Dispelling Myths and Making Progress with No-Till on the Canadian Prairies

Guy P. Lafond and George C. Clayton
Agriculture and Agri-Food Canada

1.0 Introduction

The current understanding is that 99% of food consumed by humans comes from the land (Pimental and Pimental 2000). On a global basis, there are 4.334 billion hectares of land available for annual cropping (Anonymous 2009b) but 1.966 billion hectares or 45% of arable soils worldwide are affected by one form or another of soil degradation (Lal 2007). It has also been estimated that every year, 2–12 million hectares or 0.3–0.8% of the world's arable land is rendered unsuitable for agricultural production from excessive soil degradation (den Biggelaar et al. 2004a). Wind and water erosion accounts for 84% of this degradation (den Biggelaar et al., 2004b). Given that Manitoba has 4.2 million hectares of arable land, global annual soil degradation is equivalent to 0.47 to 2.9 times the cultivated area of Manitoba.

For the Canadian prairies, Mitchell et al. (1944) reported that uncultivated native prairie soils contained from 0.2 to 0.7 percent nitrogen and that by the 1940s, barely 60 years after the first plough turned over the virgin prairie sod 15 to 40 percent of it had been lost. This trend continued so that, by the 1980s, most prairie soils had lost more than 40 percent of their initial organic nitrogen content. Thus good management to protect the soil against further degradation is critical to meet the world's future needs for food and fibre (den Biggelaar at al., 2004b) and possibly fuel to meet increasing energy needs.

Another form of soil degradation is arable land lost to urbanization. In 2008, the world reached an invisible but important milestone. More that 50% of the world's population now live in urban areas (Parsons 2008). In Canada, between 1971 and 2001, 1.2 million hectares of agricultural land was consumed for urban uses and 18% of Ontario's best Class 1 farmland is now urban (Hofmann 2001). Loss of land to urbanization also has important effects on watersheds, aquifers and micro-climates around large urban areas.

It is imperative that we do everything possible on a local, national and international level to sustain and enhance the global soil resource and that the knowledge and expertise gained on the Canadian prairies be shared freely with the rest of the world to ensure protection of the global soil resource.

Given that the major causes of soil degradation are wind and water erosion, it has long been known that the most efficient way to reduce or arrest this undesirable phenomenon is to work with surface residues and standing stubble. In order to attain this desirable state requires the reduction or elimination of tillage, the adoption of continuous cropping practices, elimination of summer fallow practices, proper crop fertility, appropriate pest management practices, appropriate seeding equipment and crop diversity. These key factors have been well investigated and are the foundation for conservation agriculture on the prairies and else where (Fowler et al. 1983; Hass 1984; Smika and Unger 1986; Hay 1986; Holm et al. 1990; Lafond and Fowler 1990).

At the recent Fourth World Congress on Conservation Agriculture (CA) in New Delhi on February 5, 2009, Shivaji Pandey, Director of FAO's Plant Production and Protection Division, endorsed conservation agriculture as the key step to meeting the long-term global demand for food and feed. CA is defined as a farming system that does away with regular plowing and tillage and promotes permanent soil cover and diversified crop rotations to ensure optimal soil health and productivity.

2.0. Some Key Historical Agricultural Developments Leading to Conservation Agriculture on the Prairies.

The early establishment of Experimental Farms across Canada after 1886 provided for a unique opportunity to document the impact of agricultural practices on prairie soils. As stated by Janzen (2001), "When the ploughs began to invert the prairie sod, scientists were already there to record the effects. And from the onset, preserving the soils was a priority." Over the next 20 years, extensive and detailed measurements of soil organic matter led Shutt (1905 in Janzen 2001) to report on its rapid decline and raise concerns about the 'permanence', now referred to as 'sustainability' of agriculture on the Prairies.

During the last 80 year period, a series of technological developments occurred which over time, paved the way to the development and widespread adoption of conservation agriculture as we know it today on the Canadian prairies.

