Old Rotation Study – Swift Current, Saskatchewan

Reynald Lemke[1], Con Campbell[2], Robert Zentner[3], Hong Wang[3]
[1] Agriculture & Agri-Food Canada, 51 Campus Drive, Saskatoon, SK, S7N 5A8.
[2]Agriculture & Agri-Food Canada, Eastern Cereals & Oilseed Research Centre, Ottawa, ON, K1A 0C5.
[3] Agriculture and Agri-Food Canada, Semiarid Prairie Agricultural
Research Centre, Box 1030, Swift Current, SK, S9H 3X2.

Summary
The "Old Rotation" experiment was initiated in 1966 at the Agriculture and Agri-Food Canada Research Centre at Swift Current, Saskatchewan. The overall objectives were to evaluate the influence of rotation length, fallow substitute crops, and nitrogen (N) and phosphorus (P) fertilizers on crop yields, grain protein, N and P uptake, moisture conservation, nutrient use efficiency, incidence of disease, and long-term changes in soil chemical, physical, and biological properties. Economic returns and non-renewable energy use efficiency from changes in the rotations were also determined. Results to date indicate that increased cropping frequency in combination with appropriate fertilizer applications resulted in the highest total annualized grain production, fostered improvements in soil quality and precipitation use efficiency, and reduced the risk of nitrate-nitrogen leaching. This long-term data set has proven invaluable for developing and testing simulation models used to represent crop growth, soil organic carbon and nitrogen dynamics, soil water and temperature status.

Introduction
The "Old Rotation" experiment was initiated in 1966 at the Agriculture and Agri-Food Canada Research Centre at Swift Current, Saskatchewan, on an Orthic Brown Chernozem with a silt-loam texture. This soil has organic carbon and nitrogen (N) contents of about 2.0 and 0.2 % (0-15 cm depth), respectively, and a surface pH of 6.5. In this region, potential evapotranspiration is often double growing season (May-August) precipitation, thus the conservation and efficient use of moisture is imperative for successful crop production. During the first decades after the land was brought into cultivation, cropping systems evolved which relied heavily on spring wheat grown in sequence with tilled summer fallow. Fallowing increases available soil water reserves for the following crop and reduces the risk of crop failure due to drought. However, by the time this study was initiated, it was well established that the frequent use of tilled fallow had negative consequences with regard to soil erosion risk, salinization, and soil and water quality. Thus producers were being encouraged to move towards more frequent cropping (less frequent fallow), more diverse crop choices, and appropriate use of commercial fertilizers. Minimizing the use of fallow raised important questions regarding the economic viability of extended rotations, and concerns about maintaining such systems over the long term without a build-up of weed, disease and environmental issues. The overall objectives of this on-going study were to evaluate the influence of rotation length, fallow substitute crops, and nitrogen (N) and phosphorus (P) fertilizers on crop yields, grain protein, N and P uptake, moisture conservation, nutrient use efficiency, incidence of plant diseases, and long-term changes in soil chemical, physical, and biological properties. Economic returns and non-renewable energy use efficiency from changes in the rotations were also determined.

