-till practices.

2. Thin Black Soil Zone

In the Thin Black soil zone at Indian Head, Lafond et al (1993) and Zentner et al (1999) reported that no-till and minimum tillage practices were more profitable than conventional tillage in all rotation (Table 17). This favorable profit picture is mainly due to 10 to 21% yield advantage for crops grown using conservation tillage practices.

Table 17. Production costs and economic return for complete cropping systems in the Thin Black soil zone, Indian Head, SK (1987–1998).

Cropping system	Tillage method	Variable cost	Total cost	Gross return*	Net return
		----------	---------- $ha^{-1}	----------	----------
Spring wheat–spring wheat–winter wheat–fallow	Conventional	178	230	283	53±97
	Minimum	185	234	280	46±96
	Zero	187	234	285	51±82
Spring wheat–spring wheat–flax–winter wheat	Conventional	228	290	373	83±124
	Minimum	231	290	396	106±116
	Zero	229	285	393	108±114
Spring wheat–flax–winter wheat–field pea	Conventional	227	298	411	113±129
	Minimum	298	298	423	126±119
	Zero	293	293	413	120±111

Shown for the following grain prices: spring wheat, \$138 t^{-1} (12% protein); winter wheat, \$129 t^{-1}; flax, \$295 t^{-1}; and field pea, \$184 t^{-1}. Inputs were valued at 1998 cost levels.
± mean follow by standard error
Source: Zentner et al 2002 Agron. J. 94:216–230.

3. Black and Gray Soil Zone

In the Black Soil zones, the effect of minimum – no-till practices in the management of mixed cropping systems is highly profitable. This is because of significant yield advantages and substantial saving on fuel, labor and machinery cost.

In Melfort, SK, Nagy (1997) has shown that one-pass direct seeding system using a 4-yr rotation of oilseed–cereal–pulse–cereal provided the highest annualized net return over less diversified cropping systems that used minimum tillage and conventional tillage practices. In this study the production costs averaged about \$7 ha^{-1} lower with minimum tillage than with conventional tillage practices and \$14 ha^{-1} lower with no-till practices (Table 18).

Table 18. Production costs and economic return for complete cropping systems in the Thick Black soil zone, Melfort, SK (1987–1998)

Cropping system	Tillage method	Variable cost	Total cost	Gross return*	Net return
		--	$ha^{-1}	-------------------------------	
Canola–Wheat–Barley–Barley	Conventional	255	335	523	188±48
	Minimum	251	324	532	203±53
	Zero	250	317	518	200±23
Canola–Barley–Field pea–Wheat	Conventional	264	342	564	224±35
	Minimum	259	335	561	226±49
	Zero	260	330	576	246±15
Canola–Field pea–Flax–Barley	Conventional	255	324	541	217±32
	Minimum	249	316	513	197±50
	Zero	251	313	549	236±37

Shown for grain prices of $149 t^{-1} for Canada Prairie Spring Red wheat, $113 t^{-1} for malt barley, $321 t^{-1} for flax, $390 t^{-1} for canola, and $195 t^{-1} for field pea. Inputs were valued at 1996 cost levels.
± mean follow by standard error
Source: Zentner et al 2002 Agron. J. 94:216–230.

Nagy and Johnson (2000) in the Gray Soil zone at Tisdale SK also reported cost advantage in favor to no-till practices (Table 20).

Table 19. Production costs and economic return for complete cropping systems in the Gray soil zone, Tisdale, SK (1994–1997)

Cropping system	Tillage method	Variable cost	Total cost	Gross return*	Net return
		--	$ha^{-1}	-------------------------------	
Canola–Wheat–Barley–Barley	Conventional	281	352	468	116±22
	Minimum	275	242	451	109±33
	Zero	278	339	438	99±63
Canola–Barley–Field pea–Wheat	Conventional	287	258	536	181±54
	Minimum	281	349	502	153±34
	Zero	284	349	506	158±65
Canola–Field pea–Flax Barley	Conventional	274	336	457	121±71
	Minimum	268	327	456	128±50
	Zero	271	326	417	91±70

Shown for grain prices of $149 t_1 for Canada Prairie Spring Red wheat, $113 t^{-1} for malt barley, $321 t^{-1} for flax, $390 t^{-1} for canola, and $195 t^{-1} for field pea. Inputs were valued at 1996 cost levels.
± mean follow by standard error
Source: Zentner et al Agron. J. 94:216–230 (2002).

In the Gray soil zone of northwestern (Rycroff) Alberta, Blomert et al (1997) also moderated cost advantage in favor of zero till practices. They reported that net returns from a mixed cereal–oilseed rotations were highest for no-till management, intermediate for minimum tillage and lowest when conventional tillage practices. They found that no-till provided cost saving of 30% ($32.65 ha^{-1}) in machinery operation and overhead, and about 24% ($1.97ha^{-1}) saving in labor.

In the Dark Brown (Location: Alliance), Black (Location: Wainwright) and Gray (Location: Plamondon) soil zones of Alberta, McAndrew et al (2002) also reported moderated cost advantage for no-till over conventional tillage practices.

Concluding Remarks

The economic analysis of the cereal-fallow rotations in zero and conventional tillage systems in the Brown and Dark Brown soils zones was carried out in the early 1990s when glyphosate prices were high

($25.00 /L) and application of N was broadcast on the soil surface rather than side banded below the soil surface. Since then there has been a significant drop in glyphosate price (< $8.00/L), more efficient fertilizer placement, a substantial increase in fuel prices, and a majority of farmers in these soil zones are now practicing diversified cropping rotations. If the economic comparison were made now between no-till and conventional tillage, by taking current glyphosate, fuel and lack of fallow into the economic benefit equation, the profit picture for no-till would be either equal or superior to conventional tillage

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SECTION 3

THE ECONOMIC, AGRONOMIC AND ENVIRONMENTAL IMPACT OF NO-TILL ON THE CANADIAN PRAIRIES.

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The Impact of No-Till on Soil Quality

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The Impact of No-till on Soil Quality

I. Introduction

On the Canadian Prairies and elsewhere, agricultural practices during the last 100 years have had a major impact on soil quality. During the early 1900s, intensive tillage (deep plowing) was the common practice on the Great Plains of North America, and this has caused a significant decline in soil quality. Since the early 1990s, however, conservation tillage practices have been increasingly adopted on Canadian farms. In 1991, no-till practices accounted for approximately 7% of the planted acres in Canada. By 2006 no-till practices had increased to approximately 46% of the planted acres in Canada

II. What is Soil Quality?

Soil quality is synonymous with soil health and is often used interchangeably in scientific literature. Soil health is determined by measuring the physical, chemical and biological properties of the soil. There are various definitions of soil quality. The Soil Science Society of America (1995) defines soil quality as *"the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation"*. Doran and Parkin (1994) have defined soil quality as "*the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality and promote plant and animal health*". Arshad and Coen (1992) indicated that "*soil quality can be expressed in terms of the sustaining capability of a soil to accept, store and recycle water, minerals and energy for production of crops at optimum levels while preserving a healthy environment"*. Soil quality depends on climate, landform, hydrology and management techniques employed. Agriculture and Agri-Food Canada defines soil quality as "*soil's fitness to support crop growth without resulting in soil degradation or otherwise harming the environment"*.

In terms of crop production, a soil has six important functions:

- Being a medium for plant growth and productivity;
- Storing and cycling nutrients and other elements within the earth's biosphere needed for crop production
- Adsorbing and infiltrating of water for crops;
- Exchanging air in the rooting zone;
- Maintaining a stable structure to resist water and wind erosion;
- Sustaining biological activity, diversity, and productivity.

Soil quality influences the ability of the soil to regulate the afore-mentioned functions. Soil quality can be measured with soil indicators such as the physical, chemical and biological indices of soil. There is a long list of soil indicators in the literature to assess changes in soil quality. Doran and Parkin (1994) suggest that improved soil quality for crop production is indicated by soil texture, depth of rooting, bulk density, infiltration, water holding capacity, structure, temperature, organic carbon, nitrogen, pH, electrical conductivity, mineral N, P, and K, microbial biomass C and N, potentially mineralizable N, and soil respiration (Table 1). Granatstein and Bezdicek (1992) indicated that an increase in infiltration, macropores, aggregate size and stability, soil organic matter, biological activity and aeration, and a decrease in runoff, bulk density, erosion, nutrient losses, soil resistance, diseases and production cost are good indicators of soil quality.

This section focuses on the effect of conservation tillage on soil quality based on several indices of physical, chemical, and biological soil quality; the emphasis is on Canadian studies.

Table 1. Indicator of Soil Health

Indicator of Soil Conditions	Relationship to soil conditions and functions
Physical	
Texture	Retention and transport of water and chemical. Estimate of degree of erosion and field variability of soil types.
Depth of soil, top soil and rooting	Estimate of productivity potential and erosion
Soil structure, soil bulk density and infiltration	Indicators of compaction and potential for leaching, productivity and potential for erosion
Water holding capacity	Related to water retention, transport and potential for erosion
Chemical	
Soil organic matter	Define soil fertility and erosion extent
pH	Define biological and chemical activity thresholds
Electrical conductivity	Define plant and microbial activity thresholds, soil structure stability and infiltration of added water
Extractable N, P, K	Defines plant available nutrients and potential of loss of soil productivity and environmental indicators
Biological	
Microbial Biomass C and N	Microbial catalytic potential and repository for C and N; early warning of management effect on soil organic matter
Potentially mineralizable N	Indicator of microbial biomass. Estimate soil productivity and N supplying potential
Soil respiration, water content and temperature	Measure of microbial activity

Source: Doran and Parkin (1994)

III. Effects of Tillage on Soil Quality

Tillage practices affect soil quality in a complex way. For example, in the short term, conventional tillage provides benefits by loosening the soil and allowing for water infiltration and oxygen to enter into it. In the long term, however, intensive tillage oxidizes organic matter and affects soil tilth, aggregation and structure. All these changes in soil quality result in dense compacted soil that influences root growth. Conservation tillage, especially no-till, retains large quantities of residues**,** resulting in an increase in organic matter content, improved soil structure, buffered soil temperatures, and allows soil to hold more water. All these changes regulate plant growth processes and crop yields.

1. Soil Organic Matter

Soil organic matter is an important indicator of soil quality and health. It is also a key factor in growing good crops and preventing erosion. It controls many physical properties (soil structure and tilth, aeration, water infiltration rate and water holding capacity), chemical properties (fertility, and pesticide adsorption) and biological properties (microbial activity). It is an important factor in the nutrient and carbon cycle. Over the last 100 years, the cultivation of grassland and forest soils on the Canadian prairie has resulted in substantial loss of soil organic matter. According to some estimates, the current soil carbon reserves in the surface layer of cultivated soils are about 30% to 50% lower than those of corresponding uncultivated sites.

There are several reasons for this decline: 1) tillage exposes the organic matter to rapid microbial decomposition, 2) crop-fallow rotation keeps the soil moist, thereby promoting microbial breakdown of SOC without adding crop residues, 3) erosion of top soil removed organic matter and 4) annual crops produced less residues than native grasslands (Boehm 2004; Lickacz and Penny 2001).

The amount of carbon content in a soil (the measure of organic matter) is controlled by a range of physical, chemical, biological and management factors and reflects the balance between accumulation and breakdown. The main factors are soil temperature, soil moisture, soil aeration, residue management, soil clay content (organic matter forms stable complexes with clay), cropping intensity and fertilization (Boehm 2004).

Tillage accelerates oxidation of organic matter by soil microorganisms through changes in temperature regime, soil water, aeration, aggregation and nutritional environment (Doran and Smith 1987). Reduced tillage systems retain large amounts of crop residues on the soil surface, keeping the soil cooler and moister. This condition slows microbial activity, thus reducing the organic matter losses. Therefore, soils closer to the soil surface under reduced tillage systems contain greater organic C and N and greater microbial biomass than under conventional tillage.

No-till normally increases the organic matter content of soils especially in non-fallow rotations. It has been shown that adoption of zero-tillage cropping systems increases the soil organic C content of the surface 15 cm of soil in the Canadian Prairie (Table 2), especially if fallow is not included in the rotation (Campbell et al 1995; Campbell et al 1996; Campbell 1998; Larney et al 1997; Nyborg et al 1995).

Table 2. Studies comparing SOC in no-till (NT) versus conventional tillage (CT)

Site	Yr	Depth (cm)	C gain (Mg ha y^{-1})	Treatment*	Reference
Steward valley, SK	11	15	3.0^{**}	NT vs CT Continuous wheat	Campbell et 1996a
Cantuar, SK.	11	15	0^{NS}	NT vs CT Continuous wheat	Campbell et al 1996a
Swift Current, SK	12	15	1.6^{**}	NT vs CT Continuous wheat	Campbell et al 1995
Swift Current, SK	12	15	0^{NS}	NT vs CT Fallow-Wheat	Campbell et al 1995
Indian Head, SK	6	15	-2.31^{NS}	NT vs CT Fallow-Wheat	Campbell et al. (1998)
Indian Head, SK	6	15	1.27^{NS}	NT vs CT Fallow-Wheat-Wheat N+P	Campbell et al. (1998)
Indian Head, SK	6	15	0.48^{NS}	NT vs CT Fallow-Wheat-Wheat N+P - straw	Campbell et al. (1998)
Elstow, SK	16	20	4.4^{**}	NT vs CT	McConkey et al 2003
Indian Head, SK	8	20	12^{**}	NT vs CT	McConkey et al 2003
Melford, SK.	25	20	4.1^{**}	NT vs CT	McConkey et al 2003
Breton, AB	11	15	7.5	NT vs CT Continuous Barley	Nyborg et al 1995
Ellerslie, AB	11	15	0^{NS}	NT vs CT Continuous Barley	Nyborg et al 1995
Lethbridge, AB	16	15	0^{NS}	NT vs CT Fallow-Wheat	Larney et al 1997
Lethbridge, AB	8	15	2^{**}	NT vs CT Continuous wheat	Larney et al 1997

** *Denotes* $P > 0.05$, NS = non significant

VanderBygaart et al. (2003) have summarized a total of 62 studies in which the difference in SOC was determined for conversion from native land to cropland, and for different tillage, crop rotation and fertilizer management practices. There was a loss of 24 ± 6% of the SOC after native land was converted to agricultural land. No-till (NT) increased the storage of SOC in western Canada by 2.9 ± 1.3 Mg ha^{-1}; however, in eastern Canada conversion to NT did not increase SOC.

In no-till systems, soil organic concentrations are usually higher at the soil surface (0 – 5 cm depth), and usually there are no differences below this depth. In a long-term study at Donnelly, Alberta, (silt loam) and Rolla, B.C, (sandy loam) soil organic C concentration was greater under no-till than under conventional tillage at a depth of 0–5 cm in the silt loam, at a depth of 0–2.5 cm in the sandy loam, and there were no differences between tillage systems below this depth (Arshad et al 1999) (Table 3).

Similarly, at Centaur in southwestern Saskatchewan, Campbell et al. (1995) reported organic carbon increases of 21% in the 0-7.5 cm depth after 11 years of direct seeding continuous wheat. However, in the 7.5-15 cm depth, there was no change in organic carbon. The overall change for the 0-15 cm depth was only 10.5%.

Table 3. Soil organic C concentration (g kg^{-1} soil) during 1994 as affected by tillage system and soil depth

Tillage Systems	Soil organic C concentration (g kg^{-1} soil)			
	0 – 2.5 cm	2.5 – 5.0 cm	5.0 – 7.5 cm	7.5 – 10 cm
Silt loam				
Conventional tillage	33.3	31.5	30.2	25.0
Zero-tillage	44.5	36.4	27.3	24.0
Level of significance	**	**	NS	NS
Sandy loam				
Conventional tillage	22.0	24.3	20.0	20.0
Zero-tillage	24.3	22.5	19.0	19.0
Level of significance	*	NS	NS	NS

* Denotes significant at $P \leq 0.1$; significant at $P \leq 0.05$ and NS = non significant respectively.
Source: Arshad et al (1999)

In a no-till system, changes in soil organic matter are generally slow to occur especially if summerfallow is included in the rotation. For example, at Swift Current, SK, Campbell et al. (1995) reported an organic C concentration change from 1.75% to 1.83% under direct seeded continuous wheat between 1986 and 1994. In a direct seeded/chemical fallow wheat-fallow rotation, the change was from 1.63% to 1.60% over the same time period. Larney et al (1997) at Lethbridge also reported greater increases in soil organic C due to the adoption of direct seeding with continuous cropping than with crop-fallow (Table 3).

2. Nutrient Availability

Nutrient availability in crop production systems is defined as the supply and absorption of chemicals (mainly – N, P, K and S) needed for plant growth and metabolism. Tillage can result in a number of changes that can directly or indirectly affect plant nutrition. In conventional tillage systems, tillage operations bury plant residues deeply in the soil where they decompose rather quickly, primarily through the decomposing action of bacteria. In a no-till system, there is no soil disturbance, plant residues remain at the surface, and there is less oxygen added to the soil. Decomposition is much slower. Slower decomposition results in an increased accumulation of organic materials and a rise in microbial biomass.

Depending upon the crop grown, residues contain large reserves of nutrients (Table 4). Soil microorganisms use crop residue as a source of energy and nutrients and in doing so release CO_2 and plant nutrients (N, P, K and S). Plant nutrients are incorporated into the microbial biomass or absorbed by the plant. When the plants or microbes die, nutrients can be recycled once again (Fig.1). Thus, adding organic matter adds energy to this system and promotes recycling.

Table 4. Nutrient concentrations of un-harvested above ground portion of plants

Crop	N	P	K	S
Alfalfa	2.09	0.18	1.78	0.28
Barley	0.69	0.07	2.37	0.17
Corn	0.95	0.10	1.45	0.17
Oats	0.70	0.06	2.57	0.23
Rye	0.48	0.09	0.97	0.11
Soybeans	0.83	0.47	0.93	0.30
Sunflower	0.80	0.15	0.92	-
Wheat	0.53	0.05	1.42	0.19

Source: National Academy of Science 1984.

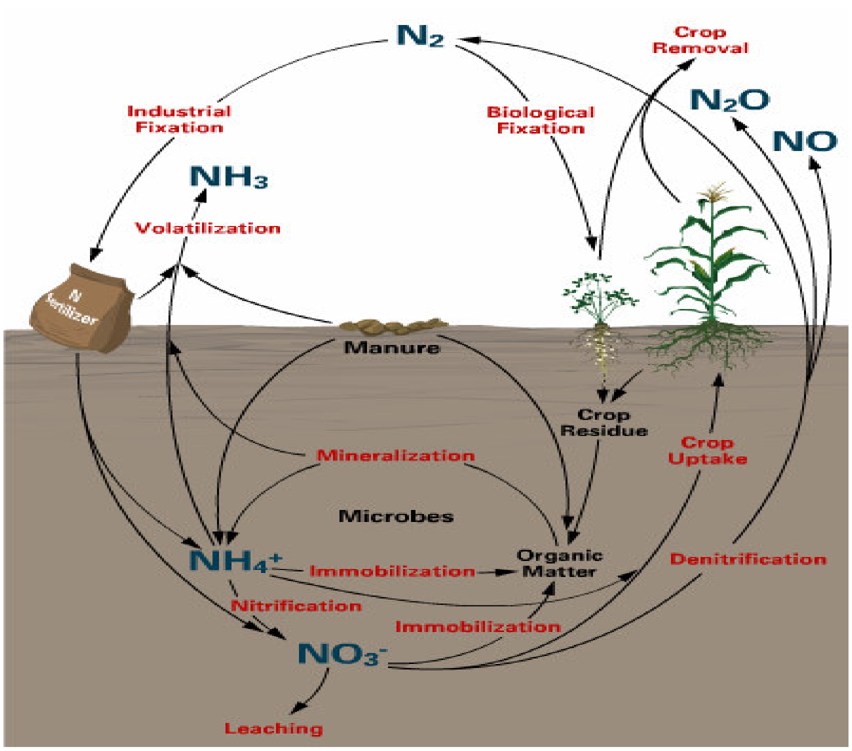

Figure 1. Simplified Nitrogen Cycle in Agro-ecosystem

Nitrogen Mineralization – Immobilization Turnover in No-till

Nitrogen mineralization refers to conversion of organic N to inorganic N (NH_4 and NO_3) as a result of microbial degradation. The reverse process of conversion of inorganic N to organic N by a microbial population is called immobilization. The processes of nitrogen mineralization and immobilization are microbial driven and are affected by the physical and chemical properties of the soil and especially the carbon content of the soil and soil management practices, including tillage.

In no-till systems, crop residues and microorganisms are concentrated near the soil surface and this may have a potential for reduced mineralization of soil organic N and increased immobilization of surface fertilization application (Doran 1980; Cochran et al 1980, Kittur et al 1984). However, long-term studies in western Canada and elsewhere have shown that initially the supply of N may be slow under zero-tillage with a greater immobilization of N fertilizer, which may lead to accumulation of organic matter. But, over a period of time, mineralization of organic matter under no-till may be equal to or greater than that of conventional tillage (Campbell et al 1995; Campbell et al 1997; Curtain et al 1996; Haugen-Kozyra et al. 1993; Selles et al 1984).

For example, in a long-term (12 year) study in the Dark Brown soil zone near Saskatoon, no-till fallow had little effect on nitrogen availability and the yield (Jowkin 1997).

Haugen-Kozyra et al (1993) studied the partitioning and cycling of labeled ^{15}N Urea in a barley-fallow system in central Alberta. They showed no significant difference in total recovery of mineral and microbial ^{15}N between the tillage systems over the growing season. However, labeled ^{15}N was 1.2 times greater under no-till than under conventionally tilled plots. The effects of zero-tillage and conventional tillage on nitrate–nitrogen (NO_3 – N) accumulation in soil are inconsistent. Grant and Lafond reported lower levels of NO_3 –N in zero till plots as compared to tilled plots. This may be attributed to lower mineralization in zero tilled plots. Similar results were also reported from central Alberta (Nyborg and Malhi 1989). In contrast, Campbell et al (1995) at Cantaur, SK, found no difference in NO_3 – N between zero tilled and conventional tilled plots in a continued wheat system, but there were increased levels of NO_3 – N in a fallow-wheat system.

Nitrogen Leaching

Nitrogen leaching is the process by which the N in NO_3 is moved downward with soil water below the rooting zone of the crop. In the dryland agriculture systems in western Canada, the leaching of nitrogen beyond the rooting zone under no-till is considered to be negligible.

Denitrification

Denitrification is a microbial process that converts NO_3 to N gases under anaerobic conditions. Denitrification can decrease the amount of mineral N in the soil in early spring when soils are cool and saturated with snowmelt water (Malhi and Nyborg 1986; Selles et al 1989). In western Canada, under some situations, no-till soils have a potential to become water saturated and therefore anaerobic. It has also been shown that no-till soils contain higher populations of denitrifying organisms as compared to conventionally tilled soils.

Nitrogen Uptake and Crop Yield

Because of the greater N immobilization and reduction in available NO_3 form under no-till, crops seeded in no-till systems often require higher N application rates to attain maximum yield especially in the initial years of moving into a no-till system. However, a study carried out in a wheat-fallow rotation in south-western Saskatchewan showed no significant differences in soil supplies of available nitrogen between the tillage fallow and no-tillage fallow treatments in years of below average and average precipitation. In very wet years, however, lower nitrogen availability was observed in the no-till fallow. This may be due to greater NO_3 –N losses by denitrification in no-till fallow in wet years (Greves and Voroney 1985).

In Brown and Dark Brown soil zones of western Canada, soil moisture limitations are known to have greater effects on crop production. In Southern Alberta, Lindwell and Anderson (1981) obtained higher yields of spring wheat on no-till fallow mainly due to increased moisture conservation compared to conventionally tilled plots. Carefoot et al (1990) also reported similar results.

Soil Phosphorus and Potassium Distribution

No-till systems that leave large portions of crop residue on the soil surface have a greatly reduced decomposition resulting in stratification of immobile nutrients such as phosphorous (P) and potassium (K) near the soil surface. Thus, zero till has the potential to alter the concentration and distribution of these nutrients in the soil profile. Studies in western Canada have shown that no-till systems coupled with broadcast or seed placed nutrient have led to the accumulation of available P and K in the 0 – 5 cm depth and a depletion of available P and K deeper in the soil profile (Grant and Bailey 1994; Lupwayi et al 2006).

Selles et al (2002) at Swift Current, SK, have shown that 12 years after converting from conventional till wheat-fallow to no-till continuous wheat, forms of P easily available to the crop accumulated in the surface 0-5.0 cm layer. In no-till fallow-wheat or the conventional wheat, the concentration of available P was uniform in the top 10 cm of the soil profile. Although soil P and K was found to accumulate near the surface in no-till fields, no negative impact on crop production was recorded in these studies due to this nutrient distribution (Selles et al 2002).

Grant and Lafond (1994) evaluated the effects of no-tillage on P and K distribution at Indian Head, SK. They found no differences in P and K levels in the soil profile between zero, minimum and conventional tillage systems. In this study, soil samples were collected from the 0 – 5 cm, 5 – 10 cm and 10 – 15 cm depths and nitrogen was mid-row banded on 32 cm (16 inch) centers, while the P, K and S fertilizers were placed in seed rows spaced on 20 cm (8 inches) centers. In another long-term (8 years) tillage study on solonetzic soil near Vegreville, AB, Malhi et al (1992) also found no effect of tillage systems on the distribution of P and K levels in the soil.

3. Soil pH

pH is a useful soil quality indicator because it influences nutrient availability, organic matter decay and nutrient release. It also influences the activity of microorganisms.