2.1. Recognized importance and benefits of surface residues and standing stubble

In the mid to late 1930s, studies conclusively showed that maintaining crop residues on the soil surface could improve water infiltration, reduce evaporation losses, reduce surface runoff, reduce wind and water erosion and conserve more water because of the increased ability to trap and hold snow (Smika and Unger 1986).

2.2. Introduction of one-way disks and discers for seeding

An important technological development was the introduction of one-way discs in the 1930's. These implements were heavy enough to do primary tillage and less aggressive than the conventional moldborg plows and left more residues on the soil surface providing for protection against wind erosion. These discs were ideal as a spring pre-seeding tillage implement. Later, seed boxes were installed on the one-way discs such that planting could be done at the same time as the primary tillage operation and even providing the opportunity to seed into standing stubble. This provided an opportunity to extend the cropping systems from a fallow-cereal to a fallow-cereal-cereal rotation thereby reducing the intensity of summerfallow, a major contributor to soil degradation. Over time the one-way discs evolved into discers equipped with seed and fertilizer boxes. Discers allowed for a high amount of seedbed utilization reducing the risks of seed-placed fertilizers. In the drier areas of the prairies, discers were essentially used as high disturbance seeding systems.

2.3. Introduction of the Noble blade, mulch tillage and air seeders

In the 1930s, the practice of strip farming was being adopted as a means to address wind erosion. Charles Noble realized that the real solution to wind erosion was to adopt stubble mulch systems (Anonymous 2009c). His endeavors led to the creation of the Noble blade. In the dry areas of the prairies, this allowed for the continued practice of summer fallow while greatly reducing the risks of wind erosion. One can argue that this technology led to the development of heavy duty cultivators, also commonly referred to as deep tillers. In turn, these heavy duty cultivators were later adapted with air delivery systems and became known as airseeders. These airseeders represented the start of what we call “high disturbance direct seeding systems” and provided better penetration, residue clearance and more overall cropping flexibility than discers.

2.4. Introduction of selective and non-selective herbicides

The introduction of the selective broadleaf herbicides 2,4-D in 1947 and MCPA in 1953 represented a huge leap forward. This was followed with the introduction of the selective wild oat herbicides diallate and later triallate in the early 1960s (Timmons 2005; Appleby 2005). These introductions allowed for more continuous cropping, especially in the moister areas of the prairies.

The 1970s and 1980s were characterized by the introduction of a large number of non-selective herbicides for covering cereal, oilseed and pulse crops stimulating crop diversification and more adoption of continuous cropping (Appleby 2005). This allowed for more opportunity to continuous crop in the drier areas of the prairies.

In 1962 and 1966, diquat and paraquat were registered as fast-acting, non-selective, non-translocated, non-residual herbicides (Timmons 2005). The introduction of these herbicides allowed for more investigations into the concept of no-till production systems.

The introduction of the non-selective herbicide glyphosate in 1971 represented a key technology for the detailed investigation of no-till or conservation agriculture production systems worldwide (Appleby 2005). However, it wasn’t until the early to mid 1980s that glyphosate became associated with no-till systems.

2.5 Introduction of winter wheat into cropping systems.

The finding that winter wheat could over-winter and avoid winter kill when seeded into standing stubble because of the insulating effect of the snow trapped by the standing stubble provided new cropping opportunities and some important agronomic benefits (Fowler et al. 1983). This provided new opportunities to continuous cropping, especially in the drier areas of the Canadian prairies. Any producer seeding winter wheat needed to use no-till production or “stubbled-in” practices thereby initiating them to no-till production concepts.

2.6 Nitrogen Management – The in-soil banding concept.

With the advent of inorganic fertilizers came the issue of placement, timing, form and rate. The first inorganic fertilizer used on the prairies in the 1950’s was mono-ammonium phosphate (MAP) fertilizer with the analysis of 11-48-00 which lent itself well to being applied with the seed. At the same time, ammonium nitrate (AN) fertilizer (34-00-00) was also available. AN was mixed with MAP creating a heterogeneous blend with an analysis of 23-23-00. This fertilizer blend (23-23-00) could be applied with the seed but with more restrictions depending on the rates because the presence of ammonium nitrate increased the potential for seedling toxicity. With urea, some of it was blended with MAP to create a blended product with an analysis of 28-28-00. The presence of urea in the blend resulted in even more restrictions for seed-placed applications because of enhanced potential for toxicity to seedlings than the previous blend with ammonium nitrate (23-23-00).