Twelve crop rotations deemed potentially suitable for south-western Saskatchewan were initially implemented (Table l). Commercial farm equipment was used to perform all cultural and tillage operations. Plots to be planted generally received one preseeding tillage operation with a heavy-duty sweep cultivator and mounted harrow to prepare the seedbed. In later years, flax, lentil and canola plots also received a harrow-packing operation. All crops were planted in early- to mid-May using a hoe press drill. Recommended crop varieties were planted each year, but the cultivars changed as new ones became available. Wheat and canola seed was treated with fungicide to control soil-borne and seedling diseases (and also an insecticide in the case of canola), while lentil and pea seed was inoculated with an appropriate *Rhizobium* culture prior to planting. Fertilizer N, initially as ammonium nitrate (34-0-0) and later as urea (46-0-0), was broadcast and incorporated with spring cultivation; P, as mono-ammonium phosphate (11-48-0), was placed with the seed. Fertilizer N rates were based on amounts of soil nitrate (0 – 60 cm soil layer) measured in individual plots from soil samples taken the previous fall. From 1967 to 1990 we used N rates recommended by the soil-testing laboratory of the University of Saskatchewan with N applied to bring total mineral N (soil N + fertilizer N) to 65 kg N ha^{-1}. Starting in 1991, rates of N fertilization were increased to meet targets of 90 kg N ha^{-1} of available N in the soil for wheat grown on summer fallow, and 73 kg N ha^{-1} for wheat grown on stubble, as per new Saskatchewan Soil Testing Laboratory recommendation guidelines. On average, all cropped treatments designated to receive P received 9 - 10 kg P ha^{-1} yr^{-1}. All in-crop weed control was based on weeds present and only recommended herbicides, rates and application methods were used. On average, fallow plots received about four tillage operations (mainly cultivator and rodweeder). In the fall, after harvest, 2,4-D was applied to all plots to control winter annual weeds. All phases of each rotation were present each year and each rotation is cycled on its assigned plots. All rotations were replicated three times. Each plot is 10.5 m by 40 m.

Eight of the original treatments remain, having undergone only minor modification. Over the years, other treatments have been revised or replaced to allow comparisons of a greater diversity of crops and/or more extended rotations (Table 2).

Major Findings

Grain Yields and Quality

During the first 18 yr (1967–1984) of the experiment, growing season precipitation (GSP) averaged 176 mm or 16% lower than the long-term mean for this region, and was less than 80% of normal in 9 of 18 years. In contrast, during the next 18 years (1985–2002), GSP averaged 230 mm and was near-normal to well-above normal in 13 of 18 years. During this time there were 6 years with severe drought conditions (1967, 1973, 1984, 1985, 1988, and 2001) that were equally distributed between the two periods. Not surprisingly, yields of N and P fertilized crops averaged 30 to 45% higher during 1985–2002 than during 1967–1984. The higher yields were attributed to a combination of the more favourable weather conditions, higher rates of N fertilizer that were applied since 1991[5,6], and to improved crop varieties and production technologies.

Analyses after 36 years found that grain yields of wheat grown on stubble averaged about 30% less than yields of wheat grown on fallow. However on a per unit area basis, total grain production is proportional to cropping frequency, with total wheat production averaging 40% more for ContW compared to F-W (Figure 1). Grain quality parameters (e.g., bushel weight), grain N concentration, and harvest index were largely unaffected by cropping frequency, instead, being strongly related to water deficit. Thus, even after 36 years of consecutive wheat crops, grain yield and grain quality measures compared very favourably to rotations with higher frequencies of fallow.

Over an entire 36-year period (1967-2002), the application of recommended rates of N fertilizer to wheat grown on stubble increased yields by more than 20%, while for wheat on fallow the increase was just over 5%. During the moister 1985-2002 time period, N fertilizer increased yields of wheat on stubble by 48%. Over the same time period, P fertilizer increased yields by 12% for wheat on stubble and 15% for wheat on fallow. Withholding N fertilizer additions on the ContW system resulted in significantly lower average grain protein levels (average 13.5 vs. 14.5%). Phosphorus concentrations in wheat grown on stubble were greater than in wheat grown on fallow due to P dilution by yield. The P concentration in wheat was directly related to rainfall.

Rotation length or cropping frequency had no effect on the yields of well-fertilized wheat grown on fallow or on stubble. Further, no yield advantage was observed for growing wheat in mixed rotations with flax[6] or grain lentil[18] as compared with monoculture wheat, although there was a tendency for wheat grown after flax to yield slightly more than for wheat grown after wheat in the 1985–2002 period. The latter effect was perhaps due to the greater soil nitrate found in the lower soil depths after flax (discussed in further detail later). The general lack of significant rotational yield benefits frequently reported in more humid regions, was attributed largely to the fact that diseases were rarely a major problem under the semiarid growing conditions.

