

## Natural Reseeding by Forage Legumes following Wheat in Western North Dakota

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### ABSTRACT

Legume pasture is rotated with wheat (*Triticum* spp.) to enhance grain production sustainability. The legume species maintain or enhance wheat yield and regenerate from the soil seed bank. Our objectives were to determine: (i) grain yield when wheat followed legume forages and (ii) if legume species regenerated naturally following wheat in western North Dakota. Ten to 30 legume species were established in field experiments in 1999, 2000, and 2001. Legumes that regenerated or persisted in the second year were terminated chemically before seeding wheat in the third year. Plots were fallowed in the second year where legumes failed to regenerate or persist. Grain yield ranged from 1290 to 4100 kg ha<sup>-1</sup> across the 3 yr when wheat followed yellow-flowered sweetclover (*Melilotus officinalis* Lam.) and was equal or enhanced compared with fallowed plots where legumes did not reseed in 2 yr ( $P < 0.05$ ). Grain yield never was enhanced and sometimes was reduced when wheat followed other legume forages compared with fallowed plots. Legume seedlings regenerated following wheat in birdsfoot trefoil (*Lotus corniculatus* L.) plots in all 3 yr, and forage production exceeded 3 Mg ha<sup>-1</sup> in 2 yr. Other legume species failed to regenerate or produced less forage than birdsfoot trefoil in at least 1 yr. Birdsfoot trefoil has potential as a regenerating pasture species, but strategies are needed to enhance grain yield in legume-wheat rotations.

THE NORTHERN GREAT PLAINS is the principal production region for hard red spring wheat (*T. aestivum* L. emend. Thell.) and durum wheat (*T. turgidum* L.) in North America. Montana, North Dakota, and South Dakota alone produced almost 9 million Mg of spring wheat on 5 million ha within the region in 2002 (USDA Natl. Agric. Stat. Serv., 2004). Over 3.5 million ha of hay were harvested in the three states during the same period. An additional 2 million ha of cropland and 29 million ha of pastureland and rangeland were grazed by livestock. The presence of both wheat and livestock across a large portion of the northern Great Plains suggests an opportunity for integrating crop and livestock enterprises in the region.

Integrated crop-livestock systems are not common in the region. Krall and Schuman (1996) estimated that <10% of agricultural land is dedicated to integrated systems. The two researchers concluded that the inability or unwillingness to integrate crop and livestock enterprises prevents benefits in environmental quality, economic diversity, and pest management from occurring. For example, wheat yield enhancements and weed pressure reductions occurred when forages were incorpo-

rated into rotations with wheat and other grain crops in the Canadian prairie region (Entz et al., 1995). Additional benefits and synergies between crop and livestock enterprises can occur when grazed pasture is rotated with wheat or other grain crops (Entz et al., 2002). A review by Martin (1996) suggested that grassy weed invasion was reduced by rotating grazed legume forages with wheat compared with cropping systems that did not include pasture.

Integrated crop-livestock systems have been developed in response to the environmental degradation and poor economic returns that occur when growing wheat in regions outside of the Great Plains. For example, wheat is rotated with clover (*Trifolium* spp.) and medic (*Medicago* spp.) pastures in Australian ley farming in an integrated crop-livestock approach that provides flexibility and diversity to dryland agriculturists (Carter et al., 1982). The annual clovers and medics regenerate from the soil seed bank and provide forage during the pasture phase for sheep (*Ovis aries* L.) and cattle (*Bos taurus* L.) as well as fix N biologically for subsequent use during the wheat phase. Ley farming comprised over 20 million ha in the wheat-sheep zone of southern Australia by the mid-1980s, as the benefits of this system compared with traditional wheat production systems became evident. These benefits included more profitable wheat production (Boyce et al., 1991), wheat pest suppression (Loomis and Connor, 1992), reduced fertilizer inputs along with improved air and water quality (Grierson et al., 1991), production of high quality forage (Mann, 1991), and soil conservation (Cocks et al., 1980).