In continuously cropped, zero tilled fields, there is a potential for soil pH to decline. This may be related to the fact that in zero till fields, fertilizer is usually placed near the soil surface and conversion of N fertilizer and soil organic matter to nitrates is an acidification process (Boehm 2004). Studies associated with long-term no-till and changes in soil pH are very limited in western Canada. In the grey wooded soil in the Peace River region of Alberta, after 10-years of no-till there was a 26% increase in soil carbon relative to conventional tillage and 0.5 units decline in soil pH (Arshad et al 1990).

4. Soil Aggregation

Soil aggregates are an important indicator of soil health as they influence the soil tilth, extent of soil erosion, nutrient release, soil moisture availability, biological activity in the soil and root growth. Soil aggregates are clumps of soil particles held together by moist clay, organic matter and by organic compounds (from bacteria and fungal hyphae). Aggregates are formed by drying, root penetration; freezing and then stabilize by clay minerals attraction and organic matter.
Aggregates can be divided into micro-aggregates (< 250 µm in diameter) and macro-aggregates (> 250 µm diameter). A well-aggregated soil has good tilth; a large number of water-stable aggregates and pore spaces, and good water infiltration and water movement. The size of the aggregate plays an important role in the erosion potential of the soil. Aggregates with diameters less than 0.5 mm are susceptible to water erosion, and wind can erode aggregates less than 0.84 mm. No-till has more water stable aggregates than conventional tillage.

Crop residue in no-till systems benefits wet aggregate stability. Dormaar and Lindwall (1989) have found more water stable aggregates and non-erodible dry aggregates (> 0.84 mm) with no-till treatment than with blade cultivated and heavy-duty cultivator treatment in dry-land studies of continuous wheat, wheat-fallow, wheat-barley-fallow rotations in southern Alberta. In another 25-year continuous wheat study in Saskatchewan, all four different fall treatments reduced the fraction of non-erodible soil aggregates when compared with straw chopped and left on the soil surface (Nuttall et al 1986). Biederbeck et al (1980) in a 20 year study also found that wet aggregate stability was reduced a lot in plots where crop residues were burned annually as compared to plots where crop residues were chopped and left on the soil surface.

Several studies in Canada have shown that winds of about 28 km h^{-1} will erode a soil in which 60% of particles are less than one mm in diameter to a depth of 2.5 cm. Anderson and Lindwall (1981), in southern Alberta, have shown that all summerfallow treatments had a relatively high proportion of fine soil particles at the end of the summerfallow season and before seedbed preparation. However, the presence of adequate quantities of crop residue with most fallow treatments reduced the risk of soil erosion by wind despite a high proportion of fine aggregates (Table 5).

Table 5. Crop residue and soil particle size, 1969 – 1976

Treatment*	Crop residue (kg ha^{-1})		% Residue conserved	% of soil particle < 1mm diam.	
	After harvest	Before seedbed preparation		After fallow tillage in fall	Before seedbed preparation in spring
B	3473	1484	43	52	54
OW	3544	169	5	46	53
FB/H	3636	2151	59	-	-
FB/H/FB	3694	1727	47	46	52
H/FB	4040	1916	47	47	49
SB/H	3542	1727	49	56	57
SOW/H	3554	787	22	-	-
H	3798	2558	67	_	-

* Denotes B= Blade cultivation (May – Sept); OW= one-way disc (May – Sept); FB/H= Blade cultivate after harvest/Herbicide (May- Sept); FB/H/FB= Blade cultivate after harvest/Herbicide (May- Sept)/Blade cultivate (Oct); SBH= Blade (May/June)/Herbicide (July-Sept).
Source: Anderson and Lindwall (1981)

Studies comparing the effects of tillage on aggregate stability and aggregate size in western Canada are limited. Franzluebbers and Arshad (1996), studied the distribution and soil organic carbon of five water-stable aggregate classes at depths of 0-50, 50-125, and 125-200 mm in a loam, a silt loam, a clay loam, and a clay soil managed for 4-16 yr under conventional shallow tillage and no-till in the Peace River region of northern Alberta and British Columbia. Water-stable aggregation improved under no-till compared with conventional tillage in coarse textured soils at a depth of 0-125 mm. This is probably because more soil organic C is sequestered within macro-aggregates under no-till compared with conventional tillage.

5. Bulk Density

Soil bulk density (the weight of the soil per unit of volume) and penetration resistance are also good indicators of soil health. These two variables provide information on soil compaction, macropores, and water and air movement in the soil for root growth. Bulk density is inversely related to pore spaces (how many pore spaces are left in the soil for air and water movement).

Optimal bulk density is different for different soil types, and is related to soil properties such as texture, organic matter, soil structure, and clay content. High bulk density (low porosity) is associated with reduced aeration and increased penetration resistance, limiting root growth and development. In cool temperate regions, soil bulk density varies from year to year due to freezing and thawing, settling by desiccation, and the kinetic energy of rainfall, and loosening by root action and soil microbe activity. Tillage also has an influence on bulk density. Over the long-term, no-till has higher organic matter, and this may lower the bulk density; however, in the short-term, no-till may increase bulk density. Bulk density that limits root growth is dependent upon soil water content and ranges from 1.3 Mg/m^3 in clayey soils to1.60 Mg/m^3 in sandy soils

Studies comparing soil bulk density between no-tilled and tilled fields are contradictory. In most of the studies, bulk density was greater in the first 5 –10 cm of soil (Grant and Lafond 1993; Franzluebbers et al 1995; Unger and Jones 1998; Lindwall et al (2008). In a long-term study at Indian Head, Saskatchewan, Grant and Lafond (1993) and Lindwall et al (2008) have shown that bulk density was greater in the first 0 – 10 cm of soil, and there were no differences in bulk density beyond this depth (Table 6).

Table 6. Effect of tillage practices on bulk density at Indian Head, Saskatchewan

	Depth	Zero-till (5 yr)	Zero-till (10 yr)	Zero- till (13 yr)	Fallow- crop Rotation	Conventional tillage
Bulk Density (Mg/m^3)	0-10 cm	1.19 $_{ab}$	1.13 $_{b}$	1.27 $_{a}$	1.10 $_{b}$	1.10 $_{b}$
	10-20 cm	1.36 $_{a}$	1.27 $_{a}$	1.48 $_{a}$	1.32 $_{a}$	1.33 $_{a}$
	20-30 cm	1.42$_{a}$	1.40$_{a}$	1.42$_{a}$	1.43$_{a}$	1.36$_{a}$

Row numbers with similar subscript letter or letters are not significantly different at P=0.05
Source: Lindwall et al (2008)

In another study at Indian Head, Saskatchewan, Grant and Lafond (1993) compared the bulk density between native grassland and short and long-term no-till soils. Native grassland has lower bulk density in the top 0 – 15 cm of soil as compared to both short and long-term zero till soils. Short-term zero tilled soils also have higher bulk density as compared to long-term zero-tilled soils (Table 7).

Table 7. The effects of the length of no-till on bulk density relative to native prairie for 0 – 15 and 15 – 30 cm soil layer

	Depth	Native	Long-term zero-till	Short-term zero-till
Bulk Density (Mg/m^3)	0 – 15 cm	0.99 a	1.40 b	1.47 c
	15 – 30 cm	1.34 a	1.34 a	1.38 a

Row numbers with similar subscript letter or letters are not significantly different at P=0.05
Source: Grant and Lafond (1993)

In a long-term (6-years) study at Innisfail (Black Chernozem) and Rimbey (Gray Luvisol) Alberta, Singh and Malhi (2006) evaluated the effects of tillage and residue management on bulk density, penetration resistance, aggregation and infiltration rate. They found bulk density in the 0–7.5 and 7.5–15 cm depths was significantly greater under no-tillage plots (1.13–1.58 Mg m^{-3}) than under tilled plots (0.99–1.41 Mg m^{-3}) in both soils irrespective of residue management. In both soils, penetration resistance was also greater under no-tilled plots than under tilled plots to 15 cm depth. Residue retention significantly reduced penetration resistance of the 0–10 cm soil in no-tilled plots but not in tilled plots.

Some studies have found no difference in bulk density between zero – minimum tillage and conventional tillage. (Bruce et al 1990**;** Lal et al 1999). In other studies no differences were observed between tillage systems (Arshad et al 1999; Carefoot et al; Miller et al 1999; and Cheng and Lindwall 1989), while in other studies, there were no differences in bulk density (Moran et al 1988; Pikul and Asae 1995).

6. Compaction

Measurements of compaction include penetration resistance (the amount of force required to push a standard diameter rod into the soil), and bulk density. Important factors affecting soil compaction are implement traffic, soil water content and bulk density. Soil texture, organic matter and surface roughness may also play an important part in compaction. Soil compaction affects root growth and movement of water and air within the soil.

In no-till, the tillage process does not disturb the channels and pores from root growth and from insect and worm activity in previous years. The pore system is left more intact, leaving continuous macropores, through which the roots may grow, or which may act as channels for possibly better air and water movement (Grant and Bailey 2004). In no-till, bulk density and penetration resistance are higher as compared to conventional tillage, especially in the upper 15 cm (Singh and Malhi 2006). However, in the deeper soil zones (15 – 45 cm), there are no significant differences in penetration resistance between no-till and conventional tillage [(Table 3) (Grant and Lafond 1991). Therefore, the negative effect on root growth due to increased penetration resistance in the surface soil layer in no-till may be inconsequential.

Table 8. Effect of tillage on penetration resistance (KP_a) after winter wheat production, averaged over three soil depths and 3 crop rotations

	Depth (cm)	Tillage system		
		No-till	Minimum till	Conventional till
Penetration resistance (KP_a)	0 – 15	1094	1024	955
	15 – 30	2130	2222	2231
	30 – 45	3245	2231	3227

Source: Singh and Malhi (2006)

7. Porosity

Pore size distribution and pore continuity plays an important and direct role in the root growth processes by determining the soil volume filled with air and water (aeration) and indirectly the root resistance to soil penetration. Large pores have poor retention for sustaining plant growth (Karlen et al., 1990), whereas smaller pores have limited aeration and may form a crust that limits plant emergence. They can also cause reduced infiltration and increased runoff (Hillel, 1982).

Tillage can affect water retention characteristics. Conventional tillage altars the soil and pore structure; in turn, these affect soil water retention. In contrast, no-till maintains the soil structure and optimizes the soil porosity.

There are limited studies in North America comparing the effect of tillage on porosity. Drees et al. (1994) found that in no-till systems, extensive biological activity resulted in a greater mean aggregate size and increased pore size compared to those in conventional tillage systems. Lal et al (1994) found more continuous pores and a higher volume of pore space in no-tillage soil than in tilled soils. Arshad et al (1999) also showed higher soil water retention in zero-tillage plots compared with tilled plots with few changes to bulk density due to redistribution of pore size classes into more small pores and fewer large pores.

8. Plant Available Water Holding Capacity

On the Canadian Prairies, precipitation increases from <350 mm in the Brown soil zone to >475 mm in the Black and Gray soil zones. Evaporation also decreases from the Brown to the Gray soil zones and, therefore, the annual water deficit decreases from about 400 mm in the Brown soil zone to little or none in the Gray soil zones. Mean annual temperature, wind speed, frost-free period, and annual growing degree-days (>5°C) also decrease from south to northwest (Table 8). In the Brown and Dark Brown soil zones, growing season moisture deficits can be limiting and affect crop productivity (Boehm 2004). The wheat-fallow system in the drier regions of the Prairies is designed to conserve moisture, but tillage intensive fallow is undesirable, as it contributes to soil erosion. Minimum – no-till systems, including chemical fallow systems, leave most of the standing stubble and crop residue on the soil surface and improving the water retention capacity of soil (Nyborg and Mahli, 1989; Carefoot et al 1991).

Table 8. Soil zone, temperature, precipitation, potential evapo-transpiration and moisture deficit for select Research Station locations on the Canadian Prairies.

Location	Soil zone	Precipitation (mm)	Evapo-transpiration * (mm)	Water deficits ** (mm)	Temperature (°C)	Wind (km h^{-1})	Frost-free period (days)	Growing degree days (>5°C)
Swift Current	Brown	334	729	395	3.3	22.8	117	1675
Scott	Dark Brown	355	635	280	1.0	14.5	96	1442
Lethbridge		413	681	268	5.0	20.4	116	1689
Indian Head	Black	427	607	180	2.0	15.8	110	1633
Lacombe		411	506	95	0.3	15.4	93	1468
Melfort		443	508	65	2.1	10.9	99	1334
Brandon		481	630	145	1.9	16.3	104	1705
Beaverlodge	Grey	467	470	3	1.6	12.2	105	1221

* Potential evapotranspiration, calculated estimate of water use by crop and loss by evaporation
** Water deficit = precipitation – evapotranspiration

Numerous studies on the Canadian Prairies have shown that soil moisture and moisture use efficiency tend to be higher under no-till systems than under conventional tillage. In Alberta, Larney and Lindwall (1989), in a long-term study near Lethbridge, investigated the performance of winter wheat under conventional, minimum and no-till in monoculture and in 2-year rotations with fallow, canola or lentils/flax. They found that no-till had relatively little impact on available water to 1.5 m depth. However, once the experiment had been established for 6–7 years, available water in the 0–15 cm depth under winter wheat in spring was greatest under no-till. Similarly, Arshad et al (1999), in a 3-year rotational study, near Beaverlodge, has shown greater soil water content of the surface 0–2 cm under no-till than under conventional tillage. The volumetric surface soil water in zero till plots was 03 ± 0.02 m^{-3} higher.

Wang et al (2004) investigated pre-seeding available soil moisture at Three Hills, Alberta. They found no-till treatments consistently had higher (10 – 33 mm) soil available moisture at 0-60 cm depth than conventional treatments. Treatment differences were smaller at 60-120 cm (Table 12).

Howard et al (2005) at Fort Saskatchewan Alberta, showed higher post-seeding soil moisture in no-tilled plots as compared to conventionally tilled plots during the early crop establishment phase; the differences in soil moisture content lasted till mid June (Table 10).

Table 9. Pre-seeding available soil water at Three Hills (2000 – 2003)

Year	Treatment	Pre-seeding available soil water	
		0 – 60 cm	60 – 120 cm
		------------------------------------ mm ------------------------------------	
2000	No-till	161 a	119 a
	Conventional till	126 a	117 a
2001	No-till	141 a	133 a
	Conventional till	131 b	112 a
2002	No-till	140 a	116 a
	Conventional till	120 b	132 a
2003	No-till	200 a	181 a
	Conventional till	182 b	157 a

*Mean followed by a different letter are significantly different at the 0.05% level of probability
Source: Wang et al (2004)

Table 10. Post-seeding available soil water at 0 – 30 cm depth at Fort Saskatchewan (1997)

Treatment	Available soil water during early crop establishment phase			
	June 6 – June 17		June 26 – July 7	
	Mean	Change/day	Mean	Change/day
No-till	22a*	- 0.5 a	21 a	- 0.6
Conventional till	23 b	- 0.4 b	21 a	- 0.6

*Mean followed by a different letter are significantly different at the 0.05% level of probability
Source: Howard et al (2005)

The increased soil moisture during the pre-seeding and early post-seeding crop establishment phase in no-tilled seeded fields is probably related to crop residue levels. No-till crop production systems retain most of the crop residue on the soil surface where it takes longer to decompose than when it is buried. The increase in residues keeps the soils cooler and moister throughout the growing season.

In Saskatchewan, Lafond (1993) at Indian Head has shown higher spring soil moisture under zero-minimum tillage than under conventional till (Table 11).

Table 11. The effects of tillage systems on total spring soil water (cm) averaged over 4 years.

Crop	Soil Depth	Tillage system		
		No-till	Minimum	Conventional
	(cm)	--------------- Spring soil water (cm) ------------------		
Field peas	0 – 30	11.7	11.8	10.1
	30 – 60	10.5	10.9	9.5
	60 – 120	20.3	21.6	19.7
Flax	0 – 30	11.7	11.3	10.5
	30 – 60	11.0	10.7	9.5
	60 – 120	20.4	19.9	18.9
Spring wheat	0 – 30	11.3	11.4	10.5
	30 – 60	10.8	10.3	10.1
	60 – 120	20.3	19.1	19.6

Source: Lafond (1993)

Recently, Lindwall et al (2000) have summarized a long-term study (11-year: 1987 – 1997) on the effects of various no-till cropping systems on available soil moisture and water use efficiency at Indian Head, Saskatchewan (Table 12). They found that the type of stubble had the largest influence on soil water conserved, irrespective of the tillage system used. For instance, in the case of field pea stubble, the amount of water stored is similar between the three tillage systems because of the inability of this stubble to trap snow.

Table 12. The effects of tillage systems on soil water conserved and used, total water used, grain yield and water use efficiency in field pea, flax and winter and spring wheat on different stubbles.

Field peas						
Tillage system	Spring Soil Water (cm)	Soil Water Used (cm)	Rain (cm)	Total Water Used (cm)	Yield (kg/ha)	Water Use Efficiency (kg/ha/cm)
Zero	24.0	9.1	21	30.0	2348	85.3
Minimum	24.2	8.9	21	29.8	2352	83.1
Conventional	22.3	7.0	21	27.9	2192	80.9
Contrast						
ZT+MT vs CT	**	*	-	*	**	ns
Flax						
Zero	24.2	9.5	21.3	39.9	1642	54.8
Minimum	24.1	9.3	21.3	30.6	1646	55.4
Conventional	22.7	8.2	21.3	29.6	1479	50.4
Contrast						
ZT+MT vs CT	**	*	-	**	**	
Spring Wheat on Fallow						
Zero	26.2	16.3	20.3	36.5	2883	80.3
Minimum	26.0	16.0	20.3	36.3	2768	78.3
Conventional	26.1	15.8	20.3	36.1	2868	86.0
Contrast						
ZT+MT vs CT	ns	ns	ns	ns	ns	ns
Spring Wheat on Field Pea Stubble						
Zero	22.9	10.4	20.3	30.6	2334	78.7
Minimum	236	10.5	20.3	30.8	2522	81.9
Conventional	23.0	10.9	20.3	31.1	2449	78.8
Contrast						
ZT+MT vs CT	ns	ns	-	ns	**	ns
Spring Wheat on Cereal Stubble						
Zero	24.3	9.8	20.3	30.0	2190	73.8
Minimum	23.4	9.2	20.3	29.4	2212	75.1
Conventional	22.8	8.2	20.3	28.5	2026	71.3
Contrast						
ZT+MT vs CT	**	**	-	**	**	ns

*, ** = Significant at the P=0,05 and P=0.01 levels, respectively; ns = not significant
Source: Lindwall et al (2000)

9. Water Infiltration

Water infiltration is also a good indictor in assessing soil health. Water infiltration influences the bulk density, aggregation, macroporosity, surface crusting and restrictive layer (soil pan) in the soil (Grant et al 2004, Boehm 2004). It has been shown that after 7 years, improved physical and chemical condition of the soils in no-till crops, results in higher water infiltration rate in both dry and wet soils (Pikul and Aase 1995). Increased water infiltration generally increases nutrient movement through the soil and also yield potential and nitrogen availability due to increased mineralization.

10. Soil Temperature

Available information from western Canada seems to indicate that during the spring pre- and post-seeding soil-warming phase, soil temperatures for direct seeded soils can be about 1 – 2 degrees C lower than in conventionally tilled soils. The cooler soils under direct seeding are mainly due to the crop residue layer on the soil surface. Thicker residue layers result in slightly cooler soil temperatures at 2.0 and 5.0 cm depth (Froebel and Howard 1999). Wang et al (2007) in a 4 year study on Thin Black Chernozemic clay loam at Three Hills, observed consistently lower soil temperatures at 5 and 10 cm in no-till treatments than in conventionally tilled treatments during the whole growing season each year (Table 13).

Table 13. Mean soil temperatures at the vegetative stage, ear development stage, and grain growth stage of wheat under no till and conventional tillage – Three Hills

Treatment	Soil temperature					
	Vegetative stage		Ear stage		Grain growth stage	
	5 cm	10 cm	5 cm	10 cm	5 cm	10 cm
	---°C ---					
2000						
No-till	10.9a	10.2a	15.0a	14.7a	18.3a	17.9a
Conventional	11.3b	10.8b	15.6b	15.2b	19.3b	18.9b
2001						
No-till	12.1a	11.2a	14.7a	14.3a	18.2a	17.7a
Conventional	14.2b	12.6b	15.8b	15.3b	19.1b	18.6b
2002						
No-till	11.2a	10.4a	17.0a	16.3a	19.7a	19.4a
Conventional	12.6b	11.8b	18.7b	17.6b	21.6b	20.8b
2003						
No-till	14.5a	14.5a	16.9a	16.9a	19.0a	19.0a
Conventional	15.8b	15.5b	18.1b	17.8b	20.6b	19.8b

*Means followed by a different letter are significantly different at the 0.05% level of probability
Source: Wang et al (2007)

Soil Temperature and Heat Stress Index

Heat stress occurs when air and soil temperatures are higher than optimum for maximum grain yield, and it affects both root and shoot development. Heat stress on shoots affects wheat grain growth, resulting in immature kernels, while heat stress on shallow roots affects the whole plant by altering the balance of photosynthates (products of photosynthesis) partitioned to the roots and shoots. Supra-optimal soil temperatures are more detrimental than air temperature for root and shoot growth. Wang et al (2007) have calculated a heat stress index (HSI) as, $HSI = \Sigma (Ti - Tc)$, where Ti is the temperature for each hour and Tc is the critical temperature of 20 °C. HSI was cumulative where Ti was greater than Tc during the growing season. The calculated HSI was higher for the conventional tillage treatments – an indication of more crop stress (Table 14). The cumulative HSI under no-till was about half that under conventional tillage over the growing season (ranged from 0.33 to 0.70).

Heat Stress Index and Cereal Yield

Wang et al (2007) have found grain yields were always higher under no-tillage than conventional tillage, and they were statistically higher in three of the four years of the study period (Table 16). The advantage was greater in the two drier years (44-147 % greater in 2000, 2002) than in the two wetter years (3-18 % greater in 2001, 2003). Over the four years, an extra 26 bu/ac of wheat was produced under the no-tillage system. There was statistically more biomass production in three of the four years. The differences in biomass (grain+straw) were greater than the difference in grain yields. In fact, over the four years, an additional 2400 lb/ac of straw was produced with no-till practice (Table 14).

The results reported in this study are in agreement with other grain yield and economic studies carried out in western Canada.

Table 14. Mean soil temperatures at the vegetative stage, ear development stage, and grain growth stage of wheat under no till and conventional tillage – Three Hills, AB. (2000 – 2003).

Treatment	Heat stress index		Biomass	Grain yield	
	5 cm	10 cm			
	——— °c ———		——— kg/ha ———	kg/ha	bu/ac
2000					
No-till	592a	185a	6936a	2323a	34.6
Conventional	851b	433b	3351b	1608b	24.0
2001					
No-till	610a	235a	7307a	2235a	33.3
Conventional	1280b	706b	5506b	1895b	28.2
2002					
No-till	1278a	896a	4090a	966a	14.4
Conventional	2402b	1698b	1574b	391b	5.8
2003					
No-till	275a	357a	6446a	2764a	41.2
Conventional	785b	540b	6361a	2676b	39.9

*Mean followed by a different letter are significantly different at the 0.05% level of probability
Source: Wang et al (2007)

11. Biological Properties

The soil contains large populations of bacteria, fungi, algae, nematodes, earthworms, soil dwelling arthropods, and cryptozoic invertebrates. These organisms interact in a very complex way with the environment affecting the decomposition of organic matter, nutrient cycling and other soil processes. For example, activities of these organisms can affect the stability of soil aggregates, porosity, structure, tilth and productivity of the soil.

Tillage practices affect a number of soil processes that, in turn, affect the community structure and dynamics of soil microorganisms. Conventional tillage breaks soil aggregates, exposing organic carbon to microbial attack, and results in increased decomposition of soil organic matter. Tillage also breaks the fungal hyphae and consequently bacterial populations are dominant in the soil. Conversely, no-till preserves the soil aggregates; these in turn protect organic carbon from microbial attack, and the result is less carbon loss. Fungal hyphae in the soil are relatively undisturbed, and fungal populations are dominant.

There are few studies in western Canada on the effect of tillage and crop residues on soil microbial populations. In no-till, almost all the crop residues are on the soil surface keeping the soil moist and cooler; this in turn increases microbial biomass, counts and diversity as compared to conventional tillage where crop residues are either incorporated in the soil or removed (Doren 1980). Biederbeck et al (1980) compared the short and long-term effects of burning of cereal straw as compared to leaving it undisturbed. They found that burning caused dramatic reduction in microbial populations in the soil.

Short-term changes in tillage practices have little or no influence on the soil microbial populations. Carter and Rennie (1982) in western Canada found no difference in microbial biomass between no-till and tilled treatment after 2 years but did find significant differences after 4 years.