Fertilizer Nitrogen and Phosphorus Balance

After 39 years (1967-2005), plots receiving both N and P each year had grain P removals averaging from 54 to 78% of fertilizer P additions[14]. Where P was applied annually and N was withheld, 13% less P was removed in the grain. On the plots receiving annual P additions, P content in the 0-15 cm soil depth using the Olsen extraction method increased linearly with time. For plots receiving both N and P it reached a maximum after 20 - 22 years and then stabilized. After 27 years of P fertilization, subplots were established where P additions were withheld. When P was withheld between 1994 and 2005, total grain production in the ContW plots was reduced slightly (by 10%), but there was no effect on the F-W-W system. Crop P removal (1967- 2005) where P was withheld in the final 12 years was equivalent to 105 and 90% of fertilizer P added to the N plus P and P-only plots, respectively (Table 3). Analysis of changes to P using the Olsen extraction method and calculated P balance indicated a critical Olsen-P concentration for this soil of about 25 kg ha^{-1}. Thus "building" Olsen-P to this point and thereafter balancing P applications with P removals would be an effective and sustainable management strategy. Results indicate that residual P in prairie soils is retained in forms that are available to plants over time; wheat crops may therefore recover close to 100% of applied fertilizer P given sufficient time.

Fertilizer has been shown to have no effect on the total amount of moisture used by the crop during a growing season. This assumes that the amount of soil moisture in the fertilized and unfertilized systems is the same at seeding. In this study a long-term cumulative effect was detected on the well-fertilized systems. These systems generally produced more crop and residues and thus conserved more over-winter precipitation leading to more moisture available annually than the less well-fertilized systems. Calculated moisture use efficiencies (MUE) for the well-fertilized systems tended to be unaffected by fertilizer (i.e. yields were higher but available moisture was also higher). However in the later years of the study, MUE began to increase on fertilized systems, presumably because the cumulative effect of the fertilizer had improved the soil quality[3].

When MUE calculations were made in terms of "precipitation use" or "water use efficiency" (WUE), which is adjusted for the inefficient storage of moisture during fallow years, the results indicate that WUE is greatest for continuously cropped systems and, overall, is increased when appropriate amounts of N and P fertilizers are applied. Expressing the efficiency of water use based on precipitation required per unit of grain produced (kg grain mm^{-1} ha^{-1}) from the complete cropping system resulted in rankings of ContW (4.6) > W-Lent (4.2) > F-W-W (4.1) > F-Fl-W (2.9)[12].

Quantification of the effect of the distribution of growing season precipitation on yield confirmed the critical benefit of receiving precipitation during the grain development and filling stages for both fallow-seeded and stubble-seeded wheat, but for the latter it also showed the importance of receiving adequate precipitation during seeding time to ensure a good plant stand. This also emphasizes the critical importance of conserving spring soil moisture by minimizing soil disturbance and maintaining soil residue cover.

Economic Returns and Riskiness

Economic analysis of the first 12 years of this study indicated that the three-year F-W-W rotation receiving recommended rates of fertilizers was the most profitable under most reasonable input and product price assumptions[16]. The application of recommended rates of N fertilizer increased net farm income for the F-W-W and ContW rotations by 6.6 and 10.5%, respectively. Use of P fertilizer in the three-year wheat rotation increased expected net farm income by an average of 20.6% [15]. It was concluded that ContW could only be recommended in periods of high expected grain prices and for producers who have the financial capability to purchase the extra resources required. Furthermore, because of the high income variability or risk associated with continuously cropped rotations, it should only be considered by producers who are willing or able to withstand major fluctuations in income. Thus, producers who expect grain prices to be low, or who have high outstanding debts, low operating capital, or are highly averse to risk, would likely do best by including some fallow in the rotation. Additionally, producers were advised to consider introducing flax, fall rye or oat hay into wheat rotations only when the price of these commodities was high relatively compared to that for wheat.

