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FINAL REPORT

"Impact of Zero Tillage on Soil Quality Changes under Crop Rotations and Fertilizer Treatments in a Black Soil"

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"Impact of Zero tillage on Soil Quality Changes under Crop Rotations and Fertilizer Treatments in a Black Soil"

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(a) *Summary*

A crop rotation experiment that was initiated in 1957 on a thin Black Chernozemic clay soil at Indian Head, and which was managed using conventional tillage, was soil sampled in 1987 and 1997 to determine treatment effects on selected soil biochemical characteristics. The rotations were: fallow-wheat (F-W), F-W-W, Continuous Wheat (Cont W), legume green manure (GM)-W-W, and F-W-W-hay) legume grass)-hay-hay (F-W-W-H-H-H). The monoculture cereal rotations were either fertilized with N&P based on soil tests or unfertilized, while the legume systems were both unfertilized. There was also a F-W-W (N+P) treatment in which the straw was harvested. The experiment was changed to no-tillage management in 1990 and, in anticipation of greater soil water storage, the fertilizer protocol was changed to satisfy the "moist soil" criteria. As a consequence, higher rates of N&P were added thereafter, resulting in an upward trend in stubble-crop yields as well as a positive yield response of wheat grown on fallow, where before there was no response to fertilizer. Because crop residues are directly proportional to yield, and crop residue C is one of the main factors that influence changes in soil organic matter, it was perhaps not surprising to find that the fertilized systems all gained organic C and total N between 1987 and 1997 while the unfertilized systems remained constant. Most of the soil biochemical characteristics assessed (organic C and total N, microbial biomass C, light fraction organic C&N, mineralizable C&N) and soil physical properties such as aggregate stability, responded to the treatments in 1997 in a manner similar to 1987. Thus, in general, there were positive responses in these characteristics when we fertilized. Increased cropping frequency, and included legume green manure or legume hay crops in cereal-based rotations. Straw harvesting from a well-fertilized fallow-wheat-wheat rotation did not influence the soil biochemical characteristics, but did result in a soil more prone to erosion. Nor did straw harvesting influence yields. Mineralizable N was lower in 1997 than in 1987, which might explain why crops grown on reduced tillage tend to have lower grain protein than those grown on conventional tillage. Soil structure seems to have been improved with the switch to no-tillage management, as evidenced by a significant increase in wet aggregate. Stability in 1997 compared to 1991: Conversion to no-tillage increased soil bulk densities but not differentially among treatments. Available P fractions were assessed only in 1997. Total P was greater in fertilized systems (as expected) but the increase was surprisingly unaffected by cropping frequency. Most of the P increases occurred in the labile inorganic P pools; surprisingly there was no effect on the organic P pools. There was also some evidence of treatment effects on the moderately labile pool of P. Neither legumes nor straw removal influenced the P pools.

(b) Executive Summary

In 1957, a crop rotation experiment was initiated at Indian Head, on a thin Black Chernozemic clay soil. There were 5 rotations: fallow-wheat (F-W), F-W-W, continuous wheat (Cont W), legume green manure-wheat-wheat (GM-W-W), and F-W-W-hay (legume-grass)-hay-hay (F-W-W-H-H-H). The three monoculture cereal rotations each had two fertilizer treatments (unfertilized vs fertilized with N+P), but the legume-containing rotations were unfertilized.. There was also one fertilized F-W-W treatment in which two-thirds of the straw was harvested from the system each crop year.

In 1987, after 30 years, soil samples were taken from the 0-7.5 and 7.5-15 cm depths of the 9 treatments and these used to assess various soil biochemical characteristics [e.g., organic C, total N, microbial biomass-C (MBC), light fraction organic C&N (LFC&LFN), mineralizable C and N (C_{min} & N_{min})]. We also measured bulk densities in 1987, and in 1991 we measured aggregate stability by dry sieving (to assess wind erodibility), and by wet sieving (to assess resistance to water erodibility).

In 1990 this experiment was converted from conventional tillage to no-tillage management. Because we anticipated that this change would lead to greater conservation of soil water, we changed the fertilization protocol so as to apply fertilizer using the criteria for "moist" conditions as set forth by the soil testing laboratory of the University of Saskatchewan. To determine if this change in cropping system had influenced the soil quality characteristics measured in 1987 and 1991, we repeated these measurements on soil samples taken in 1997. Although available P fractions were not measured in previous years, we also assessed this characteristic in our 1997 samples.

Organic C and total N were increased in the 0-15 cm depth between 1987 and 1997, but only in the fertilized treatments; the values remained constant for unfertilized treatments including GM-W-W and F-W-W-H-H-H. This response was related to increased crop residue C inputs resulting from increased crop production which occurred not only for wheat grown on stubble but also for wheat grown on fallow. The results in 1997, as in 1987 also showed the positive effect of cropping frequency and legumes in rotation on organic C and total N, and confirmed that straw harvesting had no effect on grain yields of wheat nor on orgnaic C or N.

Like organic C and total N, MBC was higher in 1997 than in 1987, likely due to the greater production and conservation of crop residues accompanying the change in management. Fertilized systems, and those containing legumes, had the highest MBC.

Unlike organic C, total N and MBC, the LFC decreased, and LFN remained constant between 1987 and 1997. These results were opposite to what we expected. We are not sure why this is; however, we should stress that LF material (partially decomposed material) is very dynamic within seasons and from year to year, being very dependent on weather conditions. Here too fertilized Cont W and the legume-containing rotations had the highest LF values.

It was difficult to compare the C_{min} measured in 1987 and 1997 because different methods of analysis were used in the two years. Generally, the treatment effects were as described for organic C and total N.

Mineralizable N (N_{min}) responded to the various treatments in a similar manner when measured in 1987 and 1997. Further, N_{min} responded to the treatments in a similar manner to the response of total N. However, N_{min} was significantly lower in 1997 than in 1987 (We had expected the opposite). Usually the more labile constituents, such as N_{min}, C_{min}, MBC, LFC and LFN, are more dynamic than organic C and total N; thus, we would expect them to increase more rapidly in response to the change in management. One possible explanation for the lower N_{min} values in 1997 maybe related to greater immobilization caused by the greater amounts of available C in a no-till system compared to conventional tillage system.

The wind erodible fraction of the soil was greater in 1997 than in 1991, despite greater crop residue cover. But dry aggregate stability is greatly influenced by current weather conditions, thus it may not give a true indication of the impact of the change in management. It was noteworthy that this was one of the few characteristics where straw harvesting was observed to have a negative influence.

In contrast to our findings with the wind erodible fraction of soil, the stability of soil aggregates to the erosive forces of water was much greater in 1997 than in 1991, reflecting the beneficial influence of increased residue cover of the soil and less physical disturbance under no-tillage management. Here too harvesting of straw reduced the water stability of aggregates. Fertilizing, cropping frequently, and the presence of legumes in rotations, increased soil aggregate stability to wind and water forces.

Phosphorus fractionation of soils sampled in 1997 showed that total P has been increased by 40 years of fertilization. This increase was similar for F-W, F-W-W, and Cont W, which contrasts with previous reports in Alberta showing this increase to be directly proportional to cropping frequency. The increase in P occurred primarily in the inorganic P pools. There was no effect of treatments on the organic P pools, as reported in the Alberta study. Some treatment effects were also evidenced in the moderately labile P pool. Neither legumes nor straw removal influenced the P fractions.

In conclusion, a change to no-tillage following years of conventional tillage will increase yields if the change in tillage is accompanied by proper fertilization. At the same time, this change in management will increase soil organic C and total N and soil aggregate stability, but may result in a decrease in the N supplying capacity of soils, possibly the result of increased immobilization. Conversion to no-tillage management without fertilization will not increase soil organic matter content.

The positive influence of fertilization, increased cropping frequency, including legumes (as green manure or hay crops) in cereal rotations, on soil organic C and total N, on other more labile soil organic characteristics, and on soil aggregation, were evident in 1997, as they were in 1987 prior to the switch to no-tillage management. Harvesting straw only showed a negative influence on soil aggregate stability; it did not influence soil organic C or total N, nor yields, even after 40 years.

