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Effect of Tillage and Cropping Frequency on Sustainable Agriculture in the Brown Soil Zone

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Summary
In the semiarid Canadian prairies where water availability is the main constraint to crop production, a 2-yr rotation of summerfallow-spring wheat (F-W), with extensive use of mechanical tillage (CT), was the predominant cropping system used for many decades. To enhance net returns and reduce soil degradation, producers have increased cropping frequency and reduced tillage [using minimum- or no-tillage (MT or NT)]. A study was initiated in 1981 on fine sandy loam, silt loam and clay soils to assess the influence of cropping frequency and tillage management on sustainable production. The results showed no effect of tillage on grain yield, crop residue production, grain protein, net returns, energy use efficiency, soil quality, or C sequestration for the F-W system. There has been a steady increase in soil C due to the change to Cont W (CT) and there was a further increase in SOC from adopting NT in the Cont W system.

Introduction
In the semiarid Canadian Prairies, water and its efficient use is key to successful dryland crop production. Historically, area producers have selected cropping systems that have relied on monoculture cereal cropping, frequent summer fallowing, and extensive use of mechanical tillage for weed control on fallow areas and for seedbed preparation[11]. These production systems proved effective in enhancing crop yields, minimizing the needs for purchased inputs, and generating higher and more stable farm incomes under the economic conditions of the day[22]. However, these same farming systems resulted in substantial soil loss by wind and water erosion, led to deterioration of the quantity and quality of soil organic matter, and contributed to soil salinization and greenhouse gas emissions[1,13,15]. This has also contributed to depletion of plant-available nutrients (especially N), and diminished overall soil productivity and environmental quality[10,13].

In recent years, declining costs for some herbicides coupled with changes in government policies and programs (e.g., grain transportation and farm safety-net programs), development of new markets and value-added opportunities, improvements in machinery design and soil management practices, and growing concerns about soil and environmental degradation have stimulated significant change in land management practices[17]. The adoption and use of extended and diversified crop rotations, together with minimum tillage and no-tillage management practices, have gained widespread acceptance among producers.

For these newer cropping systems to be sustainable in the long term they must: (i) be technically or agronomically feasible (i.e., suited to the soil and climate conditions of the area, practical to implement, and capable of producing acceptable grain yields and quality); (ii) ensure the quality of the soil, water and air resources are maintained or enhanced; and (iii) be economically viable[9,21].

In 1981 a study was initiated in the Brown soil zone of Saskatchewan on a coarse-, medium- and fine-textured soil to determine the influence of cropping frequency and method of tillage management on sustainable crop production.

Description of the Study
In 1981 the experiment was initiated on a Swinton silt loam soil (Orthic Brown) at the Semiarid Prairie Agricultural Research Centre near Swift Current, in 1982 on a Hatton fine sandy loam (Orthic Brown) located at Cantuar, 15 km NW of Swift Current, and on a Sceptre heavy clay (Rego Brown) situated near Stewart Valley, 50 km N of Swift Current. The original intent was to evaluate the effect of tillage systems on production of hard red spring wheat (Swift Current and Stewart Valley) and durum wheat (Cantuar). The tillage systems were no-tillage (NT), minimum tillage (MT) and conventional tillage (CT). Cropping frequency at each site was fallow-wheat (F-W) and continuous wheat

(Cont W) rotations. The study at Cantuar was stopped after 12 years but is still on-going at the other two sites. At study initiation the F-W was the predominant farming system in the Brown soil zone[12].

The CT system for F-W involved spraying 2, 4-D in the fall plus two to four tillage operations during the fallow period using a heavy duty cultivator and/or rodweeder, plus a single tillage operation with a heavy-duty cultivator and mounted harrows immediately before seeding with a hoe drill. The MT fallow management involved herbicides for initial weed control (until July), followed by one or two tillage operations in July-August period with a heavy-duty cultivator or wide-blade cultivator, plus a single tillage operation with a heavy-duty cultivator and mounted harrows immediately before seeding. The NT fallow areas had a fall herbicide plus two to four applications as required during the fallow period. The NT plots to be cropped were direct seeded without seedbed preparation. The NT systems also received periodic post-harvest glyphosate treatments when required for control of foxtail barley starting in 1996. In the Cont W rotations, the tillage systems were MT and NT. The MT Cont W involved a single tillage operation with a heavy-duty cultivator and mounted harrows immediately before seeding with a hoe drill. The NT Cont W was direct seeding and included occasional post-harvest glyphosate.

