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ABSTRACT

Increases in N fertilizer costs have caused some farmers to consider the use of a legume during the fallow phase of a wheat–fallow system as an alternative N source for dryland wheat. Farmers need to know how this system will affect winter wheat (*Triticum aestivum* L.) production and economic returns. The objectives of this research were (i) to determine the effect of legume green fallow on subsequent winter wheat yields and economic returns and (ii) to determine optimal legume termination dates during the legume phase. Wheat yields following three legumes [Austrian winter pea, *Pisum sativum* L. subsp. *sativum* var. *arvense* (L.) Poir.; spring field pea, *P. sativum* L.; and black lentil, *Lens culinaris* Medikus] were compared with wheat yields following fertilized traditional summer fallow. Legume biomass, biomass N, and water use were measured at four termination dates during the green-fallow phase of the rotation. Wheat yields following the annual legume were reduced, compared with traditional summer fallow, by 400 kg ha^{-1} at the earliest legume termination date and by at least 1050 kg ha^{-1} at all other dates. Economic analysis indicates that in drier than normal years, that returns are maximized when the legume is not grown during the fallow phase. In 1996, a wet year, returns were maximized when the legume was terminated at the second termination date or after 70% of the potential maximum legume water use. We found that 88% of the variability in winter wheat yield could be explained by legume water use the previous year. In general, the competitiveness of legume green fallow with winter wheat fallow is highly weather-dependent and inconsistent. At current fertilizer costs, legume N (in this system) was too expensive to be considered a reasonable alternative to chemical fertilizer.

DRYLAND CROP PRODUCTION in the central Great Plains of the United States is dominated by winter wheat–summer fallow (Haas et al., 1974). After water, N fertility is probably the most important input to profitable agriculture in the region. For many soils, this system depends on biennial additions of N fertilizer with typical rates between 35 and 70 kg N ha^{-1} (Westfall et al., 1996). The cost of commercial N fertilizers has increased significantly in recent years, and because nonrenewable fossil fuels are used to manufacture N fertilizer, fertilizer costs are projected to increase over the long term (Douglas, 1980). Informal telephone surveys, conducted by our laboratory, of four northeastern Colorado fertilizer dealers in 1991, 1995, and 1997 indicate N fertilizer costs have increased about 60% since 1991. This has prompted some farmers and researchers to consider alternative cropping systems that include legumes as both a source of N and as forage (Biederbeck et al., 1993; Gardner, 1992; Auld et al., 1982).

Historically, long-term soil-building effects, such as increased soil microbial respiration, improved aggregation, and increased N availability, have been attributed to legumes in rotation with cereal grains (Power, 1990, 1987). Haas et al. (1957) reported alfalfa (*Medicago sativa* L.) in rotation with winter wheat reduced the loss of soil N, compared with winter wheat–summer fallow. In that early research, tillage (one-way disk and moldboard plows) was used to control weeds. Although continuous cropping and wheat–legume rotations reduced soil C, the reduction was not as severe as with alternate wheat–fallow (Haas et al., 1957).

Annual legumes grown for green manure can release substantial amounts of fixed N (Miller and Hoveland, 1995). The amount of N credited by an annual legume to a succeeding crop ranges between 22 and 213 kg N ha^{-1} (Bundy et al., 1993). In Idaho, Auld et al. (1982) studied winter field pea and reported between 200 and 400 kg N ha^{-1} in the pea foliage planted in September and terminated the following June. From Bundy et al.'s work (1993), it appears that the amount of N credited to an annual legume depends on management, annual weather variability, and soil type almost as much as on the species of the legume.

For dryland producers in the western United States, an important consideration regarding growing of legumes is the cost in water use by the legume. In the central Great Plains, where average annual precipitation is between 300 and 560 mm, efficient use of the available precipitation is critical (Peterson et al., 1996).

Nielsen and Halvorson (1991) developed a simple linear equation of winter wheat grain yield as a function of evapotranspiration (ET). That equation, further refined by Nielsen (1995), is

$$\text{Grain Yield} = 17.23(\text{ET}) - 2956 \qquad [1]$$

where grain yield is in kg ha^{-1} and ET is in mm. The relationship was developed using 2 yr of wheat yield and water-use data from a field plot study where typical semidwarf winter wheat cultivars were grown. If the equation is set equal to zero, one can solve for the amount of ET required to grow the crop without producing any grain yield (about 172 mm). In other words, if only 172 mm of stored soil water plus precipitation were available in the central Great Plains during the wheat growing season, farmers in the region would have no grain to harvest. After the first 172 mm, any additional water (either stored soil water or precipitation) produces about 17.23 kg grain ha^{-1} mm^{-1} of water use. Using Eq. [1] and assuming a value of wheat grain of \$0.147 kg^{-1}, we can deduce a rough dollar value (as grain for market) for growing-season water use on one hectare of land to be about \$2.5 mm^{-1}. This type of

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Abbreviations: ET, evapotranspiration; ET_{norm}, evapotranspiration normalized on the maximum evapotranspiration measured for that year; LGY, legume yield; LG_{price}, value of legume hay; RMSE, root mean square error; TDR, time domain reflectometry; TGR, total gross returns; WHTY, wheat yield; WHT_{price}, value of wheat grain.

calculation is useful in evaluating the economics of stored water and precipitation, which is limited under semiarid dryland conditions. If a legume is allowed to grow during the traditional summer fallow period, it will use water that would have been available for the subsequent wheat crop. Legume water use during fallow should result in a reduction in subsequent wheat yield. Because of the wheat yield reduction, a legume must produce a marketable yield that has a value that is comparable to the value of the potential wheat yield loss.