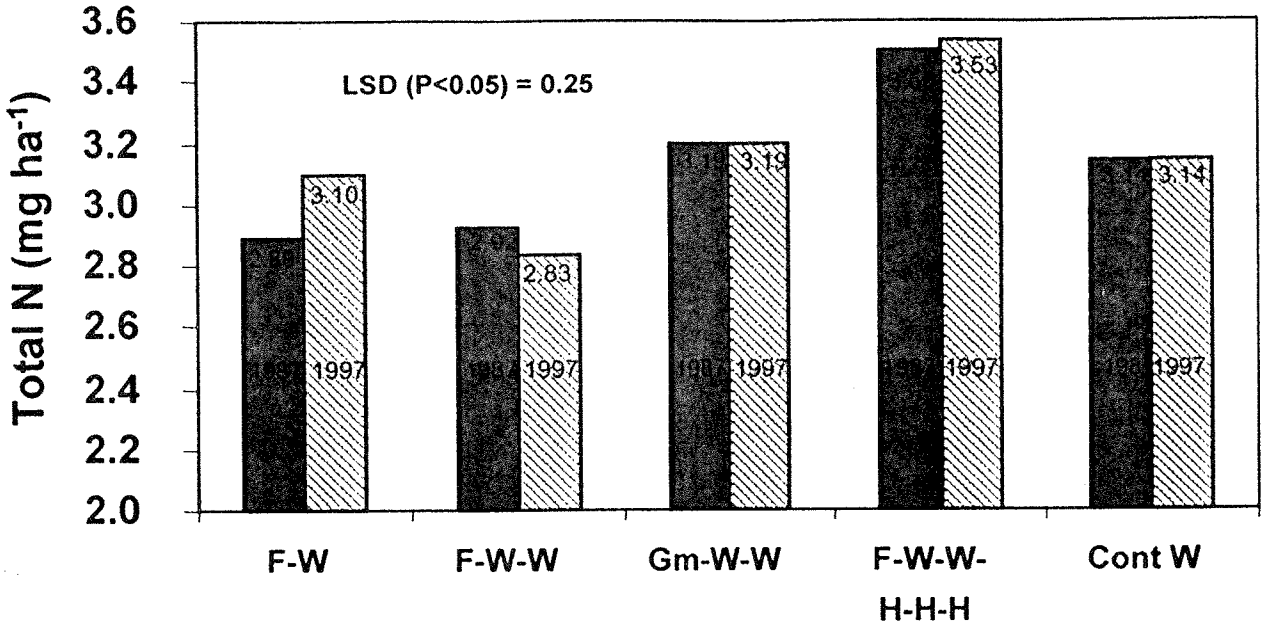
Figure Legends

Fig. 1. Effect of crop rotations, legume green manure (GM), legume-grass hay (H) crops, fertilizer (N+P), straw harvesting, cropping frequency on total Nitrogen in 0-15 cm depth, measured after 30 yr (1987) and 40 yr (1997) after initiation of experiment. (Note: Calculation based on mass per equivalent depth basis because bulk density of soil differed in 1987 and 1997). F = fallow, W = spring wheat in this and subsequent figs.

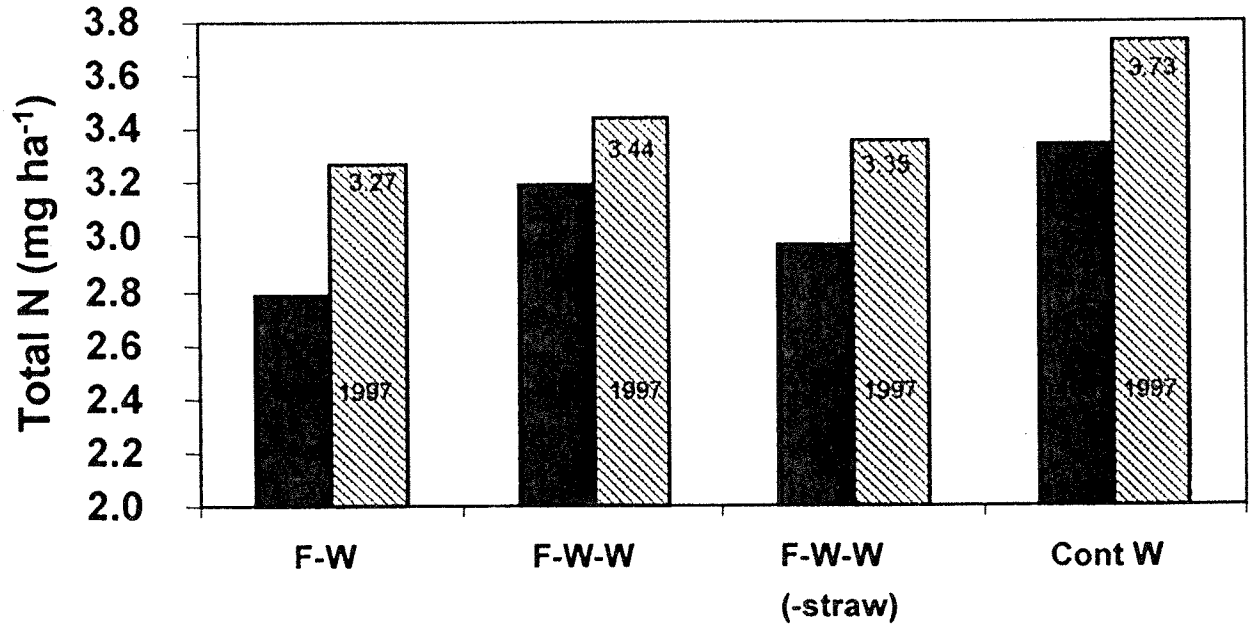
Fig. 2. Effect of crop rotations, legumes, fertilizers, straw harvesting and cropping frequency on wind erodible fraction of soil (aggregates <0.84 mm) measured in fall 1991 and 1997.

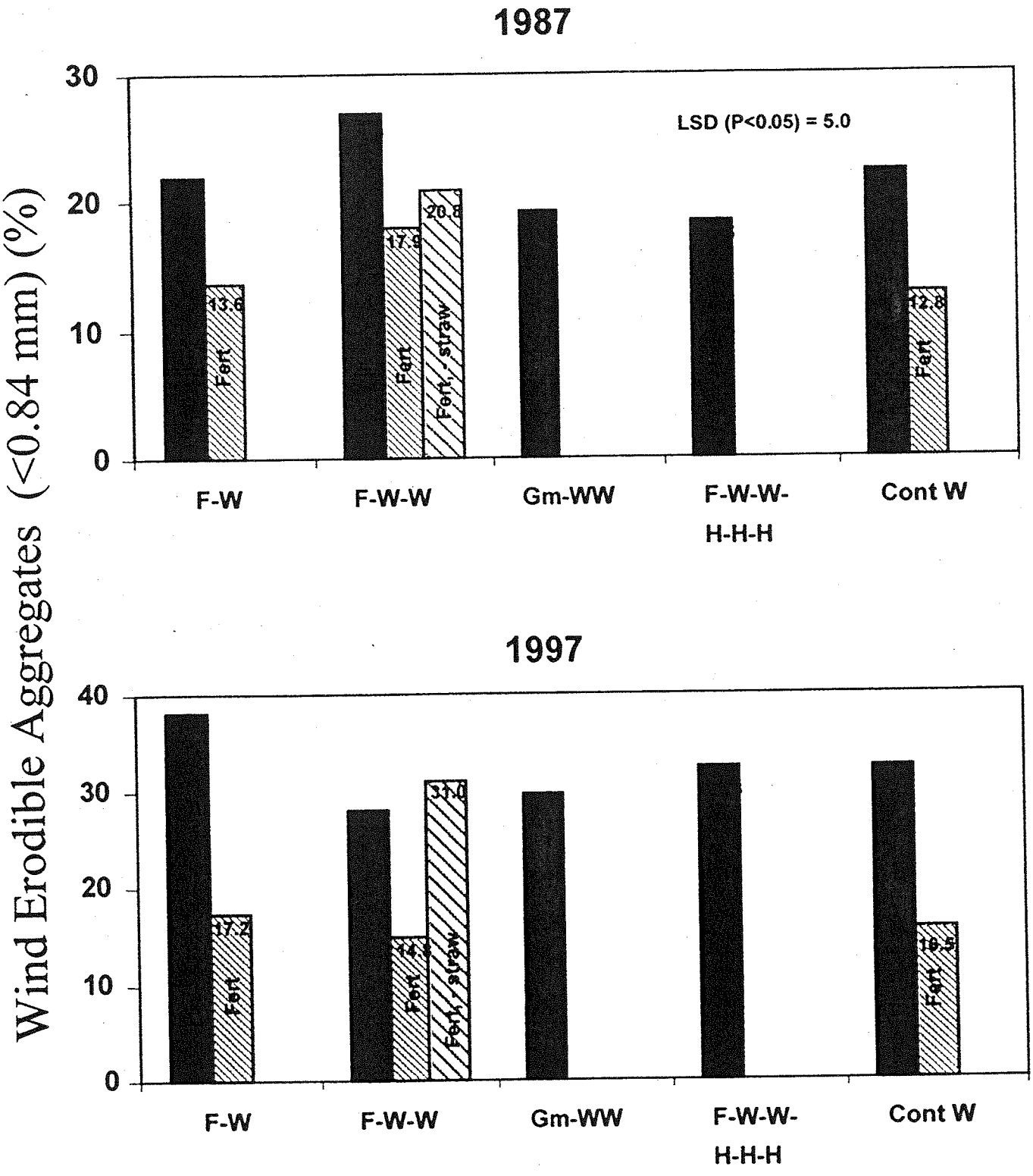
Fig. 3. Effect of crop rotations, legumes, fertilizers, straw harvesting, and cropping frequency on mineralizable Nitrogen measured in 1987 and 1997. (Soil incubated at 35°C for 16 wk; values are for 0-15 cm depth calculated on mass per equivalent depth basis.)