Efforts to export ley farming to regions outside of Australia generally have been unsuccessful. The inability to identify legume species and cultivars that are adapted to local environments explains the failure of adopting ley farming, in some instances (Springborg, 1986; Halse, 1993). Koala (1982) concluded that cultivars of several *Medicago* spp. and subterranean clover (*Trifolium subterranean* L.) used in Australia were less adapted to growing conditions in Montana than black medic (*Medicago lupulina* L.), a naturalized legume species that occurs throughout the northern Great Plains. Subsequent studies suggested that the suitability of black medic for pasture may be limited in the region (Walsh et al., 2001; Carr et al., 2005). However, other legumes showed promise as regenerating pasture species in these two studies.

Important characteristics of legume species used in Australian ley farming include the ability to regenerate from the soil seed bank following the wheat phase and to produce adequate amounts of forage to support grazing livestock (Puckridge and French, 1983). A minimum population of 200 medic seedlings m<sup>-2</sup> that regenerated from

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Published in *Agron. J.* 97:1270-1277 (2005).

Dryland Cropping Systems

doi:10.2134/agronj2005.0007

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**Abbreviations:** CP, crude protein; DM, dry matter.

the soil seed bank was considered to be necessary to maintain a productive legume pasture (Walsh et al., 2001). Research in Wyoming and North Dakota identified legumes capable of regenerating more than 200 seedlings  $m^{-2}$  and producing forage dry matter (DM) in amounts exceeding 7 Mg  $ha^{-1}$  (Walsh et al., 2001; Carr et al., 2005). However, the ability of legumes to reseed naturally when growth was interrupted by a wheat phase was not considered in either study. Four of 16 annual legume cultivars regenerated from the soil seed bank following spring wheat in a field experiment in Montana (Koala, 1982), but forage DM production was not determined.

The ability of legumes to regenerate from the soil seed bank and produce forage following wheat in a pasture-wheat system has not been demonstrated in the northern Great Plains. Our objectives were to determine: (i) the impact that legume forages have on grain yield in a legume-wheat sequence and (ii) the ability of legume forages to regenerate from the soil seed bank and produce forage following spring wheat.

## MATERIALS AND METHODS

Experiments were established on 23 Apr. 1999, 18 Apr. 2000, and 3 May 2001 on a Farnuf fine sandy loam soil (fine-loamy, mixed, superactive, frigid Typic Argiustolls) in three fields at the Dickinson Research Extension Center in western North Dakota, USA (46°53' N, 102°49' W; 760 m elevation). Spring wheat or barley (*Hordeum vulgare* L.) was grown before establishing the three field experiments. Ten legume species were sown in 1999, 30 species in 2000, and 29 species in 2001. Legume stands and forage DM production were determined during the seeding year and the following year. The ability of the legumes to regenerate from the soil seed bank was determined in the year after treatments were established. Weeds were removed manually or controlled with herbicides in plots where legumes failed to persist or regenerated poorly from the soil seed bank in the second year. Detailed descriptions of the research site location, legume treatments, and management the first 2 yr of the experiments are provided elsewhere (Carr et al., 2005).

Herbicides were used to control legume growth before seeding spring wheat the third production year following the 2-yr legume phase in each experiment. In 2001, a pre-emergent spring application of glyphosate [*N*-(phosphonomethyl)glycine] at 0.64 kg a.i.  $ha^{-1}$  was used in the experiment established in 1999. Clopyralid (3,6-dichloro-2-pyridinecarboxylic acid) at 1 kg a.i.  $ha^{-1}$  and 2,4-D amine [(2,4-dichlorophenoxy)acetic acid] at 0.56 kg a.i.  $ha^{-1}$  were applied in the fall in 2001 in the experiment established in 2000. Clopyralid and 2,4-D amine in the fall in 2002 followed with glyphosate in the spring before seeding in 2003 were applied at rates used in the other two experiments in the experiment that was established in 2001.