Biederbeck and Bouman (1994) estimated the water-use efficiency of several annual-legume species to range between 11 and 29 kg ha^{-1} mm^{-1}. Assuming 2.5% N in green legume tissue, one would have 0.28 and 0.73 kg of N in the aboveground forage per millimeter of water use. In the central Great Plains, we have measured summer crop ET values of 167 to 473 mm. Using Biederbeck and Bouman's data, and assuming 2.5% N in green tissue, one can estimate that 47 to 345 N kg ha^{-1} of aboveground fixed N could potentially be raised in the central Great Plains. At current chemical N fertilizer costs of \$0.41 kg^{-1}, one could assign a value to the legume N at between \$19 and \$142 ha^{-1}. With an intrinsic value of stored soil water or precipitation of \$2.5 mm^{-1}, the same 167 to 473 mm of water use could produce 0 to \$752 ha^{-1} in potential wheat yield. In some cases, therefore, legume N can be expensive.

With the above ideas in mind, we established an experiment with the following objectives: (i) to determine the effect a legume green fallow cropping system has on subsequent winter wheat yields and perform a simple economic evaluation of the system and (ii) to determine optimal legume termination dates during the green-fallow phase.

MATERIALS AND METHODS

This research was conducted at the USDA-ARS Central Great Plains Research Station, Akron, CO, on a Weld silt loam (fine, smectitic, mesic Aridic Paleustolls) in 1994 to 1996. The long-term annual precipitation at the location is 421 mm. The site had previously been in a dryland winter wheat–corn (*Zea mays* L.) summer fallow rotation. The 1993 corn crop was exceptional and produced more stubble than is typical. Successful planting (with the equipment available to us) and emergence of the legumes in the excess stubble was a concern. In February of 1994, therefore, the corn stubble was mowed with a flail mower and excess corn stubble was raked, baled, and removed to ease the planting process in the spring.

The experiment was arranged in a randomized split-block design with four replications (Little and Hills, 1978). A replication consisted of four main-plots, 9.1 m wide and 19.5 m long. Main-plot treatments consisted of three legume species and a traditional summer fallow plot. Sub-strip-plots consisted of four legume termination dates (for legume plots) or fertilizer treatments (for the summer-fallow plots). Each sub-strip-plot was 4.8 m in length by 9.1 m wide.

In mid-March of 1994, plots were established and neutron-probe access tubes (with 30-cm-long removable tops, removed for tillage and planting operations) were installed to a depth of 180 cm. Time domain reflectometry (TDR) wave guides also were installed in the surface 30 cm of each plot at that time. Soil excavated in the access tube installation was used to obtain volumetric soil water contents (for calibrating the neutron probe), soil inorganic N, total soil N, and total soil C, to allow for monitoring of possible changes in soil N and C dynamics that might result from the various rotations.

In 1994, weeds were controlled with a preplant application of granular trifluralin (α,α,α-trifluoro-2,6-dinitro-*N*,*N*-dipropyl-*p*-toluidine; Treflan QR5, Dow Elanco, Indianapolis, IN).[1] Trifluralin was applied at a rate of 1.1 kg a.i. ha^{-1} with a granule applicator (Gandy Corp., Owatonna, MN) attached to a Haybuster sweep-plow (Haybuster Manufacturing, Jamestown, ND). The sweep-plow had 76-cm V-blade sweeps with a following mulch treader. Application of the trifluralin granules with this equipment allowed for the simultaneous incorporation of the chemical into the top 8 cm of the surface soil at application time. In 1995, weeds were initially controlled with a preplant-burndown application of glyphosate [*N*-(phosphonomethyl)glycine] at a rate of 1.1 kg a.i. ha^{-1} sprayed over the plots with a small-plot sprayer just prior to planting. No in-crop residual herbicide was used in 1995.

Preplant soil analysis of the surface 60 cm of soil (soil saved from the neutron probe installation) indicated that soil nitrate-N averaged 26 kg ha^{-1}, which is marginal to low for typical dryland grain production in our region. On 1 Apr. 1994, Austrian winter pea, 'Trapper' spring field pea, and 'Indianhead' black lentil were inoculated with the appropriate strains of *Rhizobium leguminosarum* bacteria and seeded using a no-till drill with double-disk openers (Tye Ag-Equipment group, Lockney, TX) into main-plots. The legumes were planted in rows spaced 20 cm apart, with pea species at approximately 740 000 seeds ha^{-1} (about 95 kg ha^{-1}) and lentil at approximately 1 730 000 seeds ha^{-1} (about 35 kg ha^{-1}). The fourth main-plot was summer fallowed using sweep-plow tillage to control weeds (four operations). This plot represented the traditional winter wheat–summer fallow rotation common to the region. On 7 Apr. 1995, the experimental design described was established in a second location, 120 m south of the plots established in 1994. Soil in this second set of plots is also mapped as a Weld silt loam. This allowed for the measurement of both wheat yields and legume yields in any given year.

