12th ISCO Conference Beijing 2002

Conserving Soil and Water with Sustainable Cropping Systems: Research in the Semiarid Canadian Prairies

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Abstract: Soils of the semiarid Canadian prairies have been subjected to substantial degradation since the native grasslands were first cultivated some 120 years ago. The degradation resulted from the combined effects of soil erosion, loss of soil organic matter (SOM), nutrient export by crops, and salinization. These soil damaging processes are the legacies of intensive tillage, monoculture cropping, and overuse of summerfallow. Long- and short-term crop rotation and soil management studies, conducted in southwest Saskatchewan, have shown the great benefits of reducing summerfallow frequency and intensity of mechanical tillage, and of using crop diversification to halt or reverse soil degradation. Nitrate leaching below the rooting depth (120 cm) after over years of continuous wheat (*Triticum aestivum* L.) cropping was lower than that in cropping systems that included summerfallow every 2 or 3 years. Inclusion of annual pulses, such as lentil (*Lens culinaris* Medikus), further reduced nitrate leaching, and increased wheat grain protein concentration in 2 of every 3 years compared to wheat monoculture grown annually. Furthermore, inclusion of the pulse crop in the rotation increased soil microbial biomass by 45% to 75%, and increased SOM by 1.8 $\mathrm{Mg} \bullet \mathrm{ha}^{-1}$ as compared to wheat monoculture. Populations of rhizobia in the rhizosphere and rhizoplane of wheat roots were many thousand- to million-fold higher when grown in rotation with lentil than in monoculture. Shorter-term crop sequence studies have shown that the judicious selection of crop species and varieties arranged in appropriate sequences increases water and nutrient use efficiency by as much as 10% to 30%, decreases weed and disease pressure, and increases cereal grain yields by 5% to 15% and protein concentration by 6% to 16% at the systems level. Our research findings have assisted Canadian producers in identifying cropping systems that produce safe and nutritious food in an economically viable fashion, while conserving or enhancing soil and environmental quality.

Keywords: crop rotation, crop sequence, soil quality, summerfallow, nitrogen, biodiversity

1 Introduction

The Canadian prairies have about 32 Mha of arable land that is suited to the production of annual grain crops. The prairies account for 85% of Canada’s arable land, making it the most important agricultural region of the country. Over 40% of the cultivated land is located in the semiarid Brown and Dark Brown soil zones, two of the five soil-climatic zones of the prairies. The native vegetation of these soil zones mainly consists of xerophytic and mesophytic grasses and forbs. Since the native grasslands were first broken some 120 years ago, the soils have been subjected to substantial degradation, largely due to the combined effects of soil erosion, loss of SOM, nutrient export by crops, and salinization. These soil damaging processes are the legacies of intensive tillage, monoculture cropping, and overuse of summerfallow (Campbell *et al.*,1990; Zentner *et al.*,2001). Wind erosion is a serious problem, causing concerns about the quality of environment in which we live. Moisture deficit is the primary constraint, limiting all agricultural activities and economic capabilities. The main focus of agriculture research in this region has been to develop sustainable farming systems to conserve water, improve water use efficiency (WUE), reduce soil degradation, maintain land resources, and enhance the quality of the natural resources.

Summerfallow (i.e., leaving the land free from cropping for a 21-month period to allow the soil to replenish moisture) has been traditionally used as a means of conserving water in this dry region. However, most of the soil water stored during the fallow period results from snowmelt during the first winter, and the water storage during the summer period varies greatly depending on weather conditions and cropping systems in which the fallow was used (Campbell *et al.*, 1987). In some cases, differences in water conservation between summerfallow and fallow-substitute crops are small and the post-harvest precipitation is sufficient to replenish the soil water under the fallow-substitutes to the same level as that under conventional fallow. Other alternatives to summerfallow are also being used to improve water conservation and its use efficiency, such as cutting stubble tall to trap snow, use of new crop types to limit water losses, use of extended crop rotations to enhance overwinter water recharge, use of appropriate crop sequences to improve water use efficiency, and use of optimal crop management to reduce in-crop evaporation losses. Consequently, the summerfallow area has steadily declined in the past 20 years. For example, the proportion of summerfallow land has declined from 43% in 1976 to 36% in 1998 in the Brown soil zone, and from 40% in 1976 to 20% in 1998 in the Dark Brown soil zone. At the same time, the areas seeded to alternative crops have increased. For example, the areas seeded to dry pea and lentil in Saskatchewan have increased from less than 7,000 ha in 1976 to more than one million ha in 1998, and mustard from 19,000 ha in 1976 to 235,000 ha in 1998.

