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# Great Plains cropping system studies for soil quality assessment

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## Abstract

Interactions between environmental conditions and management practices can significantly affect soil function. Soil quality assessments may improve our understanding of how soils interact with the hydrosphere and atmosphere. This information can then be used to develop management practices that improve the capacity of the soil to perform its various functions and help identify physical, chemical, and biological soil attributes to quantify the present state of a soil and detect changes resulting from management. In protocols established by the Great Plains cropping system network, sampling and testing procedures were selected to identify physical, chemical, and biological soil attributes responsive to management that may serve as useful indicators in assessing the effects of management on the soil resource. Eight existing long-term studies from throughout the Great Plains in the central USA were used to make these assessments because, (1) many years are required for certain soil properties to change measurably; (2) annual weather causes variation in system performance; and (3) the soil pools of interest are spatially variable. This paper includes detailed descriptions of the treatments and sites, and both long-term and short-term (1999–2002) data on precipitation, temperature, and yields for each location.

**Key words:** crop rotation, tillage, no-tillage, conventional management, alternative management, soil resource

## Introduction

Soils serve a multitude of functions and play important roles in environmental quality through interactions with the hydrosphere and the atmosphere. Management of the soil resource affects how efficiently the soil performs its various functions and ultimately impacts agronomic productivity and environmental quality. There is currently a great deal of interest in improving our understanding of how soils interact with the hydrosphere and atmosphere, in developing management practices that improve the capacity of the soil to perform its various functions, and in identifying physical, chemical, and biological soil attributes that can be used to quantify the present state of the soil and detect changes in the state of the soil resulting from management.

A workshop held in 1999 identified soil quality as a major research issue. Specifically, emphasis was put on research that provides baseline information about the present status of soils, that determines how management practices affect soils, and that develops useful indicators for assessing the current status and detecting changes resulting from management.

A number of physical, chemical, and biological soil attributes have been proposed for use in assessing soil quality. Several lists of attributes have been suggested for comprising a minimum data set and combinations of attributes have been incorporated into indices having potential for assessing soil function and management impacts[1–4]. Many studies have compared various soil quality attributes under different management systems

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**Table 1.** Contrasting management treatments within eight long-term cropping systems. Treatments selected at each site differed in management intensity as characterized by either type or frequency of tillage, cropping intensity, and/or crop rotation diversity and are termed conventional (CON) or alternative (ALT).

| Location/soil series | Treatment | Crop sequence | Tillage | N rate[1] |
|---|---|---|---|---|
| Akron, CO | CON | WW–F[2] | Sweep (fallow) | Varied |
| Weld silt loam | ALT | WW–C–M | No tillage | Varied |
| Brookings, SD | CON | C–C | Chisel plow and disk | High |
| Barnes sandy clay loam | ALT | C–SB–SW–A | Chisel plow and disk | 0 |
| Bushland, TX | CON | WW–SO–F | No tillage | Varied |
| Pullman silty clay loam | ALT | WW–WW | No tillage | 0 |
| Fargo, ND | CON | DW–P | Fall plow | 0 |
| Fargo silty clay | ALT | DW–P | No tillage | 0 |
| Mandan, ND | CON | SW–F | Chisel plow and disk | Medium |
| Wilton silt loam | ALT | SW–WW–SU | No tillage | Medium |
| Mead, NE | CON | C–C | Tandem disk, 2 × | High |
| Sharpsburg silty clay loam | ALT | C–SB–SO–OCL | Tandem disk, 2 × | High |
| Sidney, MT | CON | SW–F | Tandem disk | 45 kg ha$^{-1}$ |
| Vida loam | ALT | SW–SW | No tillage | 45 kg ha$^{-1}$ |
| Swift Current, SK | CON | SW–F | Chisel plow and harrow | Varied |
| Swinton silt loam | ALT | SW–L | Chisel plow and harrow | Varied |

[1] Varied = N fertilizer application rate based on soil test results.