Each legume in the sub-strip-plots was allowed to grow for a different length of time before termination in the spring with a sweep-plow-blade machine. In 1994, legume termination dates were 31 May, 13 June, 28 June, and 8 July. In 1995, early spring temperatures were cooler than in 1994 (Table 1), which delayed development, so termination dates were 28 June, 12 July, 27 July, and 4 August. Prior to legume termination, the aboveground plant biomass (both weeds and legumes) in three random 1-m^2 areas in each plot was collected, weeds were separated from legumes, and fresh weights of each were recorded. Samples were dried in a forced-air oven at 60°C and dry weights were recorded. Each sample was ground and total C and N were measured in each individual weed and legume sample using an automated C and N analyzer (Carlo Erba Instr., Milan, Italy).

Each traditional summer-fallow main-plot was subdivided into four subplots. Individual subplots were fertilized with NH_4NO_3 applied broadcast just prior to planting wheat in the fall of 1994 and 1995. Each subplot received one of the following rates of fertilizer N: 0, 34, 68, or 102 kg N ha^{-1}. No fertilizer N was applied to the legume fallow plots. This was done to compare wheat response to chemical fertilization in summer-fallow plots to fertilization by legume-derived N from green-fallow plots.

[1] Use of company or trade names is for the benefit of the reader and does not imply endorsement by the USDA-ARS of the products named nor criticism of similar ones not mentioned.

On 26 Sept. 1994 and 27 Sept. 1995, winter wheat ('Tam 107') was planted at 2 500 000 seed ha^{-1} (about 67 kg ha^{-1}), using the same drill as used to seed the legumes. Plant-available soil P tested in the marginal range, so in both years 10 kg P ha^{-1} (triple superphosphate 0–46–0 N–P–K) was applied at planting with the seed for both wheat and legumes. On 27 July in 1995 and 12 July in 1996, wheat was harvested with a plot combine (Wintersteiger, Salt Lake City, UT) from a strip 1.5 m wide and 7.6 m long in the middle of each sub-strip-plot. Grain was cleaned using screens, grain moisture was measured using a digital moisture meter (Burrows Equipment Co., Evanston, IL), total grain weight was recorded, and grain yields were reported at 135 g kg^{-1} water content.

Soil-water-content measurements were taken to a depth of 180 cm prior to legume planting, at each legume termination date, prior to wheat planting, monthly during the wheat growing phase of the experiment, and at wheat harvest in each plot. These data, combined with daily precipitation records, were used to estimate evapotranspiration (ET) in each plot for both the wheat phase and the legume–summer fallow portion of the rotation using the water balance method described by Peterson et al. (1996).

Data were analyzed using an analysis of variance procedure for a split-block experimental design (Little and Hills, 1978), with LSD used for means separation, using SAS (SAS Inst., Cary, NC). In addition, the General Linear Models procedure in SAS was used to calculate single degree of freedom linear contrasts for comparing selected treatment means of particular biological interest. Simple linear and multiple linear regression was used to fit equations of normalized winter wheat yield loss as a function of the previous summer's legume biomass production and/or from legume ET using a regression procedures in SAS (SAS Inst., 1988, p. 125–154, 615–619, 678–701).

Modeling and Economic Analysis

Wheat and legume yields for the plots planted to Austrian winter pea and spring field pea (both of which performed similarly) were used for this part of the analysis. First, wheat and legume yields were normalized by the maximum respective wheat yield and legume yield each year. This was accomplished by dividing the wheat yield or legume yield for each individual treatment by the maximum yield of the respective crop measured that year in the plots. Legume ET was normalized by the maximum legume water use each year by dividing legume water use measured in each individual plot by the maximum water use measured in the plots for each respective year. Equations for the normalized wheat and legume yields were developed by regressing normalized yield on normalized legume ET using data from both years. Normalized yield functions were then used to generate wheat and legume yields as a function of legume ET. Total gross returns (TGR) for several different legume water-use termination points were calculated using the following formula:

$$\begin{aligned} TGR = {} & [(LGY \times LG_{price}) \\ & + (WHTY \times WHT_{price})] \\ & - (\text{planting costs} + \text{tillage costs}) \end{aligned} \quad [2]$$

where LGY is legume yield in kg ha^{-1}; WHTY is wheat yield in kg ha^{-1}; LG_{price} is the selected value of legume hay, \$0.083 kg^{-1}; WHT_{price} is the selected value of wheat grain; \$0.147 kg^{-1} planting costs, \$50 ha^{-1}, are for the cost of the legume seed, inoculant, and for the seeding operation; and tillage costs, \$15 ha^{-1} per operation, are for sweep-plow tillage during the nongreen portion of the fallow period (Vigil et al., 1997). Using Eq. [2], the TGR for the winter wheat–legume–fallow 2-yr rotation was calculated. Yields for these calculations were generated from the normalized yield functions. This allowed for the determination of reasonable legume termination dates during fallow.

