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Lentil Green Manure as Fallow Replacement in the Semiarid Northern Great Plains

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ABSTRACT

Green manures (GM) may offset inorganic N needs and improve soil quality. Study objectives were to determine effects of green manure on soil-N fertility, water use, soil quality, and yield of spring wheat (*Triticum aestivum* L.). On two treatments, lentil (*Lens culinaris* Medikus cv. Indianhead) was green manured in a green manure–spring wheat rotation. Lentil was killed by disking (GMMF) or chemicals (GMCF). Additional treatments were annually cropped wheat (AW) in a mechanical fallow (MF) or chemical fallow (CF) sequence. No inorganic N was used on GMMF and GMCF. Experiments were started in 1991 on a Williams loam (fine-loamy, mixed Typic Argiboroll) near Culbertson, MT. Green-manure treatments used 56 mm more water than fallow treatments when lentil was grown to lower-pod set. When lentil was killed at full bloom, there were no differences in water use among GM and fallow treatments. There were no differences among treatments in soil water at wheat planting. Wheat yield was 25% less on GM than on MF and CF. Soil NO_3–N (0–0.6 m) was 35% less on GM than MF and CF rotations. There were no differences in soil quality indicators of bulk density, organic C, pH, electrical conductivity, and deep NO_3–N (0.6–1.8 m) among treatments after two cycles of GM. Potentially mineralizable N was 66% greater on GM treatments than on fallow treatments. Short-term results (5 yr) show that available N limited wheat production more than did soil water on the GM treatments. Soil improvement using green manures may require many additional cropping cycles.

WATER limits crop production in the semiarid northern Great Plains and, consequently, cropping options are severely limited. In Montana alone, there are 3.7 million ha of harvested cropland (Montana Agric. Stat. Serv., 1994). Because of climatic, economic, cultural, or government program constraints, there are an additional 2.3 million ha of cultivated summer fallow, making summer fallow a common practice. Fallow has accelerated soil C loss (Rasmussen and Parton, 1994; Aase and Pikul, 1995), soil erosion (especially where there are meager amounts of crop residue cover), and development of saline seeps (Black et al., 1981). Soil-water storage efficiency of fallow ranges from about 15 to 40% (Black and Power, 1965; Tanaka and Aase, 1987). However, even with low water-storage efficiency, summer fallow provides a means of reducing risk by reducing year-to-year variability in soil water and so reducing variability in crop yield. This is important in a crop-production system where precipitation is extremely variable in both amounts and timing.

The use of legumes as soil-improving and soil-conserving crops has historically been an integral part of crop-rotation strategies. Literature reviews as early as 1917 (Pieters, 1917) of research conducted at experiment stations provide a historical perspective of green manure studies. Brown (1964) provides additional review of the literature. The aim of Pieters' 1917 review was to evaluate legumes as measured by the performance of the following crop. Pieters concluded that the value of legumes as green manures decreased from the southeastern to the northwestern United States, and that green manures were not profitable in the Dakotas and the Canadian Prairie Provinces, because green manures used soil water needed for the main crop. Conclusions from studies started in Montana in the early 1900s and reported after 28- and 43-yr periods (Army and Hide, 1959) were similar to the conclusions drawn by Pieters (1917). Green manures decreased yields of subsequent spring and winter wheat crops, compared with conventional fallow practices. Army and Hide also reported that green manures had not significantly affected soil N and C content of the top 0.3 m. They concluded that green manures are not appropriate for the semiarid wheat production areas of the northern Great Plains.

Currently there is a strong national interest in soil quality (Warkentin, 1995). There are many physical, chemical, and biological soil properties that can be used to diagnose the health of soil, but soil organic C is among the most important. Soil organic C has been identified to have a disproportionate effect on soil physical behavior (Boyle et al., 1989). An important question that is key to sustaining our soil resources has been posed by Kemper (1997) and others. Soil organic-matter levels have decreased in agricultural soils during the past 100 yr. How long will it take to rebuild soil organic matter on a degraded soil? Partial answers to these questions can be found in the results of field trials that began in the early 1900s. Brown (1964) summarized studies reported by Haas et al. (1957) from 37-yr trials conducted at 10 locations in the northern and central Great Plains and concluded that legume green manures are not effective in reducing soil loss of N and C. Results from these early studies and recent findings (e.g., Rasmussen and Parton, 1994; Staben et al., 1997) show that rebuilding soil organic matter is difficult and that the time required to effect change could be much longer than the 5 yr documented in the present report.

Legumes in crop rotations continue to gain attention

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Abbreviations: AW, annually cropped wheat; CF, conventional chemical fallow; GM, green manure; GMCF, green manure chemical fallow (lentil killed by chemical spray); GMMF, green manure mechanical fallow (lentil killed by disking); MF, conventional mechanical fallow; TOC, total organic carbon; WU, water use.

as fertilizer costs increase and society becomes concerned with chemical usage in agriculture. New strategies for managing green-manure crops have prompted optimism that green manures can be adopted for semiarid wheat production systems even in light of the literature base that suggests otherwise. The term *green fallow* has been coined to describe a green-manure farming system that is typically used as partial fallow replacement in a wheat–fallow rotation. In this system, a legume is seeded early in the fallow year, grown to about full bloom, and killed by chemicals or tillage. An important aspect of this green-fallow system is to balance water use for N_2 fixation with the water and N requirements of the subsequent wheat crop. Research on the Canadian prairies shows that annual legumes have potential as green-manure crops (Rice et al., 1993). In grain lentil–wheat rotations, there has been a gradual reduction in fertilizer-N requirement after about 6 yr (Campbell et al., 1992).