[2] Abbreviations: A = alfalfa, C = corn, DW = durum spring wheat, F = summer fallow, L = lentil, M = proso millet, OCL = oat + clover, P = field pea, SB = soybean, SO = sorghum, SU = sunflower, SW = spring wheat, WW = winter wheat.

in eastern South Dakota and western Minnesota and similar to soils common to the northern Corn Belt. Soil tests conducted in the fall of 1989, using the methods of Gelderman et al.[9] revealed 16.5 g kg$^{-1}$ organic matter, extractable concentrations of 14.8 mg kg$^{-1}$ $NO_3$-N, 9.2 mg kg$^{-1}$ P (Olsen method), and 192 mg kg$^{-1}$ K in the top 26 cm (Ap1 horizon) of the soil profile[10].

The study included three main plot conventionally tilled crop rotations (monoculture, 2-year rotation, and 4-year rotation), each subdivided into three input level subplot treatments. All crops in the rotation treatments were present each year with three replications.

For soil quality assessment, the continuous corn monoculture was selected as the CON treatment and the corn–soybean [*Glycine max* (L.) Merr.]–spring wheat (*Triticum aestivum* L.) under-seeded with alfalfa (*Medicago sativa* L.)–alfalfa 4-year rotation was selected as the ALT treatment (Table 1). Corn and soybean were planted with 76 cm row spacing. Wheat and alfalfa were seeded with a drill. No chemical inputs (fertilizers, herbicides, or insecticides) were applied to the 4-year rotation plots. Corn, soybean, and wheat were harvested at physiological maturity (corn and soybean in late September or early October; wheat in July) for grain and stover yields. Alfalfa was harvested 2 or 3 times per year.

Corn yield responded differently to inputs depending on whether it was grown in rotation with soybean or in monoculture. Corn yields were greater following soybean than in monoculture at an intermediate level of inputs but yields were similar between the two systems at a high level of inputs[8]. Pikul et al.[11] reported that soybean yield increased with starter N fertilizer in 9 of 11 years. Rotation and N fertilization affected N mineralization with highest mineralization rates observed in rotations that included a legume, especially alfalfa, and with a slight decline in mineralization rates with increasing N-fertilization rate[12]. This study has shown that corn yields can be maintained with reduced inputs when the corn is grown in rotation with soybean, soybean yields respond to starter N fertilizer, and many soil properties improved when crops were grown in rotation.

## *Bushland, TX: conservation tillage and water conservation*

A tillage study was established in 1983 on graded-terraced watersheds at the USDA-ARS Conservation and Production Research Laboratory on a Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) averaging 10 g kg$^{-1}$(0–15 cm) organic C, medium P and very high K soil test levels. The objective of this study was to compare the water conservation effects of no tillage and stubble-mulch tillage practices in winter wheat–sorghum (*Sorghum bicolor* (L.) Moench)–fallow and continuous wheat cropping systems[13]. For soil quality assessments, a single phase of the wheat–sorghum–fallow rotation was selected as the CON treatment and continuous winter wheat as the ALT treatment, both under no-tillage management (Table 1).

Sorghum was seeded in 0.76-m rows in late May or early June. Winter wheat was seeded in 0.30-m rows using a hoe-press grain drill when adequate moisture was present from late September to early November. Weeds were controlled using a combination of broad-spectrum and preplant herbicides. The plots received no fertilizers throughout the duration of the study. Wheat grain and straw were harvested at grain maturity typically in late June or early controlled only by herbicides. Nitrogen fertilizer (ammonium nitrate) was broadcast in late April prior to seeding spring wheat in early May and sunflower in late May. For winter wheat, N fertilizer was applied at the same time as for spring wheat. Winter wheat, spring wheat, and sunflower were harvested at physiological maturity in early August, mid-August, and mid-October, respectively, to determine grain and straw yield. Details on soil characterization and management information are provided by Black and Tanaka[22].