Table 1. Average monthly temperature (*T*) and total monthly precipitation (Ppn.) in Akron, CO, for the three years the study was conducted.

	1994		1995		1996		Long-term avg.	
Month	T	Ppn.	T	Ppn.	T	Ppn.	T	Ppn.
	°C	mm	°C	mm	°C	mm	°C	mm
Jan.	−1.3	10	−2.3	22	−4.0	8	−3.8	9
Feb.	−2.6	5	1.6	9	0.0	1	−1.2	9
Mar.	5.2	2	2.9	22	1.3	29	2.4	21
Apr.	8.3	83	5.3	63	8.7	10	8.1	42
May	16.1	28	8.9	144	13.1	112	13.4	77
June	22.1	6	17.3	122	19.7	66	19.2	63
July	21.9	68	21.8	40	21.8	78	22.9	69
Aug.	23.0	29	23.6	20	21.3	66	21.9	52
Sept.	18.0	7	16.3	56	15.7	90	16.8	32
Oct.	9.9	72	9.1	10	10.2	11	10.2	23
Nov.	0.6	26	4.7	15	1.5	1	2.6	14
Dec.	0.6	13	−0.2	2	−1.6	1	−2.4	10
Total Ppn.		349		525		473		421

RESULTS

Yield Responses, Water Use, and N Uptake

Precipitation received between 1 January and the end of June was 107 mm in 1994 and 385 mm in 1995 (Table 1). Favorable moisture and temperature conditions in 1995 nearly doubled legume biomass in early July, compared with that measured in 1994 (Fig. 1). As expected, we measured more aboveground legume biomass at the later termination dates in both 1994 and 1995 (Fig. 1). Austrian winter pea and spring field pea performed similarly, producing more biomass and greater aboveground biomass N than the black lentil.

Maximum aboveground legume N was measured at the second termination date in 1994 and at the third termination date in 1995. As much as 130 kg of N ha^{-1} was found in the aboveground portion of Austrian winter pea on 27 July 1995 (Fig. 1). We assume that some of this aboveground N was biologically fixed and some was taken up from the soil. In any case, the accumulated 130 kg ha^{-1} of aboveground N was produced using 420 mm of water. Chemical fertilizer N in our region of the USA cost about \$0.42 kg^{-1}. In essence, 420 mm of water produced only \$54.45 ha^{-1} worth of legume N. That same 420 mm of water, using Eq. [1], has the potential of producing 4281 kg ha^{-1} of wheat grain valued at \$629. In 1994 and 1995, growing these legumes to increase N fertility was not cost effective. Nitrogen fertilizer costs would have to increase about 12-fold before legume N would become competitive.

Greater summer rainfall in 1995 also affected subsequent wheat yields. In 1996, the best wheat yields were as much as 1500 kg ha^{-1} greater than in 1995 (Table 2). In both years, wheat yields were inversely proportional to the increase in legume biomass production and legume water use the previous year (Table 2; Fig. 2). Legumes terminated 31 May 1994 used between 34 and