Lupwayi et al (1999) studied the effects of tillage on soil microbial biomass in various crop rotations in Gray Wooded Soils at Fort Vermillion, Alberta. No-till plots in the top 8 cm had significantly higher soil microbial biomass and bacterial diversity than conventionally tilled plots

In recent years, glyphosate resistant crops have become common on the Prairies, and this has raised concerns about their affect on soil microorganisms. Lupwayi et al (2007) evaluated **s**oil microbial biomass, bacterial functional diversity and community structure, and dehydrogenase enzyme activity in glyphosate-resistant wheat–canola under no-till and conventional tillage systems. In five of 20 site-years, soil microbial in the rhizosphere was greater under conventional tillage than under no-till, regardless of glyphosate-resistant crop frequency. In bulk soil, tillage affected soil microbial biomass in five site-years, three of which had greater soil microbial biomass under conventional tillage than no-till, and vice versa in the other two. Tillage affected the functional diversity of soil bacteria in the rhizosphere in three site-years, but the effects were not consistent. There were no tillage effects on bacterial diversity in bulk soil. Dehydrogenase enzyme activity was greater under no-till than under conventional tillage in three of four cases in which tillage had significant effects. Overall, tillage and glyphosate-resistant crops had minor and inconsistent effects on soil microbial biomass, bacterial diversity and dehydrogenase enzyme activity.

Mycorrhizae

The mycorrhizae (root fungi) live either on or in plant roots. According to the infection anatomy they can be classified into two major groups: ectomycorrhizae (intercellular hyphal infections) and endomycorrhizae (intracellular hyphal infections). Endomycorrhizae are the most common type and are commonly referred as vesicular arbuscular (VA) mycorrhizae or VAM fungi. Mycorrhizae increase the uptake of water and nutrients, especially phosphorus. They also serve as a biological control of root pathogens. Roots colonized by mycorrhizae are less likely to be penetrated by root-feeding nematodes since the pest cannot pierce the thick fungal network.

Tillage has a detrimental effect on mycorrhizae colonization. VAM fungal populations decrease more under tilled soils than in no-till soils and can have serious consequences on P uptake and plant growth (Clapperton et al 1997a).

Earthworms

Earthworms play a role in the formation of soil and decomposition of plant residues. They are known to improve soil aeration, infiltration, fertility and soil conditioning. In an untilled soil environment, they maintain extensive burrows. Studies in the United States have shown that in no-till soils earthworm numbers increase by as much as 60% compared to tilled soils (Parmelee, et al 1990). In a long-term (25 year) study near Lethbridge, Alberta Clapperton et al (1997b) and Clapperton and Lee (1998) found that there were there were significantly more earthworms under no-till than under conventional tillage.

IV. Concluding Remarks

Tillage practices affect the soil qualities in a complex way. No-till, retains large qualities of residues**,** resulting in an increase in organic matter content, improved soil structure, buffered soil temperatures, and allows soil to hold more water. All these changes regulate plant growth processes and crop yields. Some of the important effects of no-till on soil qualities are:

- Increased soil organic matter: 2.9 ± 1.3 Mg ha^{-1} yr^{-1}
- Increased available plant nutrients: increase in mineralizable N. No-till also increases N immobilization. However, N – NO_3 or "available" nitrogen levels are not affected by no-till. P and K levels also increase under no-till
- No-till soils have higher microbial biomass
- Improved physical qualities: no-till soils resulted in greater aggregate stability and/or aggregate size distribution, decreased soil compaction, improved soil tilth and structure less run-off and increased water infiltration, and soil moisture contents. No-till soils also have greater bulk density in the surface horizon (0-10 cm)
- No-till soils have moderate soil temperatures and significantly less heat stress as compared to tilled soils throughout the growing season.

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SECTION 4

THE ECONOMIC, AGRONOMIC AND ENVIRONMENTAL IMPACT OF NO-TILL ON THE CANADIAN PRAIRIES.

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The Impact of No-Till on Soil Erosion

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The Impact of No-Till on Soil Erosion

I. Introduction

During the late 70s and early 1980s, extended drought periods, together with intensive and unnecessary tillage resulted in severe wind and soil erosion problems on the Canadian Prairies (Lindwall 2005). Research on the Great Plains of North America has shown that at least 1 – 1.5 tonnes of crop residue on the soil surface is required to minimize wind and water erosion, and standing and anchored residues are about four times more effective than flat residues for erosion control. During the 1970s, the trend towards larger farms and the introduction of new agricultural products such as soil-incorporated herbicides on the prairies caused substantial increases in soil erosion, and this increased public awareness of soil conservation research among farmers and various levels of government.

There were several approaches suggested to reduce erosion: (1) increase minimum and no-till, (2) increase annual cropping intensity with diversified rotations, (3) decrease summerfallow and have a corresponding increase in chemfallow, (4) increase strip farming, (5) use marginal land for forage production, and (6) use windbreaks and/or shelterbelts and grassy waterways. The main focus of these conservation efforts is to keep the soil covered with crop residues to minimize wind erosion and trap as much snow as possible during winter to conserve soil moisture. Recent advances in air-seeder technology and the drop in glyphosate prices due to patent expiry have made these conservation practices more economically feasible for farmers.

At present, over 50% of Canadian Prairie farmers have adopted conservation tillage practices (no-till: 43%, minimum tillage: 28%), and reduced fallow (60% reduction in summerfallow). In addition, most of growers are also implementing the above-mentioned soil conservation practices (extended crop rotations inclusive of perennial forage legumes, marginal land for forage production, etc.) on their farms to reduce wind and water erosion. As the result of these efforts, only a small but substantial proportion of agricultural land on the Canadian Prairies is now susceptible to soil erosion (Table 1 and Table 2).

Table 1. Agricultural land subject to unsustainable water erosion (%)

Year	British Columbia	Prairies	Ontario and Quebec	Atlantic	Canada
1981	44	29	35	41	30
1991	41	23	32	41	25
1996	44	12	31	40	15

Source: Environmental Sustainability of Canadian Agriculture: Report of the Agri-Environmental Indicator Project. Agriculture and Agri-Food Canada. 2000

Table 2. Reduction in actual water erosion risk per hectare from 1981 to 1991

Province	Cultivated land in 1991 (HA)	Resulting from cropping practice	Resulting from tillage practice	Total
		Erosion reduction per hectare (%)		
Alberta	11.06	5	8	13
Saskatchewan	19.07	5	3	8
Manitoba	5.06	6	9	15
Prairie Provinces	35.19	5.3	6.6	12

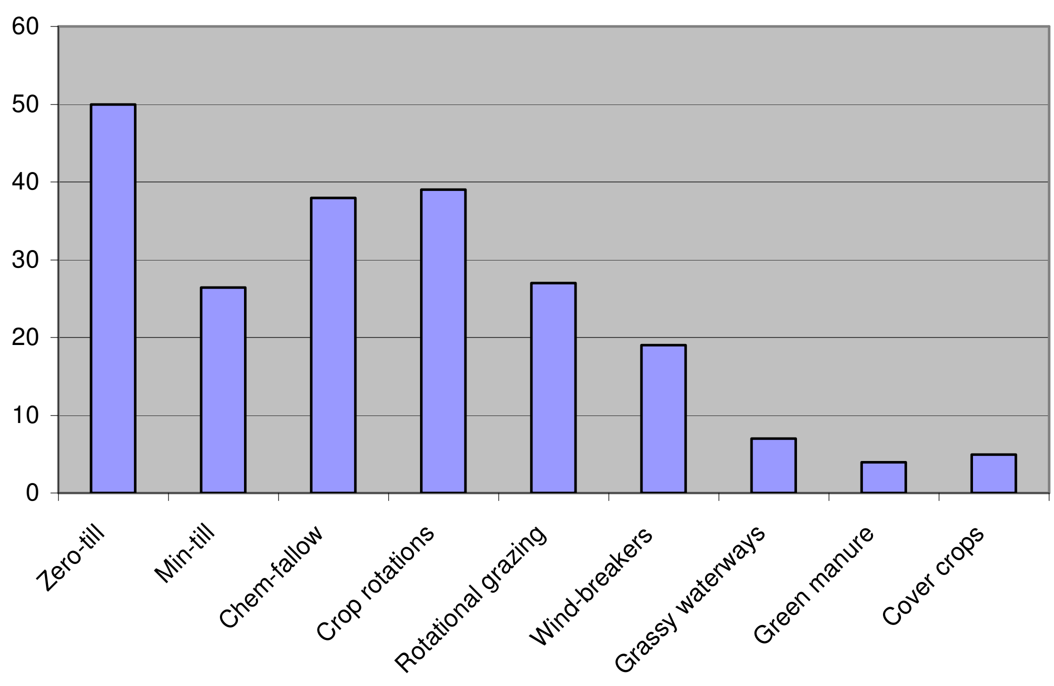
Source: Modified from Wall et al, 1995

II. Soil Conservation Practices on the Canadian Prairies

Since the1980s, growers and various levels of government on the Prairies have made significant progress to reduce water and wind erosion. As a result, a significant portion of Prairie farmers reported using one or more erosion control practices on their farms in 2006.

- No-till was used on 50.3% of seeded acres
- Reduced tillage was used on 26.4% of seeded acres
- Chemical fallow was used on 38% of the ideal acres
- On 39% of farms, there was a reported use of a forage based rotation system on some of the crop land
- On 4% of farms, there was a reported use of plowing-down of green crops (green manure)
- On 5% of farms, there was a reported use of winter cover crops
- On 27% of farms, there was a reported use of rotational grazing
- On 19% of farms, there was a reported use of wind-breaks or shelter-belts
- On 7% of farms, there was a reported use of grassed waterways

Figure 1. Percentage of farms reporting soil conservation practices: 2006 Agricultural Census Data



III. Soil Erosion

Wind and water erosion are major threats to the long-term sustainability of farming on much of the Canadian Prairies. Since the 1930s, cropping practices using tillage and use of fallow have greatly accelerated the process of erosion. Erosion reduces the soil productivity via its effects on soil qualities (Coote 1984, Sparrow 1984). Eroded soils generally are coarse, have high bulk density, poor tilth, reduced organic matter, low nutrient availability and reduced water holding capacity, these all result in reduced crop yields (Dormaar et al 1986). The average annual soil loss due to wind erosion on the Canadian Prairies is estimated to be about 160 million tonnes per year (Sparrow 1984). The Research Council of Canada (1986), indicated that annual losses associated with soil degradation cost $1.3 billion ($50.00– $62.00 per acre of agricultural land) in Canada, and this figure would increase to $2.0 billion a year by 2000, as of writing, this estimate has not been substantiated in any reports Also in western Canada, Rennie (1986) estimated the annual on-farm costs of soil erosion to be $430 million.

There are three types of soil erosion.

1. Wind Erosion

Wind erosion refers to the process of detachment, transport, and deposition of soil by wind. It physically removes the fine sand particles (0.1 – 0.5 mm), organic matter, and nutrients from the topsoil resulting in reduced soil quality. In addition to this on-site impact, wind erosion can reduce air quality during extreme erosion events and also reduce water quality if windblown sediments are allowed to drift into streams and lakes. Factors that increase the risk of wind erosion include sparse crop residue on the soil surface, strong and sustained winds (> 20 – 40 km/h at 30 cm), turbulence, dry and hot conditions and increases in the freeze and thaw cycle. The distribution of non-erodible aggregates also affects the wind erosion risk.

On the Canadian Prairies, intensive tillage along with traditional summerfallow has contributed to high levels of wind erosion, especially in drier parts of the Brown and Dark Brown soils zones.

a. The Wind Erosion Equation

The Wind Erosion Equation (WEQ) generally estimates wind erosion risk:

WEQ is $E = f\,(IKCLV)$, where:
E = Estimated average annual soil loss expressed in tons per acre per year
I = Soil erodibility factor
K = Soil ridge roughness factor
C = Climatic factor
L = Equivalent unsheltered distance across the field along the prevailing wind erosion direction
V = Equivalent vegetative cover

b. Wind Erosion Risk

Using the WEQ and other wind erosion indicators, Padbury and Stushnoff (2002) estimated that approximately 30% of cropland in western Canada is subjected to unsustainable levels of wind erosion.

Agriculture, Food and Rural Development (2005), using the existing soil landscape of Canada polygon (SLC), wind speed, soil resistance to movement and available moisture information, have developed a comprehensive wind erosion risk map for the province (Figure 3). According to this map a substantial portion of land in the Brown and Dark Brown soils are at risk of wind erosion. In western Canada, studies evaluating the effect of tillage system on wind erosion risk are limited. Larney et al (1994) near Lethbridge, Alberta, evaluated the fallow management effects on wind erodibility. Five fallow systems were compared:

- Two to four passes of a one-way disk, heavy-duty cultivator or wide-blade cultivator (conventional fallow)
- Minimum tillage (herbicides plus one pass of wide-blade cultivator in fall)
- No-till (herbicides only, chemical fallow).

There were several major findings of this research:

- A strong relationship exists between tillage intensity and residue cover. No-till conserved the highest amount of residue.
- A substantial increase in the erodible fraction from fall to spring. This was due to freezing-thawing, wetting-drying and freezing-drying which caused over-winter aggregate breakdown
- Little effect in the fall when one-way disk and heavy-duty cultivator treatments relied solely on the presence of non-erodible clods to protect the treatments from wind erosion because they had less than the critical limit of surface residue (1.12 t/ha). However, in spring, there was a slight erosion risk as they approached the critical 60% erodible fraction value (Figure 3)
- The blade cultivator, minimum tillage and no-till treatments had the best combination of residue and non-erodible clods in the fall. However, in spring, these treatments were protected solely by residue cover as the erodible fraction increased to greater than 60% due to over-winter breakdown (Figure 2).

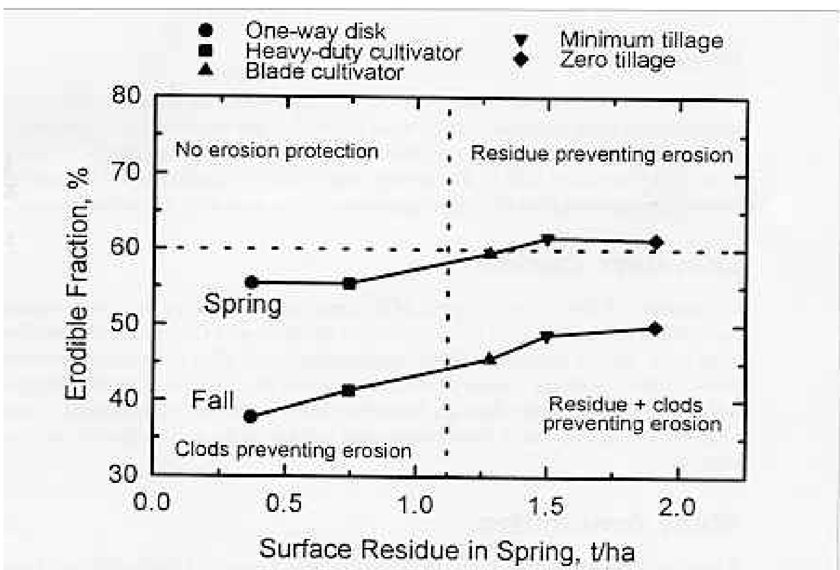


Figure 2. Fallow management and overwinter effects on wind erodibility

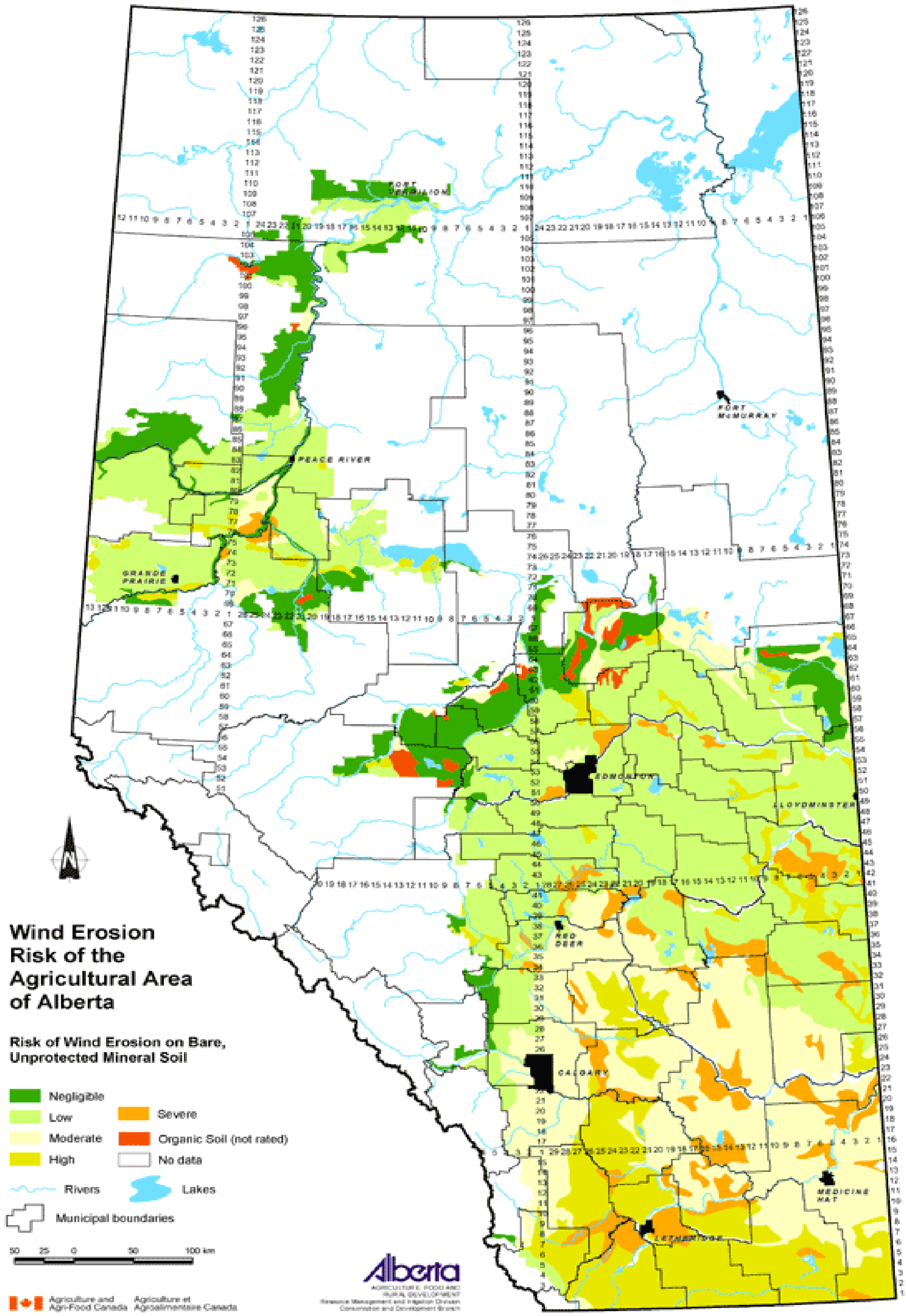


Figure 3. Wind Erosion Risk of the Agricultural Area of Alberta
Source: Coote, D.R. and Pettapiece, W.W. 1989. *Wind Erosion Risk, Alberta*. Land Resource Research Centre, Research Branch, Agriculture Canada. Publication 5255/B. Contribution Number 87-08.

2. Water Erosion

Water erosion refers to the detachment, transport and disposition of finer soil particles, organic matter and nutrients. Water erosion is a concern because it reduces water quality if these particles are carried into nearby streams and other water bodies. Factors that increase the risk of water erosion include the amount and intensity of rainfall, the erodibility of soil, slope length and steepness, snow melt, partially frozen soils, wet conditions, freeze and thaw cycles, cropping and management factors, and erosion control practices.

a. Water Erosion Equation

In Canada and the United States, researchers use the *Universal Soil Loss Equation* (USLE) to calculate soil loss by water erosion as a function of five factors:

$A = R \times K \times LS \times C \times P$

Where:
A = annual soil loss (tons/a/yr) or (tonnes/ha/yr). This is the amount, which is compared to the "tolerable soil loss" limits.
R = erosivity of rainfall and runoff, the higher the intensity and duration of rainfall, the higher the erosion potential.
K = soil erodibility factor
LS = the slope length-gradient factor
C = crop/vegetation and tillage factor.
P = erosion control practices, this reflects the effect of practices that reduce the amount and rate of the water runoff and thus reduce the amount of erosion.

b. Water Erosion Risk

Shelton et al 2000, using *The Universal Soil Loss Equation* (USLE) and its derivatives, have predicted average annual soil loss rates by water erosion on the Canadian Prairies (Table 3). According to this model, in 1996, the Prairie Provinces had 87% of cropland area at a tolerable water erosion risk. This was an improvement of 22% in water erosion risk since 1981, and this shift of cropland into the tolerable risk class from the higher risk classes can be attributed to a combination of reduced tillage, less intensive crop production, decreased summer fallow, and removal of marginal land from production

Table 3. Risk of water erosion on Canadian cropland in 1981 and 1996

Province	Cropland* (million ha)	Proportion of cropland (%) in various risk classes									
		Tolerable**		Low**		Moderate**		High**		Severe**	
		1981	1996	1981	1996	1981	1996	1981	1996	1981	1996
Alberta	10.6	75	83	15	11	8	6	2	1	<1	<1
Saskatchewan	18.8	64	90	24	5	7	5	4	1	2	<1
Manitoba	4.9	88	89	5	4	3	4	1	1	3	2
Canadian Prairies	34.3	76	87	15	7	4	5	2	1	2	1

* Includes seeded and summer fallow (tilled, but not seeded).
** Tolerable (sustainable) <6 t ha^{-1} yr^{-1}, Low=6–11 t ha^{-1} yr^{-1}, Moderate=11–22 t ha^{-1} yr^{-1}, High=22–33 t ha^{-1} yr^{-1}, Severe>33 t ha^{-1} yr^{-1}.
Source: Modified from Shelton et al 2000

Alberta Agriculture, Food and Rural Development (2005) using the existing soil landscape of Canada polygon (SLC), and *The Universal Soil Loss Equation* (USLE) have estimated the risk of water erosion on bare, unprotected mineral soils (Figure 4). According to this map, a considerable portion of cropland in Alberta is at risk of moderate, high, or severe water erosion.

Conservation tillage practices are effective in reducing the soil losses, however, studies evaluating the effects of soil erosion and tillage systems on soil productivity are limited.

In simulated erosion studies at 6 Alberta sites, erosion drastically reduced crop productivity (Larney et al 1995a). These authors showed that only 1 cm of soil loss could result in a 2 – 8% yield reduction in spring wheat, and after 20 cm soil loss, crop yields would be reduced by 5 – 40%. They also found that the addition of fertilizer and manure didn't restore productivity. In addition, they found that treatment effects at an irrigated site followed the same trends as at dryland sites, indicating that topsoil loss cannot be offset by adequate soil moisture.

In another simulated rainfall study, Nolan et al (1997) showed that for a 1 in 2 year storm in the Peace River region, reduced tillage and no-till reduced soil losses by 50 – 80 % as compared with conventional tillage (Table 4).

Table 4. Soil loss from natural rainfall in experimental plots for conventional, reduced till and no-till conditions in the Peace River region of Alberta

Measurement period	Soil loss (kg ha^{-1})		
	Conventional tillage	Reduced tillage	Zero-tillage
1	63.9	31.3	41.0
2	67.3	35.3	6.7
3	487.5	233.6	40.2
4	406.8	277.2	208.0
5	71.6	66.2	34.9
Sum	1102.5^{a}	643.6^{b}	331.7^{c}

Values followed by different letters in the sum row are significantly different at P> 0.05.
Source: Nolan et al 1997.

van Vliet et al (1993) have also shown that no-till and reduced tillage are effective in reducing annual soil losses by 81 and 53%, respectively as compared with conventional tillage (Table 5).

Table 5. Effect of tillage on total soil loss from (a) rainfall and (b) snowmelt near Dawson Creek, British Columbia (1987 – 1991)

Tillage Treatment	Runoff (mm)		Soil Loss (Kg ha^{-1})	
	Snowmelt	Rainfall	Snowmelt	Rainfall
Conventional	24.5a	19.9a	53a	536a
Reduced	12.5b	13.1b	24b	330b
Zero	28.8c	15.5b	20b	123c

Values followed by different letters in the sum row are significantly different at P> 0.05.
Source: van Vliet et al. 1993.

Several studies in the United States have also shown that soil losses were greatest from conventional tillage and least from no-till management systems (Moldenhauer 1985, Robinson and Boardman 1988, Pesant et al 1987). In light of these studies it can be concluded that the no-till crop management system is the most effective means of erosion control.