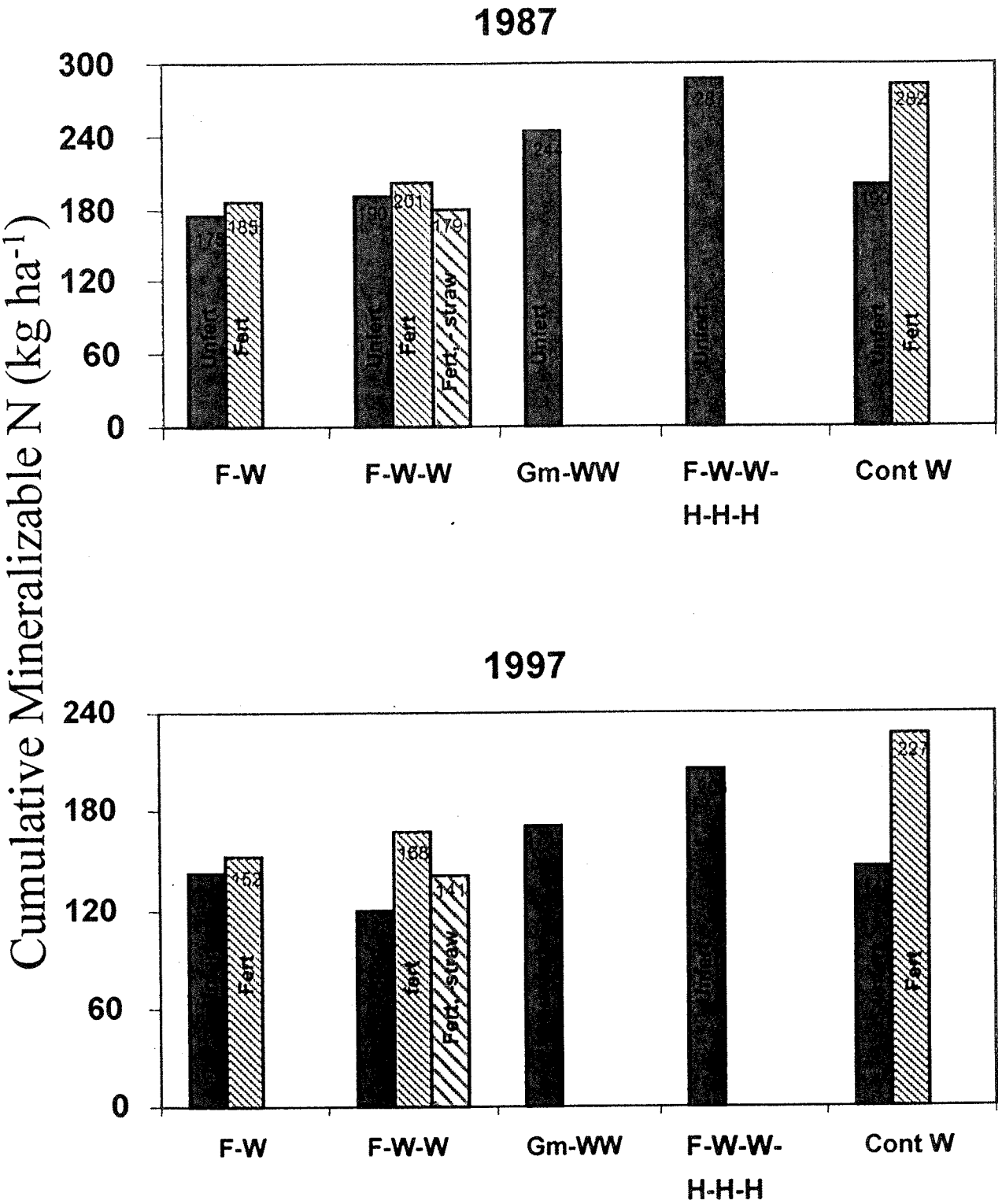
Unfertilized Systems



Fertilized Systems




1987
Wind Erodible Aggregates (<0.84 mm) (%)
30
20
10
0
LSD (P<0.05) = 5.0
13.6
17.9
20.8
12.8
Fert
Fert
Fert, straw
Fert
F-W
F-W-W
Gm-WW
F-W-W-H-H-H
Cont W
1997
40
30
20
10
0
17.2
14.4
31.0
16.5
Fert
Fert
Fert, straw
Fert
F-W
F-W-W
Gm-WW
F-W-W-H-H-H
Cont W


1987
300
240
180
120
60
0
Cumulative Mineralizable N (kg ha-1)
175
185
Unfert
Fert
190
201
179
Unfert
Fert
Fert, - straw
Unfert
Unfert
Unfert
Fert
F-W
F-W-W
Gm-WW
F-W-W-H-H-H
Cont W
1997
240
180
120
60
0
152
Fert
168
141
fert
Fert, -straw
Fert
F-W
F-W-W
Gm-WW
F-W-W-H-H-H
Cont W

(c) Technical Report

Impact of zero-tillage on soil quality changes under crop rotations and fertilizer treatments in a Black soil

Objective

To determine if 6 years of zero tillage management has affected potential fertility and structure of the surface soil, in a 40-yr crop rotation experiment in a Black chernozem at Indian Head. Further, to determine how changes in soil quality are influenced by fertilizer (N + P), legume green manure, legume hay crops, straw removal and cropping frequency.

1. Introduction

There has been a marked trend to adopt reduced tillage (direct seeding) on the Canadian prairies during the past decade. At the same time, many producers have been moving from monoculture cereals to more diversified cropping systems; they have also increased their use of fertilizers, and included more legumes in rotations. In the late 1980's, following 30 yr of a crop rotation experiment conducted on a heavy clay soil at Indian Head, we sampled soil from the various treatments and determined the effect of the aforementioned factors on various soil quality attributes (e.g. organic C and total N, N supply power, soil microbial biomass, soil respiration, soil aggregation, leaching of N & P, yield trends) (Campbell et al. 1997). We showed that it was advantageous, both from an economic and environmental standpoint, to reduce the frequency of fallowing, to use fertilizers (N & P) responsibly (i.e., based on soil test), to include legumes in the crop rotation (although we showed the need to add P to such systems otherwise yields would eventually suffer as available P diminished in soil). We could not demonstrate any negative effect of straw removal on soil quality, except with regards to a decrease in soil aggregate stability; yields were unaffected. The latter information (straw harvesting) is important, especially with regards to the current move to construction of large (>$150m) plants in Winnipeg, Man (Isobord Ltd.) and in Thorhild Alberta, to manufacture board from straw, and building of a plant in Vulcan, Alberta, to make paper from straw. We need to reassess this practice to make sure there are no negative long-term consequences for the soil environment.

During the first 34 yrs of this crop rotation experiment, conventional (mechanical) tillage was used to control weeds. However, in 1990 the study was changed to no-tillage. This is analogous to what many prairie farmers are currently doing. There is limited information on how such a change to no-tillage will influence soil quality. For example, the ability of the soil to supply N and P to plants may be reduced as N and P is immobilized or N is denitrified and this might negatively affect yields and grain protein. Our measurements will demonstrate whether conversion to no-tillage has influenced the N supplying power of soils or soil structure. Both of these factors may influence NO_3 leaching and dentrification, and thus negatively affect the environment. Because P has been applied regularly on some treatments but not on others, we will be able to determine how this has influenced the P supplying capacity of soils. Legumes can provide their own N but not P. We need to determine if the need for P additions to legume-containing systems will increase under no-tillage as compared to under conventional tillage.

To determine whether substantial changes in soil quality had occurred since the 1987 sampling which could at least be partly credited to the change to zero tillage management, we again soil sampled the Indian Head rotation experiment in spring 1997 and conducted various analyses.

2. Materials and Methods

The crop rotation experiment at Indian Head, which was started in 1957, is situated on a fine-textured, thin Black Chernozem, on the Agriculture and Agri-Food Canada Research Farm. Its description and previous results from this study have been well documented (Campbell et al. 1996a), consequently, we only present sufficient information to facilitate discussion of this report.