Hard red spring wheat was sown at 296 live kernels  $m^{-2}$  on 26 Apr. 2001, 17 May 2002, and 19 May 2003 during the wheat phase in the third year of each experiment using a commercial, low-disturbance grain drill. Wheat seedlings were counted in a 0.5- $m^2$  area at two random locations in each plot at 14 to 21 d after seeding. No in-crop applications of herbicides occurred during the wheat phase in the experiment established in 2001, but bromoxynil (3,5-dibromo-4-hydroxybenzotrile) at 0.28 kg a.i.  $ha^{-1}$  in 2002 and thifensulfuron {3-[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]-2-thiophenecarboxylic acid} at 0.02 kg a.i.  $ha^{-1}$  along with fen-

axaprop-P {[2*R*]-2-[4-[(6-chloro-2-benzoxazolyl)oxy]phenoxy]propanoic acid} plus mefenpyr [1-(2,4-dichlorophenyl)-4,5-dihydro-5-methyl-1*H*-pyrazole-3,5-dicarboxylic acid] at 0.09 kg a.i.  $ha^{-1}$  in 2003 were applied during the wheat phase in the other two experiments.

Wheat grain was harvested at maturity (Zadoks Growth Stage 92; Zadoks et al., 1974) from a 26- $m^2$  area in the center of each 56- $m^2$  plot in 2001 and from an 11.5- $m^2$  area in the center of each 25- $m^2$  plot in 2002 and 2003 using a small-plot combine (Kincaid Equip., Haven, KS).<sup>1</sup> Grain test weight and 100-kernel weight were determined from subsamples. Crude protein (CP) concentration was determined for subsamples of grain harvested in 2001 and 2003 by near infrared spectroscopy (Infratec grain analyzer, UAS Service Corp., Hawley, MN).<sup>1</sup>

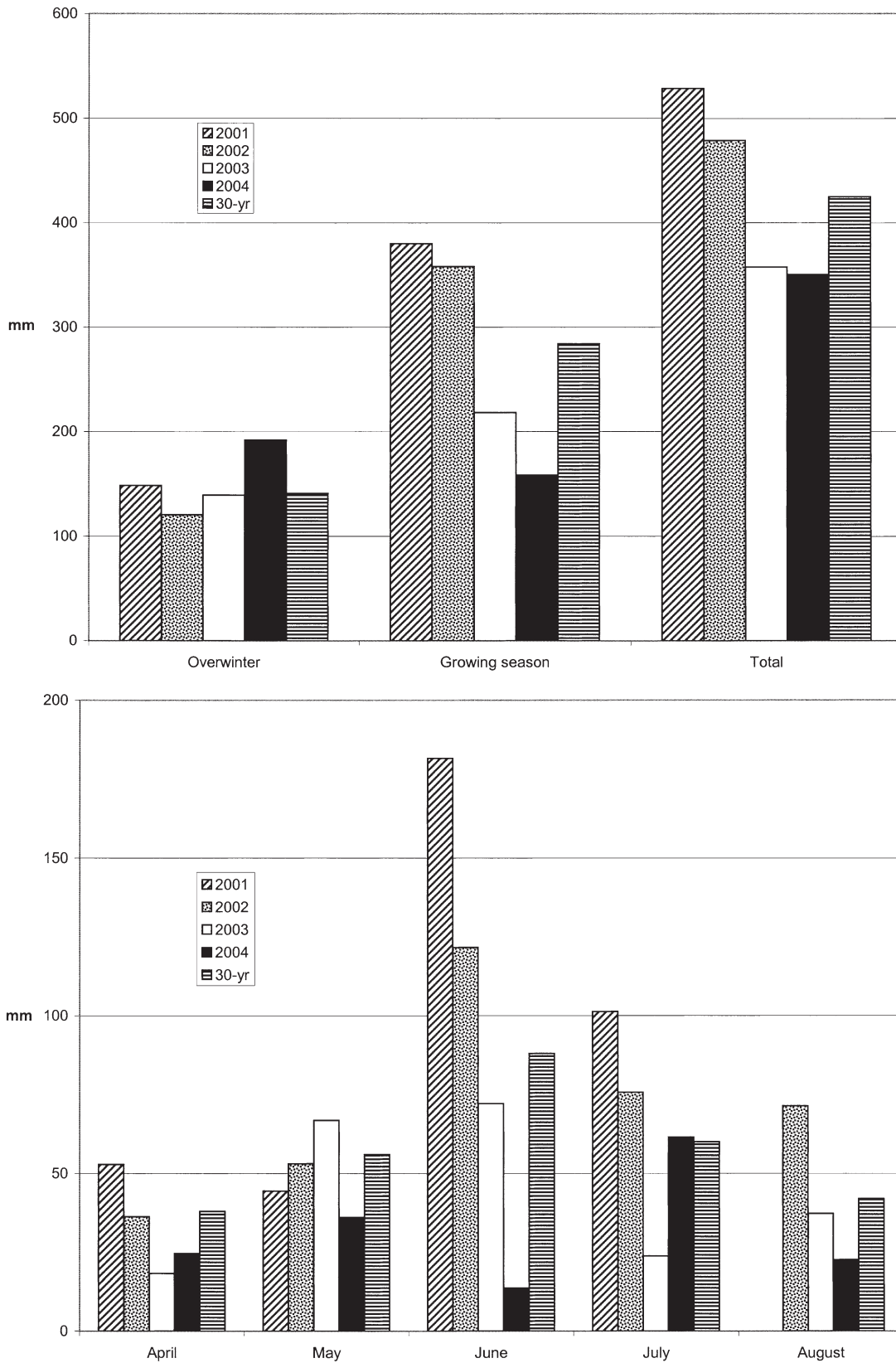
An early- to mid-May application of imazethapyr {2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid} at 0.03 kg a.i.  $ha^{-1}$  along with some hand weeding was used to control weeds following the wheat phase in the fourth year of the field experiments. The ability of legume species to regenerate from the soil seed bank was determined using the procedure described by Carr et al. (2005). Briefly, legume seedlings with opened cotyledons (BBCH Growth Stage 09; Lancashire et al., 1991) were counted in two 0.25- $m^2$  areas in each plot following spring warm up (mid- to late April). Seedlings were counted approximately 15 and 30 d later, but only those with opened cotyledons having less than two trifoliate leaves to avoid recounting seedlings. The total number of legume seedlings was determined by adding together the number of seedlings that were counted on all three dates.