In the wheat–fallow system, yield responses to N fertilization occurred in years where spring soil $NO_3$-N was low. Cultivars were not consistent in their response to N fertilization or tillage. Slight yield reductions were observed in no-tillage and minimum tillage when compared to CON tillage in some of the years[23]. With annual cropping, grain yields did not respond to tillage or N fertilization when plant available water was <300 mm. When plant available water was 300–400 mm, grain yields were greater with no-tillage than with CON or minimum tillage. When plant available water exceeded 400 mm grain yields were greatest under CON tillage[24].

In the 0–5-cm depth, N-mineralization rates were greater in the fallow phase than in the crop phase of the wheat–fallow system, were greater in the spring wheat phase of the annual cropping system than in the spring wheat phase of the wheat–fallow system, and were greater in the spring wheat and sunflower phase than in the winter wheat phase of the annual cropping system. In the 5–15-cm depth, N-mineralization rates were greater in the annual cropping system than in the wheat–fallow system[25].

As tillage intensity decreased, soil organic C sequestration increased in the annual cropping system. In the annual cropping system, no-tillage resulted in the sequestration of 233 kg $C\,ha^{-1}\,yr^{-1}$, minimum tillage resulted in the sequestration of 25 kg $C\,ha^{-1}\,yr^{-1}$, and CON tillage resulted in the loss of 141 kg $C\,ha^{-1}\,yr^{-1}$. Soil organic C was lost from all tillage treatments in the crop–fallow system. Nitrogen-fertilizer rates did not affect soil organic C[26].

This study demonstrated that conservation tillage and annual cropping could replace crop–fallow. Elimination of crop–fallow and use of conservation tillage resulted in higher annualized grain yields, higher utilization of fertilizer N, improved cycling of N, and sequestration of C in soil organic matter.

## *Mead, NE: crop rotation for increased SOM levels, and N and precipitation use efficiency*

The experiment was established in 1982 on the Agronomy Farm at the University of Nebraska Agricultural Research and Development Center near Mead, NE on a well-drained Sharpsburg silty clay loam (fine, smectitic, mesic Typic Argiudoll). This soil has an average organic matter content of 31 $g\,kg^{-1}$ and soil test P and K levels in the very high categories in the surface 7.5 cm (according to University of Nebraska Soil Testing Laboratory NebGuides). The original objective of the study was to determine the long-term effects of crop rotation and N fertilization on several crop and soil parameters.

Seven cropping systems (three monoculture, two 2-year, and two 4-year rotations) with three rates of N fertilizer were included in the study. Each phase of every rotation occurred every year for a total of 15 rotational treatments. Treatments were assigned to experimental units in factorial combinations of rotation and crop within rotation in five randomized complete blocks.

For soil quality assessments, the high N-rate subplot treatment for both the continuous corn (CON treatment) and the 4-year soybean–sorghum–oat [*Avena sativa* (L.)] + clover (80% yellow sweetclover [*Melilotus officinalis* (L.) Lam.] + 20% red clover [*Trifolium pratense*])–corn system (ALT treatment) were selected (Table 1). Nitrogen applications of 180 kg $N\,ha^{-1}$ for corn and sorghum and 68 kg $N\,ha^{-1}$ for soybean and oat + clover as they appeared in these systems were made in May or early- to mid-June. All plots were tilled once or twice with a tandem disk just prior to planting each year for all crops.

Oat was harvested at physiological maturity, usually in early July to determine grain and stover yields. Corn, soybean, and sorghum were harvested for grain and stover yields at physiological maturity, usually in September or early October.