The economic merits of cropping systems may change over time as changes to government policy, cropping practices, market opportunities, and weather patterns occur, therefore a re-assessment was undertaken for the 1985 to 2002 time period[19]. In this case results indicated that net returns were highest for the W-Lent rotation (which was not present during the first twelve years) and lowest for F-Fl-W rotation. Net returns for well-fertilized fallow containing systems and ContW were similar, contrasting with results for the earlier and much drier 12-year period. Using average costs for the 1985-2002 period, withholding N on the ContW systems decreased net returns by \$71 ha^{-1} yr^{-1}. For the F-W-W system, withholding P decreased net returns by \$18 ha^{-1} yr^{-1}, and withholding N reduced net returns by \$32 ha^{-1} yr^{-1}.

Non-Renewable Energy Use Efficiency

Analysis of the rotations indicated that non-renewable energy inputs (both direct and indirect) typically increase with increasing cropping intensity[17]. Fuel for machine operations and fertilizers, particularly N, represented the major energy inputs, each accounting for 15 to 50% of the total energy requirements of the cropping systems; pesticides typically account for less than 10% of the total. Total energy output also typically increases with cropping intensity, reflecting the greater quantities of total grain and forage produced with these cropping systems. Using recommended rates of fertilizer based on soil tests and including pulse crops in the rotation were effective in reducing non-renewable energy input requirements and/or increasing energy output, thereby contributing to improvements in overall energy use efficiency.

Plant Diseases

The severity of leaf spotting diseases of spring wheat (tan spot, stagnospora blotch, and septoria blotch) was greater in wheat grown after fallow than in monoculture continuous wheat, or in wheat after a non-cereal such as lentil or flax, particularly in years with high disease pressure[9]. Furthermore, under low N fertility conditions, tan spot levels increased in dry years, whereas P deficiency decreased leaf spot severity in years that had cool and wet springs. In contrast, common root rot was highest in wheat grown after lentil and lowest in wheat grown continuously with low N fertility. Properly fertilized continuous wheat and wheat grown after summerfallow had similar root rot levels[10].

Soil and Environmental Quality

During the first 70 to 80 years of cultivating grassland soils in western Canada, soil organic matter concentration levels declined by 40-50% and potentially mineralizable N declined by 50-65% in the surface soil layer[1]. However, this soil degradation can be halted and even reversed by using improved management practices. Conservation of plant residue on the soil surface protects the soil against wind and water erosion, reduces soil moisture losses, traps snow to increase soil moisture reserves, and provides winter protection for fall-seeded crops. Results from this study have shown that continuous cropping, particularly to cereals, using fall seeded crops and perennial forages are effective in conserving surface crop residue and promoting improved soil aggregation. Indeed, results indicate that under conventional (tillage based) management, carbon sequestration can be realized for degraded soils if converted to well-fertilized extended crop rotations such as ContW, W-Lent and the F-FRye-W (Figure 2). In addition to soil carbon sequestration rates that rivalled ContW, the W-Lent system also has lower soil-emitted nitrous oxide and fossil fuel energy use, thus net carbon dioxide equivalents contributed to the atmosphere are lower than cereal based rotations[13]. This suggests that including pulse crops in rotation with wheat and/or oilseeds may be an important option for reducing greenhouse gas emissions from agricultural activities.

Despite the desirable effects that are provided by cropping the land more intensively, such systems may also have the undesirable effect of lowering soil pH in the top 15 cm. However, results from the first 17 years of this study indicated that prudent use of N and P fertilizers decreased soil pH by about 0.5 units. It was concluded that the use of soil test recommended rates of fertilizers would not in the foreseeable future contribute to the need for corrective actions such as applying lime[2].