Forage yields were determined by harvesting plants at early flowering (BBCH Growth Stage 60–61) in a 3.7- $m^2$  area to a 6-cm height with a forage plot harvester (Swift Machine & Welding Ltd., Swift Current, SK).<sup>1</sup> A 400-g subsample from the harvested material was dried from 3 to 8 d at 50°C until a constant weight to determine moisture content. Forage yield was reported on a DM basis.

Legume treatments were in three randomized complete blocks. The three experiments were analyzed separately because some treatments were not included in all experiments and because management differed across years and experiments. The ANOVA procedure from SAS (SAS Inst., 1985) was used in the analyses with legume treatments considered fixed and blocks considered random effects. The Ryan-Einot-Garrel-Welsch multiple range test was used to reduce the likelihood of making a Type II error when the *F* test indicated that a significant difference existed between treatment means at the *P* < 0.05 level.

A weather service station within 1 km of the field experiments indicated that overwinter precipitation (September through March) was near the 30-yr average of 141 mm before seeding spring wheat in both 2001 and 2003 (Fig. 1a). Overwinter precipitation was 86 and 136% of the 30-yr average in 2002 and 2004, respectively. Growing season (April through August) precipitation was 134% of the 30-yr average of 284 mm in 2001, 126% in 2002, 77% in 2003, and 56% in 2004. Overall, greater-than-average amounts of precipitation occurred in 2001 and 2002 while lower-than-average amounts occurred in 2003 and 2004. Particularly dry conditions occurred during July in 2003 and during June and August in 2004 (Fig. 1b). Average air temperatures during the growing season were within 1°C of the 30-yr average of 15°C each year.

<sup>1</sup>Mention of a proprietary product name is for identification purposes only and does not imply endorsement or warranty to the exclusion of other products.



**Fig. 1. (a) Overwinter (September through March), growing season (April through March), and total precipitation during 2001 to 2004 and the 30-yr average at Dickinson in southwestern North Dakota, USA; and (b) monthly growing season precipitation (April through August) during 2001 to 2004 and the 30-yr average at Dickinson in southwestern North Dakota, USA.**

**Table 1.** Spring wheat grain yield and quality following selected forage legumes in Exp. 1 (2001), Exp. 2 (2002), and Exp. 3 (2003) in southwestern North Dakota, USA.†