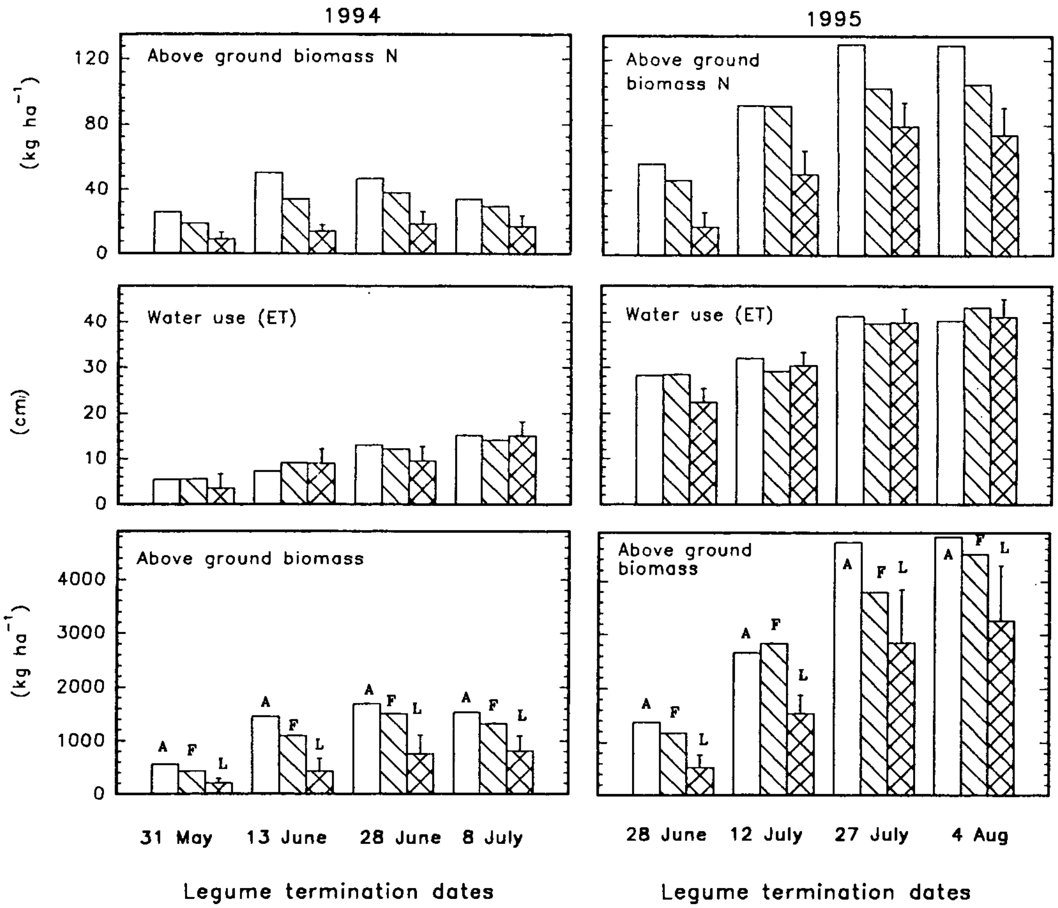

Fig. 1. Legume biomass yield, water use and total aboveground biomass N at four harvest dates in 1994 and 1995. A, Austrian winter pea; F, spring field pea; L, Indianhead black lentil. Error bars show the largest standard errors of the mean of four replicates for all three species.

55 mm of water, whereas only 20 mm of ET was lost from the summer fallow plots during the same legume growth period (Table 3). The 34 to 55 mm of ET used by the legumes terminated 31 May 1994 was statistically the same as the 52 mm of ET measured on 8 July 1994 in traditional summer fallow (Table 3). In other words, approximately one month of legume growth used as much water as three months of traditional summer fallow in 1994. Precipitation and stored soil water that would have been used by the subsequent wheat crop was used to grow legumes. For comparison, measured ET from the traditional summer fallow plots for the period between planting of the legumes in April until the last termination date on 4 Aug. 1995 was 267 mm. This 267 mm of ET was about the same as the water used by the three legumes measured at the first termination date on 28 June 1995 (Table 3). In 1995, 73% of the variability in wheat yield (R^2 = 0.73) could be ex-

Table 2. Winter wheat yields in 1995 and 1996 following three legumes in a green-fallow rotation, and the legume's water use (ET) in the previous year as affected by termination date.

Previous year's legume termination date	Austrian winter pea		'Trapper' spring field pea		'Indianhead' black lentil	
	Wheat yield	Previous year's legume ET	Wheat yield	Previous year's legume ET	Wheat yield	Previous year's legume ET
	kg ha⁻¹	mm	kg ha⁻¹	mm	kg ha⁻¹	mm
			1995			
31 May 1994	2950 (166)†	54	2910 (130)	55	2750 (188)	34
13 June 1994	2250 (156)	72	2290 (232)	90	2530 (156)	89
28 June 1994	2360 (167)	129	2080 (181)	121	2080 (182)	95
8 July 1994	1800 (68)	151	2040 (119)	141	1860 (98)	150
LSD (0.05)	403	35	516	16	200	45
			1996			
28 June 1995	4450 (374)	282	4260 (357)	303	4330 (420)	278
12 July 1995	4090 (406)	321	4210 (226)	292	3610 (458)	305
27 July 1995	2470 (290)	413	3330 (114)	396	2400 (279)	398
4 Aug. 1995	2030 (226)	403	2510 (87)	431	1560 (71)	411
LSD (0.05)	763	92	605	69	48	83

† Values in parenthesis are the standard error of the mean.

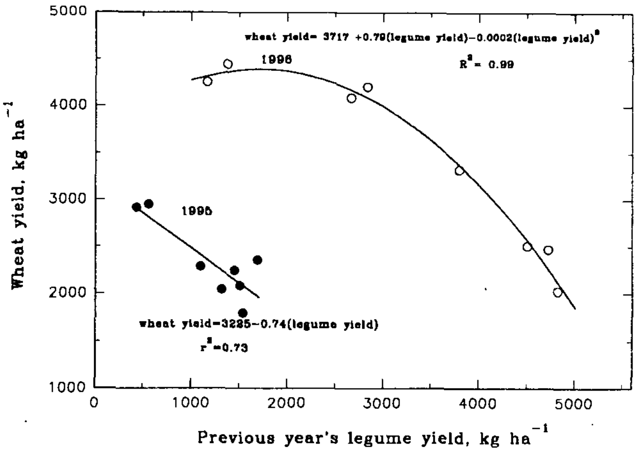

Fig. 2. Wheat yields as affected by previous legume biomass production (Austrian winter pea and spring field pea data only).