Other than limited amounts of urea placed with the seed, the majority of it was broadcast on the soil surface either in the fall or in the spring prior to seeding. This placement method quickly exposed problems that had not been observed with AN. The nitrogen responses were found to be highly variable due to volatilization losses. This led the WESTCO fertilizer company in the mid-70s to investigate ways to circumvent this problem (Harapiak 1990; Harapiak et al. 1993). They discovered that if the urea fertilizer was placed in the soil as bands, these limitations could be rectified.

One can therefore argue that the concept of in-soil fertilizer bands paved the way for further improvements in air seeding technology leading to the development of the concept of the one-pass seeding and fertilizing system involving placement of the fertilizer to the side and below the seed row or else mid-row banded between every second seed row.

3.0 Myths about No-Till Dispelled

3.1 Long-term Health of Prairie Soils

It was a myth to think that we could keep on managing our soils the way we did and expect them to keep producing like they had in the past. We were blind to the devastating effects of wind and water erosion and the degradation from many of the production practices in use (Shutt 1905 in Janzen 2001; Mitchell et al. 1944).

The facts are that in order to sustain the prairie soil resource, a combination of no-till or conservation agriculture with proper nutrient management, continuous cropping and crop diversification is required. The good news is that these practices can actually improve the overall productivity of prairie soils (McConkey et al. 2003; Lafond et al. 2008).

3.2 Impact of No-Till on Soil Temperature

One of the first concerns expressed by producers with respect to no-till was the potential effects of lower soil temperatures on germination and emergence when residues are left on the soil surface. Although these lower temperatures were indeed verified under no-till (Gauer et al. 1982), results from field studies from various locations in Western Canada did not reveal negative effects on crop emergence (Lafond et al. 1992; Arshad et al. 1999 and 2003). This is because soil temperature is only one factor influencing seed germination and crop emergence. Soil moisture and depth of seeding are also important factors and when all three are considered, the potential negative effects of no-till on crop germination and emergence did not materialize.

3.3 Crop Residue Decomposition and Residue Accumulations under No-Till.

Another common concern expressed by producers in the early adoption phases of no-till continuous cropping production systems was the potential for residue accumulation at the soil surface. The belief was that crop residues at the soil surface would decompose very slowly resulting in a rapid build-up leading to difficulties with seeding and more problems with cool surface soil temperatures hence the need for tillage.

Research showed that the nitrogen content of residues, air temperature and the location of the residues were the important factors determining the rate of residue decomposition (Janzen and Kucey 1988; Douglas and Rickman 1992). Residues at the soil surface would decompose at about two-third the rate of buried residues. This means that decomposition was rapid enough to prevent large accumulations of crop residues on the soil surface over time with no-till. When the effects of crop rotation are included i.e. different amounts and quality of crop residues, this effect was mitigated even further.

3.4. Nitrogen Fertilizer Management under No-till –One Pass Seeding and Fertilizing System.

Nitrogen fertilizer management involves four components, form, timing, placement and rate. In the initial stages of no-till, nitrogen fertilizer management proved to be a major challenge. The two placement options were seed-placed or surface broadcast and the timing for surface broadcast was either, late fall, early spring or after seeding. There were also severe limits as to how much nitrogen could be applied with the seed, depending on the fertilizer form and the amount of seed-bed utilization. It wasn't till the late 70's and early 80's that the technology for in-soil banding became possible on a commercial scale and this could be done either in late fall or prior to seeding allowing ammonium based fertilizers like urea and anhydrous ammonia to be used effectively (Harapiak 1990). Research conclusively showed that losses from volatilization with urea could be almost eliminated if it was placed in the soil and covered properly (Harapiak et al.1993; Malhi et al. 2001).

