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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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[e.g., comparing crop–fallow to annual cropping, conventional (CON) tillage to conservation tillage, or CON farming to organic farming]. Generally these studies have made inferences about management practices based on the differences in soil properties measured after the soils have been under the management treatments of interest for some time. Such studies can create data sets that quantify differences in various soil attributes due to different management systems, define the expected range and mean values for various soil attributes, and improve our understanding of management effects on the soil resource.

In spite of the number of studies conducted in this area, our understanding of the temporal variation exhibited by various soil attributes is relatively poor. Improving our understanding of the temporal dynamics will aid in designing sampling strategies (e.g., what is the optimum time during the year to assess management effects?) and assist in interpreting results. Separating temporal dynamics from responses to management will help in identifying attributes useful for assessing the effect of management practices on the soil resource.

Long-term studies that continue for at least a decade are usually required to detect management effects on the soil resource. Many years are required to average out the effect of annual weather variation and because it takes time for gradual changes to reach a magnitude detectable against spatially variable large background. Many variables can be fractioned into components (e.g., mineral soil into particle size fractions or aggregate size and stability fractions; organic C into particulate organic matter, microbial biomass C, etc.; and infiltration among tensions or pore sizes) varying in response to management. Identification of components more responsive to management than the variable as a whole would allow more rapid assessment of management effects on the soil resource.

Given the spatial variability exhibited by soil organic matter, the wide variety of soils, and the diverse management practices involved, computer models will be needed for assessing management scenarios and predicting future trends in soil properties. Long-term data are needed for validation of potential models to provide confidence in decisions based on simulation results.

The objective of this paper is to provide background information on the eight long-term cropping system studies in a Great Plains regional project, the results of which are reported in the accompanying papers. For each of the studies, this paper describes site characteristics (including weather data), management practices of the original objectives, and major findings. Within each study, the regional project selected two cropping system treatments to represent CON and alternative (ALT) practices. This paper describes those specific systems and the crop they produced.

Study Sites

Soil quality assessments were done at eight locations spanning north to south gradients in both mean annual temperature (3.6–10.5°C) and east to west gradients in annual precipitation (34.5–76.6 cm) in the Great Plains region. The eight locations are: Akron, Colorado (CO); Brookings, South Dakota (SD); Bushland, Texas (TX); Fargo, North Dakota (ND); Mandan, ND; Mead, Nebraska (NE); Sidney, Montana (MT); and Swift Current, Saskatchewan (SK), Canada. At each location, long-term experiments compared various unirrigated management systems representative of the currently predominant practices as well as ALT practices having potential for that area. A preliminary static soil quality assessment concluded that differences in soil quality existed between contrasting management practices at several of these locations[5].

Akron, CO: no-till crop rotations to replace fallow and increase performance

In 1990, the ALT crop rotation study was established at the USDA Central Great Plains Research Station to compare the predominant wheat–fallow rotation to ALT crop rotations that minimize or eliminate fallow periods[6]. Of the 23 rotations in this study, CON tillage winter wheat (*Tritium aestivum* L.)–fallow was selected as the CON treatment and no-tillage winter wheat–corn (*Zea mays* L.)–proso millet (*Panicum miliaceum* L.) as the ALT treatment (Table 1). The experiment on a Weld silt loam (fine, smectitic, mesic, Aridic Argiustolls) uses a randomized complete block design with three replications. In the CON system, wheat was planted in September–October and harvested the subsequent July. The land is then fallowed for 14 months and weeds are controlled with V-blade sweeps (3–6 operations per year depending on weather). In the ALT system, corn, millet, and wheat are seeded no-till directly into the previous crop's undisturbed stubble. Weeds are controlled with contact herbicides at recommended rates between crops, and both residual and contact herbicides are used for in-season weed control in corn and millet. Grain yields are reported at 13.5% moisture for millet and wheat and 15.5% moisture for corn. All phases of each rotation appear each year as individual experimental plots of 9.1 m × 30.5 m in size. Additional details of the plot area, tillage systems, and experimental design are given in Anderson et al.[6] and details of the soil characteristics are provided in Bowman et al.[7] Eliminating fallow using the ALT system gave mean annual yields double those of wheat–fallow[6] and increased gross returns[6].