Partial N balances calculated for the rotations indicate that more N is removed than is added, and that this N removal is inversely proportional to cropping frequency[5]. Surprisingly, change in soil N measured in the 0 to 30 cm soil depth suggests that none of the fertilized rotations have lost N, while the ContW system has actually gained N. As yet, we have no explanation of the source of the additional N in the soil. Exacerbating the N budget imbalance, results from deep coring of the plots after 37 years indicates that some nitrate appears to have leached beyond the rooting depth of spring wheat, especially under the F-W [NP] rotation[7]. Amounts of nitrate leached tended to be greater and to be located deeper in the soil profile as fallow frequency increased. However, fallow-containing systems with inadequate fertilizer N or P also showed a tendency for nitrate leaching losses because of low plant utilization of available N. Continuously cropped treatments showed little evidence of leaching loss.

Studying the soil nitrate profiles under these rotations also identified a possible problem that may require the attention of agronomists as they ascribe N fertilizer recommendations for cropping systems that include legumes. Soil nitrate appears to be building up in the lower rooting zone (60 to 120 cm) of the W-Lent system over time[4]. However, the soil tests used to base fertilizer recommendations for this study only considered nitrate in the 0 to 60 cm depth, thus over-fertilization of this system appears to be occurring. If true, it implies an inefficient use of economic resources and the potential for increased nitrate leaching and denitrification losses of N.

Soil organisms are critically important in the formation, quality and function of agricultural soils. Analysis has shown that cropping systems that include a diversity of crop types and minimize soil disturbance have higher microbial populations and microbial diversity than monoculture cropping systems that rely on mechanical tillage. Further, cropping frequency and long-term fertility management modified soil microbial community structure and function. In contrast, these factors had little effect on the total biomass of soil microbial populations[11,8]. The full impact of these changes is as yet unclear.

Agro-ecosystem modeling

Agro-ecosystem models are becoming increasingly important for site-specific analysis and development of site-adapted agricultural production systems, and on a regional or national scale for the evaluation of current land use and potential remediation measures through scenario simulations. The long-term data from the "Old Rotation" study has proven invaluable for testing a number of simulation models. These include crop growth simulation models (e.g., SPAW, DSSAT), models that simulate soil water and temperature dynamics, soil organic carbon changes (e.g., CENTURY, IBCM, Campbell model), soil nitrogen dynamics (e.g., LEACHM), and greenhouse gas emissions (e.g. DAYCENT, DNDC). Properly calibrated models are important tools for assessing the impacts of new management strategies (e.g. removing residues for bio-energy uses) and climate change scenarios.

The Future

Changes have recently been implemented to include a more diverse crop rotation and a polyculture forage treatment. It will take a number of years before we can begin to assess the impact of these important changes. Data from this study will also be utilized to inform other relatively recent research questions, such as the impact of crop type, rotation, and management on the total CO_2 footprint of the system, as well as lifecycle analysis for a suite of environmental parameters. It will be of particular value to compare these results to those from the neighbouring "New Rotation" study. Without doubt, the scientific value of this "living laboratory" will continue to accrue offering future researchers many opportunities to address as of yet undefined research questions.

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Table 1. Crop rotations deployed on the Swift Current "Old Rotation" study when the study was initiated in 1967.

Crop sequence	Fertilizer[a]	Special Features	Notes
Fallow-wheat (F-W [NP])	N & P as required		
Fallow-wheat-wheat (F-W-W [NP])	N & P as required		
Fallow-wheat-wheat (F-W-W [N])	N as required		
Fallow-wheat-wheat (F-W-W [P])	P as required		
Fallow-flax-wheat (F-Fl-W [NP])	N & P as required		
Fallow-fall rye-wheat (F-FRye-W [NP])	N & P as required		
Flax-wheat-wheat (Fl-W-W [NP])	N & P as required		Discontinued in 1984
Oat(hay)-wheat-wheat (O-W-W [NP])	N & P as required		Discontinued in 1984
Continuous wheat (ContW [P])	P as required		
Continuous wheat (ContW [NP])	N & P as required		
Continuous wheat (ContW [NP])	N & P as required	Fallow if low soil moisture	Discontinued in 1978
Continuous wheat (ContW [NP])	N & P as required	Fallow if weedy	Discontinued in 1978

[a] P = phosphorus fertilizer; N = nitrogen fertilizer; wheat = Canadian Western Red Spring wheat.