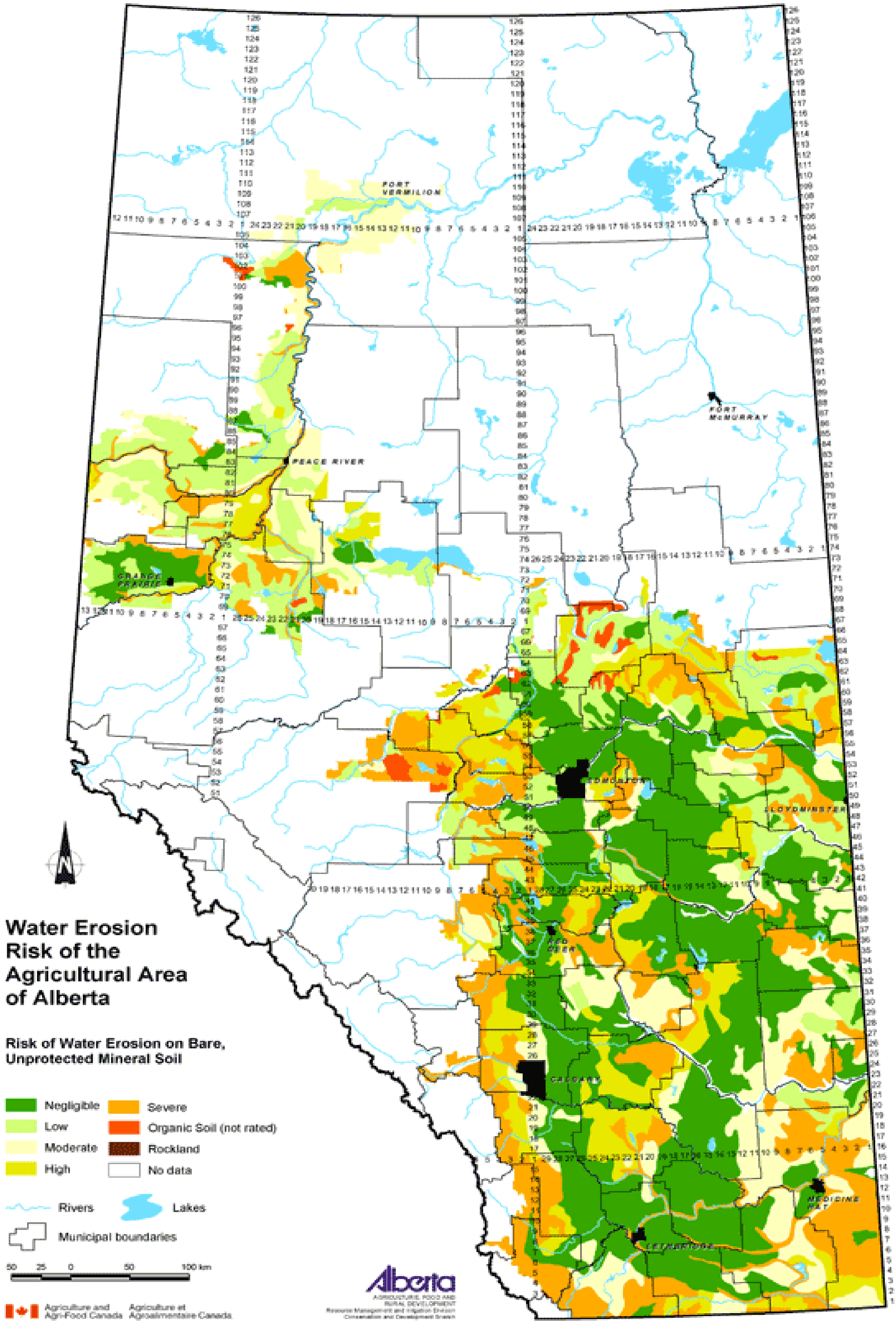


Figure 4. Water Erosion Risk of the Agricultural Areas of Alberta
Source: Tajek, J. and Coote, D.R. 1993. *Water Erosion Risk, Alberta*. Land Resource Research Centre, Research Branch, Agriculture Canada. Publication 5292/B. Contribution Number 92-05

3. Tillage Erosion

Wind and water erosion are the major forms of erosion on agricultural land. on the Canadian Prairies. However, recent research has shown a new type of erosion called tillage erosion is also of significance on hilly agricultural landscapes. In tillage erosion, soil from the upperslope is displaced by tillage equipment and deposited downhill by gravity (Grovers et al 1999). Several factors such as tillage depth, design and operation of tillage implements, and the topographic and soil properties of landscapes are important in determining the extent of tillage erosion. After many years of tillage, there is severe soil loss on hilltops and accumulation of eroded material at slope bottoms. Typically on a given hilly landscape, tillage erosion causes significant soil loss on approximately 20–30% of the area (hilltops), water erosion causes significant soil loss on approximately 30–50% of the area (backslopes of hills), and wind erosion causes significant soil loss on approximately 20–50% of the area (Lobb et al 2003).

a. Tillage Erosion Equation

Lobb et al (1999) developed the following equation for estimating the tillage erosion rate:

$A_{TE} + E_T \mathrm{E}_{L,}$

Where A_{TE} = rate of soil loss (or accumulation) by tillage erosion (t ha^{-1} yr^{-1})
E_T = tillage erosivity (t %$^{-1}$ m^{-1} yr^{-1})
E_L = landscape erodibility (% m ha^{-1}).

b. Tillage Erosion Risk

There are no studies in western Canada comparing the effect of various tillage systems on tillage erosion. However, Lobb et al (2007) have estimated the risk of tillage erosion on Canadian cropland by using the tillage erosion equation and cropping and tillage practices reported in the Census of Agriculture database. They estimated that over 50% of the cropland on the Canadian Prairies is subjected to an unsustainable level of tillage erosion (Table 6).

Table 6. Risk of tillage erosion on Canadian cropland in 1981 and 1996

Province	Cropland* (million ha)	Proportion of cropland (%) in various risk classes									
		Tolerable**		Low**		Moderate**		High**		Severe**	
		1981	1996	1981	1996	1981	1996	1981	1996	1981	1996
Alberta	10.6	47	62	24	19	26	19	3	0	0	0
Saskatchewan	18.8	29	35	14	19	52	46	5	0	0	0
Manitoba	4.9	22	44	53	38	24	18	1	0	0	0
Canadian Prairies	34.3	33	47	30	25	34	28	9	0	0	0

* Includes seeded and summer fallow (tilled, but not seeded).
** Tolerable (sustainable) <6 t ha^{-1} yr^{-1}, Low=6–11 t ha^{-1} yr^{-1}, Moderate=11–22 t ha^{-1} yr^{-1}, High=22–33 t ha^{-1} yr^{-1}, Severe>33 t ha^{-1} yr^{-1}.
Source: Lobb et al 2007.

IV. Conclusions

On the Canadian Prairies, soil erosion is the major threat to the long-term sustainability of crop production. The average on-farm cost of soil erosion in 1980 was estimated to be $430 million per year. Since the early 1990s, conservation tillage (zero and minimum tillage) and other soil conservation practices (reduced fallow, crop rotation perennial forage, wind-breaks) have been popular among prairie growers, and this has resulted in significant decline in erosion risk.

According to *The Universal Soil Loss Equation* (USLE) and other environmental indicators, there has been a decrease of 22% in water erosion risk since 1981, and this shift in cropland into the tolerable risk class from the higher risk classes can be attributed to a combination of reduced tillage, less intensive crop production, decreased summer fallow, and removal of marginal land from production. On a provincial basis, Saskatchewan has shown the most improvement, with a shift of 26% of its cropland into the tolerable risk class from the higher risk classes, followed by Alberta (8% improvement).

In spite of a 60% reduction in fallow, the risk of wind erosion is still high on the Canadian prairies. According to some estimates, approximately 30% of cropland in western Canada is subjected to unsustainable levels of wind erosion.

The concept of tillage erosion is relatively new and there are limited field studies. Lobb et al (2007) estimated that over 50% of the cropland on the prairies is subjected to an unsustainable level of tillage erosion.

The general trend of increasing conservation tillage and other soil conservation practices will result in significant decrease in the risk of erosion.

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SECTION 5
THE ECONOMIC, AGRONOMIC AND ENVIRONMENTAL IMPACT OF NO-TILL ON THE CANADIAN PRAIRIES.

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The Impact of No-Till on Non-Point Source Pollution

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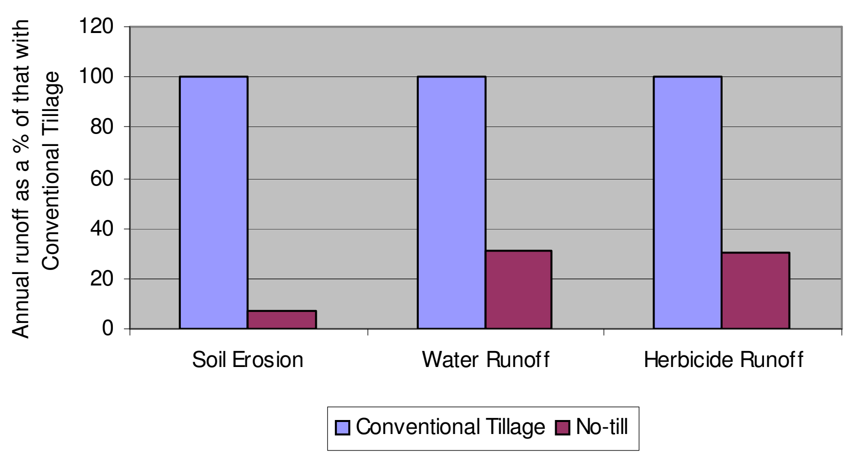
The Impact of No-Till on Non-point Source Pollution

I. Introduction

The term non-point source (NPS) pollution refers to pollution originating from diffuse areas (land surface or atmosphere) having no well-defined source. NPS pollution generally results from precipitation, runoff, infiltration, drainage, seepage, hydrologic modification, or atmospheric deposition. That leads to rainfall or snowmelt moving over and through agricultural fields. As the runoff moves, it picks up and carries away nutrients (mainly nitrates and phosphorous), sediments, animal waste, and pesticides, and deposits them in lakes, rivers, and wetlands, where it affects surface water quality and aquatic life. Agricultural activities also have the potential to directly impact the habitat of aquatic species through physical disturbances caused by tillage practices or by livestock. Conservation tillage practices protect soil from the erosive impact of wind and water and therefore have the potential to reduce the quantity of pollutants (sediments, fertilizers and pesticides) that is generated at and/or delivered from a source into lakes, streams and rivers.

In Canada, studies where conventional and no-till have been compared in terms of runoff, sediments, nutrients and pesticides are limited. However, studies in the United States indicate that zero-till practices have the potential to reduce runoff, sediments, nutrients and pesticide losses. Fawcett and Towery (2002) summarized natural rainfall studies comparing no-till with conventional tillage (moldboard plowing). They showed that, on the average (over 32 treatment-site-years of data), no-till resulted in 93 % less erosion, 69 % less water runoff and 70 % less herbicide runoff than conventional tillage (Figure 1).

Figure 1. Runoff and Erosion in No-till Watersheds Compared to Conventional Tillage Watersheds



II. No-Till Reduces Runoff

No-till practices retain 90 – 100 % of crop residues on the soil surface and protects the soil against wind and water erosion. Reductions in soil erosion are directly proportional to the amount of soil covered by crop residue. Typically, 90 % residue cover reduces the runoff of water, sediment loads and soil erosion by over 95% as compared to soils without residue cover (Table 1).

Table 1. Effects of surface residues cover on runoff and soil loss

Residue cover	Runoff (% of rain)	Runoff velocity (feet/min)	Sediment in Runoff (% of runoff)	Soil Loss (tons/acre)
0	45	26	3.7	12.4
41	40	14	1.1	3.2
71	26	12	0.8	1.4
93	0.5	7	0.6	0.3

Source: Cooperative Extension Service, Purdue University 1995.

In no-till systems, there is less runoff and more infiltration than in conventional tillage systems; consequently, this results in fewer pollutants entering streams. In Quebec, McRae et al (2000) reported a 60% reduction in surface runoff for no-till corn as compared to conventionally tilled corn. In Saskatchewan, at the watershed scale, snowmelt runoff from long-term, no-till, was less than half that from conventionally tilled fields, and runoff from summer storms was also reduced (Elliott et al., 1998). Several paired watershed studies in the United States have also shown that no-tilled fields have significantly reduced water runoff, soil erosion and pesticide runoff as compared to conventional fields (Foy and Hiranpradit, 1989; Glenn and Angle, 1987; Hall et al 1991). In a long-term study in Ohio, Edwards et al (1989) found 99% less water runoff in a no-tilled watershed as compared to a conventionally tilled watershed. The main reason for this is that in the zero tilled watershed reduced run-off improves infiltration, increases macroporosity (earthworm and root channels), and provides more continuous soil pores because they are not disrupted by tillage.

No-tillage reduces runoff by slowing the flow of rainwater or snowmelt from the field. However, by not tilling the soil, there is a concern that it may increase leaching of water, nutrients and pesticide to the ground water. There are conflicting reports in the literature about the role of no-till in enhancing leaching. Some studies have found little or no difference in leaching of water and nutrients between conventional tillage and no-till (Andreini and Steenhuis 1990; Granovsky et al 1993), while others report greater leaching in no-till soils (Dick et al 1989; Hall et al 1989; Isensee et al 1990, and Singh and Kanwar 1991) than in conventionally tilled soils. Some studies have been conducted in Alberta to determine the effect of reduced tillage and no-tillage on leaching of water and soluble chemicals. Cheng and Lindwall (1989, 1990, 1992) measured the infiltration at the soil surface and hydraulic conductivity rates for different depths of soils in southern Alberta under conventional tillage and reduced tillage. At one site they found that the infiltration rate was higher during the summer-fallow phase of reduced tillage soils, but there were no differences in hydraulic conductivity values (1989). At a second site, they found no differences in the infiltration rate between zero and conventional tillage (Cheng and Lindwall 1990). At a third site, they found that although infiltration rates were not significantly different among tillage treatments, within the tillage zone, hydraulic conductivity of reduced tillage was less than in conventional tillage, but it was greater below that zone (Cheng and Lindwall 1992). Miller and Larney (1997) measured the leaching of water and the chemicals in conventional tillage and no-till Dark Brown Chernozemic soils in southern Alberta under saturated and unsaturated conditions. Tillage treatment had no effect on leaching of water and chemicals under saturated or unsaturated conditions. It was concluded that long-term, no-till on a clay loam soil in southern Alberta, has not increased leaching of water and chemicals compared to conventional tillage. Reduced runoff in no-tillage is also associated with decreased flooding and increased soil moisture.

III. No-Till Reduces Sediments Loss

Sediments in runoff water are suspended solids (mineral and organic). They are the result of soil erosion. Sediments cause turbidity of water, reduce sunlight penetration, and reduce photosynthesis of submerged plants.

No-till reduces the amount of sediment in runoff. A study by Environment Canada suggests that sediments in runoff water from no-till fields may be reduced by 50 – 80% when compared to conventional tillage. Studies in the United States have shown up to 90% decline in the amount of sediment transported off fields under no-tillage systems as compared to conventional tillage (Mostaghimi et al 1988; Chichester and Richardson; Seta et al 1993; Gaynor and Findlay 1995). Similarly, Richardson and King (1995) compared the sediment, nitrogen and phosphorous losses in surface runoff from watersheds with heavy clay soils in central Texas, U.S.A. They found that no-till significantly reduced the loss of sediment, nitrogen and phosphorus relative to conventional tillage.

IV. No-Till Reduces Nutrients Losses

Nitrogen and phosphorus are important nutrients in agricultural systems; however, the movement of these nutrients from agricultural land into surface water that drains into lakes can cause eutrophication, which affects aquatic life and surface water quality. In agricultural soils, phosphorus binds very tightly to soil particles. Small, more chemically active clay particles attract and hold nutrients. These smaller soil particles erode more easily than larger soil particles. Anderson et al (1998) found that most of the phosphorus in runoff from Hynes Creek watershed in central Alberta occurs in a dissolved form. Therefore, any practice that reduces soil erosion also reduces phosphorus loss.

1. Phosphorus

No-till practices typically reduce soil erosion and sedimentation losses, and result in less phosphorus lost in runoff. Information on the effects of tillage systems on phosphorus loss is contradictory. Andraski et al (1985) studied phosphate losses in no-till and conventional tillage systems where fertilizer was sub-surface banded. In soybean following corn, zero till treatments reduced soil erosion by 97%, resulting in 80 to 91% reduction in phosphorus loss. For corn following soybeans, an 86% reduction in soil loss led to a 66 to 77% reduction in phosphorus lost. Blevins et al (1990) also found that conventionally tilled plots tended to lose more dissolved phosphorous then no-tilled plots. Mostaghimi (1986) and Richardson and King (1995) also reported significantly lower dissolved phosphorus losses under no-till as compared to conventional tillage. Chichester and Richardson (1992) reported that at the watershed scale, dissolved phosphorous loss tended to be lower in no-till than in conventional tillage.

Conversely, other studies have demonstrated that no-till reduced the loss of particulate and total phosphorus in surface runoff; however, it does increase the loss of soluble phosphorus to ground water (Gaynor and Findlay 1995; Bundy et al 2001). There are two main reasons for this: (1) in no-till there is a reduced runoff volume that increases the concentration of dissolved phosphorus and proportionally decreases losses of particulate phosphorus, and (2) leaching of soluble phosphorus from the crop residues (Riemersma et al 2006).

2. Nitrogen

As discussed earlier, runoff decreases with reduced tillage, resulting in less nitrogen loss although runoff concentrations may be higher. Several studies have shown that no-till reduces chemical runoff. Baker and Laflen (1983) demonstrated that a 97% reduction in sediment loss for no-till (relative to conventional tillage) resulted in a 75 to 90% reduction in total nitrogen loss for soybeans planted following corn and a 50 to 73% reduction in nitrogen loss for corn following soybeans.

No-till crop production increases the amount of soil macropores and allows for greater water infiltration, which could lead to nitrate contamination in groundwater. Fox and Bandel (1986) have shown that in a continuous corn system, there is a greater potential of nitrate leaching in no-tilled systems than in conventional systems. Izaurralde, et al (1995) has also shown increased nitrogen leaching in the soil profile under no-till compared with conventional tillage. More recent studies (Halverson, et al., 2001; Zhu, et al., 2003; and Gupta, et al., 2004) showed no difference in nitrogen leaching between tillage types. These studies emphasize that no-till has an increased risk of macropore flow that may impact N leaching.

V. No-Till Reduces Runoff of Pesticides

Pesticides and fertilizers are commonly used for the production of agricultural crops. Without the use of pesticides and crop nutrients, field crops would have significantly lower yields due to weed infestations, insect damage and plant disease. However, losses of pesticides and nutrients from treated fields to water resources create human health concerns by potentially affecting the quality of drinking water.

In rural Alberta, shallow ground water is a major source of drinking water. In recent years, concerns from non-point pollution sources, mainly nitrates and pesticides leaching from agricultural fields have increased. Several studies have documented the presence of nitrates and pesticides in streams, rivers, reservoirs and atmospheric depositions (Anderson et al 1996, Anderson and Saffran 1997, Anderson et al 1997, Cheng and Entz 1990, Hill et al, 1996, Hill et al 2001, Humphries et al 2005). The frequently detected herbicides detected in atmospheric deposition, soil sediments and surface water in Alberta are 2,4-D, MCPA, bromoxymil, dicamba, glyphosate and mecoprop (Table 2). Pesticides can enter surface water through one of four routes: 1) direct application to the aquatic vegetation, 2) through erosion, as some pesticides are adsorbed by soil particles suspended in runoff, 3) binding to the surface residues and soil that wash off treated fields, and 4) through drift from treated fields that are near water.

Table 2: Concentration ranges of the five herbicides detected in greatest amounts in Alberta (1996 - 2005)

Herbicides	Concentration Range
	----------- $\mu g\ L^{-1}$ -----------
2,4-D	< 0.025 to 53
MCPA	< 0.025 to 26
Bromoxynil	< 0.025 to 26
Dicamba	< 0.025 to 9.1
Glyphosate	< 0.2 to 6.0
Mecoprop	< 0.025 to 2.5

No-till systems leave about 80 – 90% crop residues on the soil surface after planting, protect the soil against erosion, and result in reduced volume of surface runoff relative to that of conventional tillage. As erosion is reduced, loss of sediment-associated materials (pesticides and nutrients) is also reduced. However, leaching of highly mobile pesticides appears to increase in no-till systems.

There are conflicting reports in the literature on the effect of tillage on runoff and associated pesticide losses. Hall et al (1979) compared the loss of cyanazine in runoff from no-tilled soil planted to corn in the growing seasons of 1977 through 1979 with losses from conventionally planted corn on a 14% slope. The no-tillage systems reduced runoff, erosion, and herbicide movement. For example, runoff from conventional tillage ranged from 5.5 to 22% of the runoff-producing rainfall. Soil loss from the same system ranged from 4.4 to 32.2 mg/ha. On the other hand, runoff from the no-tillage systems ranged from 0.07 to 2.5% of the runoff-producing rainfall, while soil losses ranged from 0 to 1.1 mg/ha. A review of several paired watershed studies by Fawcett et al. (2002) showed that conventional tillage fields tend to have significantly higher water runoff, soil erosion and herbicide losses as compared to reduced tilled fields. Zhang et al 1997 also reported that no-till fields have significantly reduced runoff volumes and herbicide losses as compared to tilled fields. In contrast, other researchers have found lower losses of herbicides with runoff water under conventional tillage systems than under a no-till system (Gaynor et al 1995, Smith et al 1995). Interestingly, Environment Canada's unpublished survey data collected in the last 10 years indicate similar frequency of herbicide detection in conventional and zero tillage systems (Wicklum and Gray 2009).

Residual herbicides used in the production of crops are often detected in surface runoff at concentrations exceeding their maximum contaminant levels or health advisory levels; this occurs because herbicides have a greater likelihood of moving to groundwater or surface water. With the advent of transgenic crops such as glyphosate and glufosinate-tolerant varieties, this concern about herbicide contamination of groundwater might be reduced by replacing some of the residual herbicides with ones that have a shorter, or no residual activity, are strongly adsorbed, translocated, or that act on contact. Such herbicides are thought to be more environmentally benign. In a four-year study, researchers at USDA-ARS's North Appalachian Experimental Watershed near Coshocton, OH, compared relative losses of both herbicide types when applied at a normal rate to seven small watersheds planted with glufosinate-tolerant (Liberty-Linked) corn or glyphosate-tolerant (Roundup Ready) soybean. Herbicide losses to surface water for glyphosate and glufosinate were usually much less than for residual herbicides (atrazine, alachlor and metribuzin), when calculated as a percentage of the amount of herbicide applied. Averaged for all soybean crop years, glyphosate loss was approximately one-seventh that of alachlor. Similarly, the average loss for the contact herbicide glufosinate (Liberty) was one-fourth that of atrazine, an alternative residual corn herbicide. The concentrations of atrazine in runoff were up to 240 times greater than in the established drinking water standard. Conversely, the maximum glyphosate concentration noted was nearly four times less than its established standard. Glufosinate currently has no established standard but was only detected at low concentrations and was below its detection limit 80 days after application (Shipitalo et al 2008). In light of increased economic incentives to grow more corn, soybean and canola in Canada for biofuel production, this last study suggests that herbicide losses and concentrations in runoff can be reduced by planting herbicide-tolerant varieties and replacing some of the residual herbicides with glyphosate or glufosinate herbicides.

It should be noted here that almost all of the herbicide-tolerant crops grown on the prairies of western Canada are produced in direct seeding systems. For this reason, the results of the above studies should be valid for the Alberta situation.

VI. Conclusions

- No-till fields have significantly reduced erosion (80 - 90%), less runoff volumes (50 – 80%) as compared to tilled fields.

- Runoff volume decreases with no-till, resulting in less N loss, although runoff concentrations may be higher.

- P is mainly associated with sediments. Sediment loss typically decreases with no-till, resulting in lower loss of P in run-off.

- There are conflicting reports in the literature on the effect of tillage intensity on leaching loss of crop chemicals in the soil. Some researchers have reported a decreased loss of sediment-associated pesticides, while others have reported no, or increased losses of pesticides with decreasing tillage intensity.

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SECTION 6

THE ECONOMIC, AGRONOMIC AND ENVIRONMENTAL IMPACT OF NO-TILL ON THE CANADIAN PRAIRIES.

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The Impact of No-Till on Wildlife Populations and Habitats

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The Impact of No-Till on Wildlife Populations and Habitats

I. Introduction

The three Prairie Provinces represent over 80% of the total national agricultural area of Canada and include both planted (cropland) and uncultivated acres (woodland, natural grassland, wetlands, shelterbelts). This area is the home of many bird and wildlife species and provides important breading, feeding, cover, and wintering habitats for a variety of wildlife species (Table 1). The uncultivated habitats, especially wetlands, grasslands and shelterbelts support greater numbers of wildlife species as compared to croplands (Table 2). Within the cropland habitats, cereal crops support more wildlife species than oilseed crops (Neaves and Neaves, 1998). In recent years, many wildlife species, especially songbird and duck populations have declined sharply, and many researchers have attributed this population decline to loss and degradation of natural grassland habitats due to the intensification of agricultural activities. In order to reverse this trend, it is necessary to promote agricultural practices that minimize use of fall and spring tillage, convert marginal cropland to perennial forages and pasture, and protect and restore wetland and upland habitat.

Conservation tillage practices using reduced or no-till and environmentally friendly chemicals have expanded markedly since the 1990s. In 2006, there were more than 51 million acres in conservation tillage in the three Prairie Provinces. (Census Canada 2006). Growth in conservation tillage practice is expected to continue in the future in western Canada.

No-tillage systems leave a large amount of crop residue on the soil surface and provide the least amount of soil disturbance. Crop residue provides food in the form waste grain on the soil surface and feeds waterfowl, songbirds, upland game birds, deer, small mammals, and increased populations of arthropods in spring and summer. Small mammals and many bird species depend on insects as their primary food source. Standing crop residues also provide protective cover in the winter to many wildlife species and nesting habitats in the spring. In general, the higher the amount of crop residue, the greater the value of wildlife cover. Minimal soil disturbance during the nesting and brood rearing period has the potential to save nests, chicks, and nesting hens. Moreover, when no tillage is combined with other best management practices, such as integrated pest management, crop rotation, nutrient management and conservation buffers, it can mimic "surrogate" natural grassland habitat for many birds and other wildlife populations.