Brookings, SD: ALT crop rotations and reduced purchased N inputs

In 1990, a cropping rotation–N-fertilization rate experiment was established at the Eastern South Dakota Soil and Water Research Farm near Brookings, SD. The objective of the study was to understand the interactions of soils, tillage intensity, crop rotation, and agricultural chemical inputs on crop yield and soil properties[8]. Soil at the site is a Barnes clay loam (fine-loamy, mixed Udic Haploborolls) soil with nearly level topography. This soil is typical of those found

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 pre-plant 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

July. Sorghum grain and stover were harvested after a killing freeze typically in late October or early November. Jones and Popham[13] provide further details of weed control, experimental layout, and cultural practices for these long-term plots.

Conservation tillage practices result in water conservation allowing more intensive cropping and a reduction in the incidence of fallow in the southern Great Plains. Stubble mulch tillage was found to increase infiltration and reduce runoff losses but the four or five tillage operations needed to control weeds also increased evaporation losses when compared to no-tillage[14]. No-tillage resulted in more plant available water at the end of the fallow period when compared to stubble mulch tillage. Sorghum was found to be well adapted to this region and outyielded wheat. Highest annualized yields were reported for continuous sorghum followed by wheat–sorghum–fallow, continuous wheat, and wheat–fallow[13].

Fargo, ND: no-till versus plow with increased crop diversity and decreased N fertilization

In 1977, a dryland tillage experiment was initiated on 2 hectares located 8 km NW of Fargo, ND on the NW22 research land of the North Dakota Agricultural Experiment Station. The soil is mapped as a Fargo silty clay (fine, smectitic, frigid, Typic Epiaquert) with average soil tests in the 0–15-cm depth of 41 g kg^{-1}organic matter, $pH_{1:1\ water}$ 7.7, 47 kg P ha^{-1} and 629 kg K ha^{-1}. The objective of this study was to determine the effect of tillage intensity on dry matter production and nutrient uptake by crops commonly grown in the Red River Valley[15]. Four primary tillage systems were used after the small grain crop, including fall plow, fall sweep, fall intertill (strip till), and no-till. Each tillage block was replicated four times. A rotation of sugarbeet (*Beta vulgaris* L.), spring wheat, sunflower (*Helianthus annuus* L.), and barley (*Hordeum vulgare* L.) was maintained for the first 8 years. Sugarbeet was replaced by soybean in the rotation during the next 2 years and the sweep system was changed to fall chisel.

In 1987, the rotation was switched to a small grain and grain legume rotation (one crop per year) that included spring wheat, durum (*Triticum turgidum* L.), soybean, drybean (*Phaseolus vulgaris*), and field pea (*Pisum sativum* L.)[16,17]. Tillage systems remained the same except that the intertill system was switched to fall disk in 1998. After the grain legume was harvested, the tillage system was split as before, with one half receiving no tillage and the other half receiving a chisel operation. In the spring of 1997, a nitrogen fertilizer variable was added to the study with 0, 45, 90, and 135 kg N ha^{-1} randomly split across each replication in a split block arrangement.

For soil quality assessment, the CON treatment was a small grain (durum wheat even years)–grain legume (field pea odd years) rotation using plow tillage with no N fertilizer. The ALT treatment was the same, but using no-till management (Table 1). For both treatments, grain and stover dry matter were determined at physiological maturity of each crop (late August to early September).

This study demonstrated that the response to tillage is crop dependent. When soybean is water stressed early in the growing season, early maturing cultivars are adversely affected while late maturing cultivars are not. When water stress occurs, early maturing cultivars yield better under no-tillage, and with no water stress both early and late maturing cultivars have similar yields across tillage practices[15]. Nutrient stratification observed in soils under reduced tillage did not affect dry matter and nutrient content of either soybean[18] or sunflower[20]. Sunflower seed yield and quality were not affected by reduced tillage[19]. During a normal growing season, dry bean yields were greater under no-tillage, while in wet years more intensive tillage improved yields and strip-tillage performed best averaged across all years[16]. Highest plant nutrient contents were observed with plow tillage[21]. This study demonstrated that crop performance in this soil is the result of an interaction of weather during the growing season, tillage, and cultivar.