Annual-legume species that are used for green manures have different N_2–fixation capabilities and water-use efficiencies. Biederbeck and Bouman (1994) tested water use characteristics of black lentil cv. Indianhead, Tangier flatpea (*Lathyrus tingitanus* L.), chickling vetch (*Lathyrus sativus* L.), and feed pea (*Pisum sativum* L.). Annual legumes that produce high quantities of phytomass had water-use efficiencies that were greater than legume species that produced less phytomass. Feed pea and chickling vetch used water more efficiently than other legumes tested. Townley-Smith et al. (1993) tested productivity, water use, and N_2 fixation of the same legumes used by Biederbeck and Bouman (1994), in addition to fababean (*Vicia faba* L. cv. Outlook) and seedling alfalfa (*Medicago sativa* L. cv. Moapa). Of the crops tested by Townley-Smith et al. (1993), Indianhead lentil was suggested to have the best potential as a green-manure because of low seed cost and intermediate topgrowth N yield. Our objectives were to determine the effects of green manure on soil-N fertility, water use, soil quality, and yield of spring wheat.

MATERIALS AND METHODS

The study was located 11 km north of Culbertson, MT, on a Williams loam (fine-loamy, mixed Typic Argiboroll) with about a 3% slope. Average annual precipitation is 340 mm, with about 80% of the precipitation occurring during April through September. Before the start of the experiment in 1991, wheat was grown in a fallow–spring wheat rotation with no fertilizer.

Experimental design was a randomized complete block with 4 replications and 5 treatments. Plots were 12 m wide and 15 m long. Both phases of each rotation were present every year, for a total of 36 plots. In the spring of 1991, prior to the start of the current experiment, 27 of the 36 plots were soil-sampled to a depth of 1.8 m. Samples were taken at depths of 0 to 0.08 m, 0.08 to 0.15 m, 0.15 to 0.3 m and at increments of 0.3 m to a depth of 1.8 m. Soil pH on samples from the top 0.15 m was measured using a soil/water ratio of 1:1 (McLean, 1982). Soil organic C on samples from the top 0.15 m was measured using a Carlo Erba NA 1500 C-N analyzer (Carlo Erba Instruments,[1] Milan, Italy). Soil NO_3–N, for all sample increments, was measured using an Alpkem rapid-flow analyzer (Perstorp Analytical, Clackamas, OR). The hydrometer method (Gee and Bauder, 1986) was used to determine soil texture for all depths sampled.

Phosphorus levels were built up at the start of the experiment by broadcast application of 45 kg P ha^{-1} as diammonium phosphate [$(NH_4)_2HPO_4$, 18–46–0 N–P–K] before seeding in 1991 and broadcast application of 40 kg P ha^{-1} as triple superphosphate [$3Ca(H_2PO_4)_2$, 0–44–0] before seeding in 1992. Black (1982) has shown that a one-time application of 90 kg P ha^{-1} maintained adequate soluble-P even after 12 yr on a Williams loam.

Two treatments were in conventional fallow–spring wheat rotation, where weeds during fallow were killed either by tillage (MF) or herbicides (CF). Stubble remained on CF from harvest until wheat seedbed preparation nearly 21 mo later. Glyphosate [*N*-(phosphonomethyl)glycine] and 2,4-D (2,4-dichlorophenoxyacetic acid) were used as necessary to eliminate weeds. Glyphosate was applied at 2.3 L ha^{-1} and 2,4-D was applied at 0.54 kg ha^{-1}. On MF, wheat stubble remained standing during the first winter after harvest. Medium-crown sweeps and rodweeder were used about three times during each summer to control weeds. Prior to seeding spring wheat, both MF and CF treatments received 34 kg N ha^{-1} broadcast as NH_4NO_3. This rate of N fertility was used to imitate the average rate of N applied to fallow–wheat sequences in northeastern Montana (T. Angvick, Montana State Univ. Extension, Sheridan County, personal communication, 1991). Seedbeds for both MF and CF treatments were prepared with a tandem disk followed by toolbar sweeps and rodweeder. Plots were seeded to 'Lew' spring wheat at about 2.1 million viable seeds ha^{-1} using a double disk drill with 0.2-m row spacing.

Two treatments were in a green fallow–spring wheat rotation. During part of the summer portion of the fallow year, Indianhead lentil was grown as a green manure (GM) and terminated either mechanically by disking (GMMF) or by herbicides (GMCF). A mixture of glyphosate (2.3 L ha^{-1}) and 2,4-D (0.54 kg ha^{-1}) was used to kill lentil on GMCF. Indianhead lentil was used for this green manure experiment because this legume has intermediate topgrowth N yield and the seed was available at low cost. Wheat stubble remained on GMCF from harvest, glyphosate was used for preplant weed control, and lentil was no-till seeded. On GMMF, the seedbed was prepared for lentil similarly to that for spring wheat. Lentil was inoculated with Sow-Fast (Loveland Industries, Greeley, CO) inoculant using 35 g of inoculant to 23 kg seed. Both GMMF and GMCF treatments were seeded at about 59 kg ha^{-1} using a John Deere 750 no-till drill with 0.19-m row spacing. We used a seeding rate higher than that used in other studies (Rice et al., 1993), to combat a persistent green foxtail [*Setaria viridis* (L.) P. Beauv.] weed problem. Green foxtail were virtually eliminated by the dense, closed canopy of Indianhead lentil. Seeding date was as early as 20 April and as late as 21 May (Table 1). In 1991, 1992, and 1993, lentil was killed at about full bloom (normally mid-July). Random observations of nodulation on lentil were made each year prior to killing the lentil. In 1994 and 1995, lentil was killed shortly after pods were set in the lower portion of the plant. The following spring, seedbeds for wheat were prepared on both treatments similar to the MF and CF treatments. No inorganic fertilizer was applied to the green manure treatments. One treatment was cropped annually to spring wheat (AW). Seedbed preparation and fertilizer rate were the same as MF and CF treatments.

Wheat seeding date and rate were the same for all treatments. In different years, seeding was as early as 2 April and as late as 21 May, depending on weather conditions (Table 1). A mixture of glyphosate and 2,4-D was used for postharvest weed control in 1992 and 1995 on all treatments.

[1] Mention of trade names is for the benefit of the reader and does not constitute endorsement by the U.S. Department of Agriculture over other products not mentioned.

Table 1. Growing-season precipitation and dates of planting, green-manure (lentil) termination, and first and last soil water measurements for a 5-yr study of green manure and conventional fallow in the semiarid Northern Great Plains.