We sampled five crop rotations (nine treatments) in 1987 and again in spring 1997 (Table 1). These systems included the fallow-wheat (F-W), F-W-W, and continuous wheat (Cont W) systems, all with and without N and P fertilizer. We also sampled the unfertilized legume green manure-wheat-wheat (GM-W-W), and unfertilized F-W-W-H (hay)-H-H systems. The hay was brome-alfalfa. The other system sampled was F-W-W (N + P) in which straw as harvested (about two-thirds of the straw removed each crop year).

The average annual fertilizer N and P applied to designated rotations for the period 1958 to 1996 (kg ha^{-1} yr^{-1}) were 4.0 and 5.5, respectively, for F-W; 16.0 and 6.5, respectively, for F-W-W with straw and with straw removed; and 46.0 and 9.0, respectively, for Cont W. The fertilizer was applied based on general recommendations for the crop and soil zone up to 1977 and on soil test thereafter. In 1990 the experiment was changed to no-tillage and the fertilization protocol was modified to conform to criteria for moist soil conditions in anticipation of greater water storage by no-tillage. This resulted in higher rates of N than previously (Fig. 1).

The rotation phases sampled in 1987 were the ones being fallowed or green manured and continuous wheat (Cont W). In 1997 we sampled phases on which wheat was grown the previous year.

In May 1997 we sampled the various treatments, taking soil cores (3.80 cm diam.) from the 0- to 7.5-cm and 7.5- to 15-cm depths with a Giddings soil corer. Two subsamples were taken from each of the four replicates of each rotation phase for determination of bulk density (Tessier and Steppuhn 1990).

More samples were taken from each of the two depths and the soil in each depth composited by depth and replicate. The soil was sieved (<2 mm) and crop residues remaining on the sieve discarded. One-half of each sample was air-dried and the remainder was stored field-moist at 1-3°C pending analysis for microbial biomass and C mineralization (C_{min}). Within 3 months of sampling, the air-dried soil was used for determination of total organic C and N and net N mineralization (N_{min}). Organic C and total N were determined using an automated combustion technique (Carol Erba™, Milan, Italy), as discussed previously (Campbell et al., 1996b). Mineralizable-N was determined by incubating a soil-sand mixture at 35°C and measuring cumulative nitrate- and ammonium-N generated during 16 wk, by leaching intermittently with dilute $CaCl_2$ followed by a minus-N nutrient solution and evacuating to about 60 cm of Hg (Campbell et al., 1993a).

Carbon mineralization was determined by wetting field-moist soil (50 g oven-dry weight per subsample) to field capacity, conditioning the soil for 3 days at 21°C and then incubating the soil in biometer flasks at 21°C for 14 days in 1987 and 30 days in 1997. In 1997 the evolved CO_2 was trapped in an alkali solution and measured by acid titration on days 4, 9, 16, 23 and 30. In 1987 the titrations were performed on days 2, 4, 7, 10 and 14.

Soil microbial biomass (MB) was determined by the chloroform fumigation-incubation technique (Jenkinson and Powlson, 1976), as described by Biederbeck et al. (1984). From each treatment we used 6 subsamples of field moist soil (each 100 g oven-dry weight) wetted to field capacity and pre-incubated for 3 days at 21°C. Three subsamples were fumigated with $CHCl_3$ and three were left unfumigated. Microbial biomass C (MB-C) was estimated by dividing the flush of CO_2-C by k_C factor of 0.41 (Anderson and Domsch, 1978; Voroney and Paul, 1984).

Soil aggregate stability was measured on separate soil samples taken in May and September 1991 (Campbell et al. 1993b), and in the same months in 1997. This assessment was made by dry sieving using a rotary sieve to isolate the wind erodible fraction of soil (<0.84 mm diam), and by wet sieving using a slaking technique as described by Campbell et al. (1993b).

The air dry soil taken in May 1997 was fractionated to isolate P fractions using the Hedley fractionation procedure (Hedley and Stewart 1982).

The C_{min} could not be compared over years of sampling because of difference in analytical methodology, therefore, analysis of variance was conducted for each year and depth separately to assess effect of treatment. Bulk densities were analyzed for each depth separately as a split plot with treatment as main plot and year as subplot. Bulk

densities in 1987 and 1997 differed significantly therefore, to compare results from 1997 to those obtained in 1987 (where appropriate) we expressed them on a mass per equivalent depth (MED) basis (Ellert and Bettany 1995; Campbell et al. 1998). This calculation was conducted based on the lightest mass for the 0-15 cm depth (1478.3 tha^{-1}) by subtracting an appropriate slice of soil from each of the remaining heavier samples (Campbell et al. 1998). Analysis of variance in these cases were conducted with crop rotation as main plot and year of sampling as subplot (Steel and Torrie 1980). Least significant differences (LSDs) for testing treatment effects were calculated as outlined by Steel and Torrie (1980).

Results and Discussion

3.1 Results 1987 vs 1997

Over the 10-yr period between samplings, the bulk density of the soil in the top 15 cm increased significantly, no doubt due to the reduction in tillage (Table 1). Generally, however, there was no effect of treatment on bulk density in either year. The only exception was the hay containing system in which the density of the 0-7.5 cm depth did not change over the 10 years.

Because of to the substantial change in density over the 10-yr period, proper comparison of the measurements made in 1987 to those made in 1997 required that the results be converted from a concentration basis to a mass per equivalent depth basis (Ellert and Bettany 1995; Campbell et all. 1998). These calculations were made and the results are shown in Table 2.

3.1.1 Total Organic C and N

Organic C and total N have increased by about 6% over the 10 yr period since the soils were sampled in 1987. The increases were primarily in the fertilized systems with no significant change in the unfertilized systems (Table 2). These results differ from those we obtained when we sampled these same plots in 1996 (Campbell et al. 1998). In that case, the fertilized systems appeared to maintain C at the levels observed in 1987 while the unfertilized rotations appeared to lose C. (The latter could be the result of systematic analytical error.) In any event, the interaction between rotation and fertilization is similar. It suggests a need to fertilize adequately when we adopt no-tillage management, otherwise C gains will be forfeited. The impact of fertilizer probably reflects the yield (and thus residue C inputs) response to fertilizer (cf. Fig. 2). The organic C and total N response to fertilizer was significant ($P<0.05$) in 1997 but not in 1987, likely because we increased the rate of N upon conversion to no-tillage (Fig. 1), which increased yield and residue C inputs of even wheat grown on fallow (Fig. 2a&2b). In 1997, as in 1987, organic C and total N increased with cropping frequency in fertilized but not in unfertilized systems; they were increased significantly by the legume-hay system and tended to be increased by the legume green manure system, while straw harvesting tended to decrease them (Table 2).

3.1.2 Microbial Biomass C

The rotation x year interaction was not significant ($P<0.05$), though rotation and year effects were significant (Table 2). The rotation effect was not great, with values ranging between 819 and 1138 $kgha^{-1}$ (averaged over year sampled). Generally, fertilized systems and the legume-containing systems had the highest MBC. Microbial biomass-C was 40% greater in 1997 than in 1987, possibly due to the adoption of no-tillage. In 1987 MBC constituted, on average, 2.7% of the organic C in the top 15 cm of soil; in 1997 it constituted about 3.6%. Neither cropping frequency nor straw harvesting influenced MBC in 1987 or 1997.

3.1.3 Light Fraction C&N

In 1987, the main factors influencing LFC and LFN were fertilization of Cont W, and the legume-hay rotation, both

of which increased LF (Table 2). In 1997, it was mainly fertilization of Cont W that increased LFC, while in the case of LFN, fertilization of F-W-W, and the GM and hay containing systems also increased it. Unlike organic C, total N and MBC, LFC decreased between 1987 and 1997 while LFN was constant over this period. We anticipated finding high LF values following several years of no-tillage; consequently, these results were suprising. The LFC constituted 2.7% of the organic C in the 0-15 cm depth in 1987 (same as MBC), but only constituted 2% in 1997. The LFN was about 1.2% of total N in this soil.

3.1.4 Mineralizable C and N

It was difficult to compare C_{min} results in 1987 vs 1997 because of differences in our method of analysis (see materials and methods). Perhaps this is why the C_{min} results on mass basis (Table 2) were less logical in response than when considered on a concentration basis (Table 1).

Mineralizable N (N_{min}) responded to the various treatments in a similar manner when measured in 1997 as in 1987 (Table 2). The N_{min} responses to rotation, fertilizer, cropping frequency, and straw harvesting treatments were similar to our observations for organic C and total N.