Table 1. Commonly occurring bird and mammal species in the Prairie Region of Canada

Common occurring birds	Commonly occurring mammals
Dabbling duck species: Mallard; Bluewinged Teal; Northern Pintail; Northern Shoveler; and Gadwall. **Diving duck species**: Canvasback and Redhead **Endemic grassland bird species:** Baird's Sparrow; Bobolink; Chestnut-collared Longspur; Grasshopper Sparrow; Lark Bunting; Le Conte's Sparrow; Marbled Godwit; Northern Harrier; Sprague's Pipit; Swainson's Hawk; Wilson's Phalarope, Burrowing Hawk; Ring-neck Pheasant, Burrowing Owl.	**Small Mammals:** Deer mouse, grasshopper mice, meadow voles, sedge brush voles, Richardson's ground squirrel, gofer, badger, weasels, stripe skunk, white-tail jack rabbit **Large Mammals:** Coyote; red fox; deer; antelope,

Table 2. Number of vertebrate[1] species using habitats[2] on agricultural land divided into 5 categories of activity on the Canadian Prairies mid 1990s

Cropland	Breeding	Feeding	Cover	Wintering	Staging[3]	Total
Cultivated acres:						
Cereals:	41	179	27	12	37	296
Spring wheat	10	39	6	2	6	63
Durum wheat	8	38	6	2	6	60
Oats	7	33	4	2	9	55
Barley	8	33	5	2	6	54
Other grains	8	36	6	4	10	64
Oilseeds:	2	28	1	1	2	34
Canola	1	9	0	0	0	10
Other oilseeds	1	19	1	1	2	24
Fruits and Vegetables	12	29	11	1	0	53
Other crops	1	10	0	0	0	11
Forages:	31	83	59	3	6	182
Alfalfa	11	38	25	1	3	78
Tame hay	20	45	34	2	3	104
Seeded pasture	35	62	46	14	3	161
Shelterbelts	72	111	104	33	1	321
Others (summerfallow and farm buildings)	32	82	46	21	2	183
Uncultivated acres						
Natural grassland	161	244	207	88	7	727
Woodland	237	255	257	107	3	858
Wetlands	252	383	305	68	29	1038

[1.] Vertebrates include birds, mammals, reptiles and amphibians.
[2] This includes the addition of species using the prairies as the primary and secondary habitats for breeding, feeding, shelter, wintering and staging (birds only).
[3] Activity only for birds.
Source: Neaves and Neaves 1998.

II. No-Till Enhances Habitats for Birds

In Canada and the United States, limited wildlife research involving conservation tillage has shown that no-till fields have higher densities of birds and nests. Increased abundance of wildlife in zero-tilled fields may be attributed to cover provided by crop residue, waste grain and weed seed food sources left on the soil surface, and less disturbance from field operations.

In Canada and the United States, there is limited wildlife research involving conservation tillage. Martin and Forsyth (2003) studied the abundance and productivity (nesting and brood-rearing behavior) of songbirds (savannah sparrow, Baird's sparrows, chestnut-collared longspur and McCown's longspur) in spring cereals, winter wheat, and summer fallow using either conventional or minimum tillage in southern Alberta, Canada. There were several important findings from their research:

- Abundance of most bird species and total birds was greatest in summerfallow, with the exception of Savannah sparrows, which preferred winter wheat (Table 3). In 1995 and 1996, there were more total birds in minimum versus conventional tillage

- In spring cereal plots, minimum tillage had higher density and productivity in both years relative to conventional tillage (Table 4). In winter wheat plots, the mean number of bird territories and productive territories was significantly greater in minimum versus conventional tillage in 1995 but not in 1996. In summerfallow there was no difference in number of bird territories among the tillage regimes

- Savannah sparrows in spring cereal and winter wheat and chestnut-collared longspurs in summerfallow tended to prefer minimum tillage

- McCown's longspurs and horned larks occurred more frequently on conventional than minimum till spring cereal. However, these species tended to have higher productivity in minimum till plots. Summerfallow of either tillage regime did not appear to be as productive as minimum till cereal fields for McCown's longspurs and horned larks

- Chestnut-collared longspurs occurred predominantly in minimum till summerfallow and spring cereal habitats and showed almost no productivity in conventionally managed plots

- Male Baird's sparrows occupied territories in minimum till winter and spring cereal fields in 1995, but did not attract mates; they were not detected in 1996

The authors concluded that minimum tillage appeared to confer benefits in productivity to bird species that nested in spring cereal, winter wheat, and summer fallow fields.

Table 3. Mean abundance of bird species in prairie farmland under conventional and minimum tillage regimes in Alberta, Canada, 1995 and 1996.

Species	Cover type comparisons			Tillage comparisons	
	Spring cereals	Winter wheat	Summerfallow	Conventional	Minimum
1995					
Horn lark	1.68	1.12	1.58	1.59	0.74
Savannah sparrow	1.25	1.96	1.50	1.03	2.13
Baird's sparrow	0.21	0.08	0	0	0.21
McCown's longspur	0.57	0.04	0.79	0.67	0.26
Chestnut-collared longspur	0.32	0.08	0.58		
Total birds	4.03	3.2	4.83	3.46	4.65
1996					
Horn lark	1.86	1.34	2.27	1.83	1.74
Savannah sparrow	1.18	1.79	1.27	1.30	1.55
McCown's longspur	1.36	0.19	1.18	0.72	1.08
Chestnut-collared longspur	0.14	0.04	0.47	0.03	0.39
Total birds	4.54	3.36	5.19	3.88	4.76

Source: Martin and Forsyth (2003)

Table 4. Mean productivity of savannah sparrows in prairie farmland under conventional and minimum tillage regimes in 1995 and 1996, on a per plot basis

Cover type	Productivity variables	1995		1996	
		Conventional	Minimum till	Conventional	Minimum till
Spring cereal	No. of territories	0.36	2.14 ***	0.79	1.57 *
	No. of productive territories	0.07	1.57 ***	0.21	1.00 **
	Mean productivity score	0.50	3.52 **	1.02	2.86 *
	No. of abandoned territories	0.14	0.43 ns	0.29	0.22 ns
Winter wheat	No. of territories	1.23	2.64 **	1.79	1.79 ns
	No. of productive territories	0.39	1.57 **	0.57	0.79 ns
	Mean productivity score	1.41	3.21 ns	1.28	2.45 ns
	No. of abandoned territories	0.69	0.42 ns	0.64	0.57 ns
Summerfallow	No. of territories	1.54	1.45 ns	1.33	1.20 ns
	No. of productive territories	1.15	0.82 ns	0.50	0.40 ns
	Mean productivity score	3.83	2.31 ns	1.82	1.69 ns
	No. of abandoned territories	0.39	0.36 ns	0.58	0.80 ns

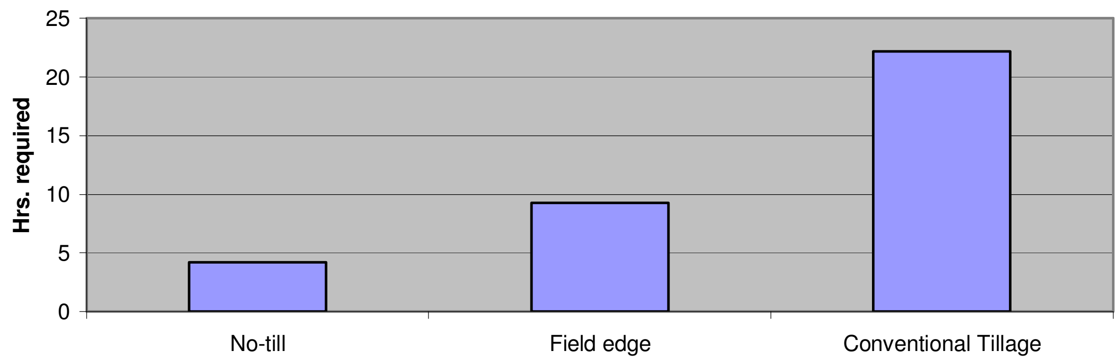
Indicates * = $P < 0.05$; ** = $P < 0.01$; *** = $P < 0.001$ and ns = not significant at $P \leq 0.05$.
Source: Martin and Forsyth (2003)

Shulter et al (2000) compared the bird communities of uplands and wetlands in four treatments: conventional farms, conservation (minimum tillage) farms, organic farms , and restored or natural (wild) sites in Saskatchewan, Canada. Of 37 different upland bird species encountered during the study, one made greater use of conventional, conservation and organic farms, four made greater use of wild sites, and the remaining species showed no preference. When all upland species were combined, higher relative abundance occurred on wild than on farmed sites, and on minimum tillage than on conventionally tilled sites. Cowan (1982) in Minnedosa, MB has also shown increased production of 25 waterfowl broods per section on no-till fields compared to 7 broods per section on conventional farms.

In southeastern North Dakota, Lokemoen and Beiser (1997) evaluated bird densities, bird nest densities, and daily survival rates on conventional, minimum-tillage, and organic farms. Mean number of nesting species and mean nest densities were higher on minimum-tillage and organic than on conventional farms. Significantly greater densities of birds were observed on reduced-tillage than on conventional farms. Daily survival rate for shore birds was greater in minimum-tillage than in organic fields. No other differences among farm type were observed.

Palmer (1995) studied bobwhite quail behavior in no-till and conventional fields in North Carolina. The research showed that quail chicks needed 22 hours to obtain their minimum daily requirement of insects in conventional soybean fields. In no-till soybean fields, only 4.2 hours were required to obtain the minimum daily requirement, about the same as the 4.3 hours required in natural fallow areas believed to be ideal quail habitat (Figure 1).

Figure 1. Time needed for Bobwhite Quail chicks to satisfy daily insect requirements



Source: Palmer 1995

III. Fall Seeded Winter Cereals Enhance Duck Populations

Direct seeding of winter cereals into standing stubble also enhances wildlife population density and diversity, especially waterfowls and other upland birds. Studies conducted by Ducks Unlimited Canada (2001) have shown that under zero-tillage, there is a higher duck density population in winter seeded cereal crops than spring-seeded cereals. There is also a higher productivity. In a two-year study in western Canada, pintails on average hatched one nest in every 72 acres of fall-seeded crops as compared to one nest in every 1,332 acres of traditional spring-seeded cropland). In this study, fall-seeded crops generated a greater number of nests – and from these nests, there was greater success in hatching ducks (Table 5).

Table 5. Evaluation of Pintail Use of Fall-seeded Cereal Grains

	Fall Rye	Spring seeded cereals
Total nests found	191	30
Pintail nests	85	19
Nest density	1.1/10 ac	0.2/10 ac
May field nest success	18.1%	5.5%

Source: Ducks Unlimited Canada

Another study, Devries et al (2008) in Saskatchewan, also found higher nesting success in fall-seeded crops than in spring-seeded crops. The average nest densities for fall-seeded cereals in 1998 was 1.14 nests per 10 acres, and in 1999, it was 1.07 per 10 acres. In spring-seeded cereals in those years nest densities were 0.17 per 10 acres and 0.028 per 10 acres respectively. The main reason for nesting success in the fall-seeded cereals is that there was no disturbance by farm machinery in the fall. In the spring, farm machinery may have destroyed nesting sites. It is also believed that songbirds and other ground nest birds are impacted in a similar way.

IV. No-Till Enhances Habitats for Arthropods

In conservation tillage, crop residues harbor insects, an important source of food for many small mammals and many bird species. In Canada, there are no studies on the effects of tillage on arthropods. However, several studies in the United States have shown that no-till fields have greater abundance and diversity of arthropods, including beneficial insects, than conventionally tilled fields (Blumberg and

Crossley 1983, Warburton and Klimstra 1984). Probably, a similar situation is also true for zero-tilled fields in Canada.

V. No-Till Enhances Habitats for Small Mammals

Crop residues in zero-tilled fields provide cover and food supply (wasted grain and weed seed) to small mammals, and, as a result, these fields tend to have greater abundance and diversity of small mammals; this can have an impact on crop production in some years. Small mammals, especially rodents in large numbers, have the potential to cause crop damage, however, the data on rodent damage is inconclusive as there are no studies in Canada, and there are few studies in the United States documenting wildlife damage in zero-tilled versus conventionally tilled fields

VI. Conservation Tillage and Pesticides

The above cited studies on conservation tillage and wildlife habitats clearly indicate that no-till fields have greater densities and more species of birds and small mammals, and there are more attractive nesting and brood rearing habitats than found within conventionally tilled fields. However, no-till fields rely on herbicides and insecticides for weed and insect control, and this can have adverse effects on wildlife. Some of the earlier studies have demonstrated such effects with the contact herbicide paraquat on mallards, northern bobwhite, ring-necked pheasant, and deer mice (Best 1985; Castrale, 1985; Nicholson and Richmond 1985). The increased attractiveness of no-till fields as nesting and brood rearing habitats has been shown to have the potential for chemical exposure to birds caused by contact transfer from adults to young, direct spraying of eggs and young, or contamination from ingesting poisoned insects or granular forms of pesticides (Wooley et al.1985).

No-till fields rely solely on herbicides and insecticides for weed and insect control, however, several studies have shown that greater use of pesticides is not necessarily required for no-till or reduced tilled farming, and in many situations such as transgenic crops (glyphosate and glufosinate tolerant crops), no-till systems use less herbicide and the ones that are used tends to be environmentally benign (Little, 1987; Flickinger and Pendleton 1994; Fawcett and Towery 2002). The use of insecticide is a concern for wildlife safety. Recent studies in which northern bobwhite chicks were exposed to direct spraying of insecticides and were allow to consume the poisoned insects show that some of the modern insecticides are less harmful than those used in the past.

1. Glyphosate and Wildlife

In North America, Latin America and Western Europe, glyphosate is the most commonly used herbicide in conservation tillage systems. It can be used prior to seeding (weed burn-down), as an in-crop treatment in glyphosate resistant crops, prior to harvest (pre-harvest), and after the crop harvest (post-harvest). Glyphosate has been evaluated in laboratory studies for toxicity on small mammals (rat, mice and rabbit), birds (bobwhite quail and mallard duck), insects and fish. These species are surrogates for wild species that might be exposed to glyphosate through various exposure routes. All these studies indicated that glyphosate does not cause adverse effects to wildlife (U.S. EPA 1993).

2. Birds

Glyphosate has been evaluated for toxicity to bobwhite quail and mallard duck in laboratory studies. These species are surrogates for wild avian species that might be exposed to glyphosate through various exposure routes. In dietary studies conducted with bobwhite quail and mallard ducks, in which the birds consumed a treated diet for 5 days, glyphosate had no effects at the highest dose tested. Reproductive tests indicated that no adverse effects on avian reproduction or hatchling development would be expected from normal use of glyphosate. Exposure of birds to glyphosate in the environment is predicted to occur at much lower levels than the levels evaluated in the laboratory studies. In addition, glyphosate has been shown to rapidly dissipate from treated vegetation, and such vegetation becomes unpalatable within 1 to 3 weeks after treatment. Therefore, the proper use of glyphosate-containing herbicides should not pose a significant risk to birds (U.S. EPA 1993). In addition to the laboratory studies, several comprehensive field studies have examined birds in natural settings where glyphosate products were used. These studies demonstrate that some species favored treated areas, while other species temporarily left treated areas because of changes in the vegetative habitat. No direct toxicity was reported in any of the studies (Giesy et al, 2000). Any form of vegetation removal would be expected to produce similar effects. Studies have shown that avian species abundance returns to pre-treatment levels when plant regrowth occurs (MacKinnon and Freedman, 1993).

3. Small Mammals

Glyphosate has been extensively tested for adverse effects on laboratory mammals, rats and rabbits. There are also many field studies in which the effects of glyphosate use on wild mammals have been examined (Sullivan and Sullivan, 2000; Sullivan 1990; Cumming et al. 1996). All these studies have shown that when glyphosate is used according to label direction, there are no unreasonable adverse effects to mammals.

4. Insects

Glyphosate have been tested for toxicity to honey bees in laboratory tests, using both oral and topical dosing. In these studies, glyphosate have no adverse effects to bees at rates much higher than would be present in treated areas. Hassan *et al. (*1988) have tested on 18 different beneficial predators and parasite. They found glyphosate was harmless to 13 species, slightly harmful to four species and moderately harmful to one species (carabid beetle). Giesy et al. (2000) have reviewed the extensive research data on glyphosate and arthropods and concluded "non-target arthropods are at minimal risk from glyphosate in offsite areas. Within treated areas, applications of the herbicide can produce changes in species diversity and in population size and structure for beneficial insects through modifications of available food sources and habitat."

VII. Concluding Remarks

Conservation tillage practices leave a large amount of crop residues on the soil surface. This usually results in an increase in bird species (waterfowl, songbirds, pintail, upland sandpiper) and productivity. Increased abundance and productivity of bird species may be attributed to cover provided by crop residue, waste grain and weed seed food sources left on the soil surface, and less disturbance from farm machinery directly destroying nests.

Fall seeded cereals especially winter wheat can be quite valuable for enhancing waterfowl (northern pintail) and shorebirds (long-billed curlews, and marbled godwits) populations, nest densities and nest success.

Several studies have also shown conservation tillage practices enhance the diversity and abundance of arthropods, including beneficial insects, which provide food for wildlife.

Extensive use of glyphosate in conservation tillage systems does not cause adverse effects to bird species, small mammals and insects.

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SECTION 7

THE ECONOMIC, AGRONOMIC AND ENVIRONMENTAL IMPACT OF NO-TILL ON THE CANADIAN PRAIRIES.

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The Impact of No-Till on Weeds, Plant Diseases and Insect Pests

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The Impact of No-Till on Weeds, Plant Diseases and Insect Pests

I. Introduction

In recent years on the Canadian Prairies, growers have made significant changes in tillage practices to reduce production costs (saving on fuel, farm machinery-life and reduced labor costs), improve profits (crop yields) and to be environmentally friendly (increased soil-organic matter, improved soil tilth, improved moisture conservation and use efficiency, and reduced soil erosion). Direct seeding practices have been adopted across a majority of acreage in Western Canada. Recent surveys by Agriculture Canada indicate that indicate that 28.3% or 7,023,214 ha of the cropped land on the Canadian Prairies is seeded with reduced-tillage and 43% or 10,671,314 ha with zero-tillage practices (Census Canada 2006).

A characteristic of direct seeding is that it retains most of the crop residues on the soil surface. This crop residue acts as insulation and impedes the rate at which thermal energy is exchanged between the soil and the atmosphere, affecting soil microclimate through reducing the wind speed near the soil surface and the heat transfer through evaporation and heat flow. This often keeps the soil temperature 1 – 2 °C cooler in direct seeded fields than in conventionally tilled fields. Crop residues also help to trap and hold the snow, enhance moisture absorption during summer rains, and results in increased soil moisture availability at seeding time and throughout the growing season.

In direct seeding systems, lack of soil disturbance, increased soil moisture and slightly cooler soil temperature can have a direct impact on certain weeds, disease pathogens and insect populations, Some species may increase with decrease tillage, while others decrease or stay the same. For example, wind disseminated weed species such as Canada thistle, dandelions, foxtail barley, narrow-leaved hawk's-beard and perennial sow-thistle are commonly associated with minimum–no-till systems, while other species like green foxtail, wild buckwheat, wild mustard and stinkweed require soil disturbance for germination and establishment and are common in conventional tillage systems. Some species, wild oats, flixweed and volunteer canola are common across tillage systems (Blackshaw 2005).

Higher moisture under reduced tillage is also associated with reduced survival of fungal over-wintering structures such as *Sclerotinias sclerotiorum,* which causes white mould in canola because they favor bacteria that attach to these structures. Similarly, populations of root pathogen (*Bipolaris sorokinina*) decreases under minimum–no-till systems, but other pathogen *Fusarium* spp (the cause of root rot in cereals) may increase. Similar to weeds and plant diseases, insect pests also respond differently to tillage practices.

Although not much research has been done in western Canada on the effect of reduced and no-till on plant diseases and insect pests, there is some information available via field surveys and field research on the effect of tillage on weed populations.

II. Impact of No-Till on Weed Populations

Field studies in North America and Europe has shown that adaptation of minimum and no-till practices can lead to changes in weed species diversity and numbers. However, recent studies in Alberta and Saskatchewan have shown year-to-year variations in climatic conditions and crop rotations had a greater effect than the tillage system (Blackshaw 2001, 2005, Derksen et al 1997).

1. Year-to-year climatic conditions

Changes in weeds dynamics within any agro-ecosystem are a result of the complex interaction between prevailing climatic conditions, crop rotations and tillage practices. Long-term studies on effects of tillage and crop rotation on weed community dynamics have shown that weed density and species composition were most affected by year-to-year differences in environmental conditions, followed by crop rotation, and then tillage intensity (Blackshaw et al 2001). Weed densities in zero-tillage were often greater in years in which above normal rainfall was received in the spring or previous fall, because crop residue and cool moist conditions of zero-tillage provides ideal conditions for seed germination and establishment. Similarly a dry spring preceded by dry fall will result in greater weed densities in conventional tillage than in zero-tillage because tillage will move the weed seed below the surface into moist soil. In years of low rainfall and above average temperatures, Russian thistle and kochia densities increased. These weeds compete vigorously with crops under dry versus moist conditions (Blackshaw et al 2006). Redroot pigweed becomes more prevalent in years with above average summer temperatures. Flixweed, downy brome and narrow-leaved hawk's-beard increase in density in wet years, especially if they are not controlled by tillage or herbicide. Similarly, dandelions and quackgrass thrive in wet years, whereas deep-rooted perennials were less affected by year-to-year variation in rainfall.

2. Crop rotations

Crop rotations and tillage intensity also influence weed community dynamics. A study was conducted at Indian Head SK. to determine weed dynamics in diversified and reduced input crop rotations under zero and conventional tillage systems (Derksen et al 1997). In-crop herbicides were similar for both tillage systems. In the low input rotations (R3 and R4) grass weed herbicide was reduced by 50% with no treatment in wheat phases. Reduced rates of narrow-spectrum herbicides were used for broadleaf weed control. Pulse crops were grown every second year in the low input herbicide and fertilizer rotation (R4). As a result, fertilizer rates in R4 were reduced to 50% of the high input rotations.

The major findings of this long-term study are:

- Total weed densities, averaged over four years, were lower in no-till than in conventional tillage at the seedling stage but were similar in late July (Table 1).
- In the fall of 1994, total weed densities in the soil seed bank were similar in both tillage systems (Table 2).
- The reduced input rotations (R 1 and R2) had equivalent or fewer weeds compared to the conventional input rotations (R3 and R4). The most diversified crop rotations (R5 and R6) had the greatest total weed densities.

Blackshaw et al (2001) studied the effect of various winter wheat rotations and tillage on crop yield and weed infestation near Lethbridge, AB. In this 8-year study weed densities were more affected by crop rotation than tillage. The highlights of this study are:

- No-till had greater weed densities than either minimum tillage or conventional tillage (Table 3). Previous studies had also reported higher weed densities in no-till system than either minimum or conventional tillage (Moyer, Lindwall and Blackshaw 1994).
- The 22 weed species in this study consisted of summer and winter annuals, perennials, and volunteer crops.
- When all years and rotation treatment were combined, weed data in May indicated that downy brome, dandelion and Russian thistle were associated with no-till, other species showed no preference to any tillage system

- The June weed data indicated that kochia, downy brome, redroot pigweed, prostrate pigweed, dandelion, and perennial sow thistle were associated with no-till. Common lamb's-quarters and wild mustered were associated with minimum tillage and stinkweed and volunteer winter wheat were associated with conventional tillage
- The October weed data indicated that downy brome and dandelion were associated with no-till, flixweed and Canada thistle were associated with minimum and conventional tillage, other species showed no preference to any tillage system
- Weed communities were different in no-till compared to either minimum tillage or conventional tillage and there were no significant differences between minimum tillage and conventional tillage (Table 3).

Table 1. Average total densities (m^{-2}, $\pm$ standard error) of all weed species: 1992 – 1995

Rotation	Zero tillage	Conventional tillage
Prior to in-crop spraying:		
R1 – Wheat – canola – wheat – lentil	219 $\pm$ 40	351 $\pm$ 42
R2 – Wheat – canola – wheat – lentil	121 $\pm$ 26	187 $\pm$ 44
R3 – Wheat – canola – wheat – lentil	190 $\pm$ 36	238 $\pm$ 34
R4 – Wheat – pea – wheat – lentil	115 $\pm$ 25	215 $\pm$ 47
R5 – Canary seed – sunola – wheat – lentil	84 $\pm$ 11	202 $\pm$ 30
R6 – Wheat – mustard – canary seed – lentil	163 $\pm$ 13	295 $\pm$ 32
July 1992-1995.		
R1 – Wheat – canola – wheat – lentil	133 $\pm$ 12	168 $\pm$ 18
R2 – Wheat – canola – wheat – lentil	102 $\pm$ 11	88 $\pm$ 9
R3 – Wheat – canola – wheat – lentil	115 $\pm$ 12	120 $\pm$ 13
R4 – Wheat – pea – wheat – lentil	84 $\pm$ 10	74 $\pm$ 7
R5 – Canary seed – sunola – wheat – lentil	99 $\pm$ 7	135 $\pm$ 15
R6 – Wheat – mustard – canary seed – lentil	141 $\pm$ 12	172 $\pm$ 18

Source: Derksen, D.A., Loeppky, H.A., and Lafond, G.P. 1997

Table 2. Average total densities (m^{-2}, $\pm$ standard error) for all weed species in the soil seed bank, fall 1994.