Parameters	1991	1992	1993	1994	1995	5-yr avg.	29-yr avg.
Soil water balance							
Precipitation (lentil growing season†), mm	178	168	198	180	185	182	
Precipitation (summer fallow‡), mm	254	273	296	232	332	277	
Wheat planting	21 May	2 Apr.	29 Apr.	18 Apr.	27 Apr.	25 Apr.	
Lentil planting	21 May	28 Apr.	10 May	20 Apr.	2 May	4 May	
Lentil termination	20 July	17 July	30 July	20 July	26 July	23 July	
First soil water measurement	22 May	2 Apr.	10 May	21 Apr.	17 May		
Last soil water measurement	30 Sept.	11 Aug.	26 Oct.	21 Oct.	20 Oct.		
Precipitation, mm							
April	68	73	5	22	28	39	30
May	67	30	26	53	40	43	52
June	113	103	60	97	61	87	75
July	41	47	131	19	86	65	52
August	12	62	94	17	118	61	40
September	65	17	4	16	12	23	36
October	7	15	3	24	29	16	19
Total	373	347	323	248	374	334	304

† Time from seeding to termination of lentils.
‡ Time from first to last soil water measurement of the year.

Soil water during the growing season was measured using neutron attenuation at 2-wk intervals to a depth of 1.8 m at 0.30-m increments. Access tubes for these measurements were located in the center of each plot. Water use (WU), which is combined evaporation and transpiration water loss, for each 2-wk interval, was calculated as

$$WU = Rain - (Soilwater_2 - Soilwater_1)$$

where Rain is the amount of precipitation occurring between biweekly soil water measurements termed $Soilwater_1$ and $Soilwater_2$. Soil water is the depth of water in the 1.8-m soil profile at each biweekly measurement. Water use for both crop and fallow was the sum of biweekly WU values for appropriate time intervals. Wheat water use was measured from seeding date to harvest date. Green-manure water use was measured from seeding date to lentil termination. Seasonal water use for both fallow and green fallow was determined from the first and last soil-water measurement of the season. The same time interval was used for water-use comparisons between fallow and green fallow. Calculations are based on the assumption that there was no water runoff from the plots and that drainage beyond 1.8 m was negligible.

Soil NO_3 and P concentrations were determined prior to wheat planting and fertilizer application. Samples for the 1993, 1994, and 1996 wheat crop-year were taken in late October of 1992, 1993, and 1995 respectively. Samples for the 1992 crop-year were not taken. Samples for the 1995 crop were taken in April 1995. Three soil cores, 35.6 mm in diameter, to a depth of 0.6 m were taken at about 3-m intervals across each plot. Each core was segmented into sample increments of 0.0 to 0.08 m, 0.08 to 0.15 m, 0.15 to 0.30 m, and 0.30 to 0.60 m for analysis. Soil NO_3 was determined using an Alpkem rapid flow analyzer. Soil P was determined using the $NaHCO_3$ method (Olsen et al., 1954).

Nitrogen mineralization was measured on soil samples taken in late October 1993 and 1995 for the 0- to 0.08-m and 0.08- to 0.15-m depths. Soil samples were air dried and ground to pass through a 2-mm sieve. Incubation vials were set up using 5 g of soil wetted to a drained-upper-limit volumetric water content of 0.21 $m^3 m^{-3}$, which corresponds to about 33 kPa. Temperature of the incubation chamber was 25°C. Vials were weighed weekly, and water was added as necessary to maintain a soil-water content of 0.21 $m^3 m^{-3}$. Sample vials were taken from the incubator at 56 d and frozen at −16.0°C to await analysis for NO_3–N.

Soil organic C was measured on samples taken in October 1992 and April 1995 from the 0 to 0.08 and 0.08 to 0.15 m soil depths. Organic C was measured using a Carlo Erba NA 1500 C-N analyzer for samples taken in 1992 and by the Walkley–Black procedure (Nelson and Sommers, 1982) for samples taken in 1995.

Soil bulk density was measured on each plot in October 1995 by taking six undisturbed cores from depths of 0 to 0.08, 0.08 to 0.15, and 0.15 to 0.30 m. Core diameter was 33 mm.

Spring wheat grain and straw yield harvest samples were obtained by cutting bundle samples at soil level from five adjacent 1-m long rows (1-m^2 area) from six locations on each plot. Bundle samples were weighed and threshed, following which the grain was weighed and straw yield was determined. Grain protein was determined on ground whole seeds using near-infrared spectroscopy (NIRS). On the green-manure treatments, lentil phytomass was sampled in a like manner. Samples were air dried, weighed and ground for N analysis. Total plant N was measured using a Carlo Erba NA 1500 C-N analyzer for samples taken in 1991, 1992, and 1993 and by Kjeldahl analysis in 1994 and 1995.

Water use, yield, and soil N were tested for significant differences among treatments using analysis of variance and least significant differences (LSD) at $P = 0.05$. Mechanical fallow was the control treatment for all comparisons. Lentil top growth and N content of top growth on the two green-manure treatments were compared using analysis of variance.

RESULTS AND DISCUSSION

In the first 3 yr of the study (1991–1993), care was taken to limit soil-water use by lentil by terminating the crop at about full bloom. Growing-season water use, defined as water use between planting date and termination date, for 1991 through 1993 averaged 172 mm for green manure (GMMF and GMCF) treatments and 140 mm for fallow (MF and CF) treatments (Table 2). At termination date (Table 1), which averaged 22 July, lentil had used 32 mm more water than fallow. Growing-season water-use measurements were consistent with our expectations that water loss from combined evapotranspiration (GMMF and GMCF) would be greater than evaporation alone (MF and CF).

By the end of summer in 1991, 1992, and 1993 there were no differences in seasonal water use among treatments. Seasonal water use is defined as water use between first and last water measurements of the season.

Although not significant, there was a consistent trend for greater seasonal water use by GM treatments than by fallow. Green-manure treatments used an average of 268 mm of water and fallow treatments used an average of 251 mm of water in 1991–1993 (Table 2). Average date of the last soil-water measurement for 1991–1993 was 22 September (Table 1).