Research under no-till conditions showed that it was possible to apply urea and anhydrous ammonia as a side-banded treatment in a one-pass seeding and fertilizing no-till system using a ConservaPak side-banding system as the test opener (Johnston et al. 1997). This study destroyed the myth that it was not possible to safely apply anhydrous ammonia at time of seeding and to apply all of the crops nitrogen fertilizer requirements using either urea or anhydrous ammonia to meet crop needs in a one-pass seeding and fertilizer no-till system. This concept was also verified with other third-party bolt-on openers capable of side-banding using urea during the seeding operation (Johnston et al. 2001). Some producers also use some of these openers to also apply anhydrous ammonia at time of seeding.

The one-pass seeding and fertilizing no-till system is now regarded as a highly efficient way of managing nitrogen fertilizers for achieving high nitrogen use efficiencies (Malhi et al. 2001; Grant et al. 2002) and also recognized as a best management practice for minimizing the potential for nitrous oxide emissions and other nitrogen losses such as from leaching and denitrification (Lemke and Farrell 2008).

3.5 No-Till and the Long-Term Impact on Weed Densities and Weed Community Shifts

A legitimate concern expressed with early adopters of no-till was the long-term impact of no-till on weed densities and the potential for major shifts in weed community composition towards more perennial type species and from selection pressure resulting from the continued use of particular herbicides (Lafond and Derksen 1996; Derksen et al.

2002). More recently, the no-till producers have expressed concern over the increase in weeds becoming resistant to herbicides. Weed control under no-till is dependent entirely on herbicides and crop management practices.

The myth that no-till producers would have to resort to tillage to stay on top of their weed problems has not yet materialized. Some producers in Saskatchewan now have 30 years of no-till on some of their fields and they have yet to resort to tillage because of an insurmountable weed problem. In general, lower weed populations were reported by farmers that practice no-till in western Canada, which is indicative of lower weed seed banks (Blackshaw et al. 2008). It should be noted that changes in weed communities occur slowly and that environment followed by crop management practices are the dominant factors influencing weed densities and communities, not the presence or absence of tillage.

3.6 No-till and the Long-Term Impact on Plant Diseases.

Another frequent concern about no-till systems was the potential for increased leaf and root diseases because of the residues left at the soil surface. However the effects of tillage systems on the incidence and severity of plant disease are small relative to the effects of environment and crop rotation (Bailey et al. 2001; Turkington et al. 2006). Nonetheless, no-till was shown to reduce the severity of common root rot in cereals. (Bailey et al. 2001). No-till reduces many crop diseases because of their direct and beneficial effects on soil biology (Krupinski et al. 2002). A healthy soil with diverse and balanced populations of soil micro-organisms will provide substantial competition against root pathogens as these often use the same organic carbon substrate. The myth about increased root and leaf disease pressure with no-till has not materialized.

3.7 Negative Impact of No-Till on Soil Physical, Chemical and Biological Properties.

A frequent concern with no-till was the potential negative impact on soil physical properties. Concerns about increased soil bulk densities resulting in reduced root penetration from wheel traffic and lack of tillage were often mentioned. This would lead to reduced crop yields over time thereby affecting long-term soil biological and chemical properties and overall soil productivity.

3.7.1 Soil Physical Properties

Concerns about the long-term negative effects of no-till on soil physical properties did not materialize. In fact, producers have observed that over time, no-till has reduced the draft of seeding implements and the carrying capacity of the soil has increased.

3.7.2 Soil Chemical Properties

The end result of current investigations is that the adoption of no-till combined with proper crop management will not only sustain soil quality but can actually improve the long-term quality and productivity of prairie soils.

3.7.3 Soil Biological Properties

Numerous no-till studies have shown that soil biology can actually be increased with no-till. Leaving crop residues on the soil surface will not lead to a reduction in nutrient cycling. In fact there are increased benefits associated with no-till when crop residues are left at the soil surface.

