Foundations for growth – The role of researchers and AAFC Research stations

Brian McConkey,

Agriculture and Agri-Food Canada, Swift Current

Brian.McConkey@agr.gc.ca

Summary

Researchers and the Agriculture and Agri-Food Canada (AAFC) Research Stations have played an essential role in developing and spreading low-disturbance direct seeding (LDDS) on the Canadian prairies. One key role was to conduct the initial trials of new conservation tillage and direct seeding technologies before they were economic viable practices. The researchers also worked directly with the innovative farmers in early conservation tillage developments and provided encouragement, advice, supporting measurements, and, sometimes, material assistance to these farmers. The researchers stepped outside of research and played a valuable role in extension of LDDS principles and practices to early technology adopters within the farming community. Researchers also played a pivotal role in geographically spread of promising technologies throughout the prairies by leapfrogging technologies across the network of Research Stations and on the land of cooperating farmers. The researchers and Research Centres have been hugely successful in refine technologies because they were uniquely able to effectively compare a wide range of variants and make measurements to determine the underlying principles and superior practices. Also the researchers were able to involve a range of scientific disciplines into the LDDS issues so that systems-approach to agronomic management within LDDS was developed. The researchers also provided the hard data of the benefits of direct seeding that undoubtedly strengthened the conviction of farmers, governments and industry that direct seeding was a successful and necessary transformation. Perhaps all the above roles may be seen as planned result of establishing and maintaining a network of skilled agricultural researchers across the prairies. One role that was certainly not planned, but which was both important and fortuitous, was that many of researchers were dedicated advocates and visionaries of direct seeding who worked selflessly to improve, promote and extend adoption of LDDS.

The Research Establishment

The Canadian government passed the Experimental Farm Station Act in 1886. This Act was in part the result of agriculture sector lobbying and favourable response of what we would now call a stakeholder focus group. This Act established 5 Stations including two on the Canadian prairies: Indian Head and Brandon (the others at Ottawa ON, Nepean, NS, and Agassiz, BC.) (OHH). These were joined by other experimental stations on the prairies: Lethbridge in 1906, Lacombe in 1907, Fort Vermillion in 1907, Rosthern in 1909 (closed in 1940), and, in 1911, Scott, Melfort, and Saskatoon. These were joined by Experimental Stations at Morden and Beaverlodge in 1915, and Swift Current in 1920. The Winnipeg Research Station was added in 1925 to focus on cereal rust. To address wind erosion and weed control issues, the last Experiment Station was opened at Regina in 1931. From the 1920s into the late 1950s, the Experiment Stations also ran over sub-stations and illustration stations to both test and extend field technologies beyond the Stations. These did not have staff or permanent facilities but were joint effort between the main Experiment Stations and cooperating farmers.

The Manitoba Agricultural College was established in Winnipeg in 1906 and became part of the University of Manitoba in 1924. The Agriculture program at University of Saskatchewan was started in 1912 while that at the University of Alberta started in 1915.

Hence, between universities and the now AAFC Research Centres and Farms, there was a well distributed network of researchers and facilities dedicated to improving farming practices.

Setting the stage – trash cover farming during the 1930s and 40s

Major soil drifting was observed in the 1917 to 1920 period over much of the prairies (Johnson 1983) including on the experimental stations themselves (OHH). A.E. Palmer of Lethbridge Station worked as early as 1920 with farmers in Monarch area to control soil drifiting. This including strip cropping and use of the "Noble blade" (wide blade cultivator) initially developed by innovative farmer C.S. Noble with helpful suggestions from researchers at Lethbridge and Swift Current Stations (Gray 1978). The close cooperation between innovative farmers and researchers at the Research Stations has been and continues to be important reasons for the successful development of better conservation tillage systems. In fact the collaboration was fundamental for wind erosion research since erosion could not be well studied in small plots (Gray 1978).