Table 2. Crop rotations currently (as of 2011) deployed on the Swift Current "Old Rotation" study.

Crop sequence	Fertilizer[a]	Notes
Fallow-wheat-fallow (F-W [NP])	N & P	
Fallow-wheat-wheat (F-W-W [NP])	N & P	
Fallow-wheat-wheat (F-W-W [N])	N	
Fallow-wheat-wheat (F-W-W [P])	P	
Fallow-flax-wheat (F-Fl-W [NP])	N & P	
Fallow-fall rye-wheat (F-FRye-W [NP])	N & P	
Fallow-canola-barley-pea-wheat (F-C-B-P-W [N,P])	N & P	Established in 2006
Continuous wheat (ContW [P])	P	
Continuous wheat (ContW [NP])	N & P	
Wheat-lentil (W-Lent [NP])	N & P	Established in 1979
Grass/legume forage (Forage [NP])	N & P	Established in 2006

[a] P = phosphorus fertilizer; N = nitrogen fertilizer; wheat = Canadian Western Red Spring wheat.

Table 3. Grain production, phosphorus (P) additions, P removal in grain, and phosphorus use efficiency (PUE) for two long-term rotations at Swift Current.

Rotation	Cumulative for the period			PUE
	Grain Yield	P Applied	P Harvested	
	(Mg ha^{-1})	(kg ha^{-1})		%
1967-1993				
ContW (NP)	38.0	259	147.6	57
F-W-W (NP)	31.3	173	111.9	65
1993-2005				
ContW (NP)	29.1	116	121.8	-
ContW (P withheld) [a]	26.3	0	105.6	-
F-W-W (NP)	21.3	74	84.0	-
F-W-W (P withheld) [a]	21.0	0	81.2	-
1967-2005				
ContW (NP)	67.1	375	269.3	72
ContW (P withheld)	64.3	259	253.1	98
F-W-W (NP)	53.4	241	195.9	79
F-W-W (P withheld)	52.7	173	193.1	112

[a] Sub-plots were created in 1993 where P additions were withheld, balance of the original plots continued to receive annual additions of P fertilizer.