Mandan, ND: conservation tillage and annual cropping to replace fallow

In 1984, a conservation tillage-cropping system study was established near Mandan, ND, to determine the long-term effects of CON, minimum, and no-tillage residue management systems on water conservation and use, N use, and crop yields. The study was intended to be long-term so that soil C, N, and P cycling could be assessed[22]. The experiment was located about 6 km southwest of Mandan, ND on a Wilton silt loam (fine-silty, mixed, superactive frigid Pachic Haplustoll). The soil pH was 6.4 and organic C concentration was 21.4 g kg^{-1} in the surface 76 mm. The area was previously cropped to sunflower in 1983, to use all available soil water and N to a depth of 1.5 m. In the fall of 1983, 45 kg P ha^{-1} as concentrated superphosphate was broadcast over the entire research area. Sodium bicarbonate extractable P in the surface 152 mm ranged from 20 to 26 mg kg^{-1} in the spring of 1984.

Two crop sequences, three residue managements, three N fertilizer rates, and two crop cultivars were included in the research. Three replicates of crop sequences, residue management, N fertilizer rates, and crop cultivars were arranged in a randomized complete block design. Specific treatments selected for the soil quality assessments were spring wheat–fallow with CON residue management leaving <30% soil surface covered by residue fertilized at a rate of 22 kg N ha^{-1} as the CON treatment, and spring wheat–winter wheat–sunflower with no-tillage residue management leaving >60% soil surface covered by residue and fertilized at a rate of 67 kg N ha^{-1} as the ALT treatment (Table 1).

CON tillage used an undercutter (81-cm sweeps) as needed between crops and a tandem disk once just prior to planting to control weeds. Under no-tillage, weeds were 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].

This study demonstrated that crop rotation generally increases crop yields, improves both N-fertilizer and precipitation use efficiency, reduces soil N available for leaching, increases soil organic matter levels, and results in greater yield stability and economic returns. Monoculture systems generally require greater management inputs and have greater agronomic[39] and economic risk.

Sidney, MT: annual cropping with no-tillage replaces CON crop–fallow

In 1983, a crop rotation experiment was initiated 11 km north of Culbertson, MT on a Dooley sandy loam (fine-loamy, mixed, Typic Argiboroll). The objective of this study was to compare crop and soil effects of CON crop–fallow and non-traditional cropping practices under tilled and no-tillage conditions[40]. Two treatments from a larger rotation experiment were selected for the present study: (i) spring wheat–fallow with CON tillage as the CON treatment, and (ii) continuous spring wheat with no-tillage as the ALT treatment (Table 1). Both phases of the spring wheat–fallow treatment appear each year. The study was laid out in a randomized complete block design with four replications, with a plot size of 30 m × 12 m.

The spring wheat–fallow treatment had no after-harvest tillage, but was disked prior to seeding for seedbed preparation. Depending on soil and weather conditions, fallowing was accomplished by either mechanical or chemical means. Spring wheat was seeded with a double-disk opener drill. All plots except fallow received 56 kg N ha^{-1} (ammonium nitrate) broadcast at time of seeding from 1983–1985. From 1986–1995 the rate was changed to 34 kg N ha^{-1} and it has been 45 kg N ha^{-1} since 1996. Fallow plots received 34 kg N ha^{-1} in every crop year. Long-term P requirements were met by applying and incorporating into the surface 5 cm of soil 560 kg P ha^{-1} $(NH_4)_2HPO_4$ (18-46-0) (N–P–K) prior to the establishment of the study. Wheat grain and straw were harvested at physiological maturity typically in late August or early September.

After 7 years there were no differences in soil P, NO_3-N, and pH for soils between annual cropping and crop–fallow. Bulk density was lower in the surface depth of the no-tillage annual cropping treatment than in the conventionally tilled crop–fallow treatment[40]. Bulk density did not change due to freeze thaw during the winter. Point resistance was 2.2 MPa in the surface layers of conventionally tilled wheat–fallow compared to 1.7 MPa in no-tilled annual cropping. Soil organic C was greater in 0–9-cm depth of the no-tillage annual cropping treatment than in the conventionally tilled crop–fallow treatment. Improved soil physical and chemical conditions in the no-tillage annual cropping treatment resulted in higher infiltration rates in both dry and wet soil[41]. This study demonstrated that, based on yield, water use efficiency, soil organic C, and bulk density, the most efficient crop and soil management system for this region was annual cropping with no-tillage.