4.0 Future of No-Till on the Prairies

4.1 Enhanced Water and Nitrogen Management

Water and nitrogen are the most limiting factors to crop production on the Canadian prairies. Research has now shown that in semi-arid areas, seeding crops into tall stubble can improve grain yields through increases in water use efficiency. This has been demonstrated for spring wheat (Cutforth et al. 1997), field pea, lentil and chickpea (Cutforth et al.2002) and canola (Cutforth et al. 2006) in the semi-arid Prairies with reported annual increases in yield on the order of 10-12%.

Given the proven improvements in water use efficiency with tall stubble and the associated higher grain yields, the strategy going into the future is too develop the necessary technology in order for no-till producers to seed between the rows and capture the full benefits of tall stubble. Technology is required to allow equipment to seed between the rows. A SmartHitch® has been introduced to allow for seeding between the rows (www.seedmaster.ca). This type of innovation needs to be supported by basic agronomic research that studies the effects of wide row spacing beyond 30 cm to make it easier for technology to assist with seeding between stubble rows.

4.2 Fine-Tuning Nitrogen Fertilizer Management

Of the four components making up nitrogen fertilizer management (timing, placement, form and rate), arriving at the correct rate is the most challenging aspect to nitrogen management. From an environmental perspective, nitrogen fertilizer is not a benign product due to its potential for leaching into ground water, contamination of surface waters and nitrous oxide emissions (Lemke and Farrell 2008).

In recent years, optical sensors have been introduced that allow for greater precision in arriving at a rate of nitrogen that matches the needs of the crops to the field and growing season conditions and capable of addressing spatial variability at a field level (Raun et al. 2002). More recently, crop specific algorithms for these optical sensors have been developed and tested for canola (Holzapfel 2007). Algorithms are being developed and tested for spring wheat, winter wheat, durum, oat and malting barley (Holzapfel et al. 2009). The results to date are very promising. A strategy is required to bring this technology to the farm gate.

4.3 Robotic Applications for Soil and Crop Management

Prairie agriculture production systems are highly dependent on non-renewable sources of energy. Even though fuel use is reduced when adopting no-till production systems, energy is required to produce herbicides which no-till production systems depend on (Zentner et al. 2004). It has been demonstrated that if reliable estimates of weed densities could be determined spatially in a field, it would be possible to reduce herbicide use on average by 54% with greater reductions depending on the crop and weeds (Timmerman Roland Gerhards and Kuhbauch 2003). These findings have important implications from an energy and environmental loading perspective. The natural solution to these problems is the development of robotic applications. Robotic applications could be extended to soil measurements such as soil moisture content, penetration resistance and crop applications such as plant health with the use of specialized fluorescence sensors.

4.4 Inclusion of More Winter Crops into Prairie Production Systems

The inclusion of winter cereals (wheat, rye and triticale) in prairie cropping systems provides many important benefits such as keeping the soil profile virtually free of nitrate thereby eliminating the potential for nitrogen losses through leaching and denitrification and providing higher nitrogen use efficiencies in certain years (Grant and Lafond 1994; Campbell et al. 2006). Adding crops with winter habits also applies different selection pressure on weeds such as wild oat (*Avena fatua*) and green foxtail (*Setaria viridis*) providing other means of controlling these weeds that have become resistant to Group 1 and Group 2 herbicides. Depending the gorwing conditions and the year, they can also escape certain plant diseases like Fusarium head blight and insect pests like the orange blossom wheat midge due to their growth habits.

The potential of winter cereals in cropping systems needs to be exploited more thoroughly in prairie cropping systems.

5.0 Conclusion

Given the overall high level of success of no-till and cropping systems on the Canadian Prairies, the question then becomes, where do we go from here? The obvious one, but not always recognized is to ensure that the public funding commitment to the current efforts is maintained. The most dangerous path to take would be to assume that we have an agricultural sector that no longer needs public support. This could only result in a slow deterioration of the industry and past efforts and the inability to respond quickly to future unforeseen problems. It should be remembered that the no-till revolution on the Prairies was based on the recognition that we needed to protect our soil resource. The economic benefits were not evident at the time. It was difficult to see how private industry could benefit from this and yet it was very important for Canada, hence the need to maintain public good research. The biggest on-going challenge for soil and crop management research and development will always remain, how will we recognize the next no-till like revolution? Where will the vision and leadership come from? Who will decide whether a new research path is required with assistance from public funding and how will we choose? Where will the funding come from? Will it have to take 80 years to recognize the problem as was the case for soil degradation and 30 years to develop the solution which culminated in the development and adoption of no-till? How can we structure our public research institutions in such a way as to recognize these over-arching possibilities?