The potential N supplying capacity of the soil (N_{min}) was significantly lower ($P<0.05$) for all treatments in 1997 compared to 1987 (Table 2). We expected the adoption of no-tillage management to result in an increase in total N (it did) and N_{min} (it did not). Further, N_{min} constituted 7% of the total N in 1987 but 5% in 1997. One might have expected that the more labile organic constituent (N_{min}) would have increased more rapidly in response to the change to no-tillage than would total N. For example, in a more detailed analysis conducted on these plots in 1995 and 1996 in which we monitored soil biochemical characteristics throughout the growing seasons, taking 8 samples per plot, we concluded that, over the 9-yr period, LFC and C_{min} increased markedly in the more fertile treatments though hardly changing in the unfertilized systems; at the same time organic C and total N hardly changed in any treatment (Campbell et al. 1999). One possible explanation for the lower N_{min} obtained in 1997 might be related to immobilization caused by the greater amounts of available C that would be in the no-till system compared to the conventionally tilled system. Supporting this hypothesis is the fact that, except for F-W, the decreases in N_{min} values between 1987 and 1997 were much greater for unfertilized systems (40-60%) than for fertilized systems (20-27%). As well, this may explain why no-till systems often support lower protein grain crops than does conventional tillage systems.

3.1.5 Soil Aggregation

Soil aggregate stability to wind erosive forces can be assessed by dry sieving analysis, while aggregate stability relative to water erosion can be assessed by wet sieving, especially using a fast wetting (slaking) procedure. The results may vary with the season when soil is sampled (Campbell et al. 1999), because of soil moisture content; thus we sampled twice, once in spring and again in fall.

The dry sieving results, (particularly in September) showed, as we found previously (Campbell et al. 1993b), that the wind erodible fraction of soil (<0.84 mm diam) was decreased by fertilizing and increased by removal of straw (Table 2). In 1997, the legume green manure and legume hay-cereal systems had no effect on wind erodible aggregates, but in 1991 both legume hay and GM systems decreased the wind erodible fraction of soil (Table 2). The wind erodible fraction of soil was greater in 1997 than in 1991, particularly in F-W and the unfertilized treatments.

The wet sieving results in May and September 1997, showed that fertilizing, including legume green manure or legume-hay crops in rotations, and cropping more frequently, all increased wet aggregate stability (Table 2). Removing straw reduced WAS in May, though not in September. These treatment effects were generally similar to those obtained in 1991. In contrast to our findings for dry sieving, aggregate stability to the erosive forces of water was much greater in 1997 than in 1991, reflecting the beneficial influence of increased residue cover for soil, and less physical disturbance.

The higher erosiveness of the soil to wind, even after years of adoption of no-tillage management, suggest that this characteristic is mainly a function of current weather conditions, as shown by Campbell et al. (1993b). However, the presence of crop residues is also important, as evidenced by the increase in wind and water erodible fraction due to straw removal. Producers who contemplate harvesting straw for use in industrial ventures must take note of the latter observation since this could hasten soil degradation.

3.2 Phosphorus Fractions in 1997

We fractionated the soil using Hedley fractionation procedure (Hedley and Stewart 1982), but present these results in terms degree of P lability by grouping some fractions (Table 3).

The results showed a significant increase in total P in the 0-7.5 cm depth due to addition of N and P fertilizers for 40 yr. However, this increase was similar for F-W, F-W-W and Cont W, which contrasts with results reported in Alberta (Dark Brown chernozemic and Luvisolic soils) where rotations had a significant influence on total P (McKenzie et al. 1992*a,b*).

The differences in P occurred primarily in the inorganic P pools, there being no significant difference in the organic P. The latter also constasts with the findings in Alberta. Not surprisingly, most of the differences in P occurred in the labile P pool and, although not significant ($P<0.05$), there were strong tendencies for effects in the moderately labile pool to mimic those in the labile P pool (Table 3). The nonlabile P, though showing some significant differences, did not show consistent trends. As reported for a Brown Chernozem by Selles et al. (1995), differences in P fractions were only significant in the 0-7.5 cm depth, though in the 7.5-15 cm depth, labile P responses were generally similar to those in the 0-7.5 cm depth. Neither legume hay crops nor straw removal influenced the total P or P fractions; the legumes because they were not fertilized and the straw removal because the P content of straw is so small.

3.3 Yield Trends

A switch from conventional tillage to no-tillage management generally results in greater moisture conservation (Lafond et al. 1992), often necessitating a requirement for greater rates of fertilizer. Consequently, in this experiment, when no-tillage was adopted in 1990, the fertilization protocol was changed so as to provide N based on soil test for "moist" conditions. This resulted in an increase in rates of N applied (Fig. 1, top).

The change to no-tillage management with increased fertilization resulted in an increased upward trend in yields (and likely crop residues) for fertilized wheat grown on fallow (Figs. 2a and 2b). Consequently, while the period from 1957 to 1989 showed no effect of fertilizer on yields of wheat grown on fallow, there is now a significant gradual yield separation of the fertilized and unfertilized treatments, much like the trend we usually observe for wheat grown on stubble (Figs. 2c and 2d). Yields of wheat grown on partial fallow in the GM-W-W system, and on fallow in the F-W-W-H-H-H rotation, were generally the same as for wheat grown on fallow in unfertilized F-W-W (fig. 2e). This indicates that the yield response in F-W and F-W-W was to the extra fertilizer applied, not to no-tillage per se. Nor have the yield resposnes of stubble crop wheat in the two legume-containing rotations changed substantially since 1990 (Fig. 2f).

If we assume that crop residue inputs are directly proportional to grain yields (Campbell et al. 1998), then the organic C and total N results (Table 2) are a reflection of the impact of fertilizer change on residue C inputs. Thus, we find no significant change ($P<0.05$) in organic C or total N in the unfertilized systems between 1987 and 1997, while the fertilized systems generally showed an increase. Because both tillage and fertilization protocol were changed at the same time in this study, we are not able to stipulate which factor accounts for the greater proportion of this response. However, **we can say that a change to no-tillage management, with corresponding adoption of proper fertilization protocol, will likely lead to enhancement of total soil organic matter in this soil in less**

than a decade. A corollary to this observation is the fact that adoption of no-tillage alone, without proper fertilization, will not increase soil organic matter.

The harvesting of straw from fertilized F-W-W rotation had no effect on grain yields (data not shown).

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Table 1. Bulk densities and C_{min}[z] in 0-7.5 and 7.5-15 cm depths under the various rotations measured in spring 1987 and 1997

Treatment	Bulk Density (g cm^{-3})		Cmin ($mgkg^{-1}$)		
	1987	1997	Mean	1987	1997
0-7.5 cm					
F-W	0.90	1.06	0.98	126	188
F-W (N+P)	0.84	1.09	0.97	123	224
F-W-W	0.92	1.03	0.97	148	231
F-W-W (N+P)	0.91	1.13	1.02	136	248
F-W-W(N+P,-straw)	0.89	1.08	0.98	119	265
GM-W-W	0.96	1.04	1.00	160	321
F-W-W-H-H-H	0.94	0.94	0.94	157	272
Cont W	0.92	1.08	1.00	142	227
Cont W (N+P)	0.97	1.03	1.00	171	309
Mean	0.92	1.05	0.98	142	254
Signif. of F ratio LSD (P<0.05)	Year***, 0.04,	Rot x y* 0.08		Rot* 32	Rot** 63
7.5-15 cm					
F-W	1.21	1.40	1.31	103	153
F-W (N+P)	1.21	1.41	1.31	99	170
F-W-W	1.15	1.39	1.27	103	170
F-W-W (N+P)	1.21	1.41	1.31	104	160
F-W-W (N+P,-straw)	1.20	1.41	1.31	91	197
GM-W-W	1.20	1.40	1.30	123	187
F-W-W-H-H-H	1.21	1.40	1.31	111	180
Cont W	1.14	1.37	1.26	96	171
Cont W (N+P)	1.22	1.39	1.31	118	169
Mean	1.19	1.40	1.30	106	173
Signif of F ratio LSD (P<0.05)		Year*** 0.025		Rot** 14	ns -

[z] C_{min} = Cumulative C mineralized in 14 days at 21°C in 1987 and in 30 days in 1997

Table 2. Effect of crop rotations, legumes, fertilizers, straw removal cropping frequency on various soil quality attributes[z] measured on a mass per equivalent depth basis (to 15 cm) assessed after 30 yr of conventional tillage (1987) and 10 yr later (1997) after a change to no-tillage in 1990

