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# The development and adoption of conservation tillage systems on the Canadian Prairies

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**Abstract**

One of the major agricultural innovations on the Canadian Prairies over the last 40 years has been the introduction of conservation tillage (CT). Conservation tillage-a system that includes minimum and zero tillage (ZT) -was introduced as an alternative to traditional (conventional) tillage (TT) to control soil degradation and to promote agricultural sustainability. The development and adoption of CT systems involved pioneer farmers, engineers, scientists, and farmer associations. By the end of the 1970s, CT started to take shape on the Prairies, but for a number of economic, technical, political and social reasons, the adoption of CT did not occur on any major scale before the 1990s. Today, more than 75% of the Prairie's cropland is under some form of CT with more than 50% under ZT. In this paper, the factors behind the development and adoption of conservation tillage technology on the Prairies in the period between 1930 and 2011 are reviewed. Then, some of the benefits of the adoption of CT on the Prairies are highlighted. The data show that CT and ZT became profitable for the majority of farmers during and after the 1990s, and that the increased use of CT contributed to the dramatic decrease in the area under summerfallow and to the increase in the area sown to canola and pulse crops. These changes contributed to the reduction of all forms of land degradation and to decreases in agricultural greenhouse gas (GHG) emissions.

**Key Words:** Conservation tillage, Zero tillage, Land degradation, Innovation development and adoption, Economic and environmental benefits

## 1 Introduction

Canada has about 38 Mha of arable land; of this, about 32 Mha is located in the Prairies (Campbell et al., 2002; Zentner et al., 2002). The Prairies area covers the south of Alberta, Manitoba, and Saskatchewan, and is divided into five soil-climate zones, Brown, Dark Brown, Black, Dark Grey, and Grey (Fig. 1). The Brown soil zones are located in the southern part and the Black and Grey soil zones are located in the northern part of the Prairies (Fig. 1). About 57% of the Prairies' arable land is located in the Black, Dark Grey, and Grey soil zones; 22% in the Dark Brown soil zone; and the rest in the Brown soil zone. The soil colour notation is an indication of the soil organic matter content that accumulated within the topsoil. The organic matter content of the surface 30 cm is about 2%, 4%, and 7% in the Brown, Dark Brown, and Black soil zones, respectively, and ranges between 1% and 10% in the Grey soil zones (Campbell et al., 1990).

In general, Black and Grey soil zones are cooler and receive more precipitation than Brown soil zones. Annual precipitation increases from 350 mm in the Brown soil zone to 475 mm in the Black and Grey soil zones. Mean annual temperatures are higher in the Brown soil zones than in the Black and Gray soil zones. Annual mean temperatures on the Prairies range, on average, between 0.3℃ and 5℃ (Campbell et al., 1990).

The main crops grown on the Prairies are: wheat, oats, barley, tame hay, flaxseed, canola, mustard, lentil,

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and peas. In 2011, the Prairies produced about 22.5 Mt of wheat, 2.7 Mt of oats, 7.4 Mt of barley, 16.5 Mt of tame hay, 0.4 Mt of flaxseed, 14.5 Mt of canola, 0.13 Mt of mustard, 1.4 Mt of lentil, and 2.5 Mt of peas (Statistics Canada, 2011).

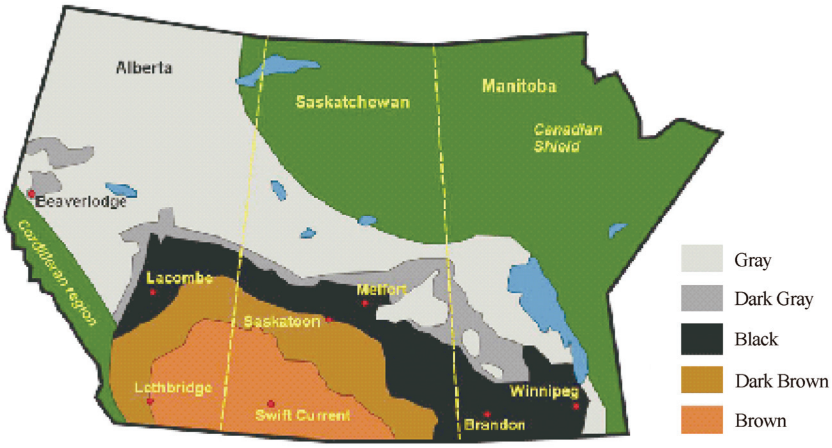


**Fig.1 Soil zones of the Canadian Prairies**

**Source: Agriculture and Agri-Food Canada (Canadian Soil Information Service) Soil map of Canada.**

On the Canadian Prairies, conservation tillage (CT) was introduced as an alternative to traditional tillage (TT) to combat soil degradation and promote agricultural sustainability. Soil degradation negatively impacts crop production through losses in nutrients, water-storage capacity, and soil organic matter, and can contributes to increases in greenhouse gas (GHG) emissions［Campbell et al., 1988, 1990; Agriculture and Agri-Food Canada (AAFC), 2010］.

By the end of the 1970s, conservation tillage technology, through the effective integration of crop residue management, chemical weed control, and specialized seeding equipment, -started to take shape on the Prairies. Today, more than 75% of the arable land on the Prairies is under some form of conservation tillage, with zero tillage (ZT) accounting for more than 50% (Statistics Canada, 2011).

The development and adoption of conservation tillage (CT) systems on the Prairies involved pioneer farmers, engineers, scientists, and farmer associations who worked together and interacted for a period of more than five decades. During this time, the innovation activities of different contributors were guided by a set of environmental, economic, technological, policy, and social factors.

The aims of this paper are to review the factors behind the development and adoption of conservation tillage systems on the Canadian Prairies in the period between 1930 and 2011. The paper will also highlight some of the economic and environmental benefits of this dramatic transformation of the Prairie landscape.

This paper is structured as follows. Section one is the Introduction. Section two describes some of the issues of world food security, population growth, and land degradation, and confirms the need for greater agricultural sustainability. Section three describes the factors underlying the development and adoption of the conservation tillage innovation on the Canadian Prairies. In particular, this section describes how environmental factors such as land degradation and climate were key drivers in the development of conservation tillage technology, while economic, technical, political, and social factors delayed its development and adoption between the 1930s and 1980s. Then, a review is presented of the driving factors that resulted in the development and adoption of conservation tillage technology between 1990 and 2011. Section four highlights some of the benefits of the adoption of conservation tillage systems on the Prairies. Finally, Section five concludes the paper.

## 2 Population growth, land degradation, and agricultural sustainability

The concept of sustainable agriculture (i. e., the ability of agriculture to provide continuous satisfaction of human needs for present and future generations in an economically and environmentally acceptable manner), has gained considerable global attention as the world population continues to grow. Each year, the global population increases by about 80 million people and it is expected to exceed 9 billion by the year 2050 (United Nations, 2005).

To satisfy global food demand for this growing population, agricultural production must increase by 70% by 2050 (UN, Food and Agriculture Organization, 2009). Yet, the UN Division for Sustainable Development (2002) indicated that natural resources are being consumed at an alarming rate, and that the capacity of resources and technologies to satisfy food demand for the growing population remains uncertain, especially as arable land is diminishing as a result of land degradation and the use of land for purposes other than agriculture. Twenty five percent of the global land area is classified as “High degradation lands”, 44% is “Stable land, slightly or moderately degraded lands”, 10% is “Improving lands”, and the rest is “Bare areas” and “Water” (UN, FAO, 2011).

On the Canadian Prairies, land degradation has been recognized as a problem by scientists for more than a century (Hopkins et al., 1946; Anderson, 1975; Gray, 1978; Janzen, 2001). The main land degradation issues on the Prairies are soil erosion, organic matter depletion, and salinity. Soil erosion is the result of three main processes: wind, water, and tillage erosion. Wind and water erosion is the movement of soil from one area to another by wind, and rainfall and runoff; respectively. Tillage erosion is the down slope movement of soil from hilltops to the base of hills by gravity with tillage operations (Lobb et al., 1995, 2005). Soil organic matter is a key indicator of soil fertility and water-holding capacity. Intensive use of TT has reduced the soil’s natural fertility by degrading soil organic matter (Campbell et al., 1988). Early researchers recognized that cultivating the soil and removing plant residues from the surface accelerated the decomposition of organic matter, destroyed soil aggregates and left the soil susceptible to erosion by wind and water (Hopkins et al., 1946). Soil salinity occurs when the soil contains a high level of dissolved salt that hinders plant growth by reducing the plant’s ability to absorb water and nutrients. Tillage, in conjunction with summerfallow, increases soil salinity by excessive and uneven soil water moving the salt with the rising groundwater, so that it accumulates (after evaporation) on the soil surface and in the root zone (AAFC, 2010).