plained by the previous year's legume growth using the fitted regression equation

$$\text{wheat yield} = 3225 - 0.74(\text{legume yield}) \quad [3]$$

where wheat yield is in kg ha^{-1} and legume yield is the previous year's legume yield in kg ha^{-1} (Fig. 2). The root mean square error (RMSE) was 227.7, and the F-value of regression was 16.4 ($P < 0.007$). In 1996, 99% of the variability in wheat yield ($R^2 = 0.99$) could be explained by the following regression equation:

$$\text{wheat yield} = 3717 + 0.79(\text{legume yield}) - 0.0002(\text{legume yield})^2 \quad [4]$$

where wheat and legume yield are as described above. The RMSE and F-value of regression were 131.7 and 185 ($P < 0.0001$), respectively. A look at the data in Fig. 1 suggests that legume biomass yields leveled off between the third and last termination dates. Between the third and last termination dates, however, the continued legume water use reduces subsequent wheat yield (Table 2). For these reasons, legume ET the previous year is probably more highly related to the subsequent wheat yield than legume biomass production. Therefore, we normalized and then combined the data of both years and found that 88% of the variability in wheat grain yield could be explained by legume ET from the previous year:

$$WHT_{norm} = 1.03 - 0.26(ET_{norm}) - 0.29(ET_{norm})^2 \quad [5]$$

where WHT_{norm} is the normalized wheat yield and ET_{norm} is the normalized legume ET of the previous year. The R^2 was 0.88, the RMSE was 0.0756, and the F-value of regression was 73.9 ($P < 0.0001$) for Eq. [5] (Fig. 3).

Others have reported similar findings with respect to yield depression after green manure crops. In a review article, Power (1990) reported that research conducted before 1960 showed that green manure crops often reduced yields of the following crop. At two locations in Montana, lower yields were measured following green-manure legumes than following summer fallow (Army and Hide, 1959). In more recent research, Zentner et al. (1996) reported less wheat yield after black lentil green fallow than after traditional summer fallow. Gardner (1992) reported data indicating that when and how the legume is terminated during the fallow period will effect soil water storage and the yield potential for the subsequent crop.

We measured higher wheat yields both years in plots that were traditionally summer fallowed and fertilized with only 34 kg of commercial N ha^{-1} than in any of the legume plots (Table 4). Soil-water depletion by legumes terminated on the first termination date in 1994 and 1995 resulted in subsequent wheat yields in 1995 and 1996 that were 500 to 800 kg ha^{-1} less than wheat yields fertilized with 34 kg of N ha^{-1} in traditional summer fallow. In 1995, we measured wheat grain yields that were 700 kg ha^{-1} greater when following nonfertilized traditional summer fallow than when following legumes terminated as early as 13 June (Table 4). In 1996, fertilizer application increased wheat grain yield by as much as 1200 kg ha^{-1} (Table 4). Grain yield response to fertilizer application in traditional summer fallow was not significant in 1995. In October 1994, preplant soil NO_3^- levels were marginal to adequate in the top 60 cm of soil after green fallow and traditional summer fallow (Table 5), yet dry conditions are thought to be the reason for a lack of a statistically significant winter wheat

Table 3. Measured evapotranspiration (ET) in summer fallow plots and in plots planted to three legumes at various termination dates.

Termination date	Austrian winter pea	Spring field pea	Black lentil	Summer fallow	LSD (0.05)
	ET				
	mm				
31 May 1994	54	55	34	20	15
13 June 1994	72	90	89	37	33
28 June 1994	129	121	95	54	45
8 July 1994	151	141	150	52	15
LSD (0.05)	35	16	45	10	
28 June 1995	282	303	278	200	NS
12 July 1995	321	292	305	238	41
27 July 1995	413	396	398	257	63
4 August 1995	403	431	411	267	59
LSD (0.05)	92	69	83	73	

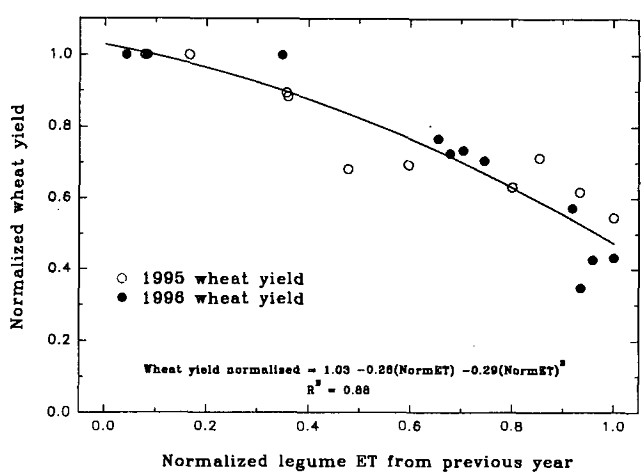

Fig. 3. Normalized wheat yields as a function of the previous year's normalized legume water use (Austrian winter pea and spring field pea data only).

Table 4. Single degree of freedom linear contrasts for comparing mean winter wheat yields following different legumes species, legume termination dates, and traditional summer fallow plots with and without fertilization.