The need to retain crop residues on the soil surface to control soil drifting was obvious during the dust bowl years of the 1930s. Palmer was instrumental in developing and promoting minimum tillage methods that left sufficient residue at the surface. Interestingly, the original term for this practice of stubble mulch farming was not accepted by prairie farmers because it suggested a degree of neatness that was not the reality. At a field day a farmer suggested the term trash cover to Palmer who adopted it enthusiastically and henceforth was often called "trash cover Palmer (Gray 1978). This need for appropriate terminology that does not bother the farmer adopters foretold later debates over the terms no-tillage and zero-tillage versus the less prescriptive direct seeding.

Much to the displeasure of AAFC in Ottawa, Palmer moved beyond his research duties into active technology transfer to farmers. He was instrumental in developing a manual aimed at farmers on soil drifting control. He was also strident advocate for trash cover farming to AAFC managers – another role that was not well received in Ottawa. However because of the magnitude of the soil drifting crisis at the time, he was able to keep his position. In many ways, Palmer became the archetype for future researchers in direct seeding in terms of conviction, work ethic, the fostering of collaborative research that involved several researchers and innovative farmers, combined with a important component of extension activities to farming community.

Other important researchers at the time also played important roles in furthering trash cover farming including W.S. Chepil, S. Barnes, J. Taggart and L.B. Thomson of Swift Current Station (Gray 1978). Taggart and Thomson were particularly instrumental in gaining broader government support.

One important development of the period was the one-way discer seeder. Many variants of this machine concept were developed by farmers during the 1930s and 1940s. R.A. Johnson, a Saskatchewan farmer, is credited with coming up with the most effective design in the early 1940s and this design was soon produced by many machinery companies including Cockshutt (Gray 1978). The discer seeder gave the prairie farmer and researcher a practical direct seeding capability, albeit with complete disturbance of the soil surface and much burying of residue.

Another role for researchers was to provide the scientific rationale for need to change farming system. By the early 20th Century, researchers such as were already aware that prairie soils were being degraded in terms of organic matter and that the contemporary farming practices were not sustainable from a soil perspective (Janzen 2001). The scientific basis of how tillage increased soil erosion was also developed (Chepil 1941; Chepil 1944; Doughty et al. 1943)

No-tillage – the initial trials from 1950s to 1975

In 1943, The Plowman's Folly by Edward H. Fowler was published. It makes a persuasive argument for abolishment of the plow and stated "no one has ever advanced a scientific reason for plowing". Several researchers on the prairies took up this challenge to develop no-tillage.

With the development of herbicides after World War II, there was immediate interest in using them to replace tillage for weed control. Early experiments into chemical seedbed preparation were done in the 1950s in Europe and the USA. By the 1960s there were a number of farmers, mostly in the eastern US, using no-tillage and the first commercial no-till drill was introduced by Allis-Chalmers in 1967.

Given the prevalence of fallow on prairies and its undeniable role is causing excessive soil erosion, , it is not surprising that major effort for eliminating tillage in the prairies was for summerfallow. In 1956 a suite of experiments on various combinations of tillage and herbicides for summerfallow, including summerfallow without any tillage (chemical fallow), were conducted at Indian Head, Lacombe, Regina, and Swift Current. This early research was summarized by C.H. Anderson in 1964 annual report to AAFC. The conclusion was that the herbicides available at the time provided inadequate control of all weeds in some years so, although tillage could be reduced, tillage could not be totally eliminated on summerfallow The first herbicide for broad-spectrum weed control, paraquat, was registered in 1962 and brought much new research interest on chemical fallow. With paraquat, satisfactory control of weeds for summerfallow became practical (Anderson 1971a; Lindwall and Anderson 1981) although combinations of tillage and herbicides were most profitable (Zentner and Lindwall 1982).

Using the discer seeder had shown that high disturbance direct seeding was provided good as or better crop yields than using fall and/or spring tillage (Bowren and Dryden 1967, 1971).

Research into low-disturbance direct seeding (LDDS) was underway in the 1960s. Anderson (1971b) reported that direct seeding with hoe- and double-disk press drill provided equal yields to that with pre-seeding tillage over the 1966-1970 at Swift Current Other researchers who were doing low-disturbance direct seeding in the late 1960s and early 1970s included Wayne Lindwall with AAFC Research Centre at Lethbridge and Ken Bowren at the AAFC Research Centre at Melfort. University researchers included Elmer Stobbe of University of Manitoba and Brian Fowler of University of Saskatchewan. Dr. Fowler's interest was to improve production of winter cereals by leaving some standing stubble after seeding to trap winter snow and LDDS became essential to expanding winter wheat production outside of southern Alberta.