Seasonal water measurements suggest that the soil-water evaporation rate on the green-manure treatments, after lentil termination, was less than that of the fallow treatments. This study did not focus on mechanisms affecting soil-water evaporation; however, surface residues and differences in soil-water content near the surface can be expected to influence evaporation rate (Pikul et al., 1985; Hammel et al., 1981). Because there were no significant differences in seasonal water use among treatments (Table 2) in 1991, 1992, and 1993, we changed management of the green manure in subsequent years. In 1994 and 1995, lentil was grown past full bloom to increase top growth and N yield.

Differences in water use among years (Table 2) by Indianhead lentil underscores an important aspect of managing green manure in semiarid climates. A balance must be achieved between using fallow season water for N production and providing adequate soil water for the subsequent wheat crop. Lentil growth was limited in 1991, 1992, and 1993 by killing the crop early. Average dry weight of lentil for 1991, 1992, and 1993 was 1679 kg ha^{-1}. In 1994 and 1995, we killed the lentil late. Dry weight of lentil for 1994 and 1995 averaged 5261 kg ha^{-1}. (The terms *early* and *late* refer to crop maturity, not calendar date.) The average kill date for the lentil crop in 1991, 1992, and 1993 was 22 July. For 1994 and 1995, the average kill date was 23 July. Average seasonal water use by lentil in 1991, 1992, and 1993 was 268 mm. In 1994 and 1995, average seasonal water use by lentil was 327 mm. The additional water used by lentil in 1994 and 1995 resulted in additional phytomass (Table 2). Average N in lentil phytomass for 1994 and 1995 was 132 kg ha^{-1}. For 1991, 1992, and 1993, average N in lentil phytomass was 31 kg ha^{-1}. Growing-season precipitation, planting, and termination date for the crops are shown in Table 1.

Efficient fixation of atmospheric N_2 by lentil requires active, N_2–fixing nodules. We qualitatively determined nodulation in the field by randomly sampling Indianhead lentil root systems prior to killing the plants. Pink to red nodules were present on the root systems every year. We cannot be certain if our green manure crop was adequately nodulated to ensure optimum N_2 fixation, nor can we be sure of what constitutes optimum

Table 2. Full-season (Seasonal) and lentil green-manure growing season (GM season) water use, with lentil dry matter (DM) yield, N content, and water use efficiency (WUE).

Fallow treatment†	Water use‡ Seasonal	GM season	Lentil parameters DM§	N content	WUE¶
	mm	mm	kg ha^{-1}	kg ha^{-1}	kg ha^{-1} mm^{-1}
1991					
MF	236	152	—	—	—
CF	239	152	—	—	—
GMMF	257	192	1027	14.4	5.3
GMCF	251	161	516	11.1	3.2
LSD (0.05)	NS	22	NS	NS	NS
1992					
MF	239	124	—	—	—
CF	234	118	—	—	—
GMMF	257	159	2527	44.9	15.9
GMCF	257	139	1254	25.4	9
LSD (0.05)	NS	26	*	*	NS
1993					
MF	282	152	—	—	—
CF	277	142	—	—	—
GMMF	295	196	2299	41	11.7
GMCF	292	184	2452	47.2	13.3
LSD (0.05)	NS	20	NS	NS	NS
1994					
MF	234	163	—	—	—
CF	236	169	—	—	—
GMMF	292	260	5749	130.4	22.1
GMCF	315	267	6903	171.6	25.8
LSD (0.05)	20	18	NS	NS	NS
1995					
MF	312	144	—	—	—
CF	307	138	—	—	—
GMMF	340	240	3974	110.4	16.6
GMCF	361	244	4417	118	18.1
LSD (0.05)	20	18	NS	NS	NS

* Significant at the 0.05 probability level, from analysis of variance.

† MF, mechanical fallow; CF, chemical fallow; GMMF, green manure mechanical fallow (lentil killed by disking); GMCF, green manure chemical fallow (lentil killed by chemical spray).

‡ Water use (to a depth of 1.8 m) defined as precipitation less soil water gain or loss. Seasonal water use: from first to last soil water measurements of the year. Green-manure growing season water use: from lentil planting to termination. (See Table 1 for range of dates over the 5 yr.)

§ Lentil crop damaged from residual 2,4-D in 1991 and 1992 and from hail in 1995.

¶ Calculated on GM-season water use: from planting to termination.

Table 3. Spring wheat yield components for crop years 1992 to 1995 in various conventional and green-manure fallow treatments.

Treatment, previous year†	Straw	Grain	Test wt.	Protein	Heads m^{-2}	Kernels head^{-1}
	kg ha^{-1}	kg ha^{-1}	kg m^{-3}	g kg^{-1}	no.	no.
1992						
MF	4530	3932	830	152	445	26.2
CF	4492	3888	830	149	447	26.0
GMMF	3027	2585	820	94	355	23.7
GMCF	3325	2853	820	130	396	23.8
AW	—‡	—	—	—	—	—
LSD (0.05)	812	734	9	24	61	NS
1993						
MF	5068	2881	771	142	416	26.4
CF	5128	3071	778	140	421	26.6
GMMF	4305	2604	775	134	366	26.0
GMCF	3557	2125	772	129	328	24.2
AW	3082	1699	750	139	323	22.0
LSD (0.05)	602	409	14	6	27	1.6
1994						
MF	4884	3095	816	128	537	20.4
CF	4238	2842	825	117	501	19.7
GMMF	3287	2294	827	103	418	18.8
GMCF	2854	2085	825	106	412	17.4
AW	2834	1838	818	104	391	17.3
LSD (0.05)	345	253	5	4	42	1.6
1995						
MF	3156	1360	777	148	—§	—
CF	3348	1476	778	145	—	—
GMMF	2550	1234	766	142	—	—
GMCF	2282	1087	762	138	—	—
AW	2287	1033	762	132	—	—
LSD (0.05)	458	187	13	3	—	—

† MF, mechanical fallow; CF, chemical fallow; GMMF, green manure mechanical fallow (lentil killed by disking); GMCF, green manure chemical fallow (lentil killed by chemical spray); AW, annually cropped wheat.

‡ Data not available for annual wheat in 1992.

§ Crop was hail damaged in 1995.