	Org C (Mg ha^{-1})			Total N Mg ha^{-1}			MBC (kg ha^{-1})			LFC (kg ha^{-1})			LFN (kg ha^{-1})		
Treatment	1987	1997	mean	1987	1997	mean	1987	1997	mean	1987	1997	mean	1987	1997	mean
F-W	28.81	31.41	30.11	2.89	3.10	3.00	821	1088	955	812	473	643	29	28	28
F-W (N+P)	29.06	32.99	31.02	2.78	3.27	3.03	743	1244	994	564	675	619	23	34	29
F-W-W	29.78	28.00	28.89	2.92	2.83	2.87	735	902	819	874	433	653	30	24	27
F-W-W(N+P)	29.85	35.06	32.45	3.19	3.44	3.32	807	1184	995	807	677	742	32	39	36
F-W-W(N+P,-straw)	28.57	33.50	31.03	2.97	3.35	3.16	764	1172	968	601	532	566	25	30	27
GM-W-W	32.49	31.24	31.87	3.19	3.19	3.19	954	1259	1107	674	578	626	32	41	37
F-W-W-H-H-H	33.61	34.49	34.05	3.50	3.53	3.51	955	1321	1138	1214	661	938	63	46	54
Cont W	30.82	30.84	30.83	3.14	3.14	3.14	847	1139	993	765	615	690	33	35	34
Cont W(N+P)	34.47	36.42	35.44	3.34	3.73	3.54	930	1311	1121	1277	1199	1238	61	67	64
Mean	30.83	32.66	31.75	3.10	3.29	3.19	840	1180	1010	843	649	764	37	38	38
Signif. of F ratio[x] LSD(P<0.05)	Rot***, 3.8	Yr**, 1.2	Rot x yr[†] 3.0	Rot***, 0.32	Yr***, 0.10	Rot x Yr[†] 0.25	Rot**, Yr*** 1 74	, 69		Rot***, Yr* 259	, 154		Rot*** 12.0		

[z] OrgC = Organic carbon, Tot N = total nitrogen, MBC = microbial biomass C, LFC and LFN = light fraction organic C&N

[y] F = fallow, W = spring wheat, GM = legume green manure, H = legume-grass cut for hay, Cont = continuous, N&P = nitrogen and phosphorus fertilizer

x †, *, **, ***, denote significance at P<0.10, <0.05, <0.01, <0.001, respectively

Table 2. (Continued)

Treatment	C_{min} ($kgha^{-1}$ day^{-1})			N_{min} ($kg\ ha^{-1}$)			Dry aggregates(<0.84 mm) (May) (%)			Wet aggregate stability (May) (%)			Dry aggregates (<0.84 mm) (Sept.) (%)			Wet aggregate stability (Sept) (%)		
	1987	1997	mean	1987	1997	mean	1991	1997	mean	1991	1997	mean	1991	1997	mean	1991	1997	mean
F-W	12.0	13.3	12.6	175	143	159	17.0	49.5	33.2	47.0	67.3	57.1	22.0	38.0	30.0	38.6	66.6	52.6
F-W (N+P)	11.5	12.5	12.0	185	152	168	12.9	38.2	25.6	52.9	71.2	62.0	13.6	17.2	15.4	44.0	66.5	55.2
F-W-W	13.1	14.5	13.8	190	120	155	22.8	37.5	30.1	53.9	59.3	56.6	26.9	27.9	27.4	47.0	55.0	51.0
F-W-W(N+P)	12.6	12.3	12.5	201	168	185	13.8	22.6	18.2	56.3	71.5	63.9	17.9	14.8	16.3	51.0	64.0	57.5
F-W-W(N+P,-straw)	11.0	15.3	13.2	179	141	160	16.0	24.1	20.1	55.8	65.5	60.6	20.8	31.0	25.9	46.0	67.5	56.7
GM-W-W	13.6	16.1	14.8	244	171	207	18.7	39.2	28.9	61.2	70.5	65.8	19.3	29.6	24.4	53.4	63.8	58.6
F-W-W-H-H-H	14.3	13.8	14.0	287	206	246	19.2	42.3	30.7	74.1	78.8	76.4	18.5	32.3	25.4	71.8	78.8	75.3
Cont W	12.5	15.07	13.7	199	145	172	27.4	43.3	35.4	57.4	68.5	63.8	22.4	32.3	27.4	49.4	56.4	52.9
Cont W(N+P)	15.2	14.7	14.9	282	227	255	17.0	24.8	20.9	68.3	76.3	72.3	12.8	16.5	14.6	67.2	78.2	72.7
Mean	12.9	14.2	13.5	216	164	190	18.3	35.7	27.0	58.8	69.9	64.3	19.4	26.6	23.0	52.0	66.3	59.1
Signif. of F ratio LSD (P<0.05)	Rot*, Yr** 2.1 , 1.0			Rot***, Yr*** 32 , 13			Rot***, Yr*** , Rot x Yr*** 5.3 , 2.7 , 5.0			Rot***, Yr***, Rot x Yr*** 3.8 , 1.6 , 3.4			Rot***, Yr***, Rot x Yr* 5.3 , 2.7 , 5.0			Rot***, Yr**, Rot x Yr** 3.8 , 1.8 , 3.5		

Table 3. Effect of crop rotations, legumes, fertilizers, and straw removal on P fractions[z] in the 0-7.5 and 7.5-15 cm depths of Indian Head Black chernozem, sampled in May 1997 after 40 yr.

Treatment	Inorganic P	Organic P	Labile P[y]	Moderately labile P[x]	Non-labile P[w]	Total P
			mg kg^{-1}			
0-7.5 cm						
(F)-W	331	238	38	309	221	569
(F)-W (N+P)	397	274	69	364	238	672
F-W-(W)	280	245	27	311	187	525
F-W-(W)(N+P)	369	268	64	354	219	637
F-W-(W)-Str(N+P)	361	271	65	359	208	632
F-W-(W)-H-H-H	336	253	45	306	238	589
Cont. W	345	258	46	321	236	603
Cont. W (N+P)	418	254	75	340	257	672
Signif. of F	**	ns	*	ns	**	**
LSD (P<0.05)	57	51	32	50	30	78
			mg kg^{-1}			
0-7.5 cm						
(F)-W	438	96	19	222	293	534
(F)-W (N+P)	467	103	33	242	296	570
F-W-(W)	428	79	14	206	287	507
F-W-(W) (N+P)	434	102	25	233	279	537
F-W-(W)-Str (N+P)	451	102	32	238	283	553
F-W-(W)-H-H-H	433	90	17	215	291	523
Cont. W	431	95	16	226	284	526
Cont. W (N+P)	489	90	33	254	293	580
Signif. of F	ns	ns	ns	ns	ns	ns
LSD (P<0.05)	47	29	17	36	39	70

[z] P fractions isolated using Hedley fractionation technique.
[y] This is composite of Resin P_i, microbial P, bicarb P_i and bicarb P_o.
[x] This is composite of NaOH-P_i and HCl-P_i.
[w] Residual P.
ns, *, **, denote not significant, and significant at P<0.05 and P<0.01, respectively.

Figure Legends

Fig. 1(a). Annual rates of fertilizer N applied to treatments; (b) growing season (1 May to 31 August) precipitation. (Note: In this and subsequent Figs. F = fallow, W = spring wheat, Cont = continuous, and parentheses denote phase concerned).

Fig. 2. Effect of fertilizer (N and P) and change to no-tillage management after decades of conventional tillage, on wheat yields: (a) & (b) wheat grown on fallow; (c) and (d) wheat grown on stubble; (e) wheat grown on green manure (GM) or fallow in legume-containing rotations; (f) wheat grown on stubble in latter rotations. (Note: H denotes legume-grass hay).

(d) **Personnel** - Dr. C.A. Campbell, Project Leader (Swift Current)
Dr. V.O. Biederbeck (Swift Current)
Dr. F. Selles (Swift Current)
Dr. G. Lafond (Indian Head)
Dr. M. Monreal (Brandon Research Centre)
Mrs. Cherie Wilson, Technician (Swift Current) (Full time)

(e) **Equipment** - No equipment purchased for >$500

(f) **Project Developed Materials** - No publications yet. Anticipate writing at least 3 scientific papers and 3 or 4 technology transfer articles based on this project.