Legume species	Cultivar	Yield			Test weight			Kernel		
		2001	2002	2003	2001	2002	2003	2001	2002	2003
		kg ha <sup>-1</sup>			kg m <sup>-3</sup>			g 100 kernels <sup>-1</sup>		
Alsike clover	–	–‡	1449 a	1557 b–g	–	740 abc	723 ef	–	2.3 a	1.8 fgh
Arrowleaf clover	Zulu	–	779 a	1187 c–h	–	742 abc	770 abc	–	2.1 a	2.1 c–g
Austrian winter pea	–	3501 b	1007 a	2162 ab	789 a	729 abc	772 abc	3.2 a	2.2 a	2.2 b–e
Alfalfa	Alfa-Graze	–	1290 a	1008 e–h	–	721 abc	721 ef	–	2.3 a	1.9 e–h
Alfalfa	Hay & Graze	–	1165 a	1091 d–h	–	714 abc	725 ef	–	2.0 a	1.8 fgh
Alfalfa	Ladak	1381 d	1306 a	952 gh	759 ab	721 abc	721 ef	3.5 a	2.1 a	1.7 gh
Alfalfa	Rangelander	–	1135 a	964 gh	–	721 abc	712 f	–	2.1 a	1.8 fgh
Alfalfa	Spredor 3	–	1165 a	1039 e–h	–	714 abc	710 f	–	2.0 a	1.8 fgh
Alfalfa	Travois	–	1266 a	924 gh	–	732 abc	721 ef	–	2.1 a	1.9 e–h
Alfalfa	Yellowhead	–	1411 a	849 gh	–	736 abc	729 c–f	–	2.2 a	1.8 fgh
Balansa clover	Bolta	–	1616 a	1219 c–h	–	764 a	738 b–f	–	2.5 a	2.0 d–h
Barrel medic	Parabinga	2760 c	1082 a	834 gh	781 ab	740 abc	762 a–e	3.3 a	2.2 a	2.1 c–g
Berseem clover	Big Bee	3210 bc	1155 a	1155 c–h	787 a	740 abc	723 ef	3.4 a	2.2 a	1.9 e–h
Birdsfoot trefoil	Norcen	1944 d	884 a	1006 e–h	749 b	732 abc	712 f	3.4 a	2.0 a	1.6 h
Black lentil	Indianhead	–	1785 a	1969 abc	–	753 ab	764 a–e	–	2.4 a	2.2 b–e
Black medic	George	3634 ab	1150 a	939 gh	783 ab	727 abc	708 f	–	2.2 a	1.7 gh
Burr medic	Santiago	–	1174 a	1112 d–h	–	747 ab	751 a–f	3.1 a	2.2 a	2.0 d–h
Chickling vetch	AC Greenfix	–	1107 a	1823 a–e	–	723 abc	759 a–e	–	2.1 a	2.2 b–e
Cicer milkvetch	Monarch	–	784 a	949 gh	–	704 bc	721 ef	–	2.0 a	1.8 fgh
Crimson clover	Tibbee	–	1237 a	1088 d–h	–	744 abc	734 c–f	–	2.3 a	2.0 d–h
Crownvetch	common	–	970 a	862 gh	–	738 abc	742 b–f	–	2.1 a	1.9 e–h
Fenugreek	–	–	1272 a	2535 a	–	749 ab	787 a	–	2.3 a	2.5 a
Hairy vetch	–	–	1213 a	1664 b–g	–	706 bc	744 b–f	–	2.2 a	2.0 d–h
Kura clover	Cossak	–	1120 a	474 h	–	693 c	725 def	–	1.9 a	1.9 e–h
Persian clover	Nitro	–	1669 a	1134 d–h	–	749 ab	732 c–f	–	2.3 a	1.9 e–h
Purple vetch	–	–	1371 a	1246 c–h	–	736 abc	731 c–f	–	2.2 a	1.9 e–h
Red clover	Red Gold	–	1203 a	1204 c–h	–	740 abc	721 ef	–	2.3 a	1.9 e–h
Rigid medic	SA 10344	–	1039 a	1892 a–d	–	725 abc	768 a–d	–	2.3 a	2.3 abc
Roughpea	–	–	1408 a	2342 ab	–	744 abc	777 ab	–	2.2 a	2.4 ab
Sainfoin	Eski	1749 d	506 a	606 h	755 ab	747 ab	759 a–e	3.3 a	2.1 a	2.0 d–h
Snail medic	Sava	3271 bc	968 a	1127 d–h	789 a	738 abc	751 a–f	3.2 a	2.2 a	2.0 d–h
Subterranean clover	Trikkala	3235 bc	–	–	792 a	–	–	3.3 a	–	–
White clover	Ladino	–	1219 a	2052 ab	–	723 abc	744 b–f	–	2.2 a	2.0 d–h
White-flowered sweetclover	–	–	1259 a	1793 a–f	–	732 abc	736 b–f	–	2.1 a	2.0 d–h
Wooly pod vetch	Namoi	–	1336 a	2253 ab	–	712 abc	712 a–f	–	1.9 a	2.1 c–g
Yellow-flowered sweetclover	–	4102 a	1287 a	1555 b–g	780 ab	732 abc	721 ef	3.3 a	2.1 a	1.9 e–h
Mean		2469	1194	1330	776	732	740	3.3	2.2	2.0
CV (%)		8.2	34.5	19.8	1.7	2.2	1.8	7.2	8.9	5.4