These early investigation of no-tillage were more feasible for Research Stations than for farmers. In Anderson's description of one major no-tillage experiment: "Economics was not considered: we wished only to ascertain whether cultivation had any beneficial effect other than for weed control".

Laying the foundation for growth– 1976 to 1990

From 1976 onward, LDDS evolved from an experiment into a successful farming system for the Canadian prairies. Although in 1976 there were few farmers using direct seeding consistently on their land, this number grew dramatically over the period.

Importantly, glyphosate was registered for general broad spectrum weed control for agriculture in 1976 and that provided weed control than paraquat, particularly for broadleaf weeds. Glyphosate could also be tank mixed with 2,4-D or dicamba that further improved broadleaf weed control. Although initially expensive, glyphosate was and remains an important weed-control tool for LDDS.

Drills for LDDS available from the US were too expensive and not entirely appropriate for the large, relatively low yielding farms of the Canadian prairies. Seed drills adapted from existing machines designed from tilled conditions were not fully satisfactory for LDDS conditions. Although limitations in seeding machines for LDDS were seen as a critical problem for widespread adoption of LDDS, the researcher community played less a critical role with machinery development than for other components of LDDS. A major reason was that there were relatively few engineers employed as researchers and those engineers, such as Sylvio Tessier (AAFC, Swift Current) and Wayne Lindwall (AAFC Lethbridge), were more involved in agronomic aspects of LDDS than machine design itself. An exception was Ben Dyck (AAFC, Swift Current) who did considerable work on direct seeding machinery (Dyck and Tessier 1986; Ulrich et al. 1995) but also devoted much of his efforts to more agronomic investigations (Campbell et al. 1993; Foster et al. 1992; McConkey et al. 1995; McConkey et al. 1996; McLeod et al. 1992).

Likely a more important reason why researchers did not play as large a role in machine development as in other areas was that many farmers had the skill, facilities, and eagerness to undertake their own machinery modification and design. Air delivery of seed and fertilizer became widely available with the Prasco air seeder in the mid 1970s. When mated with a cultivator, the combination became a relatively low-cost seeding machine capable of high-disturbance direct seeding. These open frame cultivator-based seeders were both rugged and relatively easy to modify. Some farmer-designed seeding machines loosely based on the air seeder-cultivators became the start of significant manufacturers including Conservapak (John Deere) and Seed Hawk/Seed Master. Further, several enterprising machinery manufacturing companies saw an opportunity in building equipment suitable for LDDS. Simple gravity box press hoe drills that were capable of LDDS were available from Edwards and Noble/Versatile by the mid 1980s. Other companies like Flexi-coil, Morris, and Bourgault were busy developing large seed drills from their existing cultivator businesses. By the early 1990s, there were a number of reliable seeding machines developed specifically for prairie conditions and so machinery adequacy ceased to be a critical issue for adoption of LDDS.

The major and essential roles of the researcher during this period were technology transfer and the refinement of the LDDS. Significant LDDS trials were initiated at Lethbridge by Lindwall, Scott by Stewart Brandt, Swift Current by Dyck and Tessier, and Indian Head by Guy Lafond. In many cases more of the trials were conducted off-station than on-station (Lafond et al. 1994; Lindwall et al. 1984; Tessier et al. 1990). Conducting trials on the land of cooperating farmers allowed a wider range of soil and weather conditions to be included in the research as well as providing more local examples of LDDS to show producers. The researchers also worked closely with innovative farmers using LDDS to both support the farmers and to learn from them.