6.0 References

Anonymous 2009b. The World Factbook, [Online] Available: https://www.cia.gov/library/publications/the-world-factbook/geos/xx.html [2009 Feb 3]

Anonymous 2009c. The Noble Blade. [Online] Available: http://www.abheritage.ca/abinvents/inventions/inv_ag_noble_blade.htm [2009 Feb 5]

Appleby, A.P. 2005. A history of weed control in the United States and Canada – a sequel. *Weed Sci*. 53:762-768.

Arshad, M.A. Azooz, R.H. 2003. In-row residue management effects on seed-zone temperature, moisture and early growth of barley and canola in a cold semi-arid region in North Western Canada.
Am. J. of Alternative Agriculture. 18:129-136.

Arshad, M.A., Franzluebbers and A.J., Azooz, R.H. 1999. Components of surface soil structure under conventional and no tillage in northwestern Canada. Soil and Tillage Research, 53: 41-47.

Bailey, K.L., Gossen, B.D., Lafond, G.P., Watson, P.R., Derksen, D.A., 2001. Effect of tillage and crop rotation on root and foliar diseases of wheat and pea in Saskatchewan from 1991 to 1998: Univariate and multivariate analyses. *Can. J. Plant Sci.* 81, 789-803.

Blackshaw R. E., K. N. Harker, J. T. O'Donovan, H. J. Beckie, and E. G. Smith. 2008. Ongoing development of integrated weed management systems on the Canadian Prairies. Weed Sci. 56:146-150.

Campbell, C. A., Selles, F., Zentner, R. P., De Jong, R., Lemke, R. and Hamel, C. 2006. Nitrate leaching in the semiarid prairie: Effect of cropping frequency, crop type, and fertilizer after 37 years. Can. J. Soil Sci. 86: 701–710.

Cutforth, H.W., Angadi, S.V. and McConkey, B.G. 2006. Stubble management and microclimate, yield and water use efficiency of canola grown in the semi-arid Canadian prairie. Can. J. Plant Sci. 86:99–107.

Cutforth, H.W. and McConkey, B.G. 1997. Stubble height effects on microclimate, yield and water use efficiency of spring wheat grown in a semi-arid climate on the Canadian Prairies. Can. J. Plant Sci. 77:359–366.

Cutforth, H.W., McConkey, B.G., Ulrich, D., Miller, P.R. and Angadi, S.V., 2002. Yield and water use efficiency of pulses seeded directly into standing stubble in the semiarid Canadian Prairie. Can. J. Plant Sci. 82, 681-686.

den Biggelaar, C., Lal R., Wiebe, K., Breneman, V., 2004a. The Global Impact of Soil Erosion on Productivity I: Absolute and Relative Erosion-Induced Yield Losses. *Adv Agron.* 81, 1–48.

den Biggelaar, C., Lal R., Wiebe, K., Breneman V., Reich P., 2004b. The Global Impact of Soil Erosion on Productivity II: Effects on Crop Yields and Production Over Time. *Adv. Agro*n 81, 49–95.

Derksen, D.A., Anderson, R.L., Blackshaw, R.E. and Maxwell, B. 2002. Weed Dynamics and Management Strategies for Cropping Systems in the Northern Great Plains. *Agron. J.* 94:174–185.

Douglas, C.L. Jr and Rickman, R.W. 1992. Estimating crop residue decomposition from air temperature, initial nitrogen content and residue placement. Soil Sci. Soc. Am. J. 56:272-278.

Fowler, D.B., Gusta, L.V., Slinkard, A.E. and Hobin, B.A. 1983. *New Frontiers in Winter Wheat Production*. Proceedings of the Western Canada Winter Wheat Conference. University of Saskatchewan, Saskatoon, SK. 437 pages.