The objectives of this paper were to describe some of the findings from long-term crop rotation and shorter-term crop sequence studies conducted at the Semiarid Prairie Agricultural Research Centre (SPARC), Swift Current, SK, to demonstrate the benefits of reducing summerfallow frequency and of using diversified cropping systems in conserving soil water, improving water use efficiency, and reversing soil degradation on the semiarid Canadian prairies.

2 Long-term crop rotation study

A long-term crop rotation study was initiated in 1967 at SPARC, on an Orthic Brown Chernozem (Aridic Haploboroll) with loam to silt loam texture and a pH in water paste of 6.5. The experiment was set up as a randomized complete block design with three replicates. Each test plot was 0.04 ha in size. Several facets of this experiment have been extensively reported elsewhere (Campbell *et al.*, 1990; Campbell and Zentner 1993; Zentner *et al.*, 2001). In this paper, we discuss four of the 12 crop rotation treatments involved in the experiment: fallow-wheat (F-W), fallow-wheat-wheat (F-W-W), continuous wheat (W), and wheat-lentil (W-L). These systems were fertilized with recommended rates of N and P. All phases of each rotation were present every year, and each rotation was cycled on its assigned plots. Stubble mulch, shallow (6 cm—9 cm depth) tillage was practised. The seedbed was prepared with one tillage operation, while areas being summerfallowed received an average of three cultivations. All treatments received 2,4-D applied in fall or early spring to control winter annual weeds. Fertilizer N (as ammonium nitrate) was broadcast prior to seedbed preparation in spring based on a NO_3-N soil test taken the previous fall. On average, wheat grown on summerfallow received 17 kg • N • ha^{-1}, wheat grown on wheat stubble received 40 kg • N • ha^{-1}, wheat grown on lentil stubble received 30 kg • N • ha^{-1}, and lentil received 17 kg • N • ha^{-1}. All crops received P fertilizer at 10 kg • P • ha^{-1} (as mono-ammonium phosphate). Soil samples were taken from each plot with a Giddings soil corer in the 0—15 cm, 15 cm—30 cm, 30 cm—60 cm, 60 cm—90 cm, and 90 cm—120 cm depth increments, in spring prior to seeding, at harvest, and in late-fall. These samples were used for determination of NO_3-N (Hamm *et al.*,1970), bicarbonate extractable-P (Olsen *et al.*,1954), and gravimetric soil water content. Water use efficiency was calculated as grain yield divided by the sum of growing season precipitation (1 May to 31 August) plus the difference in soil water (0—120 cm depth) between early spring and harvest. The efficiency of use of precipitation (PUE) was calculated as grain yield divided by the amount of precipitation received during the period from harvest of the previous crop to harvest of the crop in question. Separate soil samples were taken for determination of various soil characteristics. The methods used in these determinations are described for leaching (Campbell *et al.*,1993b), soil organic C and total N (Campbell and Zentner 1993), mineralizable N and C, light fraction organic C and N (Biederbeck *et al.*,1994), and wet soil aggregate stability using the 1 mm—2 mm aggregates isolated by dry sieving on a rotary sieve and employing a slaking procedure (Campbell *et al.*,1993a).

3 Short-term crop sequence study

Appropriate crop sequences allow crops to use available resources efficiently at a system level. In this study, dry pea, lentil, chickpea, oriental mustard, canola, and spring wheat were grown on tilled fallow in a randomized, complete block design with three replicates. Plots were managed using recommended agronomic practices. Mustard and wheat were fertilized such that total available N equalled 70 kg • ha^{-1} (soil plus fertilizer N). The three legumes received 2.5 kg N ha^{-1}, 5.5 kg P ha^{-1}, and 5.5 kg • ha^{-1} of granular-formed Rhizobium inoculant applied with the seed. Grassy and broadleaf weeds were controlled with herbicides to ensure that weed pressures in all plots were maintained at a minimal level. Crops were harvested individually when they reached full maturity. All plots received a post-harvest burn-off treatment with glyphosate, and then the plots were marked for the following year re-cropping.