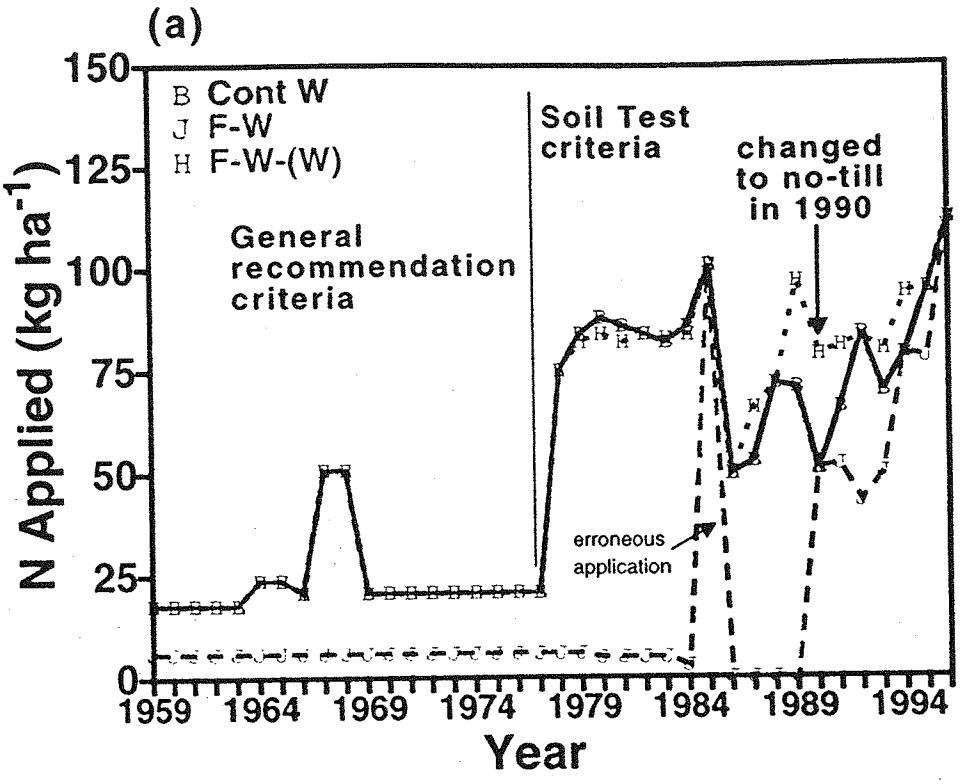
(g) **Project Photos** - None

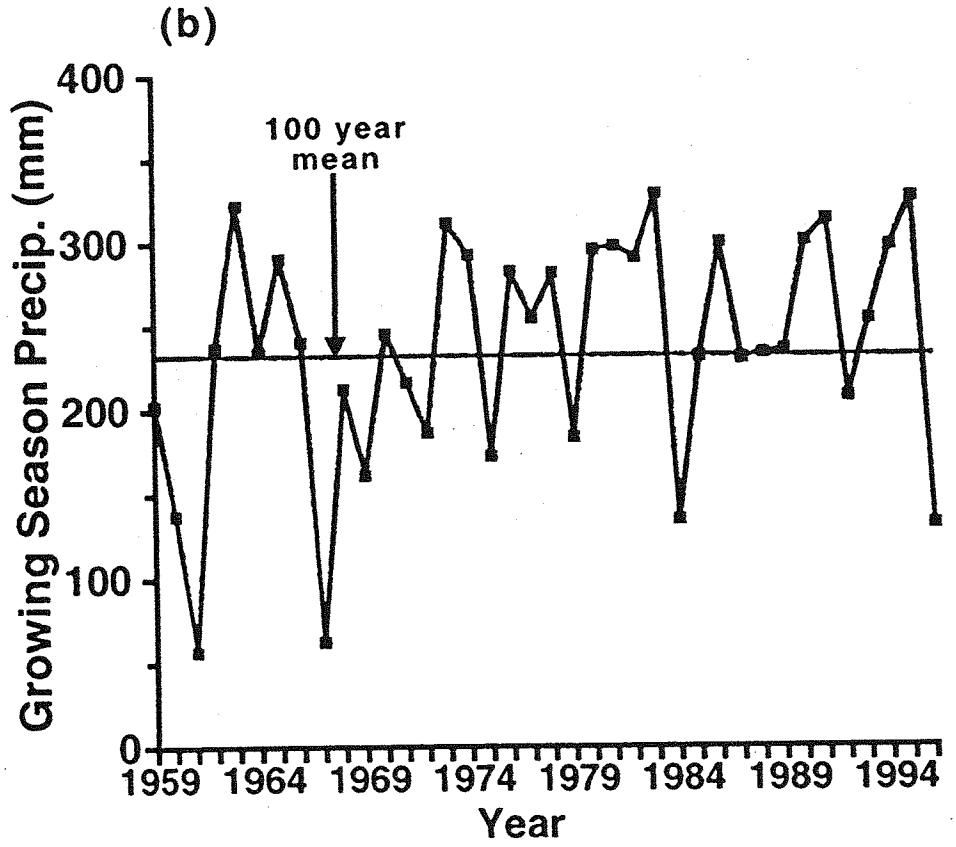
(h) **Acknowledgment** - None to date. This will be done when papers and technology transfer and other news releases are written.