N_2 fixation for this soil and climate. Average N concentration of lentil phytomass was 21.3 g kg^{-1} (calculated from the lentil dry matter and N content shown in Table 2). This is less than the N concentration (27.6 g kg^{-1}) reported by Zentner et al. (1996) for Indianhead green manures in southwestern Saskatchewan, Canada; that study was conducted from 1988 to 1993, during growing seasons with above-average precipitation.

Wheat grain and straw yields were generally lower on treatments that followed green fallow compared with conventional fallow (Table 3). Yields for 1992 and 1993 followed one cycle of green fallow, and yields for 1994 and 1995 followed two cycles of green fallow. Even after two cycles of green manure, yield and quality (protein and test weight) of grain from green fallow treatments tended to be less than the control (Table 3). Both lower yields and protein on GMMF and GMCF are indicators of possible N deficiency. Depletion of soil water by green manure during the fallow period was not the cause of lower wheat yields on green fallow treatments, because there were no significant differences in soil-water content among treatments at seeding time for either the 0- to 0.9-m depth or 0- to 1.8-m depth (Table 4).

Water use by green manures is an important consideration in semiarid areas. Average growing-season precipitation during the study was about 30 mm more than the 29-yr average (Table 1). Adequate rainfall recharged the soil profile during the fallow period, and treatment differences disappeared by spring-wheat planting time. Nevertheless, during certain times there were significant differences in water use among treatments. In years with below-normal precipitation, we expect that differences in soil water measured at the end of fallow would be present at spring wheat planting the following year. Inspection of Table 2 shows that in almost all cases significantly more water was used on GMMF and GMCF than MF and CF up to the time of lentil termination (growing-season water use). An exception was GMCF in 1991 and 1992 when there was scanty lentil growth. In 1991 and 1992, lentil was damaged from residual 2,4-D that was used for preplant weed control. Moyer et al. (1992) have shown that lentil can be damaged by 2,4-D applied 15 d before lentil seeding. After 1992, 2,4-D was not used before lentil seeding. Water use and water-use efficiencies (Table 2), for comparable amounts of dry matter production, are similar to those reported by Biederbeck and Bouman (1994) on experiments conducted at Swift Current, SK.

For some years, soil NO_3–N levels on plots going into wheat were significantly lower after green fallow and chemical fallow than after mechanical fallow (Table 5). The 4-yr average NO_3–N levels in the top 0.61 m of soil was 44.4 on MF, 34.7 on CF, 33.6 on GMMF, 22.9 on GMCF, and 11.7 kg ha^{-1} on AW treatments. Total

Table 4. Soil water at spring wheat seeding for the 0- to 0.9 and 0- to 1.8-m soil profiles, water use by spring wheat from seeding to harvest, wheat grain yield, and water use efficiency (WUE) of wheat for crop years 1992 to 1995.

Treatment, previous year†	Soil water 0.9 m	Soil water 1.8 m	Water use‡	Yield	WUE
	mm	mm	mm	kg ha⁻¹	kg ha⁻¹ mm⁻¹
1992					
MF	193	434	351	3932	11.2
CF	175	411	351	3888	11.1
GMMF	178	424	302	2585	8.6
GMCF	188	417	330	2853	8.6
AW	—§	—	—	—	—
LSD (0.05)	NS	NS	25	734	1.9
1993					
MF	193	442	312	2881	9.2
CF	201	442	297	3071	10.3
GMMF	211	450	290	2604	9.0
GMCF	203	445	284	2125	7.5
AW	180	414	254	1699	6.7
LSD (0.05)	NS	NS	20	409	1.6
1994					
MF	201	445	305	3095	10.1
CF	185	427	305	2842	9.3
GMMF	201	455	297	2294	7.7
GMCF	198	434	272	2085	7.7
AW	193	432	259	1838	7.1
LSD (0.05)	NS	NS	28	253	1.1
1995					
MF	191	437	267	1360¶	5.1
CF	198	439	267	1476	5.5
GMMF	198	432	234	1234	5.3
GMCF	188	424	226	1087	4.8
AW	191	429	218	1033	4.7
LSD (0.05)	NS	NS	20	187	NS

† MF, mechanical fallow; CF, chemical fallow; GMMF, green manure mechanical fallow (lentil killed by disking); GMCF, green manure chemical fallow (lentil killed by chemical spray); AW, annually cropped wheat.
‡ Water use to a depth of 1.8 m between planting date and harvest. Water use includes precipitation and soil water gain or loss.
§ Data not available for annual wheat in 1992.
¶ Crop was hail damaged in 1995.

Table 5. Soil NO_3–N prior to seeding spring wheat for crop years 1993 to 1996 in various conventional and green-manure fallow treatments.

Treatment, previous year†	Soil NO_3–N (by depth, m)‡ 0–0.08	0.08–0.15	0.15–0.30	0.30–0.60	0–0.60
	kg ha⁻¹				
1993					
MF	9.4	6.8	11.4	18.5	46.0
CF	7.8	5.8	10.9	17.6	42.1
GMMF	7.5	4.9	8.6	11.0	31.9
GMCF	5.6	4.4	8.4	8.4	26.8
AW	—	—	—	—	—
LSD (0.05)	2.0	1.0	2.8	4.1	6.6
1994					
MF	13.0	4.9	6.3	9.3	33.5
CF	5.5	2.0	3.8	6.4	17.7
GMMF	11.5	3.8	4.3	4.7	24.3
GMCF	5.6	1.6	2.1	3.5	12.8
AW	2.6	0.9	1.6	3.0	8.0
LSD (0.05)	2.1	1.1	1.8	2.3	5.6
1995					
MF	2.9	4.0	19.4	30.0	56.3
CF	1.7	1.1	13.2	42.9	59.0
GMMF	5.7	2.6	5.0	25.1	38.3
GMCF	4.1	1.6	7.2	19.3	32.1
AW	1.5	1.3	2.9	13.1	18.8
LSD (0.05)	1.5	2.0	4.1	9.9	11.4
1996					
MF	8.2	9.0	10.5	14.0	41.6
CF	4.1	4.1	4.4	7.2	19.9
GMMF	6.2	8.5	11.2	13.9	39.8
GMCF	5.0	4.8	4.9	5.3	20.0
AW	1.9	2.2	1.7	2.5	8.2
LSD (0.05)	3.0	2.3	3.7	5.0	10.0

† MF, mechanical fallow; CF, chemical fallow; GMMF, green manure mechanical fallow (lentil killed by disking); GMCF, green manure chemical fallow (lentil killed by chemical spray); AW, annually cropped wheat.
‡ Does not include the 34 kg N ha^{-1} added to MF, CF, and AW prior to seeding.