Swift Current, SK: crop substitution for fallow enhances soil productivity

In 1967, a crop rotation experiment was initiated at the Semiarid Prairie Agricultural Research Centre of Agriculture and Agri-Food Canada near Swift Current, SK on a Swinton silt loam (fine-loamy, mixed, calcareous, frigid Typic Haplustoll). The objectives of this study were to evaluate the influence of rotation length, summer fallow substitute crops, and N and P fertilizers on crop yields, grain protein, N and P uptake and changes in soil physical, chemical, and biological properties[42]. Two rotations within a larger rotation experiment were selected for soil quality assessment: (i) spring wheat–fallow as the CON treatment and (ii) spring wheat–lentil (*Lens culinaris* L.) (initiated in 1979) as the ALT treatment (Table 1). There are three replicates. Each phase of both rotations was present every year, but only the wheat after lentil and fallow after wheat phase was sampled in 2000 with the succeeding phase (lentil after wheat and wheat after fallow, respectively) being sampled in 2001.

In-crop weed control was achieved with post-emergent herbicides as required. Both rotations received N and P fertilizer as required based on soil nutrients present in October sampling. Crop stubbles were tilled just prior to planting. General seedbed preparation, fertilization, herbicide application, planting, harvesting and tillage practices for this experiment have been reported previously[42].

A large amount of information has been published from this study. Early publications reported agronomic production, crop N utilization, and N distribution in the soil. Wheat yields were found to be inversely related to the frequency of fallow and directly related to rainfall received during the growing season. Grain quality was also evaluated, with wheat grain protein being greatest in wheat after fallow, slightly less for continuous wheat with N fertilizer, and lowest for continuous wheat without N fertilizer. Wheat grain P concentration was directly related to rainfall received during the growing season and was greater for wheat in rotation than for wheat following fallow[42]. Utilization of N by the wheat crop was dependent on rainfall received during the growing season. During dry years, NO_3-N accumulated in the soil and this accumulation was greater for soils receiving N fertilizer. During wet years, the crop utilized NO_3-N and there were no differences between fertilized and unfertilized plots. The accumulation of NO_3-N below the rooting zone resulted in leaching losses and potential contamination of groundwater even under annual cropping[43]. Biederbeck et al.[44] reported that frequent fallow impaired soil biological activity but the trend was reversible with more intense cropping and use of adequate N and P fertilizer.

Twenty-four years after establishment of this rotation study, Campbell and Zentner[45] assessed trends in soil organic matter. They found that variation in organic matter in the 0–15-cm depth was dependent on the amount of crop residue returned to the soil. During drought years, crop 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).