The major cause of land degradation on the Prairies was TT, in conjunction with the predominant summerfallow cropping practice, which required multiple cultivations for weed control during the summerfallow season and for seedbed preparation. The alternative to TT—conservation tillage (CT)—is a system that includes minimum or mulch tillage and zero tillage (ZT). Conservation tillage can be defined as a sustainable crop production system that leaves at least 30% of crop residue on the soil surface after crop planting, or at least 1. 1 Mg $ha^{-1}$ of small grain residue on the surface during the critical soil erosion period, uses specialized seeding equipment to place seed and fertilizer in the soil with minimal disturbance, controls weeds by herbicides or by minimal cultivation and herbicides, and uses crop rotations to help break the life cycles of pests and diseases and to control weeds (Carter 1994) [4]. Thus, CT is an innovation package that consists of the successful integration of a number of components including new crop residue management practices, use of appropriate broad spectrum herbicides, specialized seeding equipment, and alternative cropping systems (i. e., crop rotations) [5].

## 3 The development and adoption path of conservation tillage innovation on the Canadian Prairies

The development and adoption path of the conservation tillage innovation on the Prairies can be divided into four time periods: the 1930s to 1940s, the 1950s to early 1970s, the early 1970s to 1980s, and the 1990s to 2010s.

### 3.1 *The 1930s and 1940s—The Dirty Thirties and the search for more sustainable agriculture practices*

In the early settlement of the Prairies, European immigrants, coming from areas characterized by high precipitation, continued to farm with moldboard plows, disks, and harrows. Using the available machinery and

[4] Zero tillage or no-tillage can be defined as a system of planting (seeding) crops into untilled soil by opening a narrow slot or trench only of sufficient width and depth to obtain proper seed coverage. No other soil tillage is done (Phillips and Young, 1973).

[5] Note that in some places in the US and Europe a cover crop (a secondary crop grown between primary crop production periods or between rows of the primary crop) is used as an alternative cropping system to prevent soil erosion, improve soil quality, help control weeds, and increase nitrogen fixation. However, in the semi-arid climate of the Canadian Prairies, the cover crop system is rarely used as the secondary crop may deplete soil moisture, creating dry conditions and stress for primary crop growth.

techniques and based on their limited knowledge of the Prairie soil and climate conditions, farmers engaged in tillage activities, which from their point of view were necessary to prepare the land for cropping (Anderson, 1975). The use of tillage rested on the belief that removal or burial of the residue from the field surface was needed to aerate the soil, improve soil structure, control plant diseases, insects, and weeds, and provide a well-prepared seedbed. Given the inherent quality and productivity of these rich Chernozemic soils, these practices were quite successful for more than a generation. Traditional tillage was the activity that symbolized the farmer's role in his rural community.

Facing the challenging and often variable semi-arid climate of the Prairies, farmers adopted summerfallow as an additional and often necessary practice in their cropping system especially in the Brown and Dark Brown soil zones. Summerfallow, which was discovered accidentally by Dr. Angus Mackay in 1886, is the practice by which land is left fallow (not cropped) for a period of 20 months, from after harvest in late September to mid-April of the following crop year (Kirk, 1938) [6]. Summerfallow is mainly used to increase soil water reserves to ensure adequate moisture to grow a crop the next growing season (Carter, 1994). Traditionally, weeds are controlled with tillage, during the summerfallow period.

In the 1930s, the Prairies experienced a period of severe drought and dust storms. As a result, the period was named the "Dirty Thirties," and the area became known as part of the "Dust Bowl", similar to much of the mid-western and northern U. S. Because of the large area under summerfallow, high winds moved millions of tonnes of topsoil from fields during the 1930s. However, this was not the only contributing factor to soil erosion at that time. Anderson (1975) indicated that the main reason was the plowing culture which was introduced on the Prairies without any adjustment to the ecological environment of this area The introduction of this culture coincided with periods of low precipitation, and coincided with a period during which large amounts of land were brought under cultivation, motivated by advanced mechanization and high grain prices during the First World War.

In the search for answers on how to control this erosion, governments, experimental farms, universities, and farmers launched co-operative efforts. Soil scientists, such as W. S. Chepil and Sidney Barnes, confirmed that tillage should be kept to a bare minimum and land should only be worked to control weeds, and trash (crop and weed residue) should be kept on the surface to reduce soil erosion (Gray, 1978) [7].

In 1935, the federal government established the Prairie Farm Rehabilitation Administration (PFRA), including the establishment of experimental substations, agricultural improvement associations (AIAs), community pastures, water projects, and shelterbelt programs. The role of PFRA was to work with experimental farms, universities, provincial agencies, and farmers to share knowledge and feedback with the objective of developing more sustainable agricultural practices. The AIAs, which were coordinated by the Dominion Experimental farms, facilitated the two-way flow of information among different participants in the network (Gray, 1978).

The result of these co-operative efforts was more sustainable practices such as trash-cover, plowless fallow, and strip-farming practices using one-way discers, duckfoot cultivators, the Morris rod weeder, and the Noble wide-blade cultivator[8]. Although these soil conservation practices could, to some degree, control soil erosion at that time, the available equipment was not fully effective in controlling weeds, and the crop residues left on the

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[6] Dr. Angus Mackay (1841-1931) , a farmer, was born near Pickering Township, Upper Canada. He moved to Indian Head, Saskatchewan at the age of 40 to start working on his own land. In 1885, the Riel Rebellion battle required farmers to transport equipment and supplies to forces in Battleford and Prince Albert. It happened that Mackay's horses weren't fit to travel and, in the same year, frost prevented him from seeding his farm, so he just used his horses to plow and harrow the field periodically to control weeds in the summer. Accidentally, he was preparing for the first summerfallow in Western Canada. The following year was very dry and Mackay's summerfallow resulted in exceptional yield, 35 bushels per acre (2. 4 t $ha^{-1}$) , while his neighbours' crops were ruined (Kirk, 1938).

[7] In addition to its impact on controlling soil erosion, crop residue left on the surface has several other benefits such as retention of snow, protection of winter crops (e. g., winter wheat) from low temperature, enhancement of the infiltration of water, and improvement in the overall health of the soil ［Saskatchewan Soil Conservation Association (SSCA) -Residue Management, 2013］.

[8] The one-way discer (diskers) is a Saskatchewan adaptation of the one-way disc plow that was invented by Charles Angell Sr. in Plains, Kansas in the 1920s. The one-way discer is a high-disturbance implement that was used to replace plowing, and combined seeding and tillage into a single operation. It worked well in heavy stubble and straw leaving it partially buried to prevent soil erosion. In short stubble, the use of duckfoot cultivators was usually preferable as the one-way discer may bury the stubble and straw completely (Hopkins et al., 1946). For a detailed description of the one-way discer seeder and other early seeding equipment used for direct seeding see Lindwall and Anderson (1977) and Anderson (1964).

surface by the blade cultivator made seeding more difficult because of trash clearance and plugging problems (Gray, 1978).

The early development of soil conservation practices happened during the Great Depression in the 1930s. This era of deprivation and uncertainty drove farmers to think solely about immediate survival. Thus, investment in new sustainable agriculture practices to replace the tillage culture was not an option for farmers. In addition, machinery companies had an economic stake in powerful tractors, tillage equipment, and in seeding equipment that worked best in tilled soil. Thus, they had no incentive to invest in the development of alternative equipment that could replace tillage and planting equipment.

## 3.2 *The* 1950*s to early* 1970*s*—*The initial trial of low-disturbance direct seeding*

There were some early efforts to develop more effective equipment for trash-cover farming and reduced tillage on the Prairies. By the 1950s, the discer with an attached seed box was introduced. The discer was a Saskatchewan innovation that left more trash on the surface; it was large and heavy enough to accomplish tillage, weed control and seeding in one pass. Saskatchewan manufacturers also contributed to the development of heavy-duty cultivators (also known as chisel plows) that could clear more trash and leave more crop residue cover than disc-type machines. Another important contribution to trash-cover equipment was the development of a coil land packer by Emerson Summach (a Saskatchewan farmer who would become the owner of Flexi-Coil Company). The coil packer could follow the contours of the land, worked in stony land, and reduced soil disturbance (McInnis, 2004). Although these equipment innovations were important contributions toward reducing tillage, tilling the soil was still considered fundamental for controlling weeds and producing a crop at that time.

The trend after World War Ⅱ was towards urbanization and consolidation of farmland into larger farms requiring larger and wider equipment. This movement resulted in increased investment in larger tractors and equipment, enabling farmers to substitute machinery for labour, and made trash-cover and strip-farming practices inconvenient.

In 1961, the first herbicide for broad-spectrum weed control, paraquat, was produced for commercial purposes by Imperial Chemical Industries in the UK and marketed by Chipman Chemicals Co. in Canada. With paraquat, replacing tillage with an herbicide to control weeds became possible before seeding, and this practise began to spread (chemfallow) [9]. In the mid-sixties several innovative farmers were successful in using existing or adapted high clearance hoe drills developed by Noble Cultivators Co., Edwards Rodweeder Co. and International Harvester for one-pass seeding. In addition, in 1967, the first no-till drill developed by Allis-Chalmers was introduced on the Prairies. With the introduction of the herbicide paraquat and some no-till drill seeders; researchers, such as C. Hank Anderson at Swift Current, Tracy Anderson and Wayne Lindwall at Lethbridge, Ken Browren at Melfort, Elmer Stobbe at the University of Manitoba, and Brian Fowler at the University of Saskatchewan began experimenting with low-disturbance direct seeding systems, and reported that with experience yields under this system were as good as those under traditional tillage systems［Lindwall and Sonntag (Eds.), 2010; Anderson and Smith, 1966］.