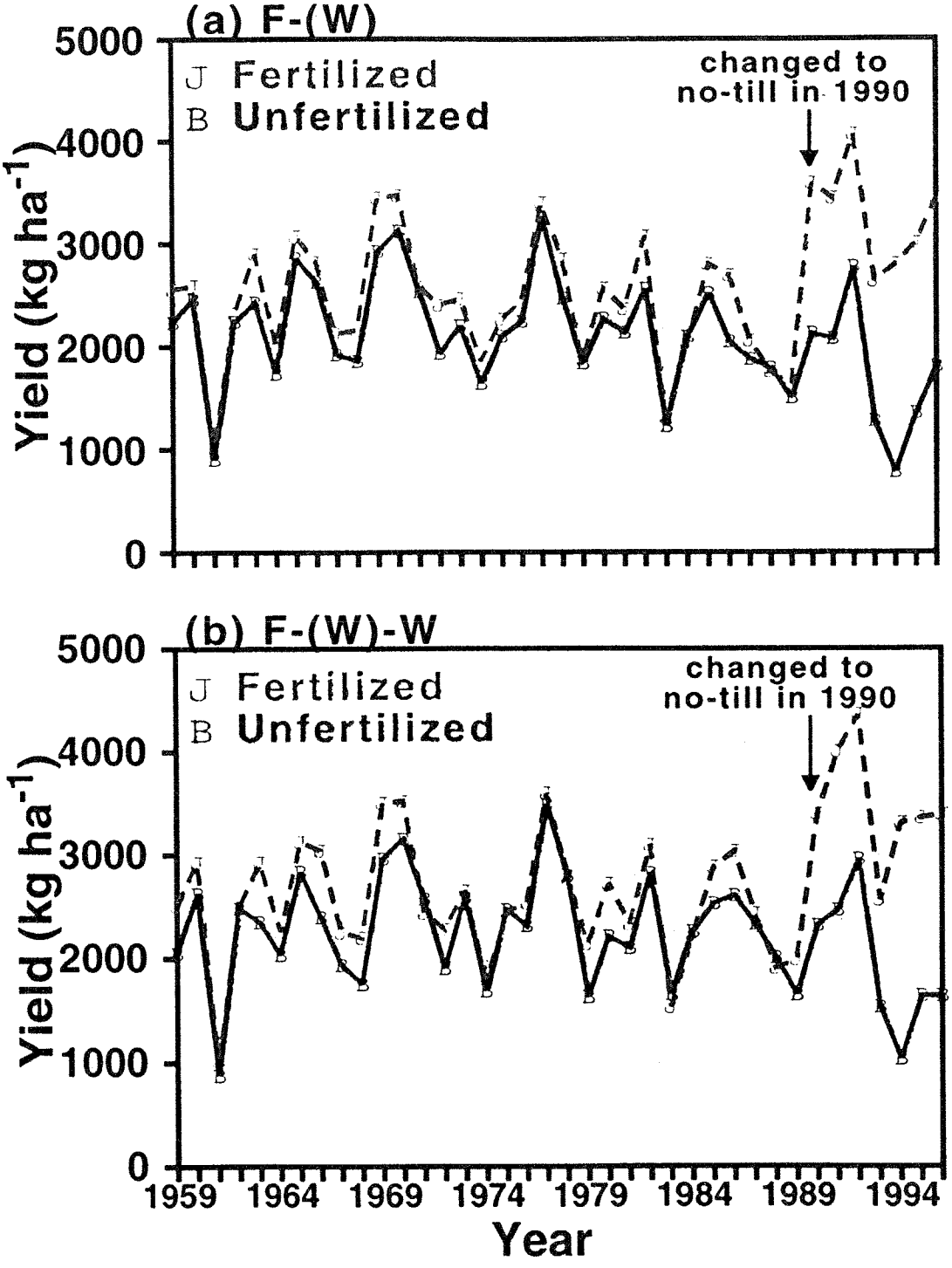
(i) **Expense Statement** -

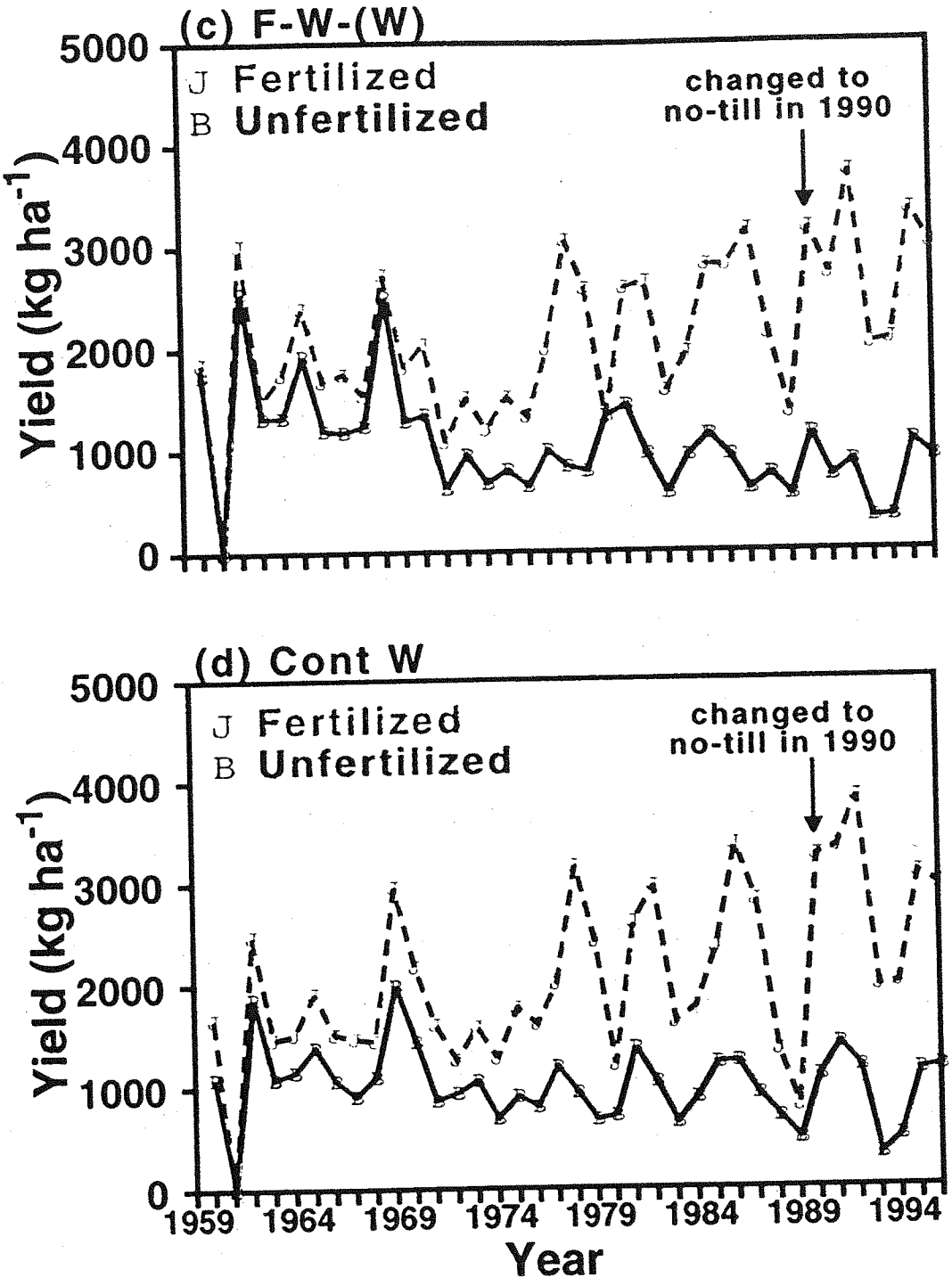
Item	Budget	Expended to date	Balance
Salary Technician	$12,746	$16,246	$-3,500
Materials, Supplies	3,580	3,580	0
Travel	174	174	0
Other Expenses	1,500	1,500	0
Total	$18,000	$21,500	$ -3500

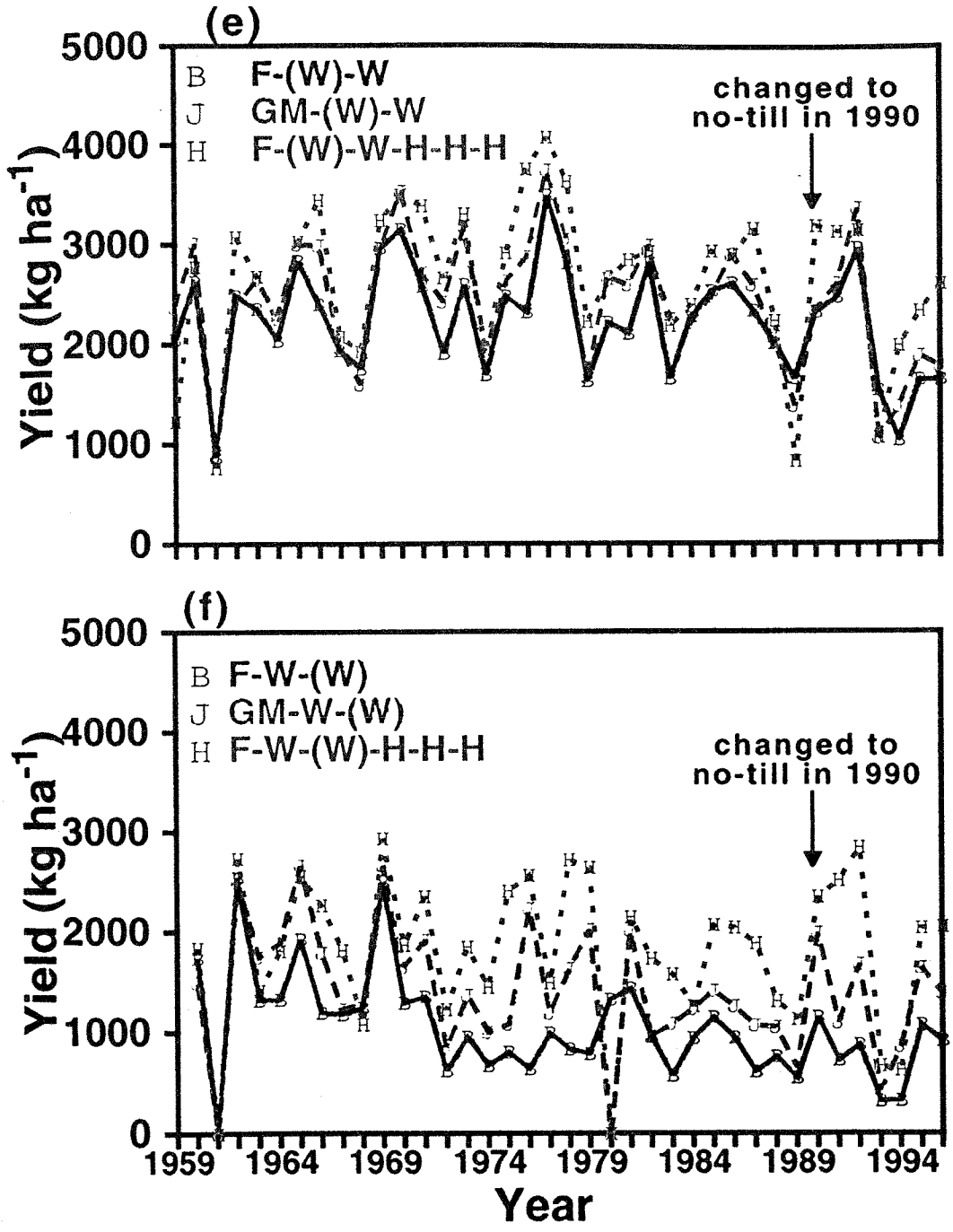
Amount outstanding to be received on approval of Final Report ($3,500)


(a)
B Cont W
J F-W
H F-W-(W)
General recommendation criteria
Soil Test criteria
changed to no-till in 1990
erroneous application
N Applied (kg ha-1)
150
125
100
75
50
25
0
1959 1964 1969 1974 1979 1984 1989 1994
Year


(b)
100 year mean
Growing Season Precip. (mm)
400
300
200
100
0
1959 1964 1969 1974 1979 1984 1989 1994
Year


(a) F-(W)
J Fertilized
B Unfertilized
changed to no-till in 1990
Yield (kg ha-1)
5000
4000
3000
2000
1000
0
(b) F-(W)-W
J Fertilized
B Unfertilized
changed to no-till in 1990
Yield (kg ha-1)
5000
4000
3000
2000
1000
0
1959
1964
1969
1974
1979
1984
1989
1994
Year


(c) F-W-(W)
J Fertilized
B Unfertilized
changed to
no-till in 1990
Yield (kg ha-1)
5000
4000
3000
2000
1000
0
(d) Cont W
J Fertilized
B Unfertilized
changed to
no-till in 1990
Yield (kg ha-1)
5000
4000
3000
2000
1000
0
1959
1964
1969
1974
1979
1984
1989
1994
Year


(e)
B F-(W)-W
J GM-(W)-W
H F-(W)-W-H-H-H
changed to no-till in 1990
Yield (kg ha-1)
5000
4000
3000
2000
1000
0
(f)
B F-W-(W)
J GM-W-(W)
H F-W-(W)-H-H-H
changed to no-till in 1990
Yield (kg ha-1)
1959
1964
1969
1974
1979
1984
1989
1994
Year