Green fallow and summer fallow fertilizer treatments one year prior to growing winter wheat	Wheat yield mean 1995	Wheat yield mean 1996
	kg ha^{-1}	
1. Austrian winter pea averaged over all four termination dates	2340 (124)†	3260 (304)
2. Spring field pea averaged over all four termination dates	2330 (118)	3570 (211)
3. Black lentil averaged over all four termination dates	2310 (116)	2980 (316)
4. All legume spp. terminated at the earliest termination date	2870 (89)	4340 (203)
5. All legume spp. terminated at the second termination date	2360 (104)	3970 (211)
6. Traditional summer fallow (SF), no fertilizer applied	3090 (137)	4200 (391)
7. Traditional SF, fertilized (34 kg N ha^{-1})	3370 (54)	5160 (161)
8. Traditional SF, fertilized (68 kg N ha^{-1})	3480 (260)	5280 (209)
9. Traditional SF, fertilized (102 kg N ha^{-1})	3250 (363)	5400 (98)
10. Traditional SF, fertilized (34 and 68 kg N ha^{-1})	3430 (124)	5220 (125)
11. Traditional SF, fertilized (34, 68, and 102 kg N ha^{-1})	3300 (98)	5280 (90)
Single degree of freedom linear contrast of means given above	*F*-value	
4 vs. 7 (first termination date vs. 34 kg N ha^{-1})	9.47**	6.13*
1 vs. 2 (Austrian pea vs. spring field pea)	0.00	2.46
1 vs. 3 (Austrian pea vs. black lentil)	0.11	1.99
5 vs. 6 (legumes terminated at second date vs. nonfertilized SF)	19.98**	0.49
4 vs. 10 (first termination date vs. 34 and 68 kg N ha^{-1})	12.32**	9.30**
4 vs. 6 (first termination date vs. nonfertilized SF)	1.77	0.19
6 vs. 7 (nonfertilized traditional SF vs. 34 kg N ha^{-1})	2.04	5.65*
7 vs. 8 (34 vs. 68 kg N ha^{-1})	0.31	0.10
8 vs. 9 (68 vs. 102 kg N ha^{-1})	1.37	0.09
6 vs. 11 (nonfertilized traditional SF vs. 34, 68, and 102 kg N ha^{-1})	2.98	10.81**

*,** Significant *F*-value at the 0.05 and 0.01 probability levels, respectively.
† Values in parenthesis are the standard error of the mean.

grain yield response in the 1995 wheat crop. In October 1995, residual nitrate levels before wheat planting were lower than in 1994. Even though a wetter summer favored greater N mineralization, the wet conditions also enhanced biomass production and N uptake. Greater rainfall also may have caused some movement of soil nitrates below the top 60 cm of soil (Table 5). And the wetter condition could have favored more surface soil denitrification. All of the above-mentioned processes could partially explain the low NO_3^- levels measured just prior to wheat planting in 1995 (Table 5). In the traditional summer fallow plots (where no plants were allowed to grow and use the mineralized N), greater amounts of mineralized N accumulated than in the legume green fallow plots (Table 5). Less available inorganic N in the surface soil prior to planting the 1996 wheat crop may have also had an effect in reducing winter wheat yields after green fallow.

Having a legume grown on the land during the fallow phase depressed subsequent wheat yields, but the type of previous legume species did not matter. In this experiment, all legume species depressed subsequent wheat yields about the same (Table 4). While legume biomass yields differ among species, water use was similar (Fig. 1). In effect, the Austrian winter pea and spring field pea produced more biomass than the black lentil for the same amount of water use. The similar water use for the three legumes tested is reflected by the similar wheat yield reductions in subsequent years (Table 2).

Table 5. Soil inorganic N in the surface 60 cm of soil prior to winter wheat planting in legume plots (terminated at the last termination date) and in traditional summer fallow.

Treatment	1994 NH_4-N	1994 NO_3-N	1995 NH_4-N	1995 NO_3-N
	kg ha^{-1}			
Austrian winter pea	6.8	35.4	5.9	3.0
Spring field pea	7.3	31.0	4.9	4.5
Black lentil	6.1	34.9	5.1	1.7
Nonfertilized summer fallow	4.8	39.0	5.8	17.9
LSD (0.05)	NS	NS	NS	6.6

Economic Analysis

Assuming a legume-hay market price of \$0.083 kg^{-1}, the value of the harvestable forage grown on the plots terminated 13 June 1994 was \$93 ha^{-1}. The value of this forage is not as great as the potential wheat yield loss from legume water use. The wheat yield measured in traditional summer fallow (fertilized with 34 kg of N ha^{-1}) was 1000 to 1100 kg ha^{-1} greater than the wheat yield measured in plots following the \$93 legume forage. The value of the wheat yield loss, \$147, is greater then the potential forage returns, \$93 ha^{-1}. The value of the legume N as fertilizer (about 40 kg N ha^{-1}) at \$0.52 kg^{-1} of N could be added as a bonus for the legume system (about \$21). However, perhaps only 40% of the biomass N might mineralize and be available for crop use in a given year (Vigil and Kissel, 1991). Even after subtracting the cost of fertilizer N used in the traditional fallow, we still cannot make up for the value of the wheat yield loss in the green-fallow system.