### **3. 2. 1** Barriers to the adoption of low-disturbance direct seeding

The barriers to the adoption of low-disturbance direct seeding system during the 1960s and early 1970s were as follows:

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[9] Weed control methods used while the crop is growing (i. e., pre-emergent and post-emerged herbicide spraying methods) are the same under TT and CT systems (University of Saskatchewan: Guide to Farm Practice in Saskatchewan, 1985). Weeds that are traditionally managed by tillage operations, including some types of winter annual and perennial weeds, are poorly controlled by in-crop herbicide and thus late fall and pre-seeding herbicide applications are required (Moyer at al., 1994). Perennial weeds (e. g., quackgrass, and dandelion) can be controlled by using pre-seeding burn-off with paraquat (or glyphosate introduced in 1974) in the early spring (Alberta Agriculture, Food and Rural Development, 2004). Winter annual weeds (e. g., stinkweed and flixweed) , which germinate in the fall and overwinter, and flower and produce seeds in the spring and summer of the following year, can be controlled in late fall or early spring (pre-seeding). Herbicides such as 2, 4-D, MCPA, and paraquat (later glyphosate) are used to control winter annuals in the fall. 2, 4-D and MCPA herbicides, which last in the soil for a few weeks, are not registered for pre-seeding weed control because of the possibility of injury to crops. The herbicide paraquat (later glyphosate) is recommended in the case of early spring control of winter annual weeds (Alberta Agriculture, Food and Rural Development, 1999). Although paraquat can control both perennial and winter annual weeds in the spring, one application to control both types cannot be achieved because of the difference in the time of application for optimal control of these types of weeds (Alberta Agriculture, Food and Rural Development, 1999). For this reason and because of the high price of paraquat herbicides 2, 4-D and MCPA were mainly used to control winter annual weeds.

(a) *Economic and Technical Barriers*: Although the introduction of the herbicide paraquat and some no-till drills provided farmers with the necessary components to produce a crop under a low-disturbance direct seeding system, the high price of paraquat and its inadequate control of many broadleaf weeds made the system impractical for most farmers. In addition, the cost and limited success of no-till drills from the U. S. and Europe (because of problems with seed placement and ineffective packing) were regarded as deterrents to the adoption of this system on the Prairies during the 1960s and early 1970s［Lindwall and Anderson, 1977; Lindwall and Sonntag (Eds.), 2010］.

(b) *Policy Barriers*: During the period between 1953 and 1973, the Canadian Wheat Board's delivery quota system, and the inclusion of summerfallow in the quota system, was seen as a deterrent to the adoption of conservation tillage on the Prairies［Lindwall and Sonntag (Eds.), 2010; Hildebrand, 1983; Sparrow, 1984］. The primary objective of the delivery quota, as set forth in 1940, was to provide producers on the Canadian Prairies and the Peace River District of British Columbia with equitable access to the transportation and marketing system (Sampson and Gerrard, 1987; Hildebrand, 1983)[10]. During the period from 1940 to 1953, delivery quotas enabled producers to deliver a quantity of grain proportional to seeded area[11]. In 1953, grain market demand dropped dramatically and the CWB was unable to accept all producers' grain deliveries. An excess stock of a particular crop under seeded area quota would only be marketed if a producer replanted it or if a future crop failed. This showed the weakness of the seeded area quota and led to the establishment of the general delivery quota system based on a producer's specific area. The general delivery quota remained in effect until 1973, and allowed producers to market aggregate crops proportional to specified area. Specified area included the area seeded to crops controlled by the quota (i. e., wheat, oats, barley, and rye), land under summerfallow, and eligible grasses and forage crops (Jolly and Abel, 1978)[12]. Including summerfallow in the category of the assignable area unfortunately encouraged producers to summerfallow. For instance, since a farmer's delivery base was constant regardless of his set of land use decisions, farmers found it more economical to increase the area under summerfallow relative to seeded area to save the cost of variable inputs per unit of output. In addition, in the case of excess stocks of a particular year, a farmer could obtain a marketing quota for grain inventory in the following year by just working the land and leaving it in fallow.

In 1969, after more than 16 years of abundant production and limited export sales, the Canadian wheat stock built up and reached about two years of average production (Jolly and Abel, 1978). This led to the introduction of the Federal Lower Inventories For Tomorrow (LIFT) program in 1970. LIFT was a one-year program designed to immediately reduce wheat inventory by reducing seeded wheat area and converting it to summerfallow or sowing it to perennial forage. Under LIFT, producers were paid \$ 6 per acre (\$ 15 $ha^{-1}$) for converting wheat area to summerfallow, and \$ 10 per acre (\$ 25 $ha^{-1}$) for seeding this land to perennial forage (Cohn, 1977). As a result, in 1971, the seeded wheat area fell by 50% and wheat inventory went down by 40%. Although this program had met its goal, it dramatically increased the area under summerfallow on the Prairies from 12 million hectares in 1969 to 15 million in 1971 (Gilson, 1980).

### 3. 3 *The early* **1970s** *to the* **1980s**—*Conservation tillage system takes shape on the Prairies*

In 1973, the market for grain received a dramatic shock after the entry of the Soviet Union in the market for the first time. The result was a decrease in North American grain reserves and a substantial increase in grain prices. In the same year, the CWB's delivery quota system was removed. In 1974, the New Domestic Feed Grains Policy (NDFGP) was introduced in Canada. This policy eliminated the CWB's control over interprovincial movement of feed grains and created a dual marketing system. This system gave farmers the option of selling their feed grains to the CWB, to companies (private and co-operative), or both (CWB, 1998). As a response to these factors, farmers increased their production by increasing the seeded area using traditional

[10] In 1939, world price declined below the floor price of \$ 0.90 per bushel (\$ 0.33$kg^{-1}$) of wheat, because World War Ⅱ closed the European market to Canadian grains, while concurrently Canadian production was above normal. Also, available long-term storage space was low. Consequently, the Canadian Wheat Board (CWB) imposed a 5,000-bushel (136 t) quota of wheat per farmer in 1939. This quota was replaced by the first delivery quota system on August 7, 1940 (CWB, 1998).

[11] During 1944 and 1952, quotas levels were open as a result of the strong grain markets after World War Ⅱ, and farmers who produced more than their quota could market the excess before the end of the crop year (Jolly and Abel, 1978).

[12] In 1972, the general delivery quota system was expanded to include land seeded to rapeseed and flaxseed, and land in miscellaneous crops such as sunflowers.

tillage systems. Intensive tillage combined with severe drought resulted in more damage to soil quality as a consequence of severe erosion in the 1970s and early 1980s ［Lindwall and Sonntag (Eds.), 2010］.

Between the 1970s and 1980s, the CT system started to take shape with the introduction of the broad spectrum and non-residual herbicide glyphosate, the development of new and diverse crop rotations, and the introduction of new seeding equipment. These elements are described as follows:

(a) *Introduction of the Herbicide Glyphosate*: In 1974, Monsanto introduced the broad-spectrum herbicide glyphosate under the trade name Roundup (Monsanto, 2011)[13]. Both glyphosate and paraquat are regarded as low-risk non-selective herbicides that can be used to control a wide range of weeds before seeding and in the fall. The price of paraquat was lower than the price of glyphosate in the 1970s, but glyphosate provided better weed control. The mode of action of paraquat provided limited control of grass species such as wild oats and volunteer cereals, and only controlled the top-growth of perennial weeds. The ability of glyphosate to move throughout the plant and reach deep into the roots provided more efficient weed control, especially controlling rooted perennials with tubers and rootstocks［Lindwall and Sonntag (Eds.), 2010］.

(b) *The Development of New Cropping Systems*: Conservation tillage systems benefitted from the use of crop rotations to help break the life cycles of pests and diseases, and controlling weeds. Between the 1970s and 1980s, advances in crop breeding produced new varieties of oilseeds and pulses that could be used in rotation with cereal crops on the Prairies[14]. In 1973, the first rapeseed to contain less than 2% erucic acid and not more than 3 mg $g^{-1}$ of glucosinolate dry meal was introduced on the Prairies by Dr. Keith Downey at the AAFC Research Centre in Saskatoon and Dr. Baldur Stefansson at the University of Manitoba. In 1979, the new rapeseed variety was registered by the Western Canadian Oilseed Association under the trade name “Canola” (McInnis, 2004)[15].

During the 1970s and 1980s, pulse crops were virtually unknown on the Prairies［Saskatchewan Pulse Grower (SPG), 2000］, although some varieties of peas were introduced from European countries (SPG, 2000). In 1978 and 1980, Dr. Alfred Slinkard, at the Crop Development Centre (CDC), University of Saskatchewan, developed new lentil varieties (Laird and Eston) that contributed to the expansion of this crop on the Prairies.