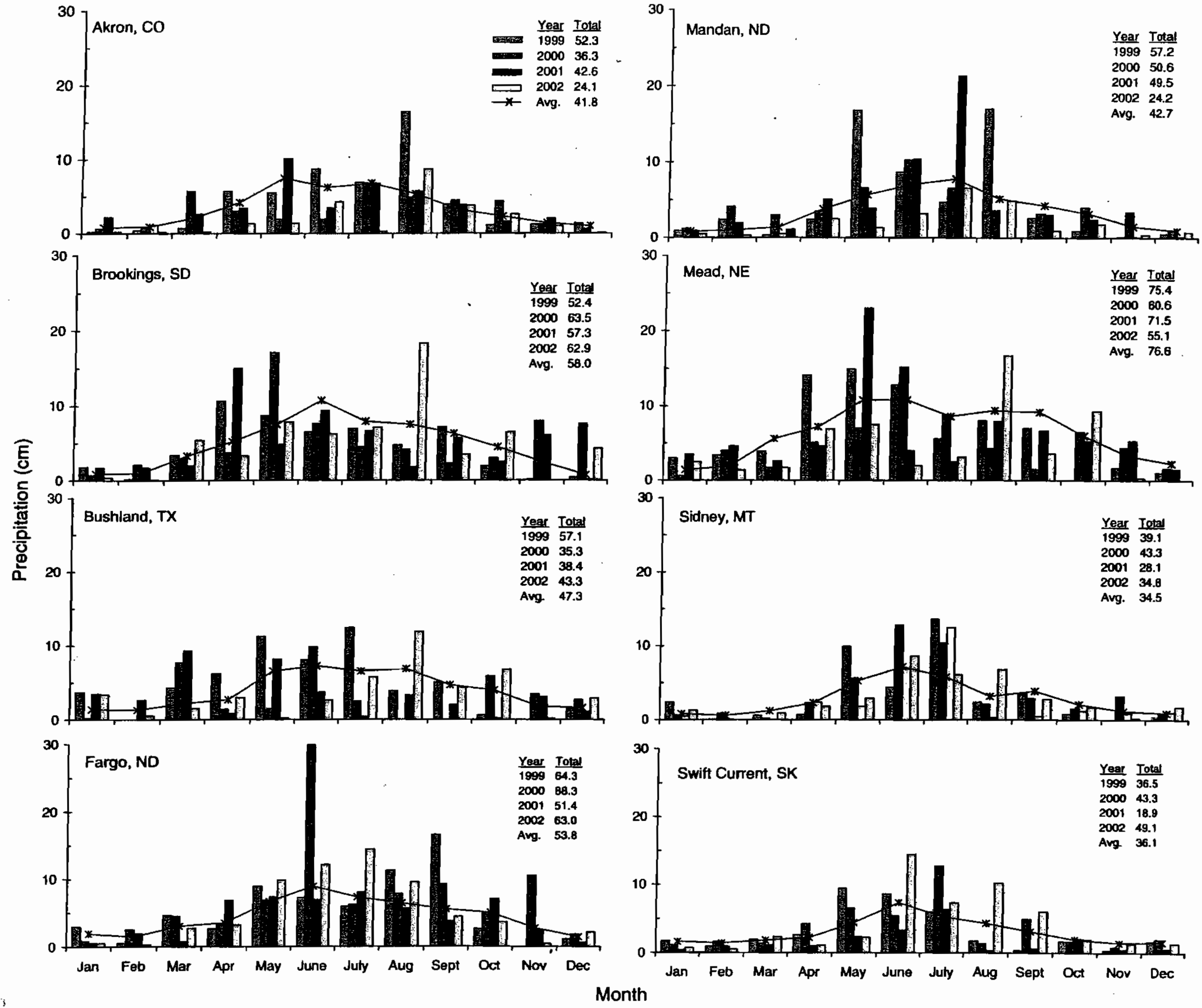

Figure 1. Monthly and yearly precipitation for 1999 through 2002 and long-term averages at each location in the regional soil quality assessment project. Location and number of years for long-term average in parentheses: Akron (93 years), Brookings (30 years), Bushland (64 years), Fargo (30 years), Mandan (30 years), Mead (30 years), Sidney (30 years), and Swift Current (117 years).

Yields for the study period were similar to long-term yields at most sites (Table 2). Higher yields at Fargo are likely due to above average precipitation during the years of the study, while slightly lower yields at Mead are likely due to below average precipitation during the years of the study.

Soil Sampling Protocol

It was planned to sample all soils three times each year from each replicate of each treatment. The actual number of sampling times, however, varied among locations. Some locations had 2- or 3-year rotations and sampling was limited to one complete rotation. Others missed some sampling times due to weather. Due to large differences in the length of the growing season across locations, soil sampling was conducted based on growth stage of the crop. Soil samples were collected prior to planting, midseason [from sorghum plots at stage 6[56] (half bloom), from wheat plots at Haun stage 8[57] (flag leaf), and from corn plots at growth stage VT[58] (tassle)] and after harvest. Samples were collected using a stratified sampling scheme so that within-row and between-row areas of the plot comprised the proper proportion of the composite sample. For small grains with row spacings of 30 cm or less, 50% of the samples were collected from within-row and 50% were collected from between-row areas of the plot. For row crops, 25% of the samples were collected from within-row and 75% of the samples were collected from between-row areas of the plot. In each plot, 15–18 cores were collected to a depth of 30 cm, sectioned into 0–7.5, 7.5–15, and 15–30-cm increments, and composited by depth. A bulk soil sample was collected from the 0–7.5-cm surface increment using a flat blade shovel at five locations within each plot. The