Gauer, E. and Shaykewich, C.F. and Stobbe, E.H. 1982. Soil temperature and soil water under zero-tillage in Manitoba. Can. J. Soil Sci. 62:311-323.

Grant, C. A., Brown, K. R., Racz, G. J. and Bailey, L. D. 2002. Influence of source, timing and placement of nitrogen fertilization on seed yield and nitrogen accumulation in the seed of canola under reduced and conventional tillage management. Can. J. Plant Sci. 82: 629–638.

Grant, C.A. and Lafond, G.P. 1994. The effects of tillage systems and crop rotations on soil chemical properties of a black chernozemic soil. Can. J. Soil Sci. 74:301-306.

Harapiak, J. 1990. Air Seeders and Fertilizer Placement. Pages 75-82 *in* Holm, F.A., Hobin, B.A., and Reed, W.B. 1990. Air Seeding '90. Proceedings of the International Symposium on Pneumatic Seeding for Soil Conservation Systems in Dryland Areas. University of Saskatchewan, Saskatoon, SK. 194 pages.

Harapiak, J. T., Malhi, S. S., Campbell, C. A., and Nyborg, M. 1993. Fertilizer N application practices, p. 251-313, *In* D. A. Rennie, et al., eds. A Review of the Impact of Macronutrients on Crop Responses and Environmental Sustainability on the Canadian Prairies. Canadian Society of Soil Science.

Hass, G.1984. The Optimum Tillage Challenge. University of Saskatchewan Printing Services. Saskatoon, SK. 280 pages.

Hay, J. 1986. Proceedings of the Tillage and Soil Conservation Symposium. Indian Head Research Farm, Indian Head, SK. 180 pages.

Hofmann, N. 2001. Urban Consumption of Agricultural Farmland in Rural and Small Town Canada Analysis Bulletin Catalogue no. 21-006-XIE Vol. 3, No. 2 (September 2001). Statistics Canada. 13 pages

Holm, F.A., Hobin, B.A., and Reed, W.B. 1990. Air Seeding '90. Proceedings of the International Symposium on Pneumatic Seeding for Soil Conservation Systems in Dryland Areas. University of Saskatchewan, Saskatoon, SK. 194 pages.

Holzapfel, C. B. 2007. Estimating nitrogen fertilizer requirements of canola (*Brassica napus* L.) using sensor-based estimates of yield potential and crop response to nitrogen. M.Sc. Thesis, University of Manitoba, Winnipeg, MB. 286 pp. Online [available]: https://mspace.lib.umanitoba.ca/handle/1993/2996 [March 29 2008].

Holzapfel, C.B., Lafond, G.P., Bullock, P., May, W.E., and Omoth, C. 2009. In-Crop Variable Rate Nitrogen Applications – On-farm Research Results. Pages 45-57 in Feeding and Fuelling the World. Proceedings of the 21st Annual Conference and Trade Show of the Saskatchewan Soil Conservation Association. February 11&12, Saskatoon, SK. 127 pages.

Janzen, H.H. 2001. Soil Science on the Canadian Prairies – Peering into the future from a century ago. *Can. J. Soil Sci.* 81:489–503.

Janzen, H.H. and Kucey, R.M.N. 1988. C,N, and S mineralization of crop residues as influenced by crop species and nutrient regime. Plant and Soil 106:35-41.

Johnston, A.M., G.P. Lafond, J.T. Harapiak, and W.K. Head. 1997. No-till spring wheat and canola response to side banded anhydrous ammonia at seeding. J. Prod. Agric. 10: 452-458.

Johnston, A.M., Lafond G.P., Hultgreen, G.E. and Hnatowich, G.L. 2001. Spring wheat and canola response to nitrogen placement with no-till sideband openers. Can. J. Plant Sci. 81:191-198.

Krupinski, J. M., Bailey, K.L., McMullen, M.P., Gossen, B.D. and Turkington, K. 2002. Managing Plant Disease Risk in Diversified Cropping Systems. *Agronomy J.* 94: 198–209.