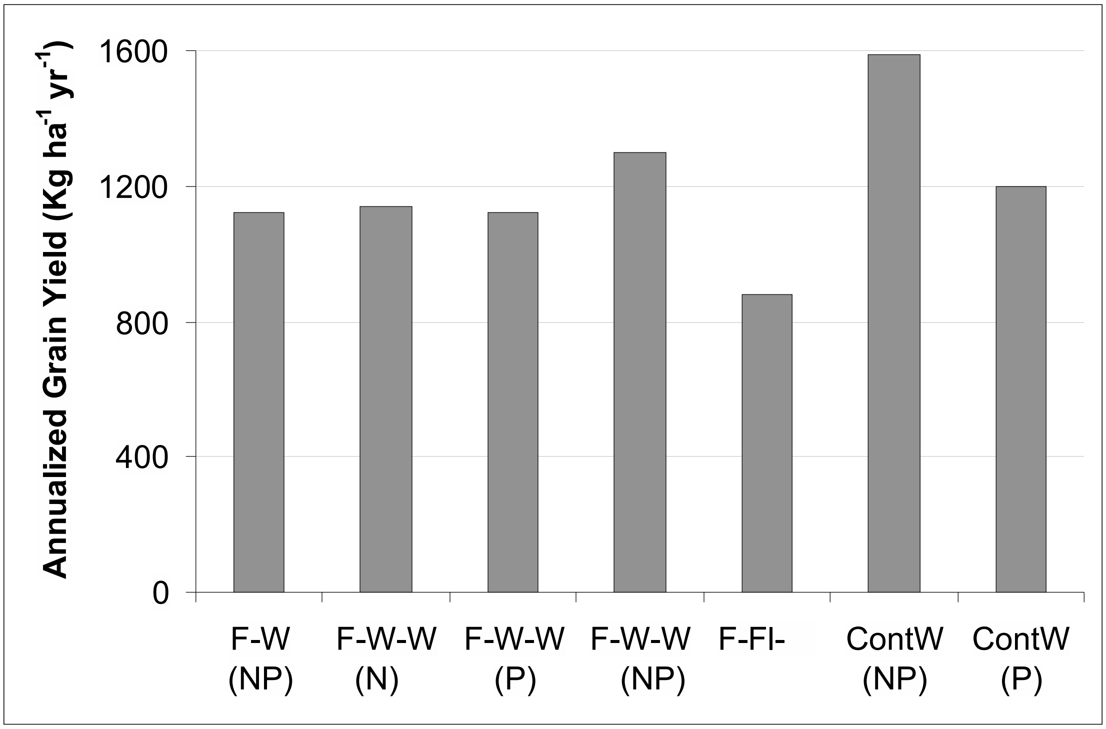

Figure 1. Average annualized grain yield (1967-2005) for selected long-term rotations at Swift Current.

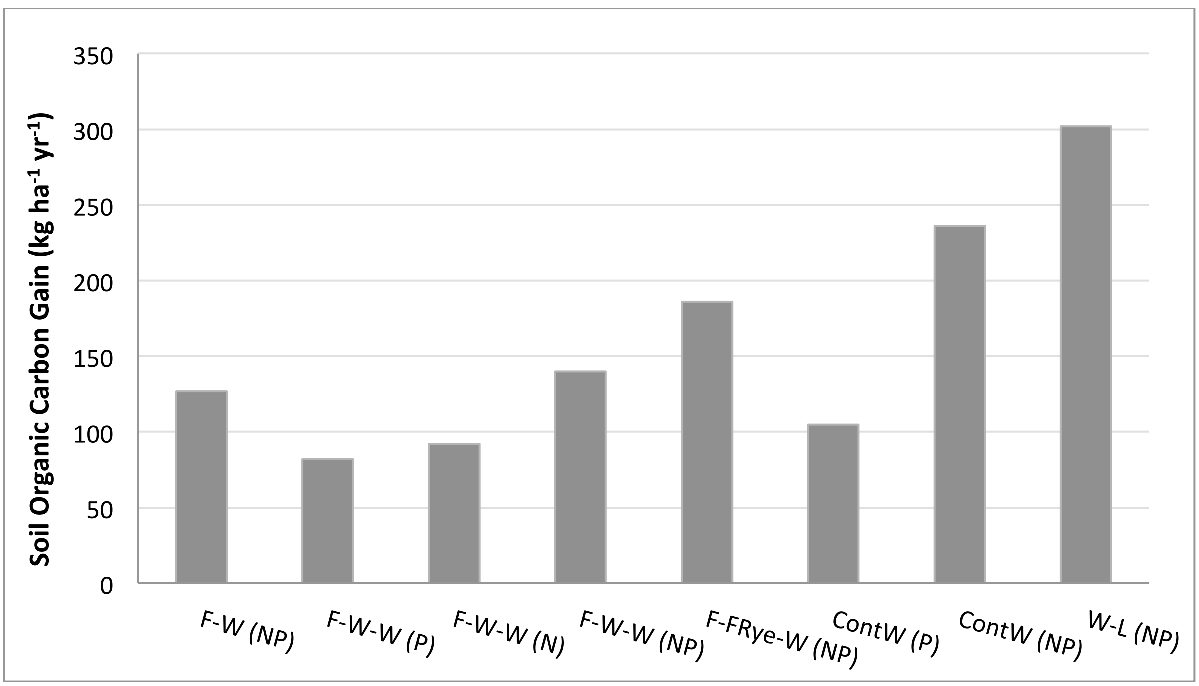

Figure 2. Average annualized soil organic carbon gain (1967-2003) for selected long-term rotations at Swift Current.

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