(c) *The Introduction of Seeding Equipment*: Between the late 1970s and 1980s, zero-tillage experiments conducted by AAFC engineers Ben Dyck and Wayne Lindwall at Swift Current and Lethbridge, helped stimulate the development of commercial no-till drills on the Prairies［Lindwall and Anderson, 1977; Lindwall and Sonntag (Eds.), 2010］. For example, the Haybuster 1206 grain and fertilizer drill was introduced in 1979 and Versatile Noble 2000 seed drill was introduced in 1983［Prairie Agricultural Machinery Institute (PAMI), 2013］.

**3.3.1** The early adoption of conservation tillage systems

Using available conservation tillage technology, a few farmers such as Jim McCutcheon (known as “the Father of Zero Tillage”), Homewood, Manitoba; Bob McNabb, Minnedosa, Manitoba; John and Shirley Bennett, Biggar, Saskatchewan; Lucien and Herve Lepage, Montmartre, Saskatchewan; Gerry Willerth, Indian Head, Saskatchewan; Ike and Rod Lanier, Lethbridge, Alberta; and Murray Sankey, Veteran, Alberta, adopted conservation tillage systems in the late 1970s. Wayne Lindwall and Kathy Larson interviewed these farmers and reported that crop production under conservation tillage systems was profitable despite the limitations of equipment and the high price of glyphosate. Also, there was a significant improvement in soil quality. However, early adopters encountered some social challenges (e. g., ridicule) because they were not cultivating the soil and sustaining the tillage culture in their community［Lindwall and Sonntag (Eds.), 2010］.

These farmers played a key role in the development of conservation tillage technology and in the promotion of its benefits. They did so by sharing their knowledge and experience through formal and informal networks with conservation tillage associations’, agents, scientists, equipment company representatives, and other farmers［Lindwall and Sonntag (Eds.), 2010］.

For instance, Lucien Lepage’s network included equipment company agents such as James Halford (ConservaPak/John Deere) and Barry Rogers (Rogers Spraying Equipment), Agriculture Canada research station representatives such as Guy Lafond and Doug Doerksen, Saskatchewan Soil Conservation Association (SSCA)

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[13] In 1974, Roundup was developed and commercialized in Malaysia and the UK, and used in the US for industrial purposes. In 1976, Roundup was commercialized for agricultural use in the US (Monsanto Company, 2011).

[14] Pulse crops include peas, dry beans, lentils, chickpeas, and faba beans.

[15] The name Canola was derived from Canadian Oil, Low Acid.

agents, and others. Gerry Willerth's network included PFRA and SSCA agents, Haybuster company agents, James Halford, Guy Lafond, and others. John Bennett's network included Manitoba Tillage Association, SSCA, and ManDak Zero Till Association agents, international conservation tillage organizations' agents, Guy Lafond, Doug Doerksen, and others. Jim McCutcheon's network included researchers such as Elmer Stobbe, Wayne Lindwall, Guy Lafond, and Jack Forbes, ManDak Zero Till Association agents, and others. Bob McNabb's networks included researchers such as Elmer Stobbe and Jim McCutcheon, Gordon McPhee, and Garth Butcher, government agents such as Dave Donaghey, producers in Manitoba and North Dakota, Manitoba-North Dakota Zero-Till Association agents, ManDak Zero Till Association agents, James Halford, and others. Murray Sankey's network included Alberta Conservation Tillage Society (ACTS) agents, early adopters such as Gordon and Spencer Hilton of Strathmore, Dan and Paul Stryker of Foremost, Bryan and Mark Perkins of Wainwright and Henry Graw, the Associated Reduced Tillage Linkages (RTL) agents, and others［Lindwall and Sonntag (Eds.), 2010］.

**3.3.2** Barriers to the adoption of conservation tillage innovation

The barriers to the adoption of CT during the 1970s and 1980s were as follows:

(a) *Economic and Technical Barriers*: Although there was early evidence that for some farmers the adoption of CT technology was profitable, many farmers operating at this time did not find CT to be economically feasible. Previous studies on the Prairies (e. g., Zentner and Lindwall, 1982; Fairbairn, 1984; Malhi et al., 1988; Zentner et al., 1991), indicated that although Monsanto started to reduce the price of Roundup in 1985, the high price of Roundup relative to the price of fuel for TT increased the cost of operation under CT and impeded the adoption of this technology on the Prairies (Fig. 2)[16]. In addition, although some farmers found the existing 1980s CT equipment (e. g., no-till drills) efficient, for the majority of farmers, the adoption of CT technology wasn't possible before the development of larger and more specialized CT equipment (e. g., air-seeders)［Lindwall and Sonntag (Eds.), 2010］.

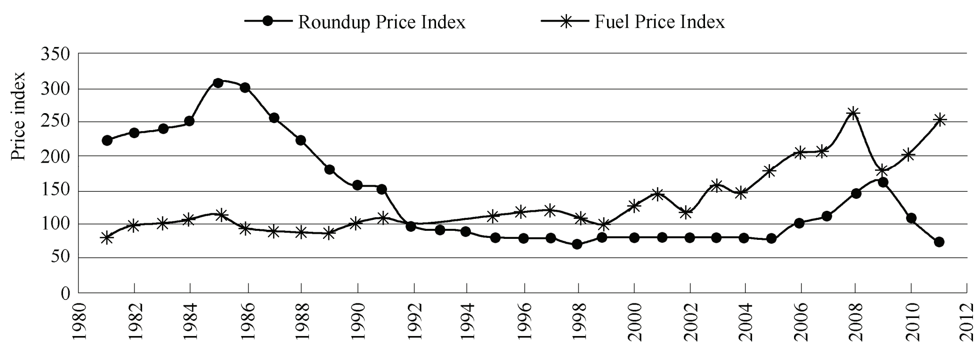


**Fig. 2 Roundup and Fuel Price Indices in Canada (1981-2011) (Index, 1992=100)**
**Source: Statistics Canada; Alberta Agriculture and Rural Development.**

(b) *Social Challenges*: Early adopters of CT technology faced social challenges because TT was not only a crop production system, but also an integral part of the farming culture. As part of a culture, TT contributed to the collective identity of the farmer, rendering him/her both technical and social values. Technically, tilling the soil was regarded as the fundamental first task in producing a crop and providing a living. Socially, the performance of the tillage task, which is shared and recognized by others in the farming community, was a function of the feedback from that community. The farmer who had his land tilled with no weeds, no stones, no trash, and cultivator furrows, wins a prize, gains prestige, and enjoys feelings of self-esteem. Thus, the introduction of any alternative technology must ensure farmers with equally potent collective identity. During the 1970s and 1980s, the conservation tillage system, based on the belief that tilling the soil is not necessary, was perceived by many farmers as incompatible with their accepted socio-cultural values and beliefs, and thus, with their collective identity as farmers (Carter, 1994; Rogers, 1995). Therefore, by adopting this system a farmer needed to deviate from his collective identity and endure a social cost.

During the 1970s, Dr. Don Rennie, soil scientist and then-Dean of the College of Agriculture at the University of Saskatchewan, took a controversial stand against the practice of traditional summerfallow and

[16] Although the Roundup patent expired in 2001, Monsanto started to decrease the price of this herbicide in 1985.

associated tillage, and warned of the long-term negative effects that this practice on increased risks of soil erosion, salinity, and organic-matter depletion. He indicated that "summerfallow is perhaps the most singular mismanagement practice that has been in vogue since this country was opened up" (Fairbairn, 1984, p.30). Although Dr. Rennie was able to attract the attention of some farmers, he met with considerable resistance from others ［Lindwall and Sonntag (Eds.), 2010］. According to Fairbairn (1984), "when Dr. Rennie became so outspoken in the 1970s, a tempestuous conference debated his views-featuring many farmers and other traditionalists who, Rennie felt, were acting like inquisitors at a heresy trial". Dr. Rennie concluded that the "summerfallow habit" was a practice that "dies hard".

In psychology and cognitive science, farmers' resistance to accept the negative effects of summerfallow can be explained in two terms: anchored and confirmation bias. After using long time dependence on summerfallow, farmers became "anchored" to that practice, thus rejected any attempts that suggested otherwise. In addition, farmers tended to exhibit a "confirmation bias" in their search for and acceptance of information. For instance, they accepted and assigned more weight to evidence that supported summerfallow, and ignored or under weighed evidence that opposed the use of this practice ［Lindwall and Sonntag (Eds.), 2010］.

**3.3.3** Increase public awareness of soil degradation

In the 1980s, soil degradation, aggravated by drought, could no longer be ignored on the Prairies. This problem prompted calls to increase efforts to raise public awareness of the negative impact of traditional tillage practices on soil quality. Three publications contributed significantly to understanding the importance of soil degradation in Canada. *Land Depletion and Soil Conservation Issues on the Canadian Prairies* by the PFRA (1983), brought together, for the first time, the available scientific data on soil erosion and estimated an annual soil loss of 277 Mt for the Prairies. *Soil at Risk: Canada's Eroding Future* by Senator Herb Sparrow (1984), alerted readers that the future of the Canadian Prairies was at risk because of soil degradation. *Will the Bounty End? The Uncertain Future of Canada's Food Supply* by Garry Fairbairn (1984) indicated that the abundance of agriculture and low food price that Canadian consumers enjoyed were at the cost of soil loss and soil degradation.