Fertilizer N was applied based on fall soil test. Fertilizer P was seed-placed, and prior to 1996, N was split between seed placed and broadcast. Since 1996, N had been side-banded. Also since 1996, the MT F-W and NT F-W received additional 25 kg N ha^{-1} to investigate if extra N would enable these systems to make better use of conserved soil water and overcome the protein deficit compared with CT W-F. In 1996, the MT and NT F-W rotations on the clay site were converted to wheat-pulse (W-P) rotation, while maintaining the long-term tillage history of the plots. The pulse crop was alternated between pea, chickpea, and lentil. In 1997, the F-W plots at the silt loam site were split, with one half of the plot maintaining the original system and the other half put into a wheat-pulse (W-P) rotation but retaining their long-term tillage history. The pulse alternated between chickpea, pea and lentil. We measured yields and grain protein[18] (Table 1), net returns and risk[23], energy-use efficiency[24], soil C and N in the 0-7.5 and 7.5-15- cm depths in all three soils every four years for the first 12 years[16,17,18] and periodically thereafter to 2007 in the silt loam (Fig. 1). Soil quality attributes [e.g., C and N mineralization (C_{min} and N_{min}), microbial biomass (MB), and light fraction organic matter] were measured at four year intervals in the first 12 years in all three soils[2,3,4,5].

Results and Discussion

Grain Yields, grain N, and above-ground plant biomass

On the sandy soil, tillage had no effect on spring soil moisture (SSM), grain yields, nor grain N[18]. On the silt loam and clay there were several instances when NT increased SSM, especially in the clay, but this extra moisture was rarely associated with increased yield or grain N (Table 1). These results were true for both F-W and Cont W. As expected, yields of wheat grown on fallow were greater than those of wheat grown on stubble in the Cont W system. The extra fertilizer N applied to NT and MT F-W increased grain protein but not the grain yield compared to CT F-W. In contrast to results from other nearby experiments, at the silt loam site, tillage has so far had no effect on pulse or wheat yields (Table 1). In the clay soil the yield of wheat following the pulse was greater than Cont W in both NT and MT. This may be related to greater available N following the pulse crop. The yield of the pulse crop following wheat was greater on NT than on MT (Table 1). On this soil the more diversified W-P rotation has improved yield performance compared to monoculture wheat.

The effect of tillage on the above-ground biomass production of wheat grown in the F-W and Cont W treatments at the silt loam site was assessed after 25 years[20]. The above-ground biomass of wheat grown on NT averaged about 250 kg ha^{-1} y^{-1} more than that of CT systems. This advantage was associated with slightly higher SSM near the soil surface, reduced root heat stress and improved soil quality of the NT system. The increased above-ground biomass was due to increased straw yields, not grain.

During the initial 14 years of study, there was noticeably lower wheat protein for NT than tilled (MT or CT) soils. This was most noticeable for F-(W) on both soils and for Cont W on the clay soil (Table 1). This effect was attributed to N immobilization with the increasing soil organic matter content under NT management. However, the additional N fertilizer on NT F-(W) helped to overcome this problem. On the clay soil, the addition of a pulse crop eliminated any long-term effect of tillage system on wheat protein.

Effect on net returns

Over the 12-yr period (1982-1993) our results showed little short-term economic incentive for producers to adopt NT management practices[14]. Although conservation tillage (MT and NT) provided savings in labor, fuel, oil, machine repair, and machine overhead (compared to CT), these savings were offset by greater expenditures for herbicides. Nevertheless, farmers in the Brown and Dark Brown soil zones have perceived large economic benefits from conservation tillage as 55% and 23% of cropland in these zones in Saskatchewan are now under NT and MT management, respectively, according to the 2006 Census of Agriculture.