In the following year, a common set of crops (wheat, an oilseed, and a pulse) was grown on the five previous crop stubbles. The oilseed crop was an argentine canola, and the pulse was either lentil or dry pea. The oilseed and wheat were fertilized to a total available N of 70 kg • ha^{-1}. The N credit from the previous pulse stubble was taken into account in the fertilizer calculation. In this manner, canola and wheat grown on the pea stubble received an average of 20 kg N ha^{-1} less than canola and wheat grown on wheat stubble. Canola and wheat grown on lentil and chickpea stubbles received 12 kg N ha^{-1} less than those grown on wheat stubble. The pea grown on wheat stubble received 7 kg N • ha^{-1} to equilibrate available N with the pea grown on pea or lentil stubble. All plots received seed-placed P at 7.4 kg ha^{-1}. Crops were managed using recommended agronomic practices. Crops were harvested individually when they reached full maturity. Water and N conservation and their use efficiencies were determined using the same methods as described earlier for the long-term rotation study. More detailed information about the crop sequence study is discussed elsewhere (Gan *et al.*,2000b).

4 Soil water conservation and water use efficiency

In the long-term rotation study, soil water content in the root zone of wheat (0—120 cm depth) prior to seeding was similar following lentil and wheat grown on stubble. This was so even though lentil stubble was shorter and less dense than wheat stubble and would therefore tend to trap less snow during winter. Spring soil water averaged 4.8 cm higher on fallow land than on stubble reflecting the benefits of summerfallowing for conserving soil water. At harvest, all wheat crops, whether grown on fallow or stubble, extracted almost all of the available water in the soil profile; however, lentil tended to extract about 1.5 cm less water than wheat. Most of the latter difference was observed in the 60 cm-120 cm depth, reflecting the shallower rooting depth of lentil. Water use efficiency averaged 7.3 kg • ha^{-1} • mm^{-1} for wheat grown on fallow, 5.9 kg • ha^{-1} • mm^{-1} for wheat grown on wheat stubble, and 3.5 kg • ha^{-1} • mm^{-1} for lentil grown on wheat stubble. However, these values do not reflect the true water inefficiencies due to sumerfallowing. The true efficiency is probably more clearly reflected in PUE. In this case, PUE is highest for wheat grown on stubble and lower when wheat is grown on fallow, reflecting that only 18% of the precipitation received over the 21-month fallow period is actually stored in the root zone of the soil (Campbell *et al.*,1987). Water use efficiency, no matter how calculated, was lowest for lentil because of its lower grain yield compared to wheat. On a rotation basis, the ranking of PUE was W > F-W-W > W-L > F-W.

In the shorter-term diversified crop sequences study, soil water use differed strongly among crop types studied (Gan *et al.*,2000a). On average, dry pea, lentil and chickpea used 31, 22, and 12 mm less soil water than wheat or oilseed. Thus, higher soil water was conserved under dry pea and lentil stubble largely due to less soil water extraction below 60 cm soil layers. After harvest, the stubble fields of these crops had 83 to 105 mm less soil water to a 120 cm depth than a fallow check. By the following spring, this difference diminished to 40 and 42 mm, showing that overwinter precipitation contributed strongly to recharge of soil available water in the stubble crop. In most cases, soil under dry pea and lentil stubbles had higher water conserved than soil under wheat stubble when measured in the spring. However, in drier years (e.g., 1997/98), soil water differences among stubble crops measured in spring were small, while in wetter years (e.g., 1999/2000) overwinter increases in soil water status were highest for wheat stubble and least for dry pea and lentil stubbles. Few differences in WUE occurred among crop stubbles. The mean WUE for wheat grown on wheat stubble was 15% to 30% less than the average responses of wheat grown on the broadleaf crop stubbles. Wheat grown on dry pea stubble had a WUE 38% greater than when grown on wheat stubble in a dry year (1998), while in wetter years (e.g., 2000), WUE for wheat grown on all broadleaf crop stubbles averaged 23% higher than wheat grown on wheat stubble.

5 Soil organic matter and other quality attributes

From the long-term rotation study, soil samples were taken six times since initiation of the experiment (1976, 1981, 1984, 1990, 1993 and 1996). Soil organic C (SOC) in the 0-15 cm depth has increased steadily in the continuously cropped rotations (W and W-L) (Campbell *et al.*,2000). When averaged over the six dates sampled, SOC was significantly higher for W (34.7 t • ha^{-1}) and W-L (36.6 t • ha^{-1}) than for F-W (31.5 t • ha^{-1}) and F-W-W (32.0 t • ha^{-1}). One measure of SOM quality is the soil's ability to mineralize or supply mineral N for plant use. This potential, when measured by aerobic incubation of soil under optimum moisture and temperature conditions in the laboratory (Biederbeck *et al.*, 1994) for samples taken in 1996, showed that the W and W-L systems had 42% higher N-supplying power than the two fallow-containing rotations. Similar responses were found in two other indices of SOM quality, i.e., potential mineralizable C and the light fraction organic C (partially decomposed crop residues). The W and W-L systems had >90% higher potential mineralizable C and 49% higher light fraction organic C than the two fallow-containing rotations. Soil aggregation is directly related to soil structural stability and tilth. In this study, wet aggregate, determined by a slaking/wet sieving technique (Campbell *et al.*,1993a) was 36% for W, 33% for W-L, and 16% for F-W, reflecting the detrimental effect of frequent summerfallowing on soil structure and quality.