To raise public awareness, several researchers assessed the cost of soil degradation on the Prairies. The PFRA (1983), Dumanski et al. (1986), and Van Kooten et al. (1989) estimated the annual cost of soil erosion on the Prairies at $ 239 million, between $ 155 and $ 271, and between $ 35.7 and $ 453.3 million, respectively. Rennie (1986) estimated the annual cost of land degradation resulting from the use of traditional tillage practices (summerfallow and invasive cultivation practices) at $ 429.2, $ 560, and $ 43.7 million in Alberta, Saskatchewan, and Manitoba, respectively.

In 1987, Senator Sparrow's report, *Soil at Risk*, led the way to the establishment of the Soil Conservation Council of Canada and of the Saskatchewan Soil Conservation Association ［Lindwall and Sonntag (Eds.), 2010］. These groups, together with other groups on the Prairies (i. e., different agriculture extension services, Agricultural Research Service (ARS) Northern Great Plains Research Laboratory (NGPRL), Alberta Conservation Tillage Society, the Manitoba-North Dakota Zero Tillage Farmers Association, the PFRA-Soil and Water Conservation Branch, Saskatchewan government's Save Our Soils programs, Wheatland Conservation Area (soil conservation clubs formed by farmers in south-western Saskatchewan), Alberta Reduced Tillage Linkages, and others) have played an important role in promoting the benefits of conservation tillage systems by responding to farmers' questions, providing technical assistance, arranging field days, and workshops for effective use of conservation tillage technology, and offering social and moral support to them (Conservation Technology Information Centre, 2009).

In addition, social interactions of early adopters of CT with other farmers in their neighbourhood played an important role in providing information on the performance of this technology, helped change the cultural beliefs that tilling the soil is necessary to produce a crop and, thus, positively influenced the adoption of CT systems in their neighbourhoods. Awada (2012) empirically analyzed the factors affecting the adoption of CT on the Canadian Prairies by using geographical data, and found that social interactions of farmers with neighbours who have already adopted CT (the neighbourhood effect) significantly and positively influenced the adoption of this technology on the Prairies. The neighborhood effect identifies that as the number of farmers who have adopted CT increases, CT became more successful and popular, social pressures or community expectations to follow traditional tillage culture decreased, and the adoption of CT increased in the same neighbourhood over time (Awada, 2012).

### 3. 4 *The* 1990*s and the* 2010*s—Farmer-developed air-seeders and the adoption of zero tillage*

In the 1990s, Saskatchewan farm implement manufacturers became leaders in the development and manufacturing of world-class, one-pass, low-soil-disturbance air-seeders, which have been exported around the world.

The concept of seeding using forced air had already been used in countries such as Australia and Germany, but had not been widely used on the Prairies (McInnis, 2004). In 1969, Jerome Bechard, a Saskatchewan innovative farmer, developed the first air-seeder in Western Canada. In 1979, Bechard acquired a Canadian patent numbered 1060720 and titled "Air Seeding System" (Fig. 3). Bechard's invention is described as follows:

*The system is designed to be used in conjunction with conventional tillage equipment such as one-way discers, deep tillage chisel ploughs, field cultivators and the like and can be utilized to plant seed and/or apply fertilizer, herbicides or both. It consists of a separate wheeled trailer carrying the weight of the seed, fertilizer, herbicides and the like, thereby eliminating any weight change from the seeding machine. The seed or granular chemicals are entrained in air stream and conveyed by headers and conduits to the seeding boots or spouts. Each component is metered from a tank by an upwardly inclined auger assembly driven by a variable speed orbital motor, and deposited into the air stream carried by a main conduit* (Canadian Intellectual Property Office, 2012)[17].

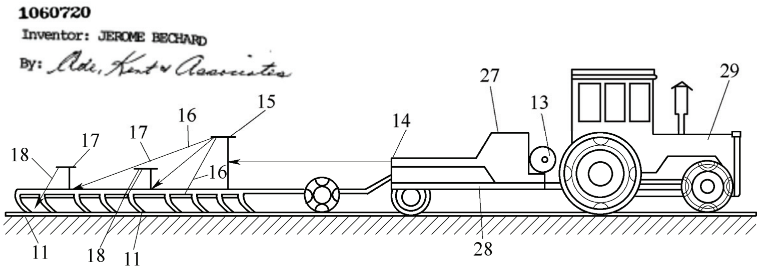


**Fig.3 Jerome Bechard Air-Seeder Attached to Cultivator**
**Source: Canadian Intellectual Property Office (2012).**

In the late 1970s, Bourgault Industry Ltd of St. Brieux, Saskatchewan acquired the Jerome Bechard system. In 1980, Bourgault manufactured its first air-seeder, Model 138, which was described by Bourgault as follows:

*The first air-seeder to be towed behind the cultivator, giving the operator an unobstructed view of all of the shanks. The Model 138 air-seeder could quickly be disconnected, freeing the cultivator for other fieldwork. This concept of a tow behind unit has served as the model for virtually all of the air-seeders currently being produced throughout the world* (Bourgault, 2013).

Other Saskatchewan companies such as Pride Industries, Leon's Manufacturing, Friggstad Manufacturing (purchased by Flexi Coil in 1984), Flexi-Coil, and Morris Industries, were also busy developing larger seed drills from their existing lines of cultivators. These companies developed a number of air-seeders specialized for Prairie conditions that combined tillage and seeding into a single operation

In 1983, James Halford, of ConservaPak/John Deere, a farmer from Indian Head, Saskatchewan, developed his own one-pass, low-soil-disturbance air-seeder. In 1988 and 1989, Halford acquired Canadian patents numbered 1239835 and 1263060, and titled "Seed/Fertilizer Placement System for Minimum Tillage Application" and "Packer Wheel Arrangement" for his inventions, respectively. Halford's 1988 invention is shown in Fig. 4, and is described as follows:

*Apparatus for seed and fertilizer placement in the ground comprises a knife followed immediately by a first tube for depositing fertilizer and a second tube spaced therefrom for depositing the seed. The second tube can be adjusted horizontally and vertically and particularly to a position scraping the side of the furrow formed by the knife to deposit the seed at the side. A packer wheel mounted on the same support as the second tube follows the second tube and runs in the furrow to press down soil over the seed and fertilizer. The packer wheel is rotationally molded from polyethylene* (Canadian Intellectual Property Office, 2012)[18,19].

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[17] For a detailed description of the Bechard 1979 invention see http://brevets-patents. ic.gc.ca/opic-cipo/cpd/eng/patent/1060720/summary. html?type =number_search.

[18] For a detailed description of the Halford 1988 invention see http://brevets-patents. ic. gc ca/opic-cipo/cpd/eng/patent/ 1239835/summary. html?type =number_search.

[19] Packer wheels were used to firm up the seedbed in the 1950's or earlier (Lindwall and Anderson 1977), but the Halford 1988 design was one of the first to help ensure adequate depth control and separation between seed and fertilizer in a direct seeding system.

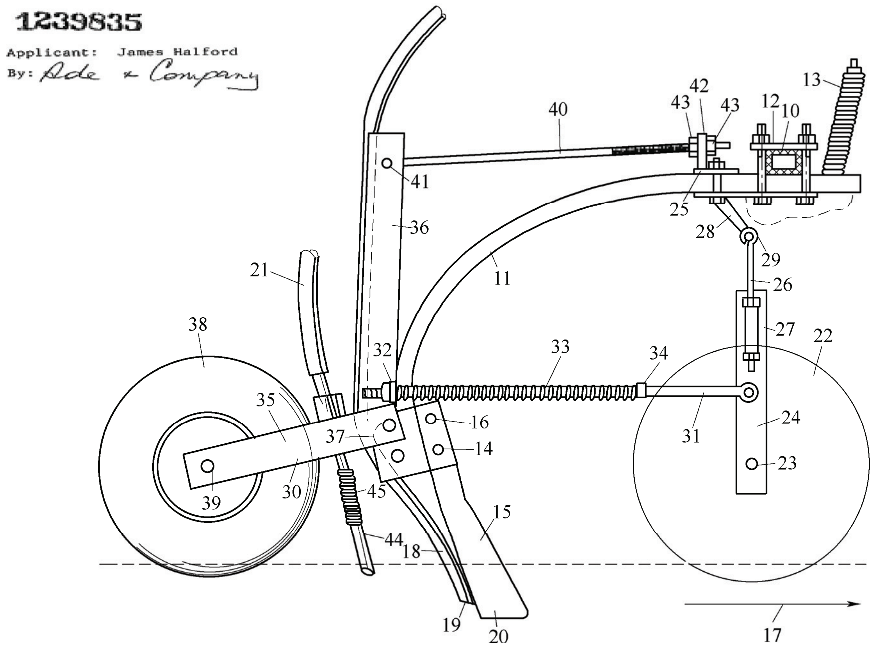


**Fig.4 James Halford Low Disturbance Air-Seeder**
**Source: Canadian Intellectual Property Office (2012).**

During the 1990s, Conserva Pak/John Deere and other companies such as Seed Hawk Inc., located in Langbank, and Seed Master located in Emerald Park, Saskatchewan, were able to produce and export a large number of low-soil-disturbance air-seeder designs that provided accurate depth of seed and fertilizer placement, and packing (McInnis, 2004).