In a review paper, Zentner et al.[25] suggested that including oilseed and pulse crops in the rotation with cereal grains contributes to higher and more stable net farm income in most soil-climatic regions, despite a requirement for increased expenditures on purchased inputs. Although we have not analyzed the recent results economically, the good agronomic performance of NT W-P system on the clay soil (Table 1) compared to monoculture wheat would be consistent with this supposition. In the Brown and Dark Brown soil zones, the wind erosion risk can be excessive with non-cereal crops, so MT and NT practices are also important to enable sustainable diversified production systems. In the semiarid prairies where the production risk with stubble cropping is high, the complete elimination of summer fallow from the cropping system may not be economically feasible during times of low crop prices. On the silt loam, Cont W was only favoured over F-W at wheat prices greater than \$147 t^{-1}.

Effect on energy use efficiency

There is growing interest in the potential for improving non-renewable energy use efficiency of traditional agricultural production activities in the Canadian prairies. Our results showed that metabolizable energy output increased with cropping frequency on the silt loam and on the clay (averaged 16751 MJ ha^{-1} for F-W and 24110 MJ ha^{-1} for Cont W), but not on the sandy loam (average 14828 MJ ha^{-1})[24]. Further, because grain yield was rarely influenced by tillage method, the latter had little influence on the overall output of metabolizable energy. Total input of non-renewable energy per unit of rotation also increased with cropping intensity (average 2585 MJ ha^{-1} for F-W and 5274 MJ ha^{-1} for Cont W). This was primarily because of the higher rates of N fertilizer that were required with stubble cropping. However, the F-W rotations have removed more N from the soil than has been added so the energy performance is not so favourable if there is due consideration of this non-renewable N source. Although the use of conservation tillage practices provided significant energy savings in fuel and machinery, particularly for F-W systems, these were largely offset by increases in the energy input for herbicides, and marginally higher rates of N fertilizer that were required for NT managed areas.

Effect on soil organic C and N

Because there was minimal effect of tillage on yield (and thus C inputs) the impact on soil organic matter was minimal in all three soils but especially in the sand[6,7,8]. However, the results revealed that, over an 11-12 yr period, there was a direct linear relationship between the increase in soil C in the 0-15 cm layer due to adoption of NT management and clay content of the three soils (Fig. 1)[8]. This could be a consequence of finer-textured soils being more capable of protecting soil organic C from mineralization than coarse-textured soils under no-tillage[19].

Because we have continued to monitor soil organic C periodically at the silt loam site we have been able to demonstrate that C in the 0-15 cm layer has remained fairly constant in the F-W rotation even in the NT (Fig. 2). This is because this rotation has not changed over the past 90-100 years and so soil C is in steady state. However, continuous cropping has provided greater C input[20] and has thus gradually increased soil C. Further, soil C has increased even more in the NT compared to MT because tillage increased C mineralization in the latter.

Effect on some other soil quality attributes

Although it took 11 yr before we observed significant treatment effects on total soil organic C and N in the coarse-textured soil, effects on the mineralizable C and N (C_{min} and N_{min}) were observed in the 0-7.5 cm layer after only 7 yr, and by 11 yr the effect on microbial biomass (MB) and specific respiratory activity (SRA) were increased in this layer as well[3]. Generally the labile soil quality attributes were greater in the NT than in the CT and MT systems, and in Cont W than in F-W systems. After 11 yr there was a direct association between labile soil quality attributes tested and straw produced.

Of the labile soil attributes assessed in the silt loam soil, only C_{min} and N_{min} showed significant response to the treatments after 4- and 8-yr, but after 12 yr, SRA was also affected by the treatments[5]. Cropping more frequently increased C_{min}, N_{min} and SRA, likely due to greater crop residue production; however, tillage, with no effect on crop residues, had no effect on the soil quality attributes. As observed in the sandy soil, the labile attributes were more sensitive to cropping frequency than was the total organic C and N.

In the clay soil, even after 11 yr, only C_{min} and N_{min} among the labile soil quality attributes were affected by the treatments[4]. Surprisingly, the labile attributes were no more sensitive to the treatments than were the total soil organic C and N.