Assessment of soil microbial ecology has shown that W-L has by far the greatest mass of live microbes, exceeding the biomass in continuous wheat by 45% and that of F-W by 75% in surface soils. Microbial communities of wheat grown after lentil were much more diverse than those under any other rotation. Despite its great microbial biomass and diversity, the W-L rotation had a lower rate of potential soil respiration, reflecting a general narrowing of residue C:N ratios and indicating a more effective bioconversion of mixed lentil/wheat residues into soil humus (Biederbeck *et al.*,2000). Furthermore, the populations of rhizobia in the rhizosphere and rhizoplane of wheat roots were many thousand- to million-fold higher when grown in rotation with lentil than in monoculture.

6 Soil N conservation and leaching

The crop sequence study showed that soil NO_3-N measured under the fallow control was 50 kg • ha^{-1} (in a 120 cm soil depth) greater than the mean of broadleaf crop stubbles (Gan *et al.*,2000b), indicating strong soil N mineralization due to wet and low crop residue conditions in the fallow control plots. There were significant differences in post-harvest soil NO_3-N to a 120 cm depth among crop stubbles. The soil NO_3-N under dry pea stubble averaged 18 kg • ha^{-1} greater than under wheat stubble regardless of soil types. Soil residual NO_3-N increased during the period from fall to the following spring for all crop stubbles, with the increased amounts being similar for legumes and wheat stubble systems. A nitrogen margin was calculated to compare crop type effects on the N budget, considering N harvested in the grain as a positive asset. The N margin was positive for the legumes and negative for wheat and oilseed, as expected, indicating effective N fixation for the legumes. Through higher seed N yields, the average N margin for dry pea was 42 kg • ha^{-1} greater than for desi chickpea and lentil, indicating greater N fixation by dry pea. This N margin is generally consistent with results of Biederbeck *et al.*,(1996) where dry pea grown for green manure purposes held 22 kg • ha^{-1} greater N in its vegetation at the time of growth termination approximately two months after seeding.

Prior to seeding in the following spring, soils under pulse stubbles generally had greater soil NO_3-N (14 to 23 kg • ha^{-1}) than was detected under wheat stubble systems in some years. However, in other years, lentil stubble did not provide greater soil NO_3-N, and soil NO_3-N under desi chickpea stubble was not different from that under wheat stubble. The lack of N effects in the latter cases was partially due to weed infestation in the previous pulse crops. Infestations of Russian thistle (*Salsola pestifer* Nels.), kochia (*Kochia scoparia* (L.) Schrader), lamb's-quarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus retroflexus* L.) and wild mustard (*Sinapis arvensis* L.) combined to create overall moderate weed infestations in lentil and chickpea plots where the potential N effects were reduced or diminished.

In the long-term rotation study, NO_3-N leaching below the rooting depth of 120 cm, with potential for contaminating groundwater, was lower under the two continuously-cropped rotations (W and W-L) than under F-W, and was also lower under W-L than under W. Campbell *et al.* (1993b) hypothesized that there was greater synchrony between N released from mineralization of lentil residues and N uptake by the following wheat crop, than for N uptake from the fertilizer N applied to the monoculture W system in spring. In the fallow soils, the deep leaching of NO_3-N, mainly through macro soil pores, occurred in years with above-normal growing season precipitation (Campbell *et al.*,1987).

7 Conclusions

In the past, the semiarid Canadian prairies have been synonymous with frequent summerfallow, intensive use of mechanical tillage for weed control and seedbed preparation, and production of monoculture spring cereals. The potential damage to the natural resources with which these cultural practices are associated is well known. The challenge to researchers has been to provide producers with alternative crop options with appropriate crop sequences that are agronomically suitable, economically viable, and that will maintain or enhance the quality of the soil-water-air environment. We believe that the foregoing evidence strongly supports the adoption of diverse cropping systems together with a reduction, or possible elimination, of summerfallow in this semiarid region. The current challenge of adopting such diversified cropping systems is to develop integrated management systems to minimize pulse crop pests and reduce production costs.

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