To help avoid problems such as plugging the seeding equipment with straw or hair pinning under CT, more attention to crop residue management is required during harvesting operations. Therefore, several farm implement manufacturers on the Prairies (e. g., Redekop Manufacturing Co., Rem Manufacturing Ltd, and Dutch Industries) developed straw choppers and spreaders, chaff spreaders, and chaff collectors to enable better residue management during harvesting operations. Note that the quantity of chaff and straw that must be managed depends on the type of crops. For instance, crops such as wheat, barley, and oats produce more straw than chaff and, thus, require the use of proper straw management that spread the straw at least 80% of the width of cut. In contrast, crops such as canola, pulses, and mustard produce more chaff than straw, and thus require a chaff management attachment that spreads chaff at least 50% of the width of cut［Saskatchewan Soil Conservation Association (SSCA)—Residue Management, 2013］[20].

To place seed and fertilizer into the soil at a depth that provides the optimal seed germination and plant development, the seeder opener must penetrate the surface residue and the soil. Because the method of seed placement varies by crop and soil types several farm manufacturers on the Prairies (e. g., Bourgault Industries Limited, Froc Industries Ltd, Dutch Industries, and K-Hart Industries) developed a variety of openers including narrow sweeps, knives and discs. Generally, the amount of soil disturbance increases from sweep to knife to disc type openers. In addition, manufacturers such as Dutch Industries, K-Hart Industries, and Valley Packing Systems designed a range of packers that are used to cover the seed with soil, and ensure sufficient seed-to-soil contact for better crop germination (SSCA, 2013)[21].

[20] Row spacing under CT varies by soil types. For instance, a row spacing of 10 in (25 cm) or less is required in the Brown and Dark Brown soil zones, while a wider row spacing is preferable in the Black and Gray soil zones (SSCA, 2013).

[21] Seed depth placement is usually 1.5 to 3 inches (2.5-7.6 cm) for wheat, 0.5 to 1.5 inches (1.3-3.8 cm) for canola, and 1 to 2 inches (2.5-5 cm) for pulses (Manitoba Agriculture, Food and Rural initiatives, 2013). Typically the depth of seeding is controlled in part by press-wheel or packer wheel that is immediately behind and often attached to the furrow opener. One of the reasons for the widespread acceptance and adoption of the air-seeders for direct seeding was that this equipment was very similar to the traditional chisel plows and field cultivators with the exception of having narrower furrow openers which cause less soil disturbance, and press-wheel packer system that helps control seeding depth.

There were two important organizations that served the Saskatchewan farm implement manufacturing industry during this period. The Prairie Implement Manufacturers Association (PIMA) was formed in 1970 to provide programs to inform, educate, share skills, and facilitate communication among its members. The other important organization, Prairie Agricultural Machinery Institute (PAMI) was an applied research, development, and testing association formed in 1971 to facilitate communication among manufacturers and farmers and to provide them with design, development, manufacturing, and assessment of equipment and components services (Encyclopedia of Saskatchewan, 2006).

**3.4.1** The adoption of zero tillage (ZT)

Between 1991 and 2011, in addition to the improvement in ZT seeding equipment and technology, three economic factors influenced the widespread adoption of ZT on the Prairies. First, the price of herbicide Roundup went from \$ 33 $L^{-1}$ in 1985 to \$ 10 $L^{-1}$ in 1992, and to \$ 6.6 $L^{-1}$ in 2011 and, thus, reduced the cost of operation under ZT (Fig. 2). Second, the interest rate on borrowed capital dropped from 13% in 1989 to 7% in 1999 and to 5% in 2011, and consequently reduced the cost of investment in new machinery (Saskatchewan Ministry of Agriculture: Farm Machinery, 1990–2011). Third, the price of fuel increased and, thus, increased the cost of operation under traditional tillage (Fig. 2). The decrease in the price of Roundup relative to the price of fuel made operations that required considerable fuel (e. g., summerfallow and tillage) more expensive than those that were less fuel intensive (e. g., conservation tillage), and stimulated farmers to switch their operations to the least costly option. Fig. 2 shows that the price ratio of fuel to Roundup was less than 1 during the period from 1980 to 1992 and greater than 1 during the period from 1993 to 2011. In addition, it was now well established that ZT systems resolved the many shortcomings of TT (Lafond et al., 1996).

Fig.5 shows the trends in tillage systems on the Prairies from 1981 to 2011. Fig.5 (b) shows that during the 1980s, the percentage of cropland under ZT on the Prairies was estimated to be between 3% and 10%. Between 1991 and 2011, the percentage of cropland area under ZT practice in Alberta, Saskatchewan, and Manitoba increased from 3%, 10%, and 5% to 65%, 70%, and 25%, respectively. In parallel, Fig.5 (a) shows the decrease in the use of TT indicating the switch from TT to ZT during the same period.

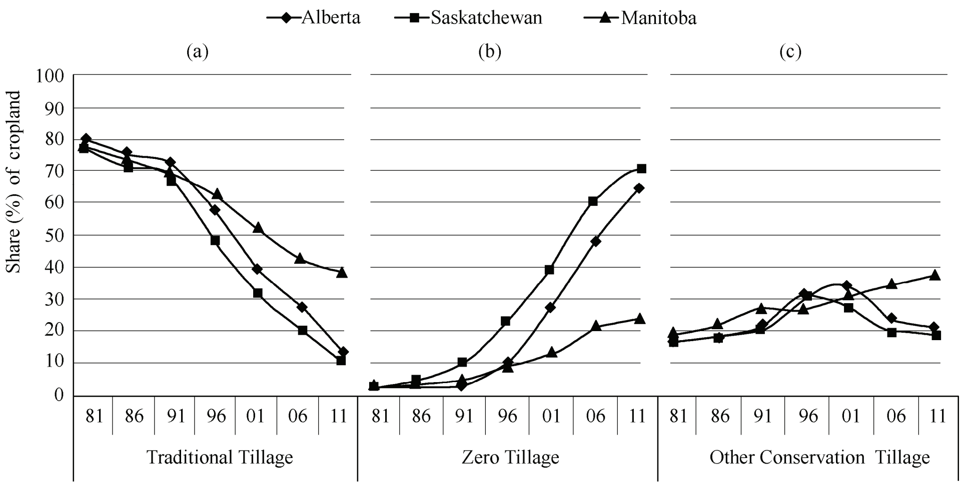


**Fig. 5 Trends in tillage systems on the Canadian Prairies (1981-2011)**
**Source: Figure based on data from AAFC (2010) ; Statistics Canada (1991-2011).**

# 4 The economic and environmental impact of the adoption of conservation tillage systems on the Canadian Prairies

(a) *Economic Impacts*: Compared to TT, eliminating or reducing tillage in preparing the seedbed, and replacing or partially replacing tillage with herbicides to control weeds when moving to CT, reduces the need for machinery operations but increases the need for herbicides. The reduction in machinery operations in turn reduces labour and fuel requirements. Awada (2012) indicated that the switch from TT to ZT increased herbicide requirement by 48% but decreased labour requirement by 31%, fuel needs by 39%, and machinery hours of operation by 45%. The decrease in machinery hours of operation under ZT decreased the cost of machinery service (i. e., investment, depreciation, insurance and repair costs), with most of this accruing in the cost of operating tractors[22]. Fertilizer requirement might be higher during the transition period from TT to ZT while the soil is rebuilding its organic matter[23]. Also, the net economic returns to farmers from producing a crop under ZT was positive during the 1990s and 2000s.

In addition to its impacts on production factors, the adoption of CT (which stimulated broader use of crop rotations) replaced, to a large degree, the area under summerfallow with canola and pulse crops. Fig. 6 shows that the area under summerfallow decreased from 7.8 Mha in 1991 to 2.05 Mha in 2011, and the area sown to canola and pulses increased from 3.1 Mha and 0.5 Mha in 1991 to 7.7 Mha and 2.1 Mha in 2011, respectively. Fig. 6 also shows that, during and after the 1990s, the total area sown to wheat (a historically dominant crop on the Prairies) decreased, and alternative crops, especially canola, increased. In 2011, for the first time on record, the area sown to canola (7.7 Mha) surpassed that of spring wheat (6.7) on the Prairies (Statistics Canada, 2011). Smith et al. (2001) indicated that the main reason for the change in the Prairie cropping patterns was the high prices of canola and pulse crops relative to the price of wheat. The use of crop rotations contributed to higher and more diversified sources of farm income by providing farmers with the opportunity of using less summerfallow and keeping fields under continuous crop production. Crop rotations also reduced the incidence of diseases and helped to control weeds.