The results on these three soils support the findings by Liang et al.[16] for six soils in the Brown, Dark Brown, and Black Chernozemic soil zones in Saskatchewan, indicating that these treatments may increase total soil organic C and N without necessarily increasing available soil N. Thus, there is more research required to unravel this anomaly.

Future

Due to resource limitations, the clay soil site will be discontinued in 2012. The plans are to maintain the silt loam site at the Semiarid Prairie Agricultural Research Centre as a long-term agro-ecosystem experiment. Tillage conversions (NT to CT and CT to NT) were undertaken in 2004 and we will continue to monitor the effects of that change relative to their longer-term counterpart systems. A low input (no fertilizer or herbicide) system was added in 2006 with high and moderate tillage intensity to provide greater range of systems.

There remain many fundamental questions regarding C and N cycling in response to rotation and soil disturbance for the Brown soil zone that can only be addressed through long-term experiments. Long-term data are essential to validate and improve process models of agricultural system behaviour. Although the focus of the study has become mostly on the effects on the soil, the long-term agronomic performance continues to be interesting.

Table 1 Effect[z] of cropping frequency and tillage[x] on grain yield and protein, spring soil water, soil test N and N fertilizer applied to spring wheat on a silt loam at Swift Current, Sask. (1982-2009).

Site	Years	Rotation[y]	Tillage	Spring NO_3-N (kg ha^{-1})	Fert N (kg ha^{-1})	Soil Water (mm)	Grain Yield (kg ha^{-1})	Grain Protein (%)
Loam	82-96	(W)-F	NT	50b	26	118c	2394b	11.6a
			MT	60b	24	108c	2432b	12.3ab
			CT	58b	24	100b	2541b	12.4b
		Cont W	NT	31a	51	69a	2014a	12.7b
			MT	30a	48	64a	2032a	12.4b
	97-09	(W)-F	NT	47b	52	119a	2338a	14.2c
			MT	55a	49	110a	2378a	14.5bc
			CT	53a	30	102c	2297a	13.0d
		Cont W	NT	28c	52	75d	1618b	14.9ab
			MT	24c	55	80d	1637b	14.5bc
		(W)-P	NT	27c	54	65e	1674b	15.0a
			MT	28c	51	65e	1690b	14.9ab
		W-(P)	NT	28c	5	59ef	1736b	
			MT	29c	5	56f	1689b	
Clay	83-96	(W)-F	NT	52b	28	149b	2667b	11.4ab
			MT	54b	25	144b	2759b	12.0bc
		Cont W	NT	32a	47	77a	1908a	11.2a
			MT	39a	44	66a	1902a	12.2c
	97-09	Cont W	NT	18e	57	60b	1937c	13.6c
			MT	18e	56	63b	1696d	14.0b
		(W)-P	NT	30b	54	66b	2096b	14.7a
			MT	29bc	54	79b	1997bc	14.7a
		(W)-F	CT	47a	33	149a	2704a	13.1d
	97-09	W-(P)	NT	25cd	5	66b	1764d	
			MT	28bc	5	65b	1527e	

[z] Means between horizontal lines not followed by same letter are significantly different at p=0.10.

[x] NT=no-till (low disturbance one-pass direct seeding), MT=minimum tillage.

[y] W-F = wheat-fallow rotation, W-P = wheat-pulse rotation, Cont W = continuous wheat, (crop) signifies the phase of the rotation.

Figure 1. Soil texture influences carbon gains in 0- to 15-cm depth of soil after 11-12 yr of no-tillage in the Brown soil zone [Adapted from 8].