Results after the first full cycle of the 4-year rotations indicated significant differences in crop responses to rotation. Corn and soybean grain yields were both significantly greater when grown in rotation as compared to monoculture systems, while sorghum yields were the same in rotation and monoculture systems[27–29]. Nitrogen fertilizer efficiency determined by using $^{15}N$ methods was shown to be greater for corn and sorghum grown in crop rotation systems with legumes than in continuous systems[30,31], while soybean utilized applied N fertilizer similarly in all cropping systems[32]. As a result, crop rotations including legumes were shown to not only require less fertilizer N for optimum yields, but also that residual soil N levels were lower in rotation systems than in the monoculture corn and grain sorghum systems, and also that residual soil N levels following soybean were less than for any of the other crops in the study[33].

Changes in soil C ranged from a small net loss in the monoculture soybean cropping system to a gain of 100–200 kg $C\,ha^{-1}\,yr^{-1}$ for cropping systems including monoculture corn and sorghum at optimum N-fertilizer rates and 4-year rotations of corn–soybean–sorghum–oat + clover and corn–oat + clover–sorghum–soybean after 8 years[34]. Compared to monocultures, corn, sorghum, and soybean grown in rotation produced more dry matter per unit of water received, thereby reducing year-to-year variability and resulting in more stable long-term production and economic returns[35,36]. The corn–soybean rotation was significantly less risky than those crops grown in monoculture[37,38].

production is reduced and organic matter declined in all rotations. In normal and above normal precipitation years, adequate fertilization and minimization of the use of fallow resulted in maintenance or accrual of soil organic matter. This long-term study has provided a wealth of information regarding crop rotation effects on soil physical, chemical, and biological properties, potential environmental impacts associated with cropping practices, and agronomic and economic performance of these cropping systems.

## Opportunity Research

These sites have been used for a number of studies but not within the original objectives. At Akron, Bowman et al.[7] determined that annual cropping increased the soil organic matter by 20% and particulate organic matter by 100%, and soluble organic C by 33% in the 0–5-cm depth when compared to wheat–fallow. However, inclusion of sunflower in a rotation resulted in lower particulate organic matter and total soil organic matter concentrations in the 0–5-cm depth Bowman et al.[46]. Bowman and Halvorson[47] found that P availability increased in the 0–5-cm depth with annual cropping, likely due to increased P recycling in residue and litter in the more intensive systems. Wright and Anderson[48] used soils from treatments differing in cropping intensity to determine that aggregate stability and glomalin (a glycoprotein produced by mycorrhizal fungi) concentration were positively correlated and increased as cropping intensity increased.

At Mandan, Merrill et al.[49] measured changes in aggregate size distribution from fall to spring, quantifying over-winter processes that affect soil susceptibility to wind erosion soil losses. Wind erosion losses from the various tillage treatments were also estimated during a drought cycle[50]. Yield reductions during severe drought were so great that residue levels, even with no-tillage, were insufficient for protecting the soil from wind erosion. The effect of drought on root growth of cereals was also studied by Merrill et al.[51]. Use of a no-tillage system resulted in greater root length growth and depth of rooting in spring wheat when compared to a CON tillage system. This enhanced root growth resulted in greater above-ground growth in 2 of the 3 years. When soil organic C results were combined with a suite of physical, chemical, and biological soil attributes, Wienhold and Halvorson[52] concluded that annual cropping resulted in improved soil quality when compared to crop–fallow and that soil quality improved as tillage intensity decreased. DeVuyst and Halvorson[53] compared economic efficiency among the systems at Mandan and found crop–fallow and CON tillage in an annual cropping system to be less efficient than CON tillage in an annual cropping system. These last two studies demonstrated that CON tillage and annual cropping improved both the soil resource and the producer's income.

CON tillage resulted in the formation of a tillage pan that was thought to reduce wheat yields in eastern Montana. Pikul and Aase[54] utilized the cropping system study at Sidney to determine if subsoiling (paratilling) would fracture the tillage pan and improve water use and yield of wheat. Subsoiling resulted in measurable improvement in cone index, bulk density, infiltration rate, and average water content. During the 3 years of this study, growing season precipitation was sufficient that improvements in water storage resulting from improved soil physical conditions did not translate into increased wheat yields. Long-term soil organic matter dynamics measured in the cropping system study at Swift Current were used to validate the Century model[55].