† Legume species were established 2 yr prior to seeding wheat, and not all legume treatments persisted or regenerated from the soil seed bank in the year prior to seeding wheat.

‡ No date because the treatment was not included.

## RESULTS

### Wheat Yield and Quality

Wheat yield was over 4000 kg ha<sup>-1</sup> and greater following yellow-flowered sweetclover compared with all other legume treatments in 2001, except for black medic (Table 1). More grain was produced following yellow-flowered sweetclover than following Austrian winter pea [*Pisum sativum* L. subsp. *sativum* var. *arvense* (L.) Poir] even though pea plots were fallowed in 2000 because plants failed to persist or regenerate from the soil seed bank. Differences in wheat yield were not detected following black medic and fallowed Austrian winter pea. Lowest wheat yields occurred following alfalfa (*Medicago sativa* L.), birdsfoot trefoil, and sainfoin (*Onobrychis viciifolia* Scop.), perhaps in part because herbicide treatments failed to kill established legume plants that subsequently competed with wheat plants for water and other growth resources.

Wheat yield averaged around 1290 kg ha<sup>-1</sup> following yellow-flowered sweetclover in 2002, and differences were not detected among plots seeded previously to different legume treatments (Table 1). We are unable to explain

the relatively low grain yield in that year since favorable amounts of precipitation were received over the winter and throughout the growing season (Fig. 1a, 1b). In addition, wheat stands averaged 230 plants m<sup>-2</sup> across treatments in 2002, and previous research has indicated that this population was adequate for optimum grain yield in western North Dakota (Carr et al., 2003).

Wheat yield was equal or superior following yellow-flowered sweetclover compared with the other legume treatments in 2003, except for fenugreek (*Trigonella foenum-graecum* L.; Table 1). Plots originally seeded with fenugreek were fallowed in 2002 because natural reseeding did not occur. Wheat yield averaged 2535 kg ha<sup>-1</sup> following the fallowed fenugreek and was similar to yield in plots of six other annual legumes {Austrian winter pea, black lentil (*Lens culinaris* Medik.), chickling vetch (*Lathyrus sativus* L.), rigid medic [*Medicago rigidula* (L.) Allioni], roughpea (*Lathyrus hirsutus* L.), and woolly pod vetch [*Vicia villosa* ssp. *dasycarpa* (Ten.) Cav.]} that also were fallowed because few legume plants regenerated from the soil seed bank in 2002. Soil water depletion is greater following yellow-flowered sweetclover compared with fallow (Badaruddin and Meyer,

1989), so less stored soil water probably was available in sweetclover plots. This may have depressed wheat yield since conditions during July in 2003 were dry (Fig. 1b).

The CP concentration of wheat grain averaged 135 g kg<sup>-1</sup> in 2001 and 159 g kg<sup>-1</sup> in 2003. Differences in grain CP concentration were not detected following legume treatments in either year. In contrast, test weight of wheat grain was comparable or heavier from plots established previously with yellow-flowered sweetclover compared with those from other legume treatments in 2001 and 2002 (Table 1). Grain test weight was lighter in 2003 following yellow-flowered sweetclover than in fallowed plots that originally were seeded with arrowleaf clover (*Trifolium vesiculosum* Savi), Austrian winter pea, fenugreek, rigid medic, and roughpea. Similarly, light grain test weights resulted when wheat was grown in birdsfoot trefoil plots compared with plots originally seeded with these five legume species in 2003 and with Austrian winter pea in 2001. No differences in grain test weight were detected when wheat was grown following birdsfoot trefoil and other legume treatments in 2002.