Researchers involved in LDDS spent much time speaking to farmers at small local meetings as well as larger government and/or industry sponsored workshops and conferences. The entire concept of LDDS was not universally accepted in the scientific community so the researchers involved in LDDS needed a strong conviction that LDDS was necessary for soil and water conservation to continue to pursue LDDS research. Hence, these motivated researchers spoke passionately about LDDS rather than just dryly communicating research data. Therefore, they were more advocates of LDDS than the scientist ideal of an unbiased observer. Dean Don Rennie of the University of Saskatchewan's College of Agriculture was a particularly passionate and effective speaker about the lasting damage to the land caused by summerfallow and the need to adopt new conservation farming systems.

The three major farmer organization involved in LDDS: the Manitoba-North Dakota Zero-Till Farmers Association, the Alberta Conservation Tillage Society, and Saskatchewan Soil Conservation Association all started during this period. A perusal of the programs of any of their annual conferences shows that researchers from AAFC Research Centres were a large proportion of the speakers. No doubt their passion and interest aligned well with those of these farmer organizations and that would explain why the researchers were frequently repeat speakers. Researchers were also directly involved in technology transfer at Research Station field days where LDDS was inevitably shown and discussed.

Several dry years that included severe wind erosion during the 1980s helped to reinforce why LDDS was necessary to both achieve better conservation of water and soils. It was an exciting time for researchers as the LDDS technology transformed from an experiment to a farming system.

One reason for the success of researchers was their determination to make the system practical and sufficiently developed for adoption. There was no sense of the scientific paper being either the goal or the endpoint of the research effort. The widespread adoption of better farming system, in terms of economic and environmental performance, based on LDDS was the researcher's ultimate goal.

Filling in the system – 1991 to date

By the mid to late 1980s, the question had changed from whether to adopt LDDS to how to best manage LDDS as a system. Therefore starting at this time and continuing to this day, the researchers played a key role in improving the LDDS system. Their multifaceted studies to evaluate the how and why are more effectively investigated in a controlled experiments than inferred from anecdotal field evidence. Importantly, the researchers were able to work collaboratively at many Research Centres so that they could test hypotheses relatively quickly and across a wider range of environments. Consequently, the researchers were able to make important advancements in nutrient management (Grant et al. 2003; Lupwayi et al. 2007; Malhi et al. 2001; Schoenau and Huang 1991; Soon and Arshad 2004), weed dynamics and control (Blackshaw et al. 2005; Derksen et al. 1993; Harker et al. 2003; Johnson et al. 2002; Kirkland 1996; Moyer et al. 1994; O'Donovan et al. 2007), crop diversification and sequencing (Gan et al. 2003; Miller et al. 2002), seeding management (Cutforth et al. 2002; Lafond and Gan 1999), and disease management (Bailey et al. 1992; Fernandez et al. 1999). The farmers were hungry for this information and so the researchers have been frequently asked to make presentations that summarized important messages to improve LDDS management as a system. It is testimony to their proactive research that no insurmountable problem has developed within LDDS.

Initially, LDDS systems were based on cereal-intensive rotations that were well suited to minimum tillage systems. In fact, with tillage, the cereal intensive systems were most sustainable because the residue of the cereal crops served to reduce the erosion risk and they were tolerant of the sometimes dry upper seedbed produced with tillage. However, with LDDS, successive cereal crops could produce too much residue. Further, weed control of some grassy weeds was difficult in monoculture cereal rotations under LDDS. The mixing of broadleaf and cereal crops worked better for both residue and weed control under LDDS. This also allowed the capturing of rotation benefits of mixing crop types. At the same time, the environment for the seed and seedling with LDDS was often better for broadleaf crops than a tilled surface. It can be said that LDDS worked better with diverse rotations and diverse rotations worked better with LDDS. Consequently the crop diversification that has occurred over the past 20 years is largely a product of LDDS.

The water conservation benefits of LDDS have been a major factor in reducing the need for aummerfallow (Brandt 1992; Campbell et al. 1992). The steady drop in summerfallow has paralleled the increase in conservation tillage and this drop is also largely a product of LDDS.

One feature of research in support of LDDS has been the fluidity and large extent of collaborations among AAFC researchers. There is no sense that developments are coming out of an individual scientist's "laboratory" that would be more the academic (and emerging current AAFC) model of research. Rather, the developments are the result of teams of integrated researchers working in several locations. Many of the researchers, such as Guy Lafond and Stewart Brandt, carried on diverse and highly effective and connected research.