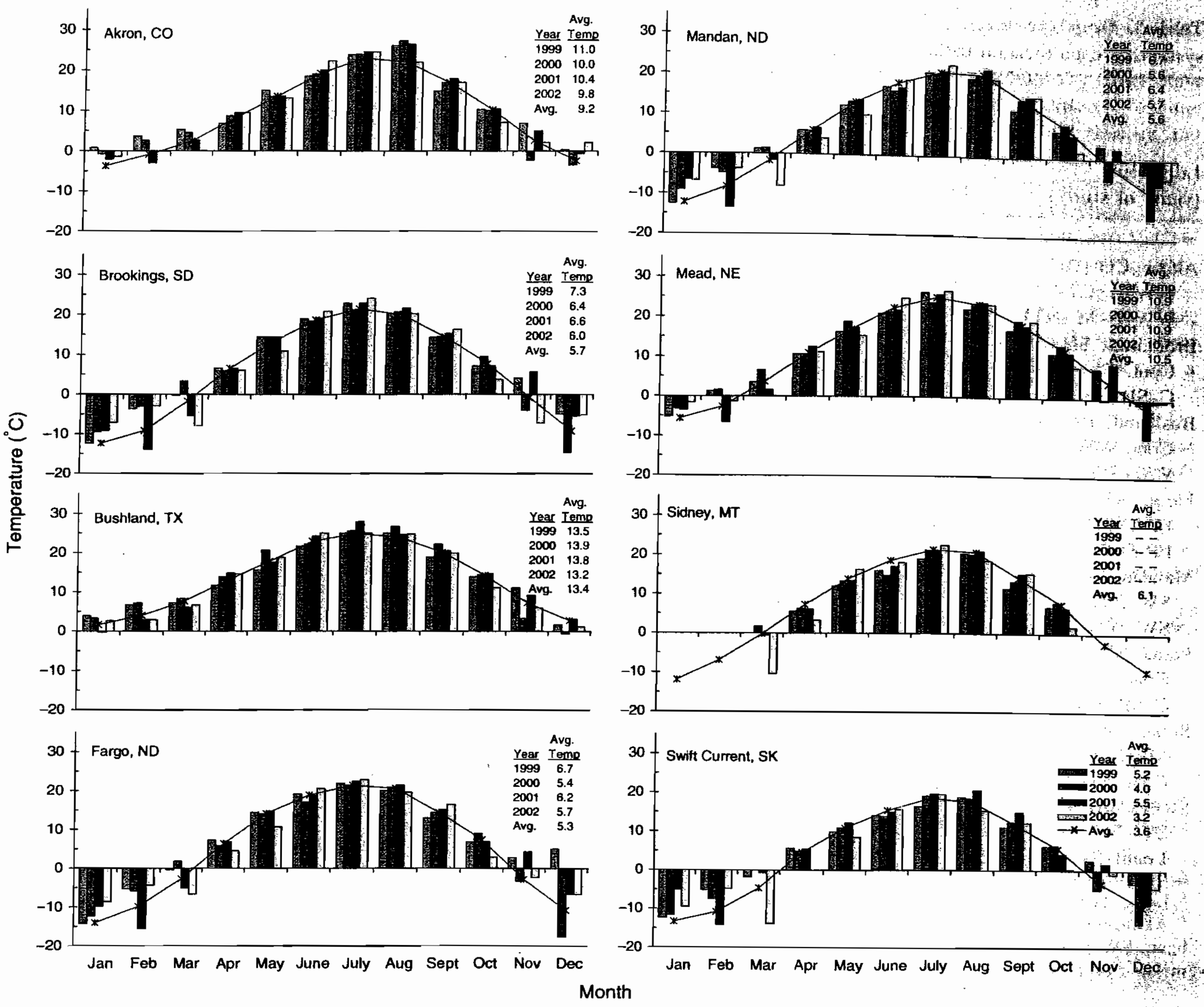

Figure 2. Monthly and yearly average ambient air temperatures for 1999 through 2002 and long-term averages at each location in the regional soil quality assessment project. Location and number of years for long-term average in parentheses: Akron (93 years), Brookings (30 years), Bushland (64 years),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

Table 2. Grain and stover dry matter yields each year and long-term (LT) averages for selected conventional and alternative management systems at each location participating in the regional soil quality assessment project.