NO_3–N does not include the additional 34 kg N ha^{-1} added to MF, CF, and AW prior to wheat seeding. Soil tests for the 1996 crop are included to show rotation effects on soil NO_3 even though grain yields for 1996 are not presented. In 1994 and 1996, there was less NO_3–N following CF than following GMMF, which is contrary to results for 1993 and 1995. We do not have an explanation for this anomaly. However, it appears that the cause of lower wheat yield following green fallow can be attributed to insufficient N rather than insufficient soil water. Further, water-use efficiency was generally lower for wheat following green fallow than following fallow (Table 4). Poor water-use efficiency is an attribute of nutrient-deficient soil (Black, 1982). Crop yields in 1995 were reduced because of hail damage; nevertheless, yields were generally lower on treatments following green fallow than fallow.

Black (1982) has shown that, on a Williams loam, the number of wheat heads per square meter increased significantly as a result of increased P and N–P fertilization. In our study, the number of wheat heads per square meter and kernels per head on plots that had been green manured (lower soil NO_3 tests) were generally significantly less than on fallow plots (Table 3). On green-fallow plots, average heads per square meter for the 3 yr of measurements was 379, compared with 461 heads per square meter on fallow plots. These measurements suggest N deficiency on the GMMF and GMCF treatments. Annual wheat had the lowest number of heads per square meter at 357.

An alternative to the fallow–spring wheat sequence or green fallow–spring wheat sequence is annual wheat production. Annual wheat yields (AW) during this study were disappointing, and consistently less than wheat following fallow or green fallow. We selected a fixed N-fertilizer rate for this experiment that was based on a county average. This rate was also used on a long-term study (Aase and Pikul, 1995) adjacent to the present experiment. Our average yield from the AW treatment in 1993 and 1994 was 31% less than yields reported by Aase and Pikul (1995), even though our cultural practices were the same. We do not have an explanation for the apparent low yield on the AW treatment compared with the yields reported by Aase and Pikul (1995). Soil water at spring wheat planting (Table 4) on the AW treatment was the same as other treatments shown in Table 4. Yield components (Table 3) for the AW treatment suggest N deficiency.

The fate of N in the top growth of the green manure crop is of primary concern when considering the effect of green manures on subsequent spring wheat. We would expect that, in time, soil-available N in a given cropping system would tend towards an equilibrium, where added organic N and inorganic N would equal N removed. There are few long-term studies in the semiarid northern Great Plains appropriate for evaluating N cycling in a crop rotation that includes green manures. Under certain field conditions, there can be significant amounts of volatile NH_3 loss from decomposition of legume green manure. Janzen and McGinn (1991) measured a 14% decrease in N content of lentil residue during 14 d. Janzen and McGinn attribute the rapid loss of N from the immature lentil residue to ammonification of labile N. Bremer and van Kessel (1992) compared the effects of lentil green manure on plant available N during one growing season after application. Climatic conditions at Outlook, SK, were similar to those of northeastern Montana. Net mineralization of ^{15}N from Indianhead lentil green manure was only 37% of that added. Sparrow et al. (1995) found that fallow was as effective as green manure in producing a barley crop in the subsequent year; they studied barley (*Hordeum vulgare* L.) yields at Delta Junction, AK, following fallow and Indianhead lentil green-manure treatments and with the barley not fertilized on either treatment. Rice et al. (1993) used Indianhead lentil green manure as a substitute for summer fallow in Beaverlodge, AB. Grain and N yield of barley following early-incorporated green manure were equal to or only slightly less than the yield following fallow. Barley was not fertilized. Results from these studies are similar to ours. There were not dramatic, N-related increases in grain yield subsequent to green manuring. In fact, yield reductions seemed to be a result of N deficiency.

Soil P was not significantly different among treatments (data not shown). For the wheat production years of 1993, 1994, and 1995, the average $NaHCO_3$–extractable P in the top 0.08 m was 33 mg kg^{-1} on fallow treatments and 29 mg kg^{-1} on green fallow treatments. At the 0.08- to 0.15-m depth, there were 11 mg kg^{-1} on fallow and 9 mg kg^{-1} on green fallow. These levels are adequate for both spring wheat and lentil.

Soil quality has been defined as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Karlen et al., 1997). As yet, there is no single quantitative measure of soil quality.

We used indicators of deep NO_3–N (0.6–1.8 m), soil bulk density, potentially mineralizable N, total organic carbon (TOC), pH, and electrical conductivity (EC) to judge differences in soil quality among treatments (Table 6). Data presented in Table 6 were from plots that were planted to spring wheat in odd-numbered years with the exception of AW. Treatments MF and CF were fallowed in even-numbered years and treatments GMMF and GMCF were green manured in even-numbered years.

Of the soil quality indicators shown in Table 6, only potentially mineralizable N (56-d incubation) on samples collected in 1995 was significantly different among treatments. Mineralizable N was also measured on soil samples collected in October 1993 from this same plot series. There were no significant differences in potentially mineralizable N among treatments for samples collected in 1993. Average NO_3–N concentration for soil from the 0- to 0.08-m depth was 27.7 mg kg^{-1} and 10.3 mg kg^{-1} for soil from the 0.08- to 0.15-m depth. (Data from the mineralization tests in 1993 are not shown in Table 6). Samples taken in October 1993 followed one crop of lentil; samples taken in 1995 followed two crops of lentil. Potentially mineralizable N does not include initial NO_3–N. Data from the 1995 mineraliza-

Table 6. Soil quality indicators measured at various depths (m) in 1995, with soil properties measured at start of experiment in 1991.