ROTATION	ZERO TILLAGE	CONVENTIONAL TILLAGE
R1 – Wheat – canola – wheat – lentil	4508 $\pm$ 424	4467 $\pm$ 430
R2 – Wheat – canola – wheat – lentil	4597 $\pm$ 387	3965 $\pm$ 251
R3 – Wheat – canola – wheat – lentil	4710 $\pm$ 391	4778 $\pm$ 499
R4 – Wheat – pea – wheat – lentil	3053 $\pm$ 338	2951 $\pm$ 302
R5 – Canary seed – sunola – wheat – lentil	5377 $\pm$ 1049	5505 $\pm$ 885
R6 – Wheat – mustard – canary seed – lentil	4890 $\pm$ 723	4820 $\pm$ 545

Source: Derksen, D.A., Loeppky, H.A., and Lafond, G.P. (1997)

Table 3. Mean weed densities in winter wheat in May averaged over years as affected by tillage intensity

ROTATION	ZERO TILLAGE	MINIMUM TILLAGE	CONVENTIONAL TILLAGE
	------------------------------- Plants m^{-2}	--	
Winter wheat – oilseed	15 (5)	5 (1)	5 (1)
Winter wheat – flax	5 (1)	11 (3)	7 (2)
Winter wheat – fallow	6 (2)	13 (18)	8 (1)
Continuous winter wheat	98 (32)	13 (12)	31 (12)
Tillage mean	31 (9) A	12 (2) B	13 (3) B

Values in parenthesis represent standard error of the mean
Tillage mean followed by same letter are not significantly different.
Source: Blackshaw et al (2001)

3. Tillage

Tillage has profound impact on weed populations. In conventional tillage, primary and secondary tillage bury the weed seeds, fragment the roots and rhizomes and kill emerged weed seedlings. Tillage, however, depletes the seedbed moisture, affecting the yield potential and promotes soil erosion. In reduced and no-till systems, herbicides are used to kill weeds, which give crops a competitive advantage over weeds. Increased herbicide use has raised concerns regarding the potential shifts in weed populations in zero-tillage (Derksen et al 2002). It is generally believed that reduced tillage will result in increased weed densities. Buhler (1995) and Froud-Williams (1988) have shown an increase in annual grasses and perennial weed species with reduced tillage practices. Pollard et al (2003) also showed an increase density in 4 annual species, a decreased density in six annual species and no change in density in 7 other annual species in no-till. In some studies, reduced tillage has resulted in an increase in volunteer crops (Derksen 2002) but not in others (Wiese 1985). In ten medium to long-term studies on the effects of tillage on weed population shifts on the Canadian Prairies Thomas et al (2004) have shown that perennial sow thistle and Canada thistle was associated with reduced and no-till, but annual species were associated with min tillage systems. Russian thistle was associated with no-till and stinkweed was associated with conventional tillage, while wild buckwheat and common lamb's-quarters were equally abundant in all tillage systems. Thus, different weeds respond differently to tillage practices. The following discussion summarizes the relevant Canadian Prairies research on the effect of tillage on emerged and seedbank weed species diversity and density.

4. Weed Seedbank

The weed seed bank is the reserve of viable weed seeds present on the soil surface and scattered throughout the soil profile and the main contributor to weed pressure in current and future crops. The seed bank consists of newly shed seeds by a weed plant as well as older seeds that have persisted in the soil. In minimum and zero-tillage systems, most of the weed seeds are at or near the soil surface (0 – 5 cm) whereas, in conventional tillage systems weed seed are distributed fairly evenly down to about 10 – 15 cm. Minimum – no-till systems keep the weed seeds close to the surface. They will have reduced dormancy, and under dry conditions can have high seed mortality, predation by insects, birds and other animals. Thus, adequate aboveground weed control in the first few years of no-till can greatly reduce the weed seed bank in the upper layer of soils (O'Donovan and McAndrew 2000). In contrast, in conventional tillage systems, seeds are buried in the soil, resulting in conditions that are conducive to seed dormancy and perpetual weed problems. It has been shown in the Pacific Northwest that downy brome seed in the soil was reduced from 5,205 seeds m^{-2} to almost 0 seed m^{-2} in 5 yrs in the continuous no-till spring cereals (Thorne et al 2007). In a long-term study in Ontario, Murphy et al (2005) have also demonstrated that over 6 yrs, seedbank declined in no-tillage systems from 41,000 to 8,000 seeds m^{-3}.

A study was conducted at Alliance, Hairy Hill, and Wainwright in northeastern Alberta to determine the effects of conventional, minimum, no-till systems on annual weed populations and the vertical distribution of weed seeds in the soil (O'Donovan and McAndrew 2000). In conventional and minimum systems weed seed was distributed fairly evenly down to about 10 cm soil zones; while in the no-till system over 70% of the seed was close to the soil surface. No-till plots had higher seeds m^{-3}. However, spring seedling populations of stinkweed, shepherd's purse and wild buckwheat (as well as green foxtail) were lowest in the zero compared to the other tillage systems (Table 4), suggesting that the requirement for herbicides for controlling these weeds in the crop may be least under no-till.

Table 4. Effect of tillage systems on weed seedling emergence in spring

Weed species	Weed seedling m^{-2} emerged in spring		
	Conventional	Minimum	Zero
Stinkweed	33	31	3
Lamb's quarters	20	16	2
Wild buckwheat	44	61	18
Green foxtail	32	18	3

Source: O'Donovan and McAndrew (2000).

5. Weed Diversity and Density

Regardless of the tillage systems, annual grasses and broadleaves, winter annuals and perennial weeds are the most troublesome weeds on the Canadian Prairies (Table 5). Depending on the weed species, minimum-no-till can increase, decrease or have no effect on the weed density. A weed survey done in Manitoba in 1995 has shown that many summer and winter annual (wild oats, volunteer canola, hemp-nettle and cleavers) and perennial weed species (dandelion, Canada thistle, quackgrass, and perennial sow-thistle) had higher densities in no-till fields. Conversely, other species (green foxtail, volunteer barley, wild mustard, redroot pigweed, volunteer flax, kochia and lamb's-quarters had higher density in conventional tillage systems. Researchers in Montana and North Dakota have also shown that certain summer and winter annual (downy brome, shepherd's-purse) readily germinate on or near soil surface in minimum-no-till systems (Donald and Nalewaja 1990).

Blackshaw et al (2001) conducted an 11 yr field study at Lethbridge AB to determine the effects of conventional, minimum and no-till on weed densities. No-till had greater weed densities than either minimum tillage or conventional tillage (Table 4). In another multi-site study (11 field experiments ranging in duration of 4 – 11 yrs) Blackshaw (2001 and 2005) and Bradshaw et al (2006) studied the effects of conventional and minimum-no-till practices on weed population dynamic. The highlights of this multi-site study are:

- Of 71 species recorded, 56% were associated with minimum –no-till, 27% were associated with conventional tillage and remaining 17% did not show any preference to either tillage systems.
- All perennial species, especially dandelions and foxtail barley were more strongly associated with minimum –no-till than with conventional tillage (Table 6).
- Biennials (biennial wormwood and yellow sweet clover) were associated minimum –no-till (Table 6)
- Native species (goldenrod and wild rose) rarely occurred in the conventional tillage but were more common in minimum-no-till systems (Table 6)
- Of 39 annual species, 44% were associated with minimum-no-till, 33% were associated with conventional tillage and remaining 23% had no preference to either tillage systems.

Table 5. Percent of producers listing specific weeds as troublesome by tillage system in various agricultural eco-regions of Alberta, Saskatchewan and Manitoba

Troublesome weed	Conventional	Minimum–zero tillage
Mixed Grasslands, Moist mixed grasslands and Fescue Grasslands eco-regions (Brown and Dark Brown Soil zones) of Alberta and Saskatchewan		
Wild oats	68	70
Wild buckwheat	47	50
Kochia	44	62
Stinkweed	34	37
Green foxtail	23	30
Russian thistle	21	21
Canada thistle	19	15
Cow cockle	16	10
Flixweed	14	18
Wild mustard	12	11
Aspen Parkland and Lake Manitoba Plain eco-regions (Black Soil zone) of Alberta, Saskatchewan and Manitoba.		
Wild oats	71	70
Wild buckwheat	45	48
Canada thistle	39	47
Green foxtail	30	26
Wild mustard	18	12
Stinkweed	18	25
Cleavers	13	11
Redroot pigweed	11	5
Hemp-nettle	11	5
Quackgrass	11	13
Kochia	5	13
Volunteer canola	9	11

Boreal Plains eco-regions (Dark Gray and Gray Soil zones) of Alberta, Saskatchewan and Manitoba		
Wild oats	70	62
Wild buckwheat	47	44
Canada thistle	42	33
Green foxtail	25	23
Stinkweed	23	33
Kochia	19	28
Cleavers	12	7
Chickweed	12	1
Dandelion	11	11
Hemp-nettle	11	3
Wild mustard	10	14
Flixweed	5	11
Quackgrass	10	11

Source: Thomas (2008), Canada Agriculture and Agri-Food

Table 6. Tillage Systems and weeds density

Weeds that have greater densities in minimum – zero tillage than in conventional tillage systems		
Common name	Scientific name	References*
Annuals		
Annual sow thistle	*Sonchus oleraceus*	1,2
Common groundsel	*Senecio vulgaris*	1,2,6
Kochia	**Kochia** *scoparia*	1,2,5,6
Pineapple weed	**Matricaria matricariodes**	1,2,5,6
Prickly lettuce	*Lactuca serriola*	1,2,5,6
Russian thistle	*Salsola iberica*	1,2,6,7
Winter annuals		
European sticktight	*Lappula echinata*	1,2
Catchweed bedstraw (Cleavers)	*Galium aparine*	1,2
Downy brome	*Bromus tectorum*	1,2,6
Green flower pepperweed	*Lepidium densifolrum*	1,2
Horseweed	*Conyza canadensis*	1,2,6
Narrow-leaved hawk's-beard	*Crepis tectorum*	1,2,3,6
Pigmy flower	*Androsace septentrionalis*	1,2
Redstem filaree (Stork's-bill)	**Erodium cicutarium**	1,2
Scentless chamomile	*Matricaria perforata*	1,2,5,6
Shepherd's-purse	*Capsella bursa-pastoris*	1,2,3,6
Wood whitlow-grass	*Draba nemorosa.*	1,2
Biennials		
Biennial wormwood	*Artemisia biennis*	1,2,
Yellow sweet clover	*Melilotus officinalis*	1,2,
Western salsify	*Tragopogon dubius*	1,2,
Perennial		
Absinth wormwood	*Artemisia absinthium*	1,2
Canada goldenrod	*Solidago canadensis*	1,2
Canada thistle	**Cirsium arvense**	1,2,6,7
Dandelion	*Taraxacum officinale*	1,2,3,6
Field horsetail	*Equisetum arvense*	1,2
Foxtail barley	*Hordeum jubatum*	1,2,6
Perennial sow-thistle	*Sonchus arvensis*	1,2,5,6,7

Wild rose	*Rosa spp.*	1,2,
Quackgrass	*Elytrigia repens*	1,2,3,6
Smooth brome	*Bromus inermis*	1,2,6
Weeds that have lower densities in minimum-zero tillage than in conventional tillage systems		
Ball mustard	*Neslia paniculata*	1,2
Common lamb's-quarters	*Chenopodium alba*	1,2
Cut leaf nightshade	*Solanum triflorum*	1,2
Dog mustard	*Erucastrum gallicum*	1,2
Green foxtail	**Setaria viridis**	1,2
Green smartweed	*Polygonum scabrum*	1,2
Oak leaf goosefoot	*Chenopodium glaucum*	1,2
Prostrate pigweed	*Amaranthus blitoides*	1,2
Redroot pigweed	**Amaranthus retroflexus**	1,2
Thyme-leaved spurge	*Euphorbia serpyllifolia*	1,2
Wild buckwheat	*Polygonum convolvulus*	1,2,4
Wild mustard	**Brassica kaber**	1,2,6
Winter annuals		
Field pennycress (stinkweed)	*Thlaspi arvense*	1,2
Volunteer crops		
Barley	**Hordeum vulgare**	1,2
Lentils	**Lens culinaris**	1,2
Peas	**Pisum sativum**	1,2
Sunflower	*Helianthus annuus*	1,2,5,6
Rye	*Secale cereale*	1,2
Weeds that have no preference across the tillage systems		
Annuals		
Barnyardgrass	*Echinochloa crus-galli*	1,2
Common chickweed	*Stellaria media*	1,2
Cow cockle	*Saponaria vaccaria*	1,2
Night flowering catchfly	*Silene noctiflora*	1,2
Prostrate knotweed	**Polygonum aviculare**	1,2
Round-leaved mallow	*Malva pusilla*	1,2
Wild oats	*Avena fatua*	1,2,7
Winter annuals		
Flixweed	*Descurainia sophia*	1,2
Volunteer crops		
Oilseed rape (canola)	*Brassica napus*	1,2
Linseed (Flax)	*Linum usitatissimum*	1,2
Mustard	*Brassica juncea*	1,2
Wheat	*Triticum aestivum*	1,2

[*] 1= Blackshaw (2005); 2 = Blackshaw et al (2006); 3 = Derksen, D.A. et al 1993; 4 = Foster (1986); 5 = Holm (1988); 6 = Moyer et al (1994); 7 = Thomas et al 2004

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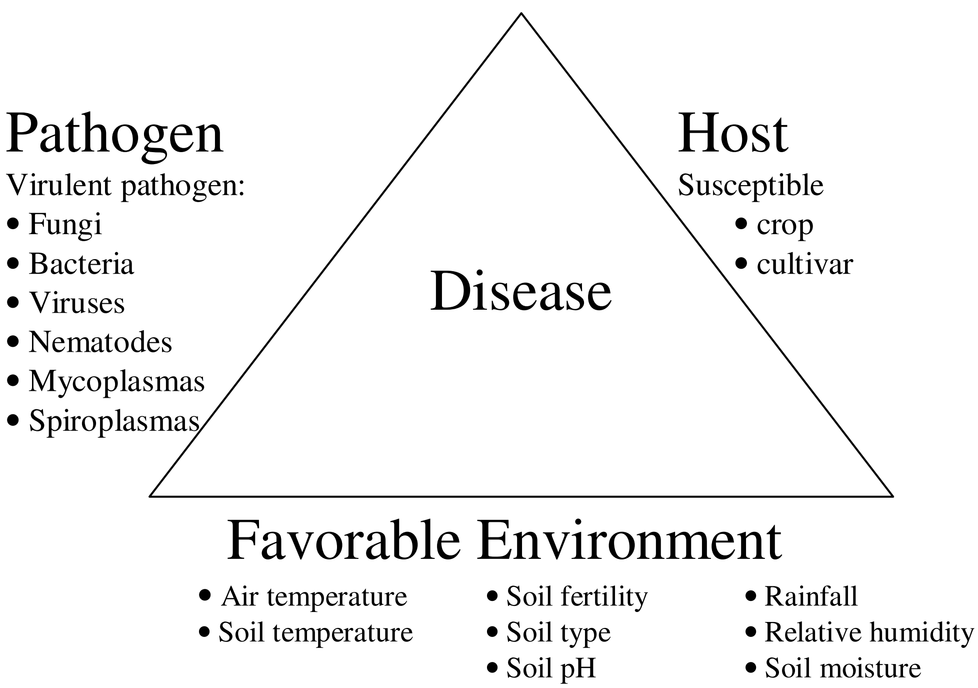
III. Impact of No-Till on Plant Diseases

The presence and severity of a plant disease in any crop is determined by the dynamic interaction of a susceptible crop (host), a causal agent (pathogen), and favorable environmental conditions such as damp weather and warm temperatures (Fig 1). This interaction is known as the plant disease triangle. All three factors are required for disease development. If any one element is missing, disease will not occur. Management practices that modify the host, pathogen or environment will influence the incidence and severity of diseases.

Fig. 1. Plant Disease Triangle



Reduced tillage systems retain large quantities of crop residue on the soil surface altering the physical and chemical properties of the soil and soil environment, plant growth, and microbial populations. Crop residue retention also keeps the soil surface cooler and moister than conventional tillage systems. These changes influence the development of certain residue and soil-borne pathogens resulting in the increase in some diseases, especially those that survive on old crop residues (Bailey 1992), while others decrease or stay the same. In contrast, conventional tillage buries the crop residue in the ground and, therefore, effectively reduces or eliminates the inoculum sources for certain plant pathogens (Tekauz and Howard (1988). Intensive tillage, however, promotes conditions favorable to soil erosion. Studies in western Canada have shown that the environment, cropping sequences, and selection of varieties exert a much larger influence on disease development than tillage system.

There are conflicting reports in the literature on the incidence and severity of plant diseases in reduced tillage systems. Some of the earlier studies have documented an increased incidence and severity of disease levels in reduced tillage as compared to cultivation, while others showed a decrease or no effect. For example, it has been shown that the incidence of *Rhizoctonia* root rot of wheat increases under zero tillage (Rovira and Venn 1985) while other studies have shown that "take-all" root rot of wheat occurs less frequently in zero-minimum tillage systems (Bailey et al 1992; Boosalis et al 1991). Foliar diseases of wheat (including winter wheat) and pea were not affected substantially by tillage. The severity of tan spot and septoria leaf blotch in wheat was similar under zero and conventional tillage (Gossen and Bailey 2000). These conflicting studies make it very hard to make generalizations on the effect of zero-minimum tillage on plant diseases.

The following discussion focuses on residue borne plant diseases in cereal, oil-seed and pulse crops that are influenced by reduced tillage.

1. Common Root Rot

Common root rot is a soil borne fungal disease of wheat, barley and grasses. It is caused by the complex of *Cochliobolus sativus* and *Bipolaris sorokiniana* = (*Helminthosporium sativum*) and *Fusarium* species. Initial symptoms of common root rot in either wheat or barley originate on young seedlings from soil or seed borne inoculum. Infection causes brown lesions on the roots, coleoptiles, and leaves. On the Prairies, common root rot is estimated to cause annual yield losses of about 10% in barley (Bailey et al 2003). In western Canada, common root rot generally decreases in zero-minimum tillage (Bailey and Duczek 1995). In one study, the disease levels were significantly lower under no-till in 6 of 10 years at Scott and 3 of 7 years at Swift Current. (Reference) In an 11-year study in Alberta, the incidence of common root rot showed no consistent difference in severity between minimum and conventional tillage. However, disease tended to occur less under minimum tillage during most years of the study (Conner et al 1987). A crop rotation and tillage trial study at Indian Head, Bailey et al (1992) (Table 1).

Table 1. Effect of tillage on common root rot severity and isolation of pathogens from crown and sub crown nodes (%) in trails at Indian Head Saskatchewan in 1992 and 1993

Tillage	Severity (0-3 scale)		*Bipolaris sorokiniana*		*Fusarium* species	
	1992	1993	1992	1993	1992	1993
Conventional	1.70 a	0.74 a	57 a	71 a	83 a	76 a
Zero	1.50 a	0.47 b	43 b	42 b	88 a	86 b

Letters that are same within the column are not statically different at P = 0.05
Source: Bailey et al 1992

2. Leaf Spot Diseases

On the Canadian Prairies, three important foliar diseases of wheat are tan spot caused by *Pyrenophora triticirepentis*, septoria nodorum blotch caused by *Septoria nodorum* and septoria tritici blotch caused by *Septoria tritici*. These diseases can cause yield losses of up to 50 %. Among these, tan spot, is the most destructive leaf spot disease found in all wheat growing regions of western Canada and Ontario. Tan spot fungus survives winter on wheat plant residues, and this disease is often associated with no-till. Tan spot can occur on leaf surfaces. Initially, small, dark brown to black spots appear on the lower leaves. Subsequently, the spots enlarge into lens shaped lesions (Bailey et al 2003). The effect of tillage on these foliar diseases is variable. Trials in Saskatchewan conducted in 1987 – 1990, showed that reduced tillage did not significantly change the severity of tan spot and septoria nodorum in 3 of 4 years; crop rotation seems to have had more effect on the severity of these foliar diseases (Bailey 1992). All three diseases were more severe on spring wheat after cereal than after peas or fallow. In a field survey of Manitoba, Gilbert and Woods (2001) also found an inconsistent impact of reduced tillage system in spring wheat foliar diseases of spring wheat: septoria nodorum blotch, septoria tritici blotch, spot blotch and tan spot (Table 2)

Table 2. Effect of reduced tillage systems on foliar disease levels in spring wheat

Pathogen	Southeastern Manitoba		Southwestern Manitoba	
	Conventional Tillage	Reduced Tillage	Conventional Tillage	Reduced Tillage
S. nordum blotch	8.6	5.1	8.8	10.4
S. tritici blotch	35.7	39.1	34.0	16.1
Spot bloch	20.1	18.6	9.7	6.7
Tan spot	7.1	6.9	9.9	18.1

Source: Gilbert and Woods. 2001. Can. J. Plant Sci. 81:551-559.

In Ontario, crop sequence and tillage treatments did not affect the severity of foliar diseases of winter wheat, but they did affect the importance of individual diseases, with tan spot becoming more important under no-till than under conventional tillage (Sutton and Vyn 1990).

3. **Browning Root Rot** (*Pythium spp*)

Browning root rot or Pythium root rot is a seedling disease caused by *Pythium* spp in wheat, barley and other grasses. The fungus lives as spores in the soil and on over-wintering crop residues. This seedling disease reduces stand establishment by causing seed decay or seedling blight before or shortly after emergence. In Canada, no-till or reduced tillage may favor *Pythium* growth, as this pathogen prefer cool and wet soils which are commonly associated with no-till (Bailey et al 2003)

4. **Take-All** (*Gaeumannomyces graminis* var. *tritici)*

Take-all is the major root disease of wheat, barley, rye and other grasses in Canada. It is caused by the soil borne fungus *Gaeumannomyces graminis* var. *tritici*. Visual symptoms of take-all are occurrence of stunted plants with few tillers, “whiteheads” and blackened roots.

The effect of reduced tillage on the incidence and severity of take-all is variable. Boosalis et al (1991) have shown that “take-all” occurs less frequently in reduced tillage systems versus conventional tillage. Bailey et al (1992) have also shown a reduced incidence of take-all under reduced tillage. However, research in the U.S. Pacific Northwest has found increased incidences of take-all under reduced tillage.

5. **Net Blotch of Barley (***Pyrenophora teres)*

Net blotch is a common foliar disease of barley in Canada caused by *Pyrenophora teres.* The disease affects the leaves, leaf sheaths and glumes. Early symptoms on the leaves are light brown spots, which may enlarge into narrow, dark brown streaks extending across and down the leaf, forming a distinct net-like pattern. The affected part turns brown, and the entire leaf may die if infection is severe. Stems, sheaths, and kernels may be affected. The spores of net blotch may be on seed or crop residue. Infection is favored by long periods of high humidity or moisture.

The effect of tillage on the severity of net-blotch of barley is inconsistent. In an extensive survey of commercial barley fields under conservation and conventional tillage systems in central Alberta, Turkington et al (1995) found lowest levels of net blotch under conventional tillage, intermediate under minimum tillage and highest levels in zero tilled fields. In another study at Alliance, La Corey, and Viking, Alberta, Kharbanda et al (1997) found lower incidence and severity of net blotch in no-till as compared to conventional tillage. The mean net blotch severity from all locations under zero-till and conventional-till was 2.9 and 3.8 in 1992 and 7.3 and 7.9 in 1993, respectively.

6. **Fusarium Diseases** *(Fusarium spp)*

A complex of *Fusarium* species are important crop disease pathogens. They may attack roots of cereals, pulses and oilseeds resulting in seedling blight and root rot, or they may attack the heads of cereals, causing fusarium head blight (FHB). Fusarium head blight (FHB) of wheat is a major problem in the cereal growing regions of Manitoba and Saskatchewan; they cause serious direct losses in yield, test weight and in price discounting due to the presence of fusarium damaged kernels and their associated mycotoxin deoxynivaleno (DON). In Canada, it is mainly caused by *Fusarium graminearum (*teleomorph *Gibberella zeae).* Other species linked to FHB are *F. avenaceum*, *F. culmorum*, *F.poae.* Crop residue at the soil surface is a principal source of inoculum for FHB; burying cereal crop residues may be an effective way to control FHB but spores of FHB can persist in the soil for a long-time and can be brought back to the surface in subsequent years.

In a 5-year study in eastern Saskatchewan on the effects of various agronomic practices, including tillage on FHB in spring wheat has shown that tillage system in 3 of the 4 yrs had a significant effect on the severity of FHB (Table 3). In general, wheat fields under minimum-till had the highest severity of FHB and the lowest under zero till (Fernandez et al 2005). In this study environmental conditions and susceptibility of cultivars were the most important factors affecting the development of FHB. Miller et al (1998) also found that weather conditions are more influential than tillage practices in the development of FHB.

Table 3. Effect of tillage system on the mean Fusarium head blight (FHB) index in wheat crops sampled eastern Saskatchewan, from 1999 to 2002

Year	Number of fields	Tillage system		
		Conventional	Minimum	Zero
		----------------------------- -- % ---		
1999	88	0.33 a*	0.22 ab	0.09 b
2000	117	1.99 ab	3.39 a	1.80 b
2001	188	8.90 ab	9.95 a	6.25 b
2002	2.5	0.28	0.52	0.31

*Mean FHB index within a year followed by a different letter are significantly different according to least significant differences.
Source: Fernandez et al 2005. Crop Sci 45:1908-1916

In a 3-yr study, Dill-Macky and Jones (2000) monitored the effects of previous crop residues and tillage practices on Fusarium Head Blight of wheat at Morris, Minnesota. Fusarium head blight incidence and severity were greatest when wheat followed corn and least when wheat followed soybeans. Incidence and severity of fusarium head blight were lower in conventional tillage plots than in either minimum tillage or no-till plots.