We also developed a relationship between normalized legume yield and normalized legume ET (Fig. 4):

$$LGY_{norm} = 0.124 - 1.94(ET_{norm})^{0.5} + 2.77(ET_{norm})^{0.75} \quad [6]$$

where LGY_{norm} is the normalized legume yield. The R^2 was 0.81, the RMSE was 0.183, and the *F*-value of regression was 42.2 ($P < 0.0001$) (Fig. 4). Equations [5] and [6] were then used to generate yields for a range of seasonal ET values for economic analysis.

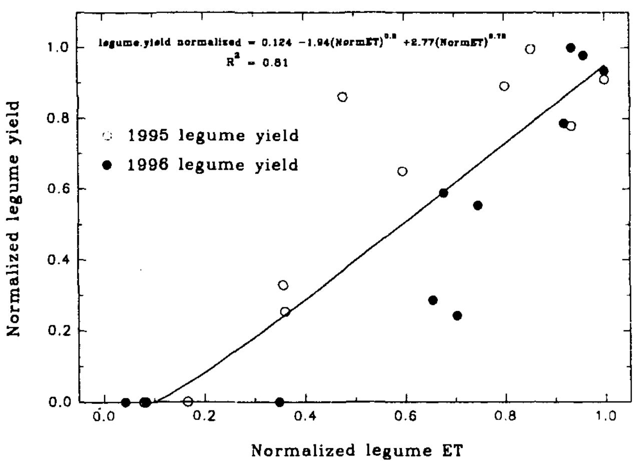

Fig. 4. Normalized legume yields as a function of legume water use (Austrian winter pea and spring field pea data only).

From the economic analysis, we determined that for a year combination similar to 1994–1995 (green fallow followed by winter wheat), a legume should not be grown at all. Maximum returns would be achieved by growing only winter wheat in the sequence (Fig. 5). In years similar to the 1995–1996 combination, maximum economic returns would be achieved by allowing the legume to grow to approximately 70% of its maximum total seasonal water use (Fig. 5). During the 1995 year, that would correspond to about the first week of July (very close to our second legume termination date, 12 July).

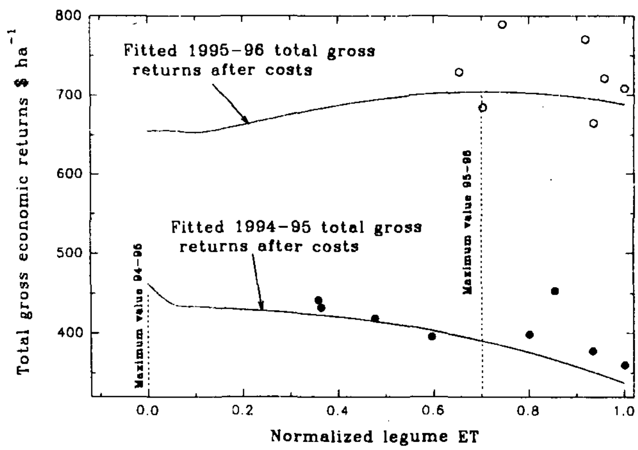

Fig. 5. Total gross returns (TGR) for the two-phase system after subtracting variable costs of seeding the legume and tillage during green fallow. The solid line is calculated from wheat and legume yields generated from the fitted equations given in Fig. 3 and 4 and from the economic value of wheat grain and legume hay. The open and filled circles are calculated from the actual average wheat and legume yields harvested from the plots containing spring field pea and Austrian winter pea terminated at four termination dates.

SUMMARY

Compared with traditional fallow, green fallow reduces subsequent winter wheat yields. Eighty-eight percent of the variability in wheat grain yield reduction (calculated as a percentage of the maximum achieved in a given year) could be described by a quadratic equation based on the previous year's legume ET. Legume water use during the summer fallow phase reduces subsequent winter wheat yields by as much 15.2 kg ha^{-1} per millimeter of legume ET. This correlates well with water-use production functions that have been developed for winter wheat in our region, where the slope of the linear relationship between water use and grain production is 17.2 kg ha^{-1} of grain per millimeter of water use (Nielsen, 1995). The economically optimum legume termination date is highly weather-dependent. In a wet year (1995), the optimum termination date was after the legume had used 70% of its maximum water use that season, which occurred about 12 July. Since weather patterns in the central Great Plains are quite variable, the economically optimum termination date will oscillate from year to year based on accumulated heat units and precipitation. In a dry year (1994), the economically optimum situation is to not grow a legume at all. It is interesting that in 1994 (a drier and warmer year than in 1995) the legume had used 70% of its maximum water use by 13 June (one month earlier than in 1995). In wet years, the combination of the legume for hay and wheat grain for market is more economically favorable than traditional wheat fallow. At current costs for fertilizer N, legume N (as used in this system) is too expensive to be considered a reasonable alternative to chemical fertilizer.

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