Differences in kernel weight were not detected when wheat was grown following legume treatments in 2001 and 2002 (Table 1). Heavier kernels were produced in 2003 when wheat followed fenugreek and other legume treatments that were fallowed in 2002 compared with kernel weights produced in plots where forage legumes reseeded naturally or persisted the previous year. Large kernel size probably was favored in 2003 in plots that were fallowed the previous year since grain fill occurred during July in 2003 when only 24 mm of precipitation was received (Fig. 1b).

### Forage Legume Regeneration and Forage Yield following Wheat

Over 200 seedlings m<sup>-2</sup> regenerated from the soil seed bank for eight legume species in at least 1 of the 3 yr following the wheat phase (Table 2). A minimum of 200 seedlings m<sup>-2</sup> is considered necessary to maintain productive legume pasture in Australian ley farming (Walsh et al., 2001). Regenerating seedling numbers were equal or greater for black medic compared with other legume species and ranged from around 550 to 4375 m<sup>-2</sup>, depending on the year. Comparable numbers of seedlings

regenerated from the soil seed bank for yellow-flowered sweetclover in 2003. Fewer seedlings occurred for yellow-flowered sweetclover than black medic in 2004, but over 3000 seedlings m<sup>-2</sup> occurred for both species in that year. Only around 170 yellow-flowered sweetclover seedlings m<sup>-2</sup> occurred in 2002. Fewer seedlings occurred in birdsfoot trefoil than black medic plots in all 3 yr, but seedling numbers always exceeded 200 seedlings m<sup>-2</sup> for both species. More than 200 seedlings m<sup>-2</sup> also occurred for alsike clover (*Trifolium hybridum* L.), kura clover (*Trifolium ambiguum* Bieb.), red clover (*Trifolium pratense* L.), and white-flowered sweetclover (*Melilotus alba* Medik.) in 2 yr and in 1 yr for white clover (*Trifolium repens* L.).

Balansa clover (*Trifolium michelianum* Savi) showed limited ability to regenerate from the soil seed bank following the wheat phase. Fewer than 100 seedlings m<sup>-2</sup> occurred in either 2003 or 2004. Likewise, fewer than 200 seedlings m<sup>-2</sup> occurred for 22 other legume species following the wheat phase included in our study (data not presented), suggesting that these species have limited potential for regenerating pasture in a pasture–wheat rotation.

Total forage DM production exceeded 3 Mg ha<sup>-1</sup> for birdsfoot trefoil following the wheat phase in 2002 and 2003. Forage DM production was less for yellow-flowered sweetclover than birdsfoot trefoil in 2002. However, differences were not detected between the two legume species for forage DM yield in 2003. Likewise, white-flowered sweetclover produced comparable amounts of forage DM compared with birdsfoot trefoil in 2003. White-flowered sweetclover was not included with birdsfoot trefoil and yellow-flowered sweetclover in the experiment that was harvested for forage DM in 2002. Dry conditions in 2004 (Fig. 1b) prevented the three legume species from producing more than 0.5 Mg ha<sup>-1</sup> of forage DM.

Forage DM production was 2.5 Mg ha<sup>-1</sup> for black medic in 2002. However, black medic produced <500 kg ha<sup>-1</sup> of forage DM in both 2003 and 2004. Likewise, alsike clover produced only 500 kg ha<sup>-1</sup> of forage DM in 2003 and even less in 2004. Forage production was <500 kg ha<sup>-1</sup> both years that kura clover was grown. The inability of the two clover species and black medic

**Table 2.** Mean count and standard deviation after regeneration from the soil seed bank for legume species with more than 200 seedlings m<sup>-2</sup> following spring wheat in Exp. 1 (2002), Exp. 2 (2003), and Exp. 3 (2004) in southwestern North Dakota, USA.