## Weather and Crop Yields

The locations used in this study all experience continental climates, characterized by large variation in temperature and precipitation both within a year and among years. Precipitation and temperature recorded during the 4 years of this study typify the variation experienced in this region. Below average annual precipitation occurred at Akron in 2000 and 2002; at Brookings in 1999; at Bushland during 2000–2002; at Mandan in 2002; at Mead during 2000–2002; at Sidney in 2001; and at Swift Current in 2001. Above average annual precipitation occurred at Akron in 1999; at Brookings in 2000 and 2002; at Bushland in 1999; at Fargo in 1999, 2000, and 2002; at Mandan during 1999–2001; at Sidney in 1999 and 2000; and at Swift Current in 2000 and 2002 (Fig. 1).

For crop performance, variation in precipitation within a year is likely more important than total annual precipitation. For example, in 1999 Akron received nearly 11 cm of precipitation above the normal amount but the extra precipitation was all received in August, after the wheat crop was harvested, and was therefore not available to the crop. Nearly all locations have similar examples of large precipitation amounts received during a thunderstorm, skewing the annual total precipitation amount (Fig. 1). When large amounts of precipitation are received over a short time the potential for runoff losses is great and the precipitation is not available to the crop. Extended periods of below normal precipitation (e.g., spring of 2000 and 2002 at Akron) can result in water stress for the crop. The effect of this stress on yield is dependent on the growth stage of the crop.

With the exception of 2002 at Swift Current, the study period was a time of normal or above average annual temperatures at all locations (Fig. 2). Many of the above average annual temperatures recorded in this study result from warmer than average periods during the winter (e.g., Akron in February and March of 1999). Warmer than average temperatures during winter likely have little effect on crop performance. Warmer than average temperatures during the growing season can negatively effect yields if they are severe enough and occur during a critical growth stage (e.g., head development in wheat and silking in corn).