Moreover, including pulse crops in rotation with cereals provided farmers with additional benefits by reducing the costs of nitrogen (N) fertilizer in the year of growing the pulse crop and in the subsequent year of growing the grain crop (Grant et al., 2002; Zentner et al., 2002). Pulses reduce fertilizer N requirements because of the nitrogen-fixing symbiotic bacteria in root nodules that are able to fix atmospheric N in a form that plants can use (Zentner et al., 2002). On the Prairies, nitrogen is the most important nutrient for crop growth and a major concern with regard to environmental sustainability ($NO_3$ leaching can reduce ground water quality and $N_2O$ emissions can increase the GHG effect and global warming) (Zentner et al., 2002). In addition, the pulse crop increases soil available N and, increases grain protein of wheat thereby increasing its value (Zentner et al., 2002).

The major concerns with the adoption of conservation tillage systems are the shifts in weed species and the evolution of weed populations resistant to herbicides. Some winter annual, biennial, and perennial weeds may increase under CT (Blackshaw, 2005; Derksen et al., 2002; Buhler, 1995), although Blackshaw et al. (2005a, 2005b) indicated that the use of integrated weed management (IWM) systems could reduce weed densities under CT. The authors found that IWM systems that include crop rotation, seeding date (i. e., early spring), seeding rate (i. e., 100% or 150% recommended), fertilizer application (i. e., fall or spring), and in-crop herbicide rate (i. e., 50% or 100% of recommended), have the potential to lessen weed populations and thus, to reduce the reliance on herbicide methods. The reduction in herbicide use reduces problems of herbicide-resistant weeds, the potential for injury to rotational crops from herbicide carryover, and public concerns regarding the environmental/health effects of pesticides. The economic analysis of IWM systems showed that the use of these systems under CT is profitable (Smith et al., 2006; Upadhyay et al., 2006).

(b) *Environmental Impacts*: The increased use of CT contributed to the reduction of all forms of land degradation on the Canadian Prairies. Figures 7, 8 and 9 show the improvement in soil quality as a result of the use of CT systems.

Fig. 7 represents the percentage of cropland area that falls into five soil erosion risk classes measured by the rate of soil loss due to the combined effects of water, wind and tillage erosion (AAFC, 2010)[24]. Between 1991 and 2006, the percentage of cropland area in the Very Low soil erosion risk class in Alberta, Saskatchewan, and Manitoba increased from, 63%, 48%, and 63% to 87%, 87%, and 79%, respectively. During this period, the prairies' cropland area in the Moderate, High, and Very High soil erosion risk classes decreased, on average, by

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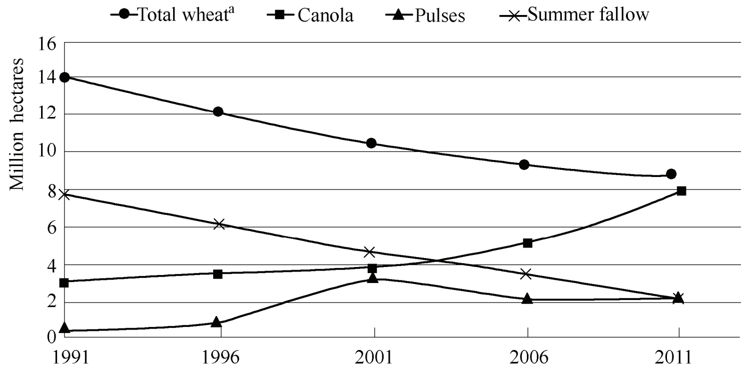
22 Awada (2012) and Nagy (1997) compared the purchase price of equipment under TT and ZT system and found that although the purchase price of seeding equipment under ZT system (i. e., air-seeder) was higher than under TT system (i. e., press drill) , eliminating the need for tillage equipment under ZT system reduced machinery total purchase price.

23 Tillage breaks up organic particles, thus increasing soil nitrogen (N) mineralization but decreasing soil organic matter (SOM) level which is the source of mineralizable N. CT maintains and increases SOM level but requires fertilizer N to start building this level. Therefore, it might be required to increase fertilizer N applications during the transition period (3 to 4 years) from TT to CT to rebuild a targeted SOM level (Montana State University, Extension, 2008).

24 The AAFC (2010) uses the SoilERI to estimate the risk of soil erosion at the Soil Landscape of Canada (SLC) polygon scale. The risk of soil erosion is measured by the rate of soil loss and reported into five classes: Very Low is when an area loses less than 6 t $ha^{-1}$ $yr^{-1}$, Low loses 6 to 11 t $ha^{-1}$ $yr^{-1}$, Moderate loses 11 to 22 t $ha^{-1}$ $yr^{-1}$, High loses 22 to 33 t $ha^{-1}$ $yr^{-1}$, and Very High loses more than 33 t $ha^{-1}$ $yr^{-1}$.

about 12%. The reduction in tillage erosion risk exceeded that of wind and water erosion (AAFC, 2010).




Statistics Canada, Census of Agriculture 1991−2011

[a]Total wheat includes: spring wheat, winter wheat, and durum wheat

**Fig. 6 Trends in agricultural land use on the Canadian Prairies 1991−2011**

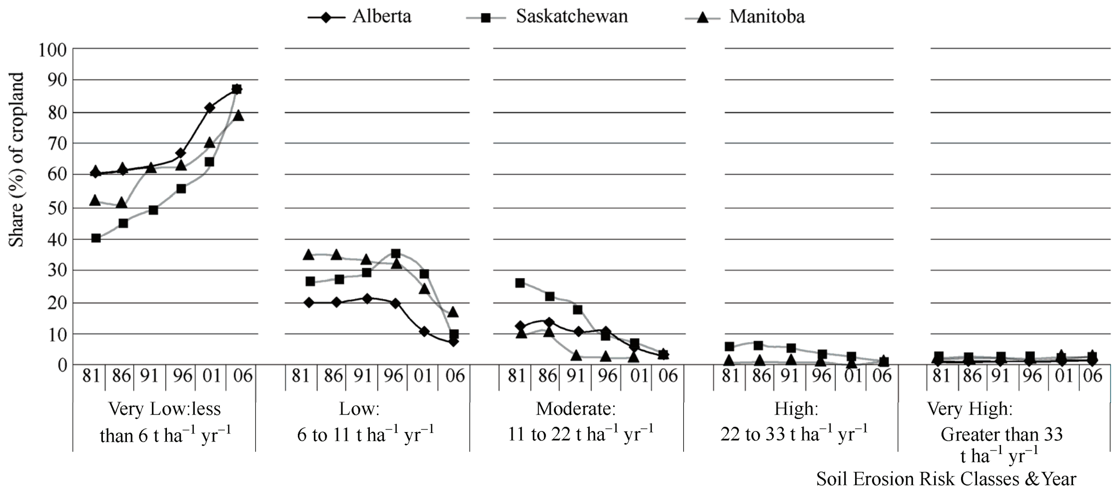



**Fig. 7 Soil erosion risk on the Canadian Prairies (1981-2006)**
**Source: Figure based on data analysis by Agriculture and Agri-Food Canada (2010).**

Fig. 8 represents the percentage of cropland area that falls into five soil organic carbon (SOC) change classes[25]. In 2006, 28%, 69% and 31% of the cropland areas in Alberta, Saskatchewan, and Manitoba were in the Large Increase SOC class, respectively. This is a significant improvement over 1981 when only 1%, 0, and 12% of these areas were in this class.

Fig. 9 represents the percentage of cropland area that falls into five soil salinization risk classes[26]. Between 1991 and 2006, the percentage of cropland area in the Very Low soil salinity risk class in Alberta, Saskatchewan, and Manitoba increased by around 5%, 4%, and 20%, respectively. During this period, the prairies' cropland areas in the Moderate, High, and Very High risk of salinization classes decreased on average by around 5%.

The improvement in soil quality not only enhances crop productivity, but also increases wildlife habitat ［Lindwall and Sonntag (Eds.), 2010; Best, 1986; Warburton and Klimstra, 1984; Cowan, 1982］. Warburton and Klimstra (1984) found evidence that CT provides better habitat that supports more abundant and sustainable wildlife populations than TT. The authors indicated that crop residue retention and reduced tillage operations

[25] The AAFC (2010) uses the Century model ［National Renewable Energy Laboratory (NREL) , 2007］ to estimate the rate of change in the soil organic carbon (SOC) in Canadian agricultural soils as a result of the change in management practices since 1951. The percentage of cropland falls into five SOC change classes expressed in kg per hectare per year. The five classes are Large Increase gains more than 90 kg $ha^{-1}$ $yr^{-1}$, Moderate Increase gains 25 to 90 kg $ha^{-1}$ $yr^{-1}$, Negligible Increase changes by 25 to −25 kg $ha^{-1}$ $yr^{-1}$, Moderate Decrease loses −25 to −90 kg $ha^{-1}$ $yr^{-1}$, and Large Decrease loses more than −90 kg $ha^{-1}$ $yr^{-1}$.