Lafond, G.P. and D.A. Derksen. 1996. The long term potential of conservation tillage on the Canadian prairies. Can. J. Plant Pathology 18:151–158.

Lafond, G.P. and Fowler, D.B. 1990. *Crop Management for Conservation*. Proceedings of the Soil Conservation Symposium. University of Saskatchewan, Saskatoon, SK. 297 pages.

Lafond, G.P., Loeppky, H. and Derksen, D.A. 1992. The effects of tillage systems and crop rotations on soil water conservation, seedling establishment and crop yield. Can. J. Plant Sci. 72:103-115.

Lafond, G.P., Walley, F., Schoenau, J., May, W.E., Holzapfel, C.B., McKell, J., and Halford, J. 2008. Long-term vs short-term conservation tillage. Pages 28-43 in Proceedings of the 20th Annual Meeting and Conference of the Saskatchewan Soil Conservation Association. Feb 12 &13, Regina SK. 185 pages.

Lal, R. 2007. Anthropogenic Influences on World Soils and Implications to Global Food Security. Adv. Agronomy 93, 69-93.

Lemke, R. and Farrell, R. 2008. Nitrous Oxide Emissions and Prairie Agriculture. Prairie Soils and Crops. 1:11-15

Malhi, S.S., Grant, C.A., Johnston, A.M., and Gill, K.S. 2001. Nitrogen fertilization management for no-till cereal production in the Canadian Great Plains: A review. *Soil & Tillage Res*. 60:101–122.

McConkey, B.G., Liang, B.C., Campbell, C.A., and Curtin, D., Moulin, A., Brandt, S.A., and Lafond, G.P. 2003. Crop Rotation and Tillage Impact on Carbon Sequestration in Canadian Prairie Soils. *Soil & Tillage Research* 74:81–90.

Mitchell, J., Moss, H.C and Clayton, J.S. 1944. Soil Survey Report #12. University of Saskatchewan. 259 pages.

O'Donovan, J.T., McAndrew, D.W., and Thomas, A.G. 1997. Tillage and nitrogen influence weed populations dynamics in barley (*Hordeum vulgare* L). *Weed Technol.* 11:502–509.

Parsons, G.F. 2008. Managing Change: Prospects, Opportunities and Issues in Saskatchewan's Agricultural Future. Pages 147-172 in Proceedings of the 20th Annual Meeting and Conference of the Saskatchewan Soil Conservation Association. Feb 12 &13, Regina SK. 185 pages.

Pimentel, D., Pimentel, M., 2000. Feeding the world=s population. Bioscience 50, 387.

Raun, W. R., Solie, J. B., Johnson, G. V., Stone, M. L., Mullen, R. W., Freeman, K. W., Thomason, W. E. and Lukina, E. V. 2002. Improving nitrogen use-efficiency in cereal grain production with optical sensing and variable rate application. Agron. J. 94: 815–820.

Smika, D.E. and Unger, P. W. 1986. Effects of surface residues on soil water storage. *Adv. Soil Sci*. 5:111–138.

Timmermann Roland Gerhards, C. and Kuhbauch, W. 2003. The economic impact of site-specific weed control. Precision Agriculutre 4: 249-260.

Timmons, F.L. 2005. A History of Weed Control in the United States and Canada. *Weed Sci.* 53:748–761.

Turkington, T.K., Xi, K., Clayton, G.W., Burnett, P.A., Klein-Gebbinck, H.W., Lupwayi, N.Z., Harker, K.N., and O'Donovan, J.T. 2006. Impact of crop management on leaf diseases in Alberta barley fields, 1995–1997. *Can. J. Plant Pathol*. 28:441–449.

Zentner, R.P., Lafond, G.P., Derksen, D.A., Nagy, C.N., Wall, D.D. and May W.E. 2004. Effects of tillage method and crop rotations on non-renewable energy use efficiency for a thin Black Chernozem in the Canadian Prairies. Soil & Tillage Res. 77:125–136.