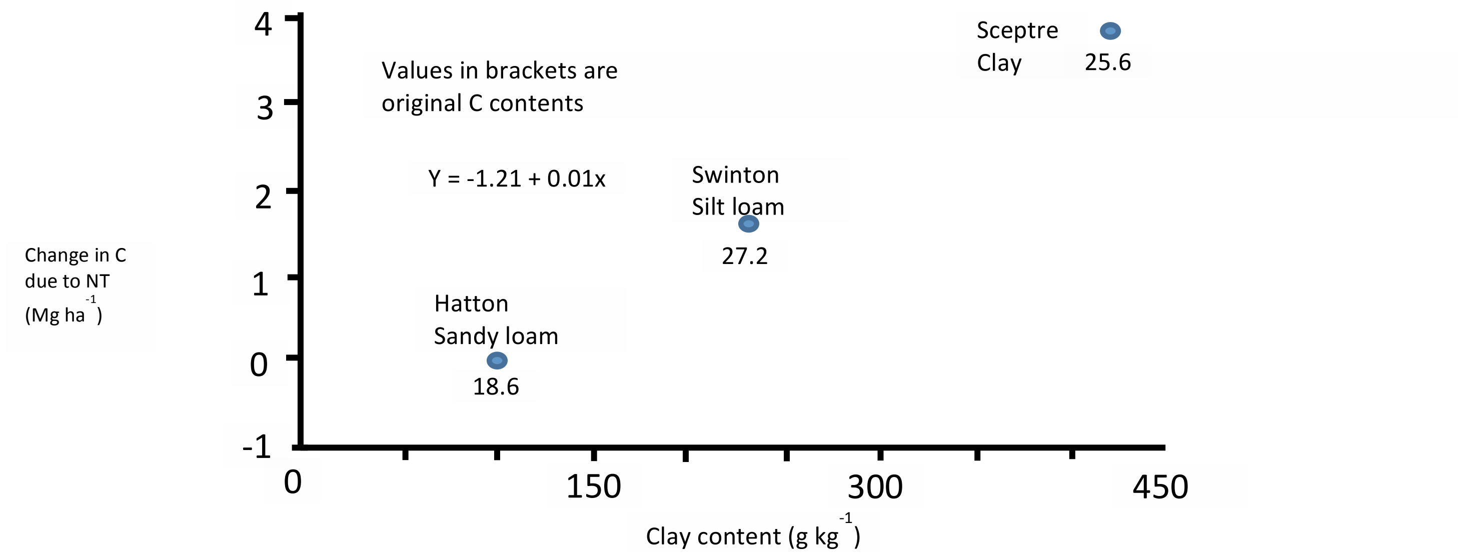
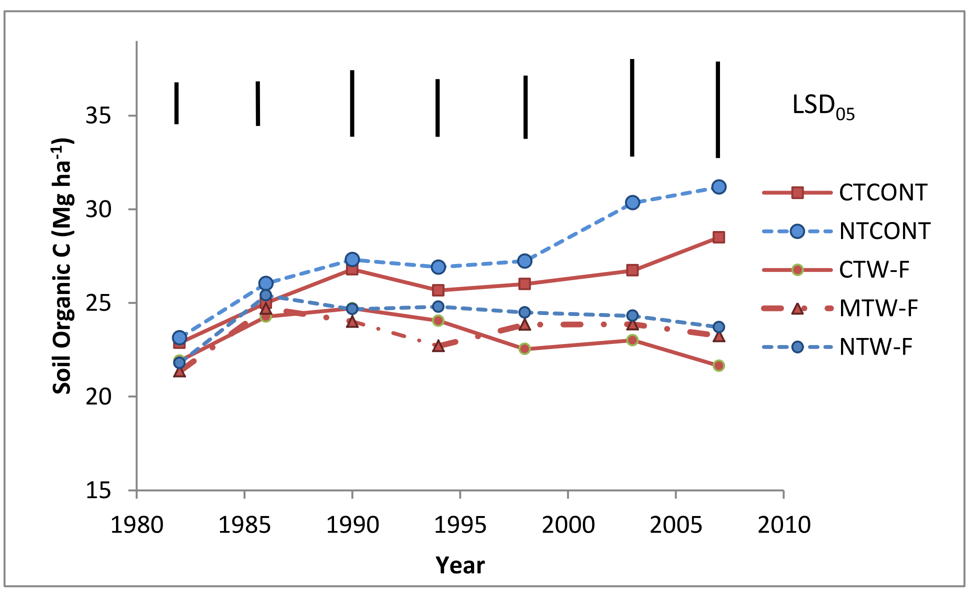


Figure 2. Effect of tillage and cropping frequency on soil organic carbon in the 0-15 cm depth on the silt loam site (1982-2007).



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