	Yield											
	Grain				Mean		Stover				Mean	
Location (years of study)	**1999**	**2000**	**2001**	**2002**	**4-year**	**LT**[1]	**1999**	**2000**	**2001**	**2002**	**4-year**	**LT**
	Mg ha^{-1}											
Akron, CO (10)												
WW–F (CT)[2]	2.4	0	3.5	0	1.5	1.1	4.1	–	5.3	–	2.4	2.4
WW–C–M (NT)[2]	1.1	2.4	2.2	0.8	1.4	1.5	2.7	4.8	4.4	1.4	3.3	3.4
Brookings, SD (7)												
Cont. C[2]	5.4	5.5	5.3	4.5	5.2	6.4	5.9	4.7	5.1	4.4	5.0	–
C–SB–SW/Alf–Alf[2]	7.8	2.4	2.6	0	3.2	–	7.5	5.6	–	8.4	–	–
Bushland, TX (20)												
Cont. WW (NT)	1.9	1.5	1.9	0.2	1.4	–	7.2	4.2	3.8	0.3	3.9	–
WW–SG–F (NT)	3.1	2.4	–	0.8	–	–	10.9	3.3	–	3.3	4.4	–
Fargo, ND (15)												
FP–D (Plow)[2]	2.6	2.5	2.5	2.1	2.4	2.1	2.5	5.9	1.8	4.6	3.7	3.5
FP–D (NT)[2]	2.8	2.4	2.4	1.6	2.3	2.0	2.7	5.6	2.3	3.9	3.6	3.5
Mandan, ND (12)												
SW–F (CT)	1.6	–	–	–	1.6	1.1	4.2	–	–	–	4.2	1.8
SW–WW–SF (NT)[2]	1.7	3.2	–	–	2.4	1.7	4.5	–	–	–	4.5	3.4
Mead, NE (20)												
Cont. C	8.8	6.5	6.6	6.0	7.0	7.1	6.9	5.0	6.2	4.3	5.6	6.2
C–SB–SG–OCL[2]	8.9	2.7	4.2	0.7	4.1	4.6	8.8	5.9	7.7	2.2	6.2	5.6
Sidney, MT (13)												
SW–F (CT)	1.0	1.9	1.4	–	1.4	1.2	1.7	–	1.7	–	1.7	1.7
Cont. SW (NT)	1.7	2.7	2.1	–	2.2	1.9	4.4	–	3.7	–	4.1	3.0
Swift Current, SK (23)												
SW–F	–	–	2.3	–	1.5	1.3	–	–	3.2	–	2.5	2.2
Lentil–SW	–	2.4	0.4	–	1.7	1.6	–	4.9	1.5	–	3.3	3.1

[1] Long-term averages for each management system (no. of years in parentheses by location).
[2] Abbreviations: WW = winter wheat, F = fallow, CT = CON till, M = millet, C = corn, NT = no-till, Cont. = continuous, SB = soybean, SW = spring wheat, Alf = alfalfa, FP = field pea, D = durum, SG = sorghum, OCL = oat + clover, SF = sunflower. '–' Indicates missing data or fallow.

Short funding cycles and the requirement for scientists to publish frequently make maintenance of long-term studies difficult[62]. Long time-series are often needed to analyze economic risk and performance[53], evaluate the role of agriculture in C sequestration and global change[63], and determine management effects on soil functions[59–61,64]. The diversity of cropping and tillage system treatments, soils, and climatic conditions in these studies allows inferences from various assessments about long-term effects. These types of studies are required to make determinations about changes in soil properties (especially physical, chemical, and biological) that occur slowly over time, but they also can be used to evaluate short-term effects on crop production. Information from these sites has played a key role in better understanding potential agronomic performance of cropping and soil management systems in this region. In addition, the information has been used to study environmental impacts associated with these systems and the economic implications of shifting from the CON practice to more intensive or diverse systems. These systems also provide information for model validation that allows simulation into the future. Such results should be of value for developing effective policy.

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