Treatment†	NO_3–N, 0.6–1.8‡	Soil bulk density‡ 0–0.08	0.08–0.15	0.15–0.30	Mineral-izable N, 0–0.08‡	pH§ 0–0.08	0.08–0.15	EC§ 0–0.08	0.08–0.15	Organic C§ 0–0.08	0.08–0.15	Sand 0.15–0.3	0.6–0.9	Clay 0.15–0.3	0.6–0.9
	kg ha^{-1}	Mg m^{-3}			mg kg^{-1}			dS m^{-1}		g kg^{-1}		%			
Measured in 1995 (spring or fall)															
MF–wheat	50.8	1.39	1.68	1.56	25.8	6.4	6.5	0.12	0.14	7.9	7.2	—	—	—	—
CF–wheat	58.7	1.40	1.66	1.56	42.7	6.3	6.4	0.12	0.11	8.2	8.3	—	—	—	—
GMMF–wheat	41.6	1.35	1.77	1.49	58.7	6.5	6.5	0.13	0.14	7.5	7.2	—	—	—	—
GMCF-wheat	39.4	1.38	1.65	1.53	54.8	6.7	6.6	0.14	0.13	7.6	6.4	—	—	—	—
AW	56.0	1.32	1.58	1.45	56.5	6.4	6.7	0.13	0.13	7.9	8.4	—	—	—	—
Mean	48.2	1.37	1.67	1.52	47.7	6.5	6.5	0.13	0.13	7.8	7.5	—	—	—	—
CV, %	32.9	4.9	5.8	7.4	33.5	3.9	3.3	18.7	16.7	12.6	16.8	—	—	—	—
LSD (0.05)	NS	NS	NS	NS	24.6	NS	NS	NS	NS	NS	NS	—	—	—	—
Measured at the start of the 5-yr experiment (spring 1991)¶															
Mean	102.7	—	—	—	—	6.8	6.6	—	—	9.1	8.7	66.8	57.1	17.1	24.4
CV, %	61.8	—	—	—	—	2.7	3.8	—	—	15.9	15.8	2.3	20.7	7.3	29.8

† MF, mechanical fallow; CF, chemical fallow; GMMF, green manure mechanical fallow (lentil killed by disking); GMCF, green manure chemical fallow (lentil killed by chemical spray); AW, annually cropped wheat.
‡ Nitrate-N, soil bulk density, and mineralizable N: Sampled in the fall of 1995, after 3 crops of spring wheat and 2 crops of lentil.
§ pH, EC (electrical conductivity), and organic C: Sampled in the spring of 1995, after 2 crops of spring wheat and 2 crops of lentil.
¶ The sampling grid in the spring of 1991 included 27 of the 36 plots used for this study.

tion tests suggest a trend for improved N reserves on treatments that have been annually cropped (AW, GMMF, and GMCF) compared with fallow–wheat treatments.

It is difficult to draw conclusions whether a given treatment improved or degraded the soil resource during the short life (5 yr) of this experiment. Some initial soil conditions are shown in Table 6. Organic C and pH measurements in 1995 are similar to the 1991 measurements. Interestingly, the coefficient of variation (CV) for TOC and pH for 1995 measurements is about the same as the CV for 1991 measurements. Staben et al. (1997) found no differences in total organic C, after 4 to 7 yr, between treatments in grass and fallow–wheat rotation. Staben suggested that, in a semiarid environment, more time was necessary for changes in TOC to occur.

The quantity of deep NO_3–N (0.6–1.8 m) was not significantly different among treatments in 1995 (Table 6), and there was a decrease in NO_3–N from 1991 to 1995. Water use studies for this area suggest that there is only a slight potential for leaching of NO_3–N with annual cropping during years with normal rainfall (Aase and Siddoway, 1982). However, leaching problems can develop on some soils after many years of summer fallow (Brown et al., 1983). Average summer rainfall for 1991 to 1995 was 30 mm more than the 29-yr average (Table 1). We cannot be certain whether there was water flux past the 1.8-m depth and, consequently, we cannot be certain whether NO_3–N was flushed from the profile or utilized by the crops. We can only conclude that no treatment increased the concentration of NO_3–N at the 0.6- to 1.8-m depth.

CONCLUSION

In 3 out of 5 yr, there were no differences in soil water use by green fallow as compared with soil water loss from fallow. In those years, lentil growth was terminated at about full bloom, when average dry weight of lentil was about 1680 kg ha^{-1}. Green fallow used more water than fallow when lentil matured past full bloom, with an average lentil dry weight of about 5260 kg ha^{-1}. In all years, soil-profile water content to a depth of 1.8 m was the same for green fallow and fallow in the spring of the wheat year, suggesting that the profile filled to an upper drained limit. We expect that, in years with below-normal precipitation, a soil-water deficit created by growing green manures past full bloom would be carried over into the following year. Soil NO_3–N on green fallow treatments (which did not receive supplemental N) was 35% lower than on fallow treatments. Wheat yield was 25% less on green fallow than on fallow treatments, and our conclusion is that N rather than soil water limited wheat yields on green fallow–spring wheat rotations. Potentially mineralizable N following two complete rotations was 66% greater on green manured treatments than on fallow treatments. These results were encouraging, because they show that an improvement in soil fertility using green manure may be possible. Additional work is necessary to assess N-use efficiency, economic returns, and the potential to rebuild soil organic matter in these fallow systems. For example, we designed our experiment with the expectation that green manures could provide the N requirement for subsequent spring wheat. This expectation may have been too optimistic, considering the limitations of climate (semiarid) and soil (sandy loam with less than 1% organic C). Green manures may provide some of the N requirement of spring wheat in semiarid environments. However, in addition to green manure, supplemental N will be required to achieve yields comparable to wheat that has been inorganically fertilized to meet yield potential. Green manure in rotation with spring wheat requires more intensive management than traditional fallow wheat. In addition to N management, soil water use by green manures, especially in low rainfall years, must be carefully monitored. Prediction of soil-water depletion using plant measurements could provide an additional tool that would simplify green-fallow management.

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REFERENCES

Aase, J.K., and J.L. Pikul, Jr. 1995. Crop and soil response to long-term tillage practices in the northern Great Plains. Agron. J. 87:652–656.