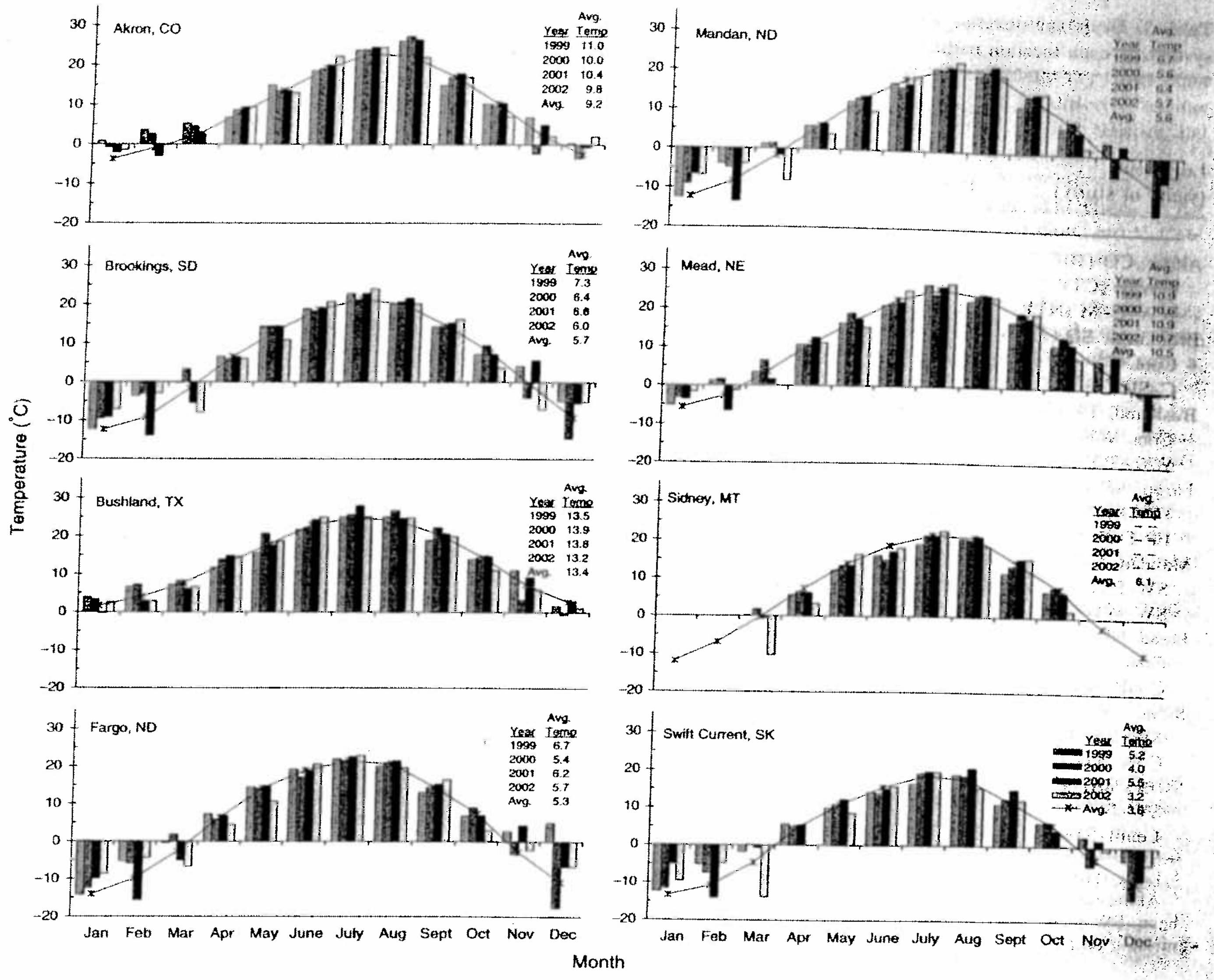

**Figure 2.** Monthly and yearly average ambient air temperatures for 1999 through 2002 and long-term averages at each location in the regional soil quality assessment project. Location and number of years for long-term average in parentheses: Akron (93 years), Brookings (30 years), Bushland (64 years), Fargo (30 years), Mandan (30 years), Mead (30 years), Sidney (30 years), and Swift Current (117 years).

composite soil sample was stored in plastic bags at 4°C until processed for analysis, and the bulk soil sample was immediately air-dried and stored for further processing.

The mass of the composite soil sample was recorded and a subsample (~20 g) was oven-dried for determination of gravimetric soil water content. The dry mass of the composite sample was then calculated and bulk density determined using the soil probe diameter, number of samples, and depth increment to calculate the volume of soil. A subsample of the field-moist composite soil sample was packaged with ice and sent to the USDA-ARS laboratory in Lincoln, NE for determination of biological soil attributes. The remainder of the composite sample was air-dried. The subsample (~25 g) of the air-dried soil was sent to USDA-ARS laboratory in Morris, MN for fatty acid analysis, a subsample (~50 g) was sent to the USDA-ARS laboratory in Lincoln, NE for determination of loss-on-ignition organic matter and particulate organic matter, and the remaining composite sample was retained at the sampling location for determination of additional soil chemical properties. The bulk soil sample was air-dried and sent to either the USDA-ARS laboratory in Lincoln, NE (Swift Current, SK; Bushland, TX; and Fargo, ND) or Beltsville, MD (Akron, CO; Brookings, SD; Mandan, ND; and Sidney, MT) for determination of aggregate size distribution, aggregate stability, and glomalin concentration. See accompanying papers for descriptions of specific methods[59–61].

## Conclusions

Long-term studies such as those described above provide an invaluable resource, on which assessments proposed in this series of papers can be tested both temporally and spatially.

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