[26] The AAFC (2010) uses a unit-less Salinity Risk Index (SRI) that contains weightings for factors influencing the salinization process.

increase habitat complexity and thus, improve benthic invertebrate and small mammal communities.

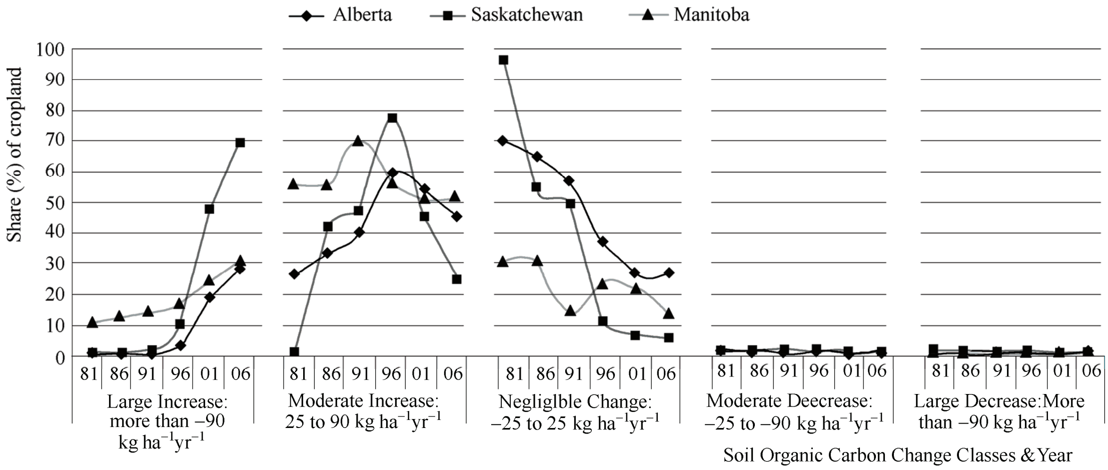



**Fig. 8 Soil organic carbon change on the Canadian Prairies (1981−2006)**

**Source: Figure based on data analysis by Agriculture and Agri-Food Canada (2010).**

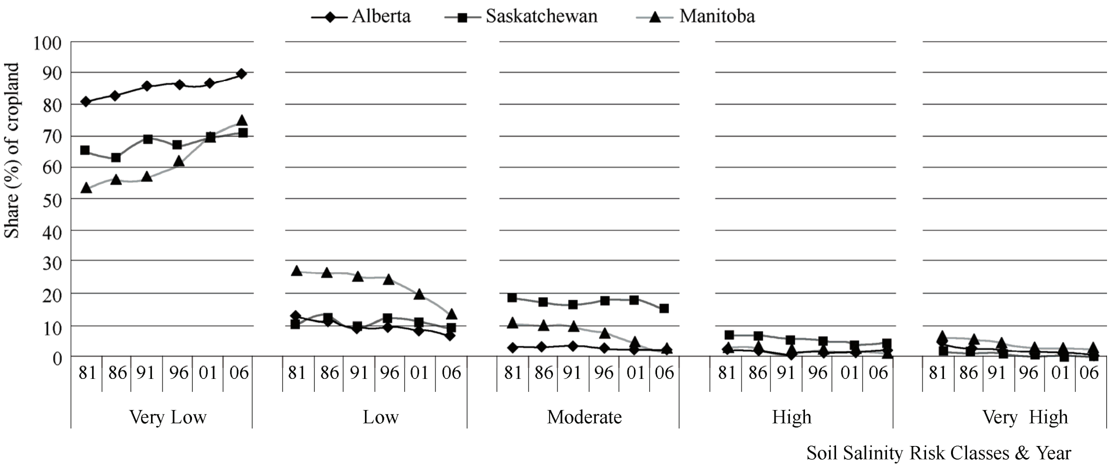



**Fig. 9 Soil Salinization Risk on the Canadian Prairies (1981−2006)**

**Source: Figure based on data analysis by Agriculture and Agri-Food Canada (2010).**

In addition to its impacts on soil quality, conservation tillage has other environmental benefits such as carbon sequestration and reducing carbon dioxide emitted during fossil-fuel combustion by farm equipment. Conservation tillage systems improve carbon sequestration by storing the organic matter in the soil. When soil is tilled, the top layers are turned over, air mixes in, and soil microbial activity increases over baseline levels. As a result, soil organic matter is broken down rapidly, and carbon is lost from the soil into the atmosphere. Moreover, since traditional tillage requires more machinery passes than conservation tillage, emissions of carbon dioxide from energy use and fossil fuel consumption are higher than under conservation tillage［AAFC, 2010; U. S. Department of Agriculture (USDA), 2001］.

In Canada, net agricultural greenhouse gas (GHG) emissions (excluding fossil-fuel emissions) decreased from 45.3 Mt $CO_{2e}$ in 1981 to 44.8 Mt $CO_{2e}$ in 2006 (AAFC, 2010). GHGs emitted from agriculture are nitrous oxide $N_2O$ and methane $CH_4$, while carbon dioxide $CO_2$ can be either emitted or absorbed (AAFC, 2010). This decline in GHG has occurred despite an increase in $CH_4$ emission from 21.7 Mt $CO_{2e}$ in 1981 to 27.9 Mt $CO_{2e}$ in 2006; and an increase in $N_2O$ emission from 22.6 Mt $CO_{2e}$ in 1981 to 28.7 Mt $CO_{2e}$ in 2006. The increase in $CH_4$ and $N_2O$ emissions are mainly due to an increased animal population during this period. The 1.1% reduction in net agricultural GHG emissions in Canada occurred as the soil changed from a 1Mt $CO_{2e}$ source of emissions in 1981 to an 11.7 Mt $CO_{2e}$ sink of emissions in 2006, thus offsetting the increased $CH_4$ and $N_2O$ emissions. The change in soil $CO_{2e}$ was mainly due to the widespread adoption of conservation tillage technology on the Prairies, particularly in Saskatchewan (AAFC, 2010). The contribution of conservation tillage in the reduction of GHG emissions helps Canada meet its commitment under the Copenhagen Accord to reduce GHG emissions by 17% from 2005 levels by 2020 (Environment Canada, 2012)[27].

## 5 Conclusion

For a number of economic, technical, political and social reasons, traditional tillage (TT) remained the dominant method of land cultivation on the Canadian Prairies from the time of European settlement until the last decades of the 20th century. The result of practicing TT was loss of soil resilience that led to soil degradation on the Prairies. Beginning in the 1970s and 1980s, however, the alternative to TT—conservation tillage (CT)—took shape on the Prairies after the introduction of the broad-spectrum herbicide glyphosate, advances in crop breeding, and development of commercial no-till drills. Between the 1990s and 2010s, factors such as the advances in CT equipment, along with the decrease in the price of glyphosate, lower interest rates on machinery investment, the increase in the price of fuel, and increased public awareness of the negative impact of TT practices stimulated greater adoption of CT systems on the Canadian Prairies.

The widespread adoption of CT systems in the last 30 years led to a significant agricultural transformation of the Prairie landscape. The transformation embodied new knowledge and understanding of the biophysical environment, and new ways of managing land. The result is a new, more sustainable agricultural production system, replacing the traditional tillage culture with one offering superior economic and environmental advantages. These included economic advantages such as increased cropping intensity and diversity, coupled with reduced operating costs in machinery operations, fuel, and labour. Environmental advantages include improvement in soil health and resilience, soil physical, chemical and biological properties, restoration and enhancement of wildlife habitat, and reduction in agricultural greenhouse gases (GHGs) emissions.

As noted in section 2, agricultural innovation for sustainable development is necessary to satisfy human needs for a growing population. The continued slow adoption of sustainable practices, in both developed and developing countries, call for continued innovation and research to better understand and overcome local constraints to improved, more sustainable practices. This paper suggests that the acceptance and expansion of conservation tillage on the Canadian Prairies resulted from the confluence of superior economic and market opportunities, enhanced and targeted research programs, and expanded social and information networks involving innovative farmers, producer self-help groups, and enabling government policies.

Attractive economic conditions associated with a variety of crop diversification options and lower production costs helped Canadian producers using CT/ZT with opportunities to gain a competitive advantage in local and international markets. Often, consumers will pay a premium for food and fibre products produced in a more sustainable manner. Canada is one of the few countries where soil carbon levels are increasing as a consequence of the widespread adoption of CT/ZT, and this provides producers with the opportunities to gain a competitive advantage by having their products' carbon footprint certified (labeled), promoting a "green" label or Canada brand. In addition, the reduction of GHG emissions will help Canada meet its commitment under the Copenhagen Accord to reduce GHG emissions by 17% from 2005 levels by 2020.

The future vitality of conservation tillage on the Canadian Prairies will depend on the ability to solve problems of continual evolution of agro-ecological issues. These efforts must be supported with continued research and innovation on integrated multi-tactic weed management, crop rotations, cultivar selection, pest and disease suppression, and nutrient management to enhance the sustainability of conservation tillage systems.

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