Several researchers, such as Guy Lafond, adopted LDDS within their entire research programs well before it was the predominant tillage practice in their areas. Making LDDS the normal Research Station practice helped to further convince farmers that LDDS was the way of the future and ensured that all information generated within their research programs were relevant to LDDS systems.

Also the researchers were able to evaluate how LDDS were impacting the soil and the broader environment (Biederbeck et al. 1997; Bremer et al. 1994; Campbell et al. 1999; Janzen et al. 1998; Larney et al. 1997; Lemke et al. 1999; McConkey et al. 2003; Zentner et al. 2004). This information has gone to inform government policy in areas such as greenhouse gas mitigation.

Conclusions

The Canadian prairies were fortunate to have a good network of research centres with researchers of tremendous ability and dedication. These researchers played many critical roles for the development, adoption, and improvement of LDDS: conducting initial trials to show it was possible, providing the research that laid the foundation of practical LDDS, transferring technology from and to farmers, spreading the LDDS geographically, developing the scientific basis for successful systems approach to LDDS, providing the hard scientific evidence of the benefits of LDDS, and advocating for LDDS. The Without doubt the prairie direct seeding research community and the AAFC Research Centres have played an instrumental role in the success of direct seeding in transforming the prairie landscape.

References

Anderson, C.H. 1971a. Comparison of tillage and chemical summerfallow in a semiarid region. Can. J. Soil Sci. **51**: 397-403.

Anderson, C.H. 1971b. Tillage and seeding practices for 1971. *Edited by* C.D.o. Agriculture, Swift Current.

Bailey, K.L., Mortensen, K., and Lafond, G.P. 1992. Effects of tillage systems and crop rotations on root and foliar diseases of wheat, flax, and peas in Saskatchewan. Can. J. Plant Sci. **72**(2): 583-591.

Biederbeck, V.O., Campbell, C.A., and Hunter, J.H. 1997. Tillage effects on soil microbial and biochemical characteristics in a fallow-wheat rotation in a Dark Brown soil. Can. J. Soil Sci. **77**: 309-316.

Blackshaw, R.E., Moyer, J.R., Harker, K.N., and Clayton, G.W. 2005. Integration of agronomic practices and herbicides for sustainable weed management in a zero-till barley field pea rotation. Weed Technology **19**(1): 190-196.

Bowren, K.E., and Dryden, R.D. 1967. Methods of seeding spring wheat on summerfallow in the black soil area of Manitoba and Saskatchewan. Canadian Agricultural Engineering **9**: 101-102, 126.

Bowren, K.E., and Dryden, R.D. 1971. Effect of fall and spring treatment of stubble land on yield of wheat in the black soil region of Manitoba and Saskatchewan. Canadian Agricultural Engineering **13**(1): 32-35.

Brandt, S.A. 1992. Zero vs conventional tillage and their effects on crop yield and soil moisture. Can. J. Plant Sci. **72**: 679-688.

Bremer, E., Janzen, H.H., and Johnston, A.M. 1994. Sensitivity of total, light fraction and mineralizable organic-matter to management-practices in a Lethbridge soil. Can. J. Soil Sci. **74**: 131-138.

Campbell, C.A., Zentner, R.P., McConkey, B.G., and Selles, F. 1992. Effect of nitrogen and snow management on efficiency of water-use by spring wheat grown annually on zero-tillage. Can. J. Soil Sci. **72**: 271-279.

Campbell, C.A., Zentner, R.P., Selles, F., McConkey, B.G., and Dyck, F.B. 1993. Nitrogen management for spring wheat grown annually on zero-tillage: yields and nitrogen use efficiency. Agron. J. **85**(1): 107-114.

Campbell, C.A., Biederbeck, V.O., McConkey, B.G., Curtin, D., and Zentner, R.P. 1999. Soil quality—Effect of tillage and fallow frequency. Soil organic matter quality as influenced by tillage and fallow frequency in a silt loam in southwestern Saskatchewan. Soil Biology and Biochemistry **31**: 1-7.