Aase, J.K., and F.H. Siddoway. 1982. Evaporative flux from wheat and fallow in a semiarid climate. Soil Sci. Soc Am. J. 46:619–626.

Army, T., and J.C. Hide. 1959. Effects of green manure crops on dryland wheat production in the Great Plains of Montana. Agron. J. 51:196–198.

Biederbeck, V.O., and O.T. Bouman. 1994. Water use by annual green manure legumes in dryland cropping systems. Agron. J. 86:543–549.

Black, A.L. 1982. Long-term N–P fertilizer and climatic influences on morphology and yield components of spring wheat. Agron. J. 74:651–657.

Black, A.L., P.L. Brown, A.D. Halvorson, and F.H. Siddoway. 1981. Dryland cropping strategies for efficient water-use to control saline seeps in the northern Great Plains, U.S.A. Agric. Water Manage. 4:295–311.

Black, A.L., and J.F. Power. 1965. Effect of chemical and mechanical fallow methods on moisture storage, wheat yields, and soil erodibility. Soil Sci. Soc. Am. Proc. 29:465–468.

Boyle, M., W.T. Frankenberger, Jr., and L.H. Stolzy. 1989. The influence of organic matter on soil aggregation and water infiltration. J. Prod. Agric. 2:290–299.

Bremer, E., and C. van Kessel. 1992. Plant-available nitrogen from lentil and wheat residues during a subsequent growing season. Soil Sci. Soc Am. J. 56:1155–1160.

Brown, P.L. 1964. Legumes and grasses in dryland cropping systems in the northern and central Great Plains: A review of the literature. USDA Misc. Publ. 952. USDA-ARS, Washington, DC.

Brown, P.L., A.D. Halvorson, F.H. Siddoway, H.F. Mayland, and M.R. Miller. 1983. Saline-seep diagnosis, control, and reclamation. USDA Conserv. Res. Rep. 30. U.S. Gov. Print. Office, Washington, DC.

Campbell, C.A., R.P. Zentner, F. Selles, V.O. Biederbeck, and A.J. Leyshon. 1992. Comparative effects of grain lentil–wheat and monoculture wheat on crop production, N economy and N fertility in a Brown Chernozem. Can. J. Plant Sci. 72:1091–1107.

Gee, G.W., and J.W. Bauder. 1986. Particle size analysis. p. 383–411. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Haas, H.J., C.E. Evans, and E.F. Miles. 1957. Nitrogen and carbon changes in Great Plains soils as influenced by cropping and soil treatments. USDA Tech. Bull. 1164.

Hammel, J.E., R.I. Papendick, G.S. Campbell. 1981. Fallow tillage effects on evaporation and seedzone water content in a dry summer climate. Soil Sci. Soc Am. J. 45:1016–1022.

Janzen, H.H., and S.M. McGinn. 1991. Volatile loss of nitrogen during decomposition of legume green manure. Soil Biol. Biochem. 23: 291–297.

Karlen, D.L., M.J. Mausbach, J.W. Doran, R.G. Cline, R.F. Harris, and G.E. Schuman. 1997. Soil quality: A concept, definition, and framework for evaluation. Soil Sci. Soc Am. J. 61:4–10.

Kemper, W.D. 1997. Organic matter: 100 years to bring it down. How long to bring it back? Natl. Conserv. Tillage Digest. January 1997:2, 20–21.

McLean, E.O. 1982. Soil pH and lime requirement. p. 199–224. *In* A.L. Page (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Montana Agricultural Statistics Service. 1994. Montana Agricultural Facts 1993. Montana Agric. Statistics Service, Helena.

Moyer, J.R., P. Bergen, and G.B. Schaalje. 1992. Effect of 2,4-D and dicamba residues on following crops in conservation tillage systems. Weed Technol. 6:149–155.

Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. *In* A.L. Page (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Olsen, S.R., C.V. Cole, F.S. Watanabe, and L.A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circ. 939. U.S. Gov. Printing Office, Washington DC.

Pieters, A.J. 1917. Green manuring: A review of the American experiment station literature. J. Am. Soc. Agron. 9:62–82, 109–126, 162–190.

Pikul, J.L., Jr., R.R. Allmaras, and S.E. Waldman. 1985. Late season heat flux and water distribution in summer-fallowed Haploxerolls. Soil Sci. Soc. Am. J. 49:1517–1522.

Rasmussen, P.E., and W.J. Parton. 1994. Long-term effects of residue management in wheat–fallow: I. Inputs, yield, and soil organic matter. Soil Sci. Soc. Am. J. 58:523–530.

Rice, W.A., P.E. Olsen, L.D. Bailey, V.O. Biederbeck, and A.E. Slinkard. 1993. The use of annual legume green-manure crops as a substitute for summerfallow in the Peace River region. Can. J. Soil Sci. 73:243–252.

Sparrow, S.D., V.L. Cochran, and E.B. Sparrow. 1995. Residual effects of harvested and green-manured legumes on a subsequent barley crop in a subarctic environment. Can. J. Plant Sci. 75:453–456.

Staben, M.L., D.F. Bezdicek, J.L. Smith, and M.F. Fauci. 1997. Assessment of soil quality in conservation reserve program and wheat–fallow soils. Soil Sci. Soc. Am. J. 61:124–130.

Tanaka, D.L., and J.K. Aase. 1987. Fallow method influences on soil water and precipitation storage efficiency. Soil Tillage Res. 9:307–316.

Townley-Smith, L., A.E. Slinkard, L.D. Bailey, V.O. Biederbeck, and W.A. Rice. 1993. Productivity, water use and nitrogen fixation of annual-legume green-manure crops in the Dark Brown soil zone of Saskatchewan. Can. J. Plant Sci. 73:139–148.

Warkentin, B.P. 1995. The changing concept of soil quality. J. Soil Water Conserv. 50:226–228.

Zentner, R.P., C.A. Campbell, V.O. Biederbeck, and F. Selles. 1996. Indianhead black lentil as green manure for wheat rotations in the Brown soil zone. Can. J. Plant Sci. 76:417–422.