7. **Leaf Rusts of Wheat and Barley, Crown Rust of Oats**

Cereal rust is caused by Puccinia species: *Puccinia recondite* (wheat), *Puccinia hordei* (barley) *and Puccinia coronata* (oats). Wind-blown spores, originating from infested cereals in the United States, spread rust infection. Thus reduced tillage practices have no influence on disease development.

8. **Ergot (***Claviceps purpurea***)**

Ergot is caused by *Claviceps purpurea* which infects the developing grains of cereals and grasses. Cool and moist conditions at flowering favor ergot infections. There are no studies in western Canada documenting the effect of tillage on ergot development. However, in a reduced tillage system ergot bodies remain at or near the soil surface, thereby increasing the risk of infections in a second year. Ergot bodies in soil survive only one year; therefore, rotating away from cereals for one or two years is very effective in reducing ergot production

9. **Loose Smut** (*Ustilago nuda)*

Loose smut is caused by *Ustilago nuda.* It is a common disease of wheat and barley. Cool moist conditions at flowering time favor loose smut development. Symptoms of the disease first appear when the head emerges from the boot. The kernels and glumes have been converted to masses of black spores. Spores are dislodged and scattered by wind soon after emergence and infect the adjacent plants. The fungus infects open flowers and becomes established in the embryo of the developing seed. Because this is a seed borne disease, tillage has no effect on disease incidence and severity.

10. **Common Bunt - Stinking smut** *(Tilletia caries and T. foetida)*

Common bunt or stinking smut is caused by the fungi *Tilletia caries and T. foetida*. These fungi over-winter as spores on the seed surface. When infested seeds are sown, smut spores germinate, penetrate the seedling and grow within the cereal host until the heads develop. Smut fungi replace all or most of the grain head and form masses of black smut spores instead of seeds and chaff. These spores are released at grain harvest and contaminate the surface of other healthy kernels. Because this is a seed borne disease, tillage has no effect on the development of common bunt.

11. **Alternaria Black Spot - Grey Leaf Spot** *(Alternaria brassicae* and *Alternaria raphan)*

Alternaria black spot in Alberta occurs wherever canola is grown. It is caused by two species of the *Alternaria* fungus: *Alternaria brassicae* and *Alternaria raphani*. The symptoms of this disease appear in early summer on lower leaves as circular, pale to brownish grey lesions with darker concentric lines. Leaf spots may vary in size and color depending on environmental conditions. Leaf spots produce spores, which subsequently infect pods and stems, forming circular, black or dark brown spots, which may elongate into irregular blackish mottled lesions. *Alternaria* fungi survive the winter on infected crop debris, seed, and on mustard family weeds. It is particularly prevalent on stinkweed.

There is no available information on the effects of tillage on the incidence and severity of *Alternaria* black spot in canola. *Alternaria* black spot fungi survives on diseased crop residues. It is generally recommended that diseased stubble should be incorporated into the soil if canola is to be grown on an adjacent field the following year. A crop rotation with at least three years of non-cruciferous crops between canola crops will reduce air-borne spores from crop residue. Cruciferous weeds and volunteer canola should also be controlled during the rotation.

12. **Blackleg** (*Leptosphaeria maculans*)

Blackleg is a common disease of canola in western Canada. This disease is caused by *Leptosphaeria maculans*. This fungus attacks the cotyledons, leaves, stems and pods. The weakly virulent form usually infects plants near maturity and results in shallow stem lesions. The highly virulent form of the fungus attacks the crop earlier in the season, developing dry sunken cankers at the base of the stem, often completely severing plants at the base of the stem. By mid-July, plants may start falling over. Airborne spores produced on residue are the main source of infection in subsequent crops.

Burial of infected canola residue has long been recommended as a practice to speed up the decomposition of canola residue and reduce disease inoculum. However, recent studies at Beaverlodge, Alberta, and Carman, Manitoba, have found that no-till does not increase the risk of blackleg as long as a crop rotation with cereals and pulses is maintained (Turkington et al 2000; Guo et al 2005).

13. **Sclerotinia Stem Rot** (White Mould) (*Sclerotinia sclerotiorum*)

Sclerotinia stem rot is a common disease of canola in moister parts of canola growing regions of western Canada. The fungus over-winters as sclerotia and can survive for a number of years in the soil, but burial is believed to decrease its viability. The effect of tillage on survival of sclerotia is poorly studied, and no generalizations can be made to aid in management of the pathogen. There is evidence that leaving the sclerotia on the soil surface enhances degradation whereas burying the sclerotia enhances survival. It is thought that the more dramatic changes in temperature and moisture on the soil surface are deleterious to sclerotia (Saskatchewan Agriculture 2009). According to Pearse, " It is possible that the harsh winters experienced in the prairies and corresponding freeze-thaw cycles may cause sufficient stress to sclerotia left on the soil surface to facilitate their breakdown. The breakdown of sclerotia is favored by high moisture, and moisture at the soil surface as a result of heavy residue could increase microbial degradation of sclerotia" (Pearse, 2002).

14. **Pea Root Rot** *(Fusarium spp., Pythium spp. and Rhizoctonia solani)*

In Alberta, a complex of organisms causes pea root rot: *Fusarium solani* f sp. pisi, *Pythium* spp. and *Rhizoctonia solani*. Affected plants are stunted and yellow, loose lower leaves and die prematurely. The lower stem turns black or brown. Roots are pinched off and rotted. Fusarium solani f sp. pisi infections may be distinguished from the others by the reddish brown external color of the roots. High moisture and warm soil temperatures (18 to 25°C) favor root rot development of all of these fungi (Turkington et al 2000).

It is generally believed that reduced tillage practices help to reduce the incidence of pea root rot. A study conducted at Fort Vermilion from 1993 to 1996 have shown significantly less root rot of pea in zero-tilled fields than in conventional-till fields (Table 4).

Table 4. The influence of tillage regime on pea root rot severity, Fort Vermilion, 1993- 1996

Tillage	Percent disease severity[1]				
	1993	1994	1995	1996	Overall Mean[1]
Conventional	51.3a	41.8a	64.7a	30.5a	47.1a
Zero	30.8b	35.0a	47.6a	16.7a	32.5b
Overall Mean[1]	41.0b	38.4b	56.1a	23.6c	

[1]Means for the tillage treatments, within each year, followed by different letters were significantly different
Source: Turkington et al (1997).

15. **Ascochyta Blight of Pulses** (leaf and pod spot) *(Ascochyta pisi and Ascochyta lentis)*

The fungus *Ascochyta pisi* causes Ascochyta blight in field peas whereas in lentils it is caused by *Ascochyta lentis.* Infested seed and previously infected crop debris are sources for this organism. The fungus does not over-winter in soil. Symptoms start with a brown speckling of the lower leaves, eventually spreading upwards to the newer leaves and pods. These lesions are often dotted with small fruiting bodies called pycnidia. Cool, wet conditions favor disease development.

Destruction or burial of infected crop residues has often been recommended as a cultural practice to control Ascochyta blight. At Saskatoon, SK., a field study was conducted from 1995 – 1998 to look at the impact of burial on the survival of *Ascochyta lentis* on lentil residue. In that study, infected lentil residue was buried at 0, 5 and 10 cm depths. Although the breakdown of lentil residue was more rapid with burial, burial did not have a substantial impact on the long-term survival of A. lentis (Gossen 2001), indicating zero or minimum tillage does not appear to affect the development of ascochyta blight in lentils.

In other studies at Indian Head and Saskatoon, it was shown that at least two non-host crops were needed between successive lentil or chickpea crops to substantially reduce inoculum of the pathogens that cause Ascochyta blight of lentils and chickpea. (Gossen and Derksen 2003, Gossen and Miller 2004). In an another study at Saskatoon it was shown that Ascochyta blight of lentils was not affected by tillage (Bailey et al. 2000). However, ascochyta blight was not present at the site until late in the trial and lentil was always grown in a 4-year rotation

In light of these studies, it appears that weather conditions and crop rotation rather than tillage are the most important factors determining disease risk. Stubble management practices such as straw chopping during combining, or harrowing to spread out residue on the soil surface, can help speed the decomposition of pulse residue.

16. Anthracnose of Lentil (*Colletotrichum truncatum*)

The fungus *Colletotrichum truncatum* causes anthracnose in lentils. Infested seed and previously infected crop debris are sources for this organism. It has been found that the resting structures of the pathogen causing anthracnose in lentils (*Colletotrichum truncatum*) survive longer if they are buried than at the soil surface (Pearse 2002), therefore, tillage seems to have no effect on anthracnose.

17. Mycosphaerella Blight and Ascochyta Foot Rot (*Mycosphaerella pinodes and Ascochyta pinodella*)

Mycosphaerella blight is the most common disease of field peas in western Canada. Two different fungi are responsible for this disease: *Mycosphaerella pinodes* and *Ascochyta pinodella*. These organisms may be found on seed, on crop residue, and in the soil. Mycosphaerella blight may be found on the leaves and stems as purple spots. Foot rot symptoms usually appear on the stem near the soil surface as bluish black discolorations. Both fungi thrive in wet environments. *Mycosphaerella pinodes* is an aggressive pathogen causing yield losses of up to 75 per cent. Both of these fungi are stubble, seed and soil borne. Studies in western Canada have shown that reduced tillage has no effect on Mycosphaerella blight under a diverse crop rotation (Pearse 2002).

Table 5. Effect of zero-minimum tillage on crop disease in western Canada

Crop	Disease	Disease source	Effect of zero tillage	Reference
Cereals: Wheat Barley Oats	Common root rot	Soil, residue	Decrease	Bailey et al 1992
	Tan spot		Variable	Bailey 1992; Gilbert and Woods 2001, Sutton and Vyn 1990
	Pythium root rot	Soil, residue	Increase	Bailey 2003
	Leaf spots	Soil, residue	Variable	
	Take-all	Residue	Variable	
	Fusarium head blight	Soil, residue	Variable	
	Rust	Soil, seed	No effect	
	Loose smut	Seed	No effect	
	Common bunt	Soil, seed	No effect	
	Ergot	Residue	Slight increase	
Oil-seeds: Canola Mustard	Seedling blights	Soil	Decrease	
	Blackleg	Residues	No effect	Turkington et al 2000; Guo et al 2005
	Sclerotinia	Soil, residue	Decrease	
Pulses: Peas Lentils	Mycosphaerella blight	Soil, seed, residue	No effect	Pearse 2002
	Ascochyta blight	Crop residue	No effect	Gossen 2001; Gossen and Derksen 2003, Gossen and Miller 2004
	Anthracnose	Seed, crop residue	No effect	Pearse 2002
	Pea root rot	Soil, residue	Decrease	Turkington et al 1997

18. Glyphosate Use and Root Rot and Fusarium Outbreaks

No-till relies heavily on pre-seed burndown application of glyphosate for weed control. In recent years in the U.S and Canada, it has been alleged that glyphosate use can lead to an increase in root rot disease and Fusarium head blight severity by inhibiting the growth of fungi that compete with these diseases. Hanson and Fernandez (2002) investigated the effect of different glyphosate herbicides on the vegetative growth of *P. tritici-repentis* and select *Fusarium* spp. The glyphosate significantly increased the growth of *P. tritici-repentis* with differences from 4 to 44% compared to the control after 5 days of incubation. *Fusarium avenaceum* [*Gibberella avenacea*] showed similar results with 6 to 21% increased growth. In another 5-year study at Swift Current, Saskatchewan, Fernandez et al (2005) showed pre-seed application of glyphosate in no-tilled fields had significantly increased fusarium head blight in spring wheat. Elsewhere, Larson et al (2006) in the U.S. also showed that an increase of glyphosate application on Roundup Ready sugar-beet leads to an increase in root rot disease severity caused by *Rhizoctonia solani* and *Fusarium oxysporum* of sugar beet in greenhouse studies. The increase in disease does not appear to be fungal-mediated, since in vitro studies showed no impact of glyphosate on fungal growth or reproduction with any fungal isolates tested. It was concluded the increase in disease is a result of a change in plant metabolism following glyphosate application.

Fusarium root rot complex causes a "Sudden Death Syndrome" and is a major problem in soybean production. In growth chamber and greenhouse experiments glyphosate treatment caused significant increases in disease severity and infection of roots as compared to untreated check (Sanogo 2000). In field experiments, preseed application of glyphosate in Roundup Ready soybeans caused a significant increase in Fusarium disease as compared to the untreated check.

These studies indicate precautions need to be taken when some soil borne diseases are present if weed management for cereals and Roundup Ready crops is to include glyphosate treatments.

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IV. Impact of No-Till on Insect Pests

Similar to weeds and plant diseases, insect pests respond differently to tillage practices. Populations of some species increase under reduced tillage, while others decrease. Dosdall (2003) has summarized the pest response to reduced tillage in cereal and oil-seed crops. Some pest species like grasshoppers, wheat stem sawfly, and root maggots tend to be more damaging to crops under reduced tillage systems, others like flea beetles and cutworms cause greatest crop losses with conventional tillage (Table 1).

Table 1. Effect of Reduced Tillage on Pest Insects

Insect species	Response to Reduced Tillage	Reason for effect	Reference
Wheat and other cereals			
Cutworm	Increase	Cutworm moths prefer to lay eggs in cool moist fields with unincorporated crop residue.	Turnock et al 1993; Dosdall 2003
Wheat stem sawfly	Increase	Larvae of stem sawfly over-winter in unincorporated crop residues	Runyon et al 2002; Dosdall 2003
Orange wheat blossom midge	Increase	Undisturbed soil is an ideal habitat for over-wintering cocoons of orange wheat blossom midge.	David 2004; Dosdall 2003
Grasshopper	Increase	Less soil disturbance favors survival of grasshopper eggs.	Lundgren and Sreenivasam 2009; Dosdall 2003.
Flea-beetle	Decrease	Micro-climate (cool and moist) provided by reduced tillage is not a preferred habitat for flea beetles. They have a preference bright sunlight and relatively warm temperatures.	Dosdall et al 1999; Dosdall 2003
Root maggot	Decrease	Crop residue and cool moist conditions of reduced tillage are a preferred habitat to egg-laying flies. However, in no-till fields there is a abundance of two species of predatory beetles that feed on root maggot larva were more numerous in the zero-tilled plots	Holiday 2009
Cabbage seedpod weevil	Not affected		Dosdall 2003
Lygus bug	Not affected		Dosdall 2003

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IV. Concluding Remarks

No-till has an impact on weeds, diseases, and insect species diversity and numbers. Many broad-leaf weeds decrease in no-till; however, some grassy weeds and perennial weeds increase. Studies in Alberta and Saskatchewan have shown that year-to-year variation in climatic conditions and crop rotations have a greater impact on weeds than tillage systems.

There are conflicting reports in the literature on the incidence and severity of plant diseases in minimum and no-till systems. Some of the earlier studies documented an increased incidence and severity of disease levels in no-till as compared to cultivation, while others showed a decrease or no effect.

Similar to weeds and plant diseases, insect pests respond differently to tillage practices. Populations of some species increase under minimum and no-till while others decrease.

Weeds, plant diseases, and insect pests respond differently to tillage practices. However, these changes can be managed though integrated pest management techniques.

SECTION 8

THE ECONOMIC, AGRONOMIC AND ENVIRONMENTAL IMPACT OF NO-TILL ON THE CANADIAN PRAIRIES.

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The Impact of No-Till on Greenhouse Gas Mitigation

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I. Introduction

Carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) are the major greenhouse gases (GHG) that contribute to global warming and they are implicated in climate change, environmental health and economic welfare for human beings (Table 1). Since 1750, the concentration of CO_2 has increased by 35%, CH_4 has increased by 155%, and the concentration of N_2O has increased by 18%. And between 1970 and 2004, global GHG emissions due to human activities have increased by approximately 70%. The main sources of anthropogenic emissions are from the burning of fossil fuel, deforestation, livestock enteric fermentation, paddy rice farming, use of manure, and inorganic fertilizers.

Table 1. Summary of major greenhouse gases influenced by human derived sources

Greenhouse gas	Pre-industrial concentration	Concentration in 2005	Annual rate of increase since 1750	Co_2 equivalent global warming potential	Main human-derived sources
CO_2	280 ppm	379 ppm*	1.8 (0.5%)	1	Fossil fuel; deforestation
CH_4	0. 8 ppm	1.77 ppm	0.015 (0.9%)	11	Livestock, rice paddy
N_2O	288 ppb	310 ppb**	0.8 (0.25%)	300	Fertilizer, manure

* parts per million by volume; ** parts per billion by volume.
Source: Environment Canada (2008)

II. Terms and Definitions

Greenhouse Gases – nitrous oxide (N_2O), methane (CH_4), carbon dioxide (CO_2)
Carbon Sequestration – refers to carbon stored in the soil as soil organic matter
Carbon Storage – carbon stored in the soil as plant debris, roots, and soil organic matter. One tonne of carbon removes 3.667 tonnes of CO_2
Carbon reservoir – where carbon is stored i.e. soils, forests and crop plants
Sink – an activity that transfers carbon from the atmosphere to a reservoir such as soil, trees or crops
Source – an activity that releases CO_2 and other gases to the atmosphere

III. Greenhouse Gas Emission Trends in Canada

Total greenhouse gas (GHG) emissions in Canada in 2007 were 747 Mt of CO_2 eq., an increase of 4.0% from 2006 levels, and of 0.8% from 2004 levels. Overall, the long-term trend indicates that emissions in 2007 were about 26% above the 1990 total of 592 Mt. This trend shows a level 33.8% above Canada's Kyoto target of 558.4 Mt (Table 2).

Table 2. Greenhouse gas emissions in Canada

	GHG emissions for selected years (1990–2007)								
	1990	1995	2000	2002	2003	2004	2005	2006	2007
Total GHG (Mt of CO_2 Eq)	592	642	718	717	741	743	734	721	747
Change Since 1990 (%)	N/A	8.3	21.2	21.0	25.1	25.4	24.0	21.7	26.2
Annual Change (%)	N/A	2.8	3.7	0.9	3.4	0.2	-1.3	-1.7	4.0
Average Annual Change (%)*	N/A	1.7	N/A	2.1	1.9	1.8	1.6	1.3	1.5

* Average annual change since 1990.

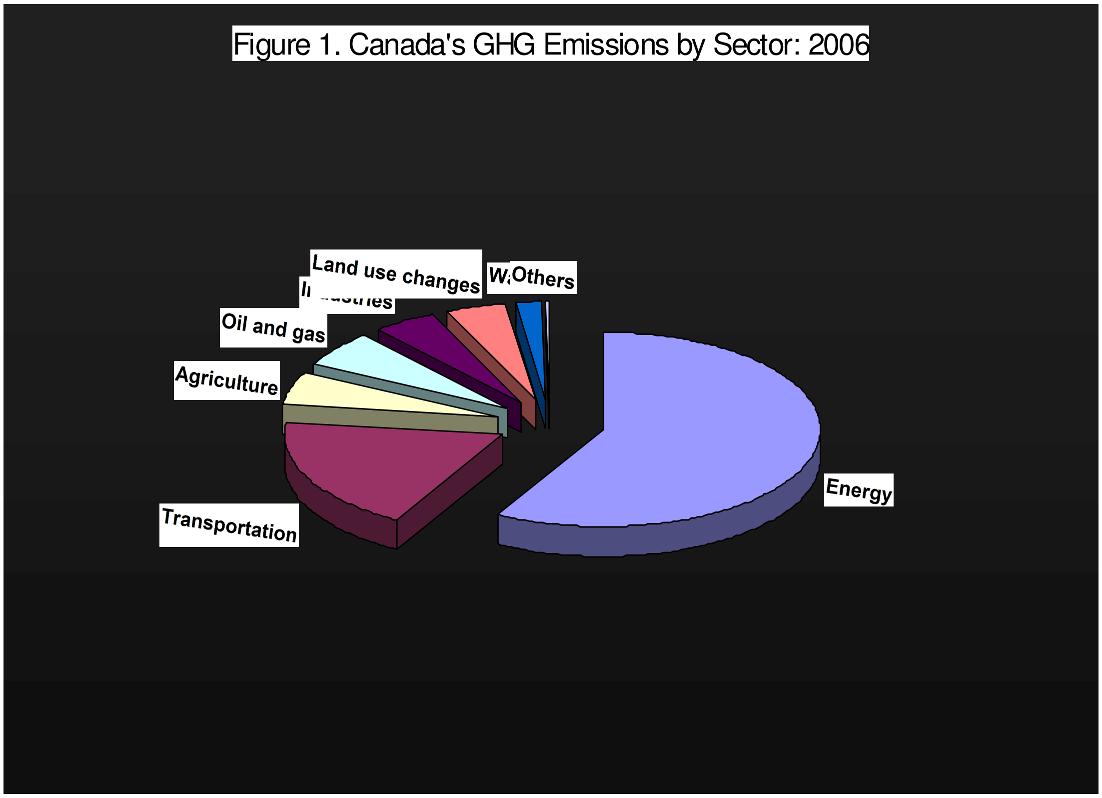


Figure 1. Canada's GHG Emissions by Sector: 2006

Source: Environment Canada (2008)

IV. Canada's Green House Gas Emissions by Sector

In 2006, the energy sector along with transportation accounted for about of the 82% of the total GHG emissions (Figure 1). The agricultural emissions accounted for about 8.6% of the total 2006 GHG emissions.

Green House Gas Emissions: Agricultural Sector

All these emissions are from non-energy sources; N_2O accounts for about 56% of sectoral 2006 emissions and CH_4 for about 44%. CH_4 and N_2O are the main farm related GHG emissions; CO_2 represents a very small portion of agricultural GHG emissions. The main sources of CH_4 emissions in agriculture are from animal production, namely enteric fermentation and from manure management and storage, while N_2O is released mainly from synthetic fertilizer application (loss of N via volatilization, denitrification, leaching, erosion and runoff), manure management on pasture, range and paddock, and crop residue decomposition, while CO_2 emissions are from organic matter and burning of crop residues (Table 3).

Table 3. Summary of Estimated Emissions of Greenhouse Gases Agricultural Land: 1990 -2006

GHG Source Category		*GHG Emissions*				
		kt CO2 Eq.				
		1990	2003	2004	2005	2006
Agricultural Total		49,000	53,000	55,000	63,000	62,000
Enteric Fermentation		18,400	26,000	24000	25,000	24,000
— CH_4	Dairy Cattle	3,360	3,010	3,010	2,900	2,900
	Beef Cattle	14,400	18,600	20,00	21,000	20,000
	Others	640	1,010	1,010	1000	1,000
Manure Management		6,700	8,100	8,400	8,200	8,000
— CH_4	Dairy Cattle	740	660	660	640	630
	Beef Cattle	670	790	830	940	910
	Swine	1,100	1,600	1,500	1,600	1,600
	Poultry	70	90	90	90	90
	Others	20	20	40	40	40
— N_2O All Animal Types		4,100	5,000	5,300	4,900	4,800
Agricultural Soils		20,000	22,000	22,000	30,000	30,000
Direct Sources (N_2O)		11,000	11,000	12,000	15,000	15,000
Synthetic Nitrogen Fertilizers		4,800	5,800	5,800	7,000	7,100
Manure Applied as Fertilizers		1,900	2,100	2,100	2,300	2,300
Crop Residue Decomposition		3,800	3,600	3,600	5,200	5,500
Cultivation of Organic Soils		60	60	60	60	60
Conservation Tillage[1]		–220	–580	–630	–910	–840
Summerfallow		730	440	430	730	690
Irrigation		320		-	370	360
Pasture, Range, Paddock Manure (N_20)		3,200	4,000	4,300	3,900	3,800
Indirect Sources (N_2O)		6,000	6,000	7,000	11,000	11,000

[1] The negative values reflect a reduced N_2O emission due to the adoption of conservation tillage
Source: Environment Canada 2008

V. CO_2 Emissions and Removals in Agricultural Soils

Approximately 83% of the cultivated agricultural land occurs in the western Canada. Tillage and land management practices have an influence on rate of decomposition of soil organic matter, affecting organic carbon storage in the soil. This change in soil organic carbon determines whether CO_2 will be released into the atmosphere or sequestered (sink) in the soil. Land management practices that sequester CO_2 include conservation tillage and reduced summerfallow practice (Table 4). In contrast, management practices that emit CO_2 to the atmosphere include tillage intensive cropping systems and summerfallow, agricultural lime applications and cultivation of organic soils. The other farm related CO_2 emissions are fertilizer application (fertilizer manufacture is energy intensive, requiring 2 litre of diesel fuel for 1 kg of nitrogen, one liter of petroleum fuel produces 2.5 kg of CO_2 (producing 5 kg CO_2E) and burning of fossil fuel in tractors, vehicles, manufacture of machines and herbicides. For example, herbicide manufacture uses 2-10 L/kg fuel energy equivalent.

In 1990 agricultural soils were sequestering about 2.8 Mt whereas, in 2006, this figure has increase to 9.6 Mt of CO_2. The main reason for this increase in CO_2 storage is due to substantial growth in conservation tillage acres and a significant reduction in summerfallow acres (Campbell *et al*., 1996; Janzen *et al*., 1998; McConkey *et al*., 2003). Between 1990 and 2006, conservation tillage acres have grown by about 24 million acres on the Canadian prairies, and this has resulted in a substantial increase in CO_2 sink (from –1,5 Mt in 1990 to –5.0 Mt in 2006). Similarity, between 1990 and 2006 total summerfallow acres on the Prairies declined by 55% between 1990 and 2006, resulting in substantial increase in CO_2 sink (from -3.1 Mt in 1990 to -6.8 Mt in 2006) (Environment Canada 2007) (Table 4).