Chepil, W.S. 1941. Relation of wind erosion to the dry aggregate structure of a soil. Scientific Agriculture **21**: 488-507.

Chepil, W.S. 1944. Utilization of crop residues for wind erosion control. Scientific Agriculture **24**(7): 307-319.

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**(4): 681-686.

Derksen, D.A., Lafond, G.P., Thomas, A.G., Loeppky, H.A., and Swanton, C.J. 1993. Impact of agronomic practices on weed communities: tillage systems. Weed Science **41**(3): 409-417.

Doughty, J.L., Chepil, W.S., Staple, W.J., Lehane, J.J., Milne, R.A., Warder, F.G., and Budd, A.C. 1943. Report of investigations. Soil research laboratory, Swift Current, Sask. pp. 31-55.

Dyck, F.B., and Tessier, S. 1986. Zero till drill developments at the Swift Current research station. *In* Annual Canadian Society of Agricultural Engineering Meeting, Saskatoon, Sk. p. various pagination.

Fernandez, M.R., McConkey, B.G., and Zentner, R.P. 1999. Effects of tillage method and fallow frequency on leaf spotting diseases of spring wheat in the semiarid Canadian prairies. Soil and Tillage Research **50**: 259-269.

Foster, R.K., Townley-Smith, L., and Dyck, F.B. 1992. Seeding method and nitrogen effects on two Canadian wheat types. Journal of Production Agriculture **5**(4): 540-545.

Gan, Y.T., Miller, P.R., McConkey, B.G., Zentner, R.P., Stevenson, F.C., and McDonald, C.L. 2003. Influence of diverse cropping sequences on durum wheat yield and protein in the semiarid Northern Great Plains. Agron. J. **95**(2): 245-252.

Grant, C.A., Johnston, A.M., and Clayton, G.W. 2003. Sulphur fertilizer and tillage effects on early season sulphur availability and N:S ratio in canola in western Canada. Canadian Journal of Soil Science **83**(4): 451-463.

Gray, J.H. 1978. Men against the desert. Western Producer Prairie Books, Saskatoon, SK.

Harker, K.N., Kirkland, K.J., Baron, V.S., and Clayton, G.W. 2003. Early-harvest barley (Hordeum vulgare) silage reduces wild oat (Avena fatua) densities under zero tillage. Weed Technology **17**(1): 102-110.

Janzen, H.H., Campbell, C.A., Izaurralde, R.C., Ellert, B., Juma, N.G., McGill, W.B., and Zentner, R.P. 1998. Management effects on soil C storage on the Canadian prairies. Soil and Tillage Research **47**: 181-195.

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.

Johnson, E.N., Kirkland, K.J., and Stevenson, F.C. 2002. Timing of pre-seeding glyphosate application in direct-seeding systems. Canadian Journal of Plant Science **82**(3): 611-615.

Johnson, W.E. 1983. Soil conservation: Canadian prairies. *In* Dryland Agriculture. *Edited by* H.E. Dregne, and W.O. Willis. American Society of Agronomy. pp. 259-272.

Kirkland, K.J. 1996. Use of incorporated and non-incorporated granular trifluralin for annual grass control in barley (Hordeum vulgare), wheat (Triticum aestivum), and canola (Brassica napus). Weed Technology **10**(4): 907-913.

Lafond, G.P., Derksen, D.A., Loeppky, H.A., and Struthers, D. 1994. An agronomic evaluation of conservation-tillage systems and continuous cropping in East Central Saskatchewan. J. Soil Water Conserv. **49**(4): 387-393.

Lafond, G.P., and Gan, Y.T. 1999. Row spacing and seeding rate studies in no-till winter wheat for the Northern Great Plains. Journal of Production Agriculture **12**(4): 624-629.

Larney, F.J., Bremer, E., Janzen, H.H., Johnston, A.M., and Lindwall, C.W. 1997. Changes in total, mineralizable and light fraction soil organic matter with cropping and tillage intensities in semiarid southern Alberta, Canada. Soil and Tillage Research **42**: 229-240.