Table 4. Emissions and Removals Associated with various Land Management Changes on Croplands since 1990

Land Management Practices	Land Management Change	Emissions/Removals (Gg CO2 Eq)				
		1990	2003	2004	2005	2006
Crop rotation	Increase in perennial forage	–1814	–4337	–4567	–4000	–4200
Change in tillage	Increase in annual forages	3188	3885	3954	4300	4400
	Conventional to Reduced -till	–908	–1017	–997	–980	–960
	Conventional to No-till	–563	–3345	–3571	–3800	–4000
	Other Tillage Change	NO	–323	–358	–390	–420
Changes in summerfallow	Increase in summerfallow	1619	1298	1276	1300	1200
	Decrease in summerfallow	–4688	–7466	–7646	–7900	–8000
Residual Emissions[1]		337	2267	2336	1800	–1900
Total Mineral Soils		**–2830**	**–9037**	**–9573**	–9700	–10100
Cultivation of Histosols		296	296	296	300	300
Liming		204	288	288	290	290
Perennial woody crops		38	45	40	25	21
Total Cropland Remaining Cropland		**–2292**	**–8408**	**–8954**	–9100	–9600

[1] These net residual CO2 emissions come from conversion of forestland and grasslands to croplands that occurred more than 20 years prior to the inventory year.

Source: Environment Canada 2008

A. The Carbon Cycle in Agriculture

The atmosphere contains 780 billion tonnes of carbon as CO_2. A crop plant absorbs some of this carbon via photosynthesis and transforms it into carbohydrates, cellulose and other sugars. Each plant uses some of the carbon compounds to meet its energy needs and converts them back into CO_2 via respiration. Some of the carbon remaining in the plant is then removed from the system when the plant is harvested; the rest ends up in the ground and is transformed into CO_2 again by microbes in the soil. Whether a soil is a source or a sink depends on its history and management practices, including tillage. "Assume that 6.3 t C ha^{-1} are fixed by plant by photosynthesis and 2 t C ha^{-1} is put back into atmosphere via respiration, leaving 4.3 t of organic C ha^{-1} in the crop biomass. If 1.3 t C ha^{-1} is harvest, the remaining 3 t C ha^{-1} will end up in the ground in the form of crop residue and is transformed into CO2 by soil microbes. The soil is storing carbon, if the amount of C leaving the soil is less than 3 t C ha^{-1} (Figure 1). Conversely, soil is losing C if more than 3 t C ha^{-1} from the added residues. Depending up on the land history and land management practices, soils can source or sink for carbon". Boehm (2003).

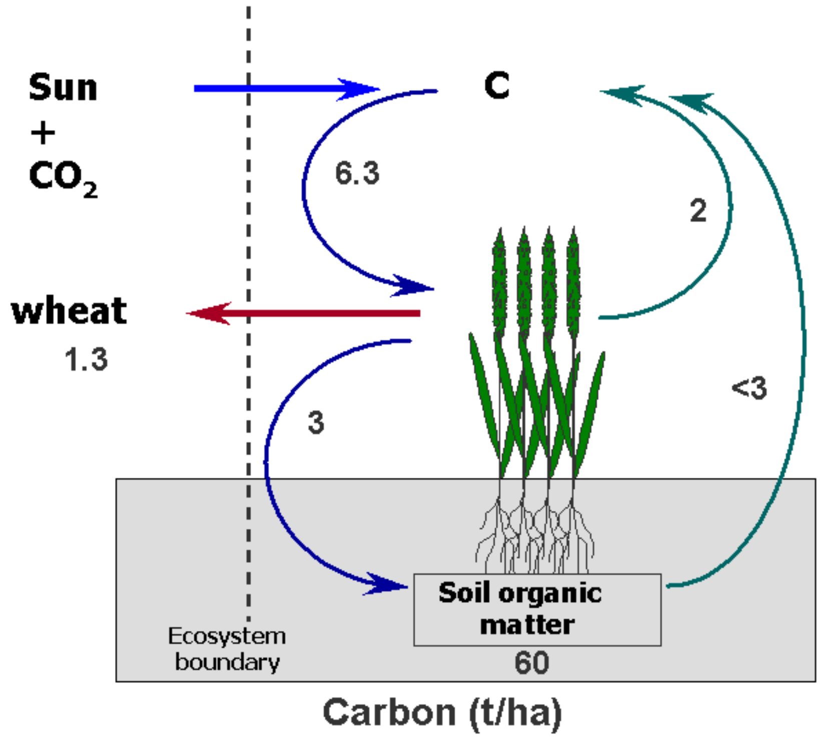


Figure 2. Carbon cycle in Agriculture
Source: Boehm (2003

B. Green House Gas Mitigation Potential of Agricultural Sector

Carbon sequestration is an important process in reducing GHG emissions, as one tonne of carbon stored in the soil reservior is equivalent to 3.67 tonnes of carbon dioxide emissions. Agricultural soils have the ability to sequester carbon, however, it is dependent on climate, soil type, cropping systems and tillage management practices. Studies in western Canada have shown that soil conservation practices offer large opportunities to sequester atmospheric carbon and store that carbon into soil carbon organic matter (sinks). Some of these sink enhancing management practices are:

- Increase conservation tillage, especially no-till acres – between 1990 and 2006, conservation tillage acres have grown by about 24 million acres on the Canadian prairies. In Alberta and Saskatchewan, approximately 54% of land is under no-till management (Stats Canada 2006, Hoffman 2008). This practice alone has resulted in a carbon gain of 1.22 t CO_2 eq ha^{-1} yr^{-1} (McConkey et al 1999) (Table 6).
- Decrease summerfallow acres – since 1990s, on the Canadian prairies, area of cropland in summerfallow has dropped steadily from 22.3 million acres to 9.9 million acres by 2006, a decline of 55.6 % (Stats Canada 2006).
- Use perennial legumes, pulses, and/or forages in crop rotations – since 1990s, forages in rotations have increase by 27%.
- Increase permanent cover – the Prairie Farm Rehabilitation Administration has shown that under a permanent cover program (PCP) there is the potential for the land to sequester between 5.4 and 5.7 million tonnes of carbon/yr.

- Improve grazing management – in addition to carbon sequestration, this practice may reduce emissions of CH_4 and N_2O.
- Increase shelterbelts or agro-forestry – trees and grasses are planted along streams and croplands to prevent soil erosion and nutrient runoff into waterways and to increase carbon storage through sequestration.
- Improve crop nutrition through efficient application of fertilizers and organic amendments without sacrificing crop productivity.

C. No-till and Carbon Sequestration Rate in Western Canada

In side by side comparisons on carbon sequestration between no-tilled fields with reduced frequency of summerfallow and conventionally tilled fields in Saskatchewan, McConkey et al (1997) found that no-till managed fields, on average, sequestered 0.77 tonnes more of carbon per ha per year than the conventionally tilled fields (Table 5).

Table 5. Soil carbon gains in no-till systems in Saskatchewan

Zone - Location--Texture	Comparison	Years in LDS	Soil Carbon in upper 20 cm (t C ha^{-1})		Carbon gain (t $ha^{-1}y^{-1}$)
			LDS	Conv.	
Brown - Limerick - Loam	Low disturbance continuous cropping vs. Conventional tillage wheat-fallow	6	37.1	33.1	0.7
Brown - Kindersley - Clay	Low disturbance continuous cropping vs. Conventional tillage wheat-fallow	6	23.5	18.7	0.8
Dark Brown - Biggar - Loam	Low disturbance continuous cropping vs. Conventional tillage wheat-fallow	7	45.3	43.8	0.2
Dark Brown - Perdue - Sandy Loam	Low disturbance continuous cropping vs. Conventional tillage wheat-fallow	10	46.0	40.4	0.6
Dark Brown - Unity - Loam	Low disturbance continuous cropping vs. Conventional tillage wheat-fallow	4	73.5	69.0	1.1
Black - Indian Head - Loam	Low disturbance continuous cropping vs. Conventional tillage wheat-wheat-fallow	20	74.1	57.3	0.8
Black - Indian Head - Loam	Low disturbance continuous cropping vs. Conventional tillage wheat-wheat-fallow	13	65.2	57.3	0.8
Dark Gray - Arborfield - Loam	Low disturbance continuous cropping vs. Conventional tillage continuous crop.	9	59.4	49.5	1.1
Gray - Prince Albert - Loam	Low disturbance continuous cropping vs. Conventional tillage continuous crop.	7	43.2	36.6	0.9

Source: McConkey et al (1997)

Based on the analysis of plot data on carbon sequestration on Canadian Prairies, McConkey et al (1999) developed coefficients on a yearly basis for CO_2 emissions for the various soil zones across the prairies. These coefficients have been adopted for the Sink Table and the Ag Table (Table 6) in the calculations to estimate the national potential for CO_2 sequestration for 2008 – 2012. Using these coefficients, and assuming an adoption rate for no-till of 2.0 to 2.8%, the Prairie Provinces have the potential to sequester 14,734,408 tonnes of carbon per year (Table 7).

Table 6. Sequestration Rates for Reduced/No-Till and Reduced Summerfallow on Prairie Croplands

Soil Zone	Brown	Dark Brown	Black	Gray	
Reduced/No-Till					
Medium Texture/Mid-slope (tonnes CO2/ha/yr)	0.73	1.34	1.34	1.46	
Percent Cropland by Soil Zones					
Alberta	24.9	29.1	17.4	28.6	
Saskatchewan	40.7%	32.3%	22.0%	5.0%	
Manitoba		44.0%	48.0%	8.0%	
Weighted Sequestration Rate					Provincial Rate
Alberta	0.18	0.39	0.23	0.42	1.22
Saskatchewan	0.30	0.43	0.29	0.07	1.10
Manitoba	0.00	0.59	0.64	0.12	1.35

Source: (McConkey et al., 1999)

Table 7. Annual sequestration of carbon dioxide per year in the Prairie Provinces

Province	Zero-till (ha)	Rate of Carbon Sequestration* (t ha^{-1} y^{-1})	Carbon dioxide sequestration (tonnes CO_2 y^{-1})
Manitoba	829,903	1.22	1,012.481
Saskatchewan	8,028,946	1.10	8,831,860
Alberta	3,622,274	1.35	4,890067
Total			14,734,408

Source: McConkey et al (1999)

D. Soil Sink Potential of Agricultural Land in Western Canada

In Canada, conservation practices on the farmland offer a large opportunity to sequester carbon and consequently enhance the soil carbon sink. In 1999, Agriculture and Agri-Food, Canada (AAFC) developed the Sink Table model, which estimates a national potential of 18.3 Mt CO_2 per year on cultivated land for the first commitment period of 2008 – 2012 and 8.1 Mt CO_2 by the second commitment period of 2013 – 2017. (p.95, Sinks Options Paper). This model is based on the follow assumption Maintain 1999 adoption rate for reduced/no-till (equivalent to an annual average 2.0% increase [range: 0.5% to 2.8%])

- Maintain existing rate (1999) of reduction in conventional summerfallow acres.

These national estimates of soil carbon sequestration do not take into account other soil conservation activities such as pasture management, conversion of marginal land into permanent grass cover and restoration of wetland habitat. If these practices are factored in, the national estimates for carbon sequestration potential for the first commitment period will be much higher.

Recently, Boehm (2003), has revised the estimated the sink potential of agricultural soil, using AAFC's Canadian Economic and Emissions Model for Agriculture (CEEMA). This model is based upon the following carbon sequestration coefficients (Table 8)

Table 8. Carbon sequestration coefficients based on expert opinions and CEEMA model

	Brown Soils	Dark Brown Soils	Black Soils	Non-prairie Soil
No-till	0.73	0.73	1.34	0.54
Reduced Summerfallow	0.15	0.16	0.08	
Increased Forages	-	0.94	2.44	2.44
Permanent Cover	0.88	1.15	3.3	3.3

Source: Boehm 2003

The first analysis estimated the sink potential of both no-till and summerfallow systems based upon 1991 and 1996 census data. Initial conservative analyses for adoption of these systems to 2010 estimated that Canadian agricultural soils could sequester 4.2 Mt of carbon dioxide per year. However, this conservative analysis was too low; already by 2001 farmers had adopted both no-till and a reduction in summerfallow acres at greater than expected rates. A second less conservative analysis, based on a 25% increase in adoption of no-till, showed that it was possible to sequester an extra 3.1 Mt of carbon dioxide per year. Further carbon dioxide removal could be achieved through above BAU reductions in summerfallow acreage, and above BAU increases in permanent cover crops, and improved management of grazing land and agro-forestry. When actual figures for 2001 were used in the model, even higher estimates (14.1 Mt of carbon dioxide per year) of potential carbon dioxide sequestration resulted. If farmers were to adopt further sink-enhancing practices, even more carbon dioxide could be removed from the atmosphere. The release of the 2001 Census of Agriculture data indicated that by 2001 Canadian producers had already exceeded the adoption rates of no-till and reduced summerfallow that had been projected to 2008. The scenarios were re-run using trend lines developed from the 2001 census. It is now estimated that Canadian agricultural soils could remove about 10 Mt of carbon dioxide per year in the commitment period under BAU. Further adoption of sink-enhancing practices at low, medium and high rates could remove additional carbon dioxide (about 5 Mt at low rates to about 17 Mt at high rates) (see Table 9).

Table 9. Soil Sink Potential of Agricultural Sector in Canada (million tonnes CO_2e/year)

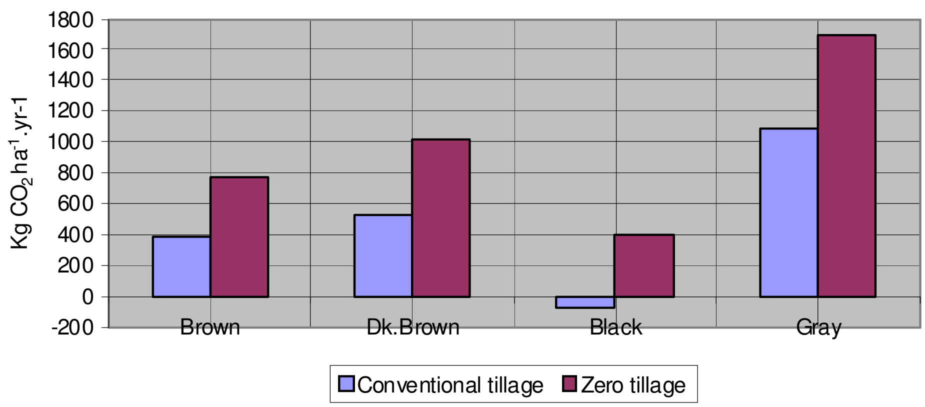
Adoption Rate	1996 Census	2001 Census		
	Medium	Low	Medium	High
2010 Business-As-Usual Sink Scenario (Change from BAU)	- 4.2	- 9.7	- 9.7	- 9.7
Sink Enhancing Practices				
Increase no-till	- 3.1	- 2.6	- 6.6	- 10.4
Decrease summerfallow	- 2.5	- 1.0	- 2.2	- 3.6
Increase permanent cover	- 0.7	- 0.3	- 0.5	- 0.8
Improve grazing management	- 2.1	- 0.5	- 1.0	- 2.0
Greenhouse Source Reducing				
Nutrient management	- 0.9	- 0.5	- 1.1	- 1.3
Feeding management	- 0.7	- 0.5	- 0.8	- 1.1
Total	**- 14.1**	**- 15.3**	**- 22.4**	**- 29.9**

Dumanski et al (2004) also showed that by adopting the best management options such as reduction in summerfallow, conversion of fallow areas to hay or continuous cereals, fertilization to ensure nutrient balance, and adoption of soil conservation measures has the potential to sequester about 50-75% of the total agricultural emissions of CO_2 in Canada for the next 30 years.

E. Carbon Sink Potential of Agricultural Land in Alberta

In 1999, AAFRD developed a carbon sequestration model, which estimates carbon gains in various soil zones across Alberta. This model consists of the soil and residue modules and incorporates two tillage systems (conventional and no-till) and four cropping systems (fallow, forage, cereals, oilseeds). According to this model, Alberta's agricultural land had the potential to sequester 4.7 – 9.0 million tonnes of CO_2 yr^{-1} (Sauve 2000). Mean carbon sequestration rates predicated from this model indicated that sequestration is dependent on soil type and tillage practices. In general, net gains after five years were greatest in no-till systems rather than in conventional tillage (Figure 3).

Figure 3. Comparison of carbon sequestration rates between conventional tillage and zero tillage



More recently, Goddard (2001) has revised the estimate annual carbon sequestration rates for the various soil zones in Alberta (Table 10), using the following assumptions:

- By the end of 2011, 48% of cultivated cropland will be in reduced/zero-tillage systems
- The rate of carbon sequestration was assumed to be approximately equivalent to the rate of carbon loss of soils since cultivation. McGill and Reinl (1981) estimated organic matter losses of 30-50% since cultivation. A loss of 35% over 70 years yields a loss rate of 0.5% per year. Assuming the same rate for the reverse process, there will be a 5% increase in carbon in 10 years.
- The bulk density was assumed to be 1.2 Mg m^{-3} to a soil depth of 15 cm for all soils.
- The following factors were used in the estimation: organic matter to carbon (*0.57) and carbon to CO_2 equivalent (*44/12).

Table 10. Soil Sink Potential of Agricultural Sector in Alberta (million tonnes CO_2e yr^{-1})

Soil Zone	Black	Brown	Dark Brown	Dark Gray	Gray	Total
Percent cultivated of total farm area	52	37	54	45	24	
Initial soil organic matter (SOM) (%)	10	5	7	8	4	
Organic matter increase (%)	5	5	5	5	5	
Final organic matter %	10.5	5.25	7.35	8.4	4.2	
Marginal SOM increase (mg^{-ha})	9	4.5	6.3	7.2	3.6	
Mg of $Carbon^{-ha}$	5.13	2.565	3.591	4.104	2.052	
CROPLAND No-TILL (%)	44.8	44.8	44.8	44.8	44.8	
Mg of Carbon	7,832,197	1,221,926	3,194,785	2,676,473	1,359,214	16,284,596
Tonnes of carbon increase yr^{-1}.						1,628,459

These estimates correlate well with other estimates such as the Sink Table estimates and those provided by McConkey et al (1999) coefficients.

	Tonnes of $C0_2$ yr^{-1}	Tonnes of C yr^{-1}
McConkey	4.8	1.3
The SinksTable	5.5	1.5
Goddard	5.9	1.6
Sauvé	4.7-9.0	1.8

VI. Nitrous Oxide Emissions

Nitrous oxide (N_2O) is linked to global warming and destruction of the ozone layer. The effectiveness of N_2O as a global warming gas on a molecular basis is estimated to be more than 300 times that for CO_2 (1 kg N_2O = 300 kg CO_2 equivalent). Soils are the major source of N_2O emissions. It is estimated that about 50 - 80% of N_2O emitted from the biosphere atmosphere to the agricultural soils. The nitrification and denitrification processes are the major sources of N_2O in agricultural soil, and these are influenced by soil $NH_4{}^+$ and NO_3 – N concentrations, water content, temperature, available C, pH, aeration, time of the year, crops and cropping systems, and tillage practices.

A. Impact of No-Till on Nitrous Oxide Emissions

Because of the lack of soil disturbance, no-till soils are moister; there is reduced aeration, more organic matter, and an increased microbial biomass near the soil surface. These conditions are thought to favor increased N_2O emissions as compared to conventional tillage. However, there is no general agreement in the literature on the relationship between N_2O emissions and tillage. The main reason for this lack is that nitrous oxide emissions have seasonal variability. Agricultural soils in western Canada (prairies) freeze during winter. Studies have shown that about 70 % of nitrous oxide losses occur during the spring thaw (Lemke et al 1998); therefore, in order to get definite and absolute measurements on N_2O losses, it is necessary to include both the spring thaw period and the growing season in the calculation of the annual flux of N_2O emissions.

Researchers in Saskatchewan and Quebec have reported higher N_2O emissions from no-till compared to conventional tillage fields in wheat and corn during the growing season (Aulakh et al 1982; 1984a; 1984b; Mackenzie et al 1997; 1998). There are also some studies from Alberta, Saskatchewan and elsewhere, which have reported lower emission in no-till soils as compared to conventional tillage

(Lemke et al 1999; Lemke et al 2001, Lemke 2004, Rochette et al 2007). Lemke et al (1999) studied the cumulative losses (spring thaw + growing season) of N_2O under zero (ZT) and conventional tillage (CT) in Alberta Parkland agroecosystems. They found nitrous oxide emissions during the spring thaw period were consistently higher on CT as compared to ZT plots; however, N_2O emissions during summer were slightly higher, similar, or lower on ZT plots compared to those under CT. Combined estimates (spring plus summer) of N_2O loss under ZT were equal to or lower than those under CT plots (Table 11). A recent study using stimulation models also concluded that N_2O emissions tended to be similar or lower on NT compared to CT systems in western Canada (Lemke et al 2001, Lemke 2003).

Table 11. Estimated losses of N_2O-N (kg ha^{-1}) from zero and conventional tillage plots**.**

Site	Year	Spring thaw		Growing season		Total	
		ZT	CT	ZT	CT	ZT	CT
Ellerslie	1993	0.225	0.472	1.382	1.037	1.607	1.509
Ellerslie	1994	0.155	0.164	0.317	0.690	0.472	0.854
Ellerslie	1995	0.214	1.010	na	na	na	na
Breton	1993	0.042	0.141	0.173	0.173	0.215	0.314
Breton	1994	0.041	0.047	0.115	0.403	0.156	0.162
Breton	1995	0.088	0.135	na	na	na	na

Source: Lemke et al 1999

B. Impact of Additional Soil Management Practices on Nitrous Oxide Emissions

More recently, Grant et al (2006) developed the Denitrification-Decompostion model to estimate the impact of change in management practices on N_2O emissions in seven major soil regions in Canada, for the period 1970 to 2029. Their model predicated about 33% less N_2O emissions for a change from conventional tillage to no-tillage in western Canada. Some of the main findings of this research are:

- Elimination of summer fallow in a crop rotation resulted in a 9% decrease in N_2O emissions, however, with substantial emissions occurring during the wetter fallow years when N had accumulated.
- Increasing N-fertilizer application rates by 50% increased average emissions by 32%, while a 50% decrease of N-fertilizer application decreased emissions by 16%
- In general, a small increase in N_2O emissions was predicted when N-fertilizer was applied in the fall rather than in the spring.
- The management practices that have the greatest potential to reduce the combined N_2O and CO_2 emissions are conversion from conventional tillage to permanent grassland, reduced tillage, and reduction of summer fallow. The estimated net greenhouse gas (GHG) emission reduction when changing from cultivated land to permanent grassland ranged from 0.97 (Brown Chernozem) to 4.24 Mg CO_2 equiv. ha^{-1} y^{-1} (Black Chernozem) for the seven soil regions examined. When changing from conventional tillage to no-tillage the net GHG emission reduction ranged from 0.33 (Brown Chernozem) to 0.80 Mg CO_2 equiv. ha^{-1} y^{-1} (Dark Gray Luvisol). Elimination of fallow in the crop rotation lead to an estimated net GHG emission reduction of 0.43 (Brown Chernozem) to 0.80 Mg CO_2 equiv. ha^{-1} y^{-1} (Dark Brown Chernozem).
- The results from this work indicate that conversion of cultivated land to grassland, the conversion from conventional tillage to no-tillage, and the reduction of summerallow in crop rotations could substantially increase C sequestration and decrease net GHG emissions.

Crop rotations that include legumes also have an impact on N_2O emissions. It has been shown that substituting a pulse crop for a cereal or oilseed crop in a rotation reduces the overall N_2O emissions from that rotation. The main reason for this decrease is that nitrogen fertilizer induced N_2O emissions are avoided in the year that the pulse crop, especially pea and lentil is grown because no nitrogen fertilizer is applied (Lemke et al 2007). Recently Sprout et al (2008) investigated the effect of crop rotations on N_2O emissions in different tillage systems in the Dark Brown soil zone, near Three Hills Alberta. When averaged across the rotation phase treatments, no-till plots showed 30 % less N2O emission as compared to conventional till plots (Table 12)

Table 12. Average annual loss of N_2O-N (g ha^{-1}) from selected rotations at the Three Hills plots.

Rotation	Conventional Tillage	No-till
Canola – Barley – Pea – Wheat	1314 a	1203 a
Canola – Wheat	1923 a	1059 a
Wheat – Fallow	2206 a	1370 a
Mean[1]	1814 a	1210 b

[1] Mean for tillage system averaged across rotation
Values followed by the same letter are not statistically different (p<0.1)
Source: Sprout et al (2008)

VII. Concluding Remarks

In 2006, the agricultural sector accounted for about 8.6% of the total 2006 GHG emissions. All these emissions are from non-energy sources; N_2O accounts for about 56% of sectoral 2006 emissions and CH_4 for about 44%.

Greenhouse gas mitigation potential from adoption of best management practices: (1) nutrient management (matching N to crop requirement), (2) soil management (increase use of no-till, decrease use of summerfallow, increase use of permanent cover), (3) grazing management (decrease cattle stocking rate and rotational and complimentary grazing), and (4) agroforestry (shelterbelts) are high. The recent climate change model estimates Canadian cropland can store or sequester as much as 22 million tonnes of atmospheric carbon dioxide per year by using no-till practices. Proper grazing management such as rotational grazing, and improved grass production can store another 3 million tonnes of carbon dioxide. It is further estimated that no-till practices along with reduced summerfallow can store from 0.3 to 0.5 tonnes of carbon per hectare per year. However, there is high variation in this estimate resulting from uncertainty about fluxes in N_2O from these systems.

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