Lemke, R.L., Izaurralde, R.C., Nyborg, M., and Solberg, E.D. 1999. Tillage and N source influence soil-emitted nitrous oxide in the Alberta Parkland region. Can. J. Soil Sci. **79**(1): 15-24.

Lindwall, C.W., and Anderson, D.T. 1981. Agronomic evaluation of minimum tillage systems for summer fallow in southern Alberta. Can. J. Plant Sci. **61**(2): 247-253.

Lindwall, C.W., Sawatzky, B., and Jensen, T. 1984. Zero tillage in southern Alberta. *In* Proceedings of the 21st Annual Alberta Soil Science Workshop, Edmonton, Alberta. pp. 128-136.

Lupwayi, N.Z., Clayton, G.W., O'Donovan, J.T., Harker, K.N., Turkington, T.K., and Soon, Y.K. 2007. Phosphorus release during decomposition of crop residues under conventional and zero tillage. Soil and Tillage Research **95**(1/2): 231-239.

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 and Tillage Research **60**(3/4): 101-122.

McConkey, B.G., Dyck, F.B., and Peru, M. 1995. Evaluation of powered-rod based packing systems for air seeders. *In* Soils & Crops, University of Saskatchewan, Saskatoon. pp. 398-405.

McConkey, B.G., Campbell, C.A., Zentner, R.P., Dyck, F.B., and Selles, F. 1996. Long-term tillage effects on spring wheat production on three soil textures in the Brown soil zone. Canadian Journal of Plant Sciences **76**: 747-756.

McConkey, B.G., Liang, B.C., Campbell, C.A., Curtin, D., Moulin, A.P., Brandt, S.A., and Lafond, G.P. 2003. Crop rotation and tillage impact on carbon sequestration in Canadian prairie soils. Soil and Tillage Research **74**(1): 81-90.

McLeod, J.G., Dyck, F.B., Campbell, C.A., and Vera, C.L. 1992. Evaluation of four zero-tillage drills equipped with different row openers for seeding winter wheat in the semi-arid prairies. Soil Tillage Res. **25**(1): 1-16.

Miller, P.R., Waddington, J., McDonald, C.L., and Derksen, D.A. 2002. Cropping sequence affects wheat productivity on the semiarid northern Great Plains. Can. J. Plant Sci. **82**(2): 307-318.

Moyer, J.R., Rosman, E.S., Lindwall, C.W., and Blackshaw, R.E. 1994. Weed management in conservation tillage systems for wheat production in North and South America. Crop Protection **13**(4): 243-259.

O'Donovan, J.T., Harker, K.N., Clayton, G.W., Hall, L.M., Cathcart, J., Sapsford, K.L., Holm, F.A., and Hacault, K. 2007. Volunteer barley interference in spring wheat grown in a zero-tillage system. Weed Science **55**(1): 70-74.

Schoenau, J.J., and Huang, W.Z. 1991. Anion-exchange membrane, water, and sodium bicarbonate extractions as soil tests for phosphorus. Communications in Soil Science and Plant Analysis **22**(5&6): 465-492.

Soon, Y.K., and Arshad, M.A. 2004. Tillage, crop residue and crop sequence effects on nitrogen availability in a legume-based cropping system. Canadian Journal of Soil Science **84**(4): 421-430.

Tessier, S., Peru, M., Dyck, F.B., Zentner, F.P., and Campbell, C.A. 1990. Conservation tillage for spring wheat production in semi-arid Saskatchewan. Soil Tillage Res. **18**(1): 73-89.

Ulrich, D.J., Selles, F., Dyck, F.B., and Nasr, H.M. 1995. Evaluation of furrow openers for conservation tillage. Research Branch, Agriculture and Agri-Food Canada, Swift Current, Sk. p. various pagination.

Zentner, R.P., and Lindwall, C.W. 1982. Economic evaluation of minimum tillage systems for summer fallow in southern Alberta. Can. J. Plant Sci. **62**(3): 631-638.

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 rotation on non-renewable energy use efficiency for a thin Black Chernozem in the Canadian Prairies. Soil Tillage Res. **77**(2): 125-136.