Legume species	Cultivar	Seeding rate†	2002		2003		2004	
		no. m <sup>-2</sup>	no. m <sup>-2</sup>	SD	no. m <sup>-2</sup>	SD	no. m <sup>-2</sup>	SD
Alsike clover	–	1690	–‡	–	493 a	188	872 a	487
Birdsfoot trefoil	Norcen	480	304 a	118	650 a	307	1485 a	1659
Black medic	George	600	549 b	141	1692 b	884	4376 c	985
Kura clover	Cossack	260	–	–	340 a	446	359 a	424
Red clover	Red Gold	600	–	–	547 a	83	272 a	70
White clover	Ladino	1010	–	–	19 a	32	830 a	222
White-flowered sweetclover	–	870	–	–	1453 b	216	1428 a	507
Yellow-flowered sweetclover	–	230	172 a	66	1280 b	605	3155 b	491
Mean		342			813		1597	
CV (%)		58			110		98	

† Number of live kernels sown to establish treatments 2 yr before seeding wheat.

‡ No data because the treatment was not included in the field experiment.

Letters differing in columns indicate differences between forage crop treatments at the  $P < 0.05$  level using the Ryan–Einot–Bariel Welsch multiple range test.

to produce adequate amounts of forage DM to support grazing suggests poor potential as regenerating pasture species in a legume–wheat rotation even though the three species reseeded naturally following the wheat phase (Table 2).

Red clover produced  $<2$  Mg ha<sup>-1</sup> of forage DM following wheat in 2003. The amount of forage produced in 2004 was so limited that yield was not determined because forage could not be harvested mechanically. The red clover treatment was not included in the experiment harvested in 2002. Red clover regenerated from the soil seed bank following wheat in both years that the legume treatment was included in field experiments (Table 2). The clover species also had been identified as a potential pasture crop in previous research (Carr et al., 2005). However, red clover probably is not adapted as a regenerating pasture species in legume–wheat rotations because of limited forage yield potential following the cereal phase.

## DISCUSSION

Past research had identified birdsfoot trefoil and red clover as capable of regenerating from the soil seed bank in western North Dakota in the year after stands first were established (Carr et al., 2005). Results of this study indicate that both legume species will reseed naturally following wheat in a legume–wheat rotation. Forage DM production by regenerating birdsfoot trefoil is sufficient to support grazing by livestock in most years. However, forage production by red clover may be inadequate to support grazing. These results along with those of previous research suggest that birdsfoot trefoil can be grown as a regenerating forage species in a pasture–wheat rotation in the northern Great Plains patterned after Australian ley farming.

Results of this investigation indicate that both white- and yellow-flowered sweetclover can regenerate from the soil seed bank following wheat in a legume–wheat rotation. The biennial growth habit of sweetclover may require a 2-yr legume phase when rotated with wheat since forage DM and seed production could be limited in the first year. However, observations by Stoa (1941) indicated that a 2-yr sweetclover stand can produce enough seed to support regeneration from the soil seed bank for several years. Results of the present study suggest that forage DM in the first year may be sufficient to support grazing by livestock in some years although careful management is needed to prevent bloat and other grazing concerns (Helm and Meyer, 1993). The potential of biennial sweetclover in a pasture–wheat rotation should be investigated more thoroughly. Annual sweetclover exists, and work also is needed to determine if annual sweetclover is better suited to ley farming than biennial sweetclover.

Balansa clover, berseem clover (*Trifolium alexandrinum* L.), black medic, burr medic (*Medicago polymorpha* L.), crimson clover (*T. incarnatum* L.), and Persian clover (*T. resupinatum* L.) were identified as regenerating legume species in previously reported research (Carr et al., 2005). Only black medic regenerated from the

soil seed bank following wheat in the present study, and  $<1$  Mg DM ha<sup>-1</sup> was produced by black medic in 2 of 3 yr. These six legume species seem to have limited potential as regenerating legume species in a pasture–wheat rotation in western North Dakota and similar climatic regions.

The ability of legume species to maintain or enhance wheat yield in a pasture–wheat rotation compared with fallow–wheat or more diverse crop rotations must be demonstrated before ley farming will generate much interest among wheat producers in the northern Great Plains. Spring wheat yields never were elevated and sometimes were depressed following birdsfoot trefoil in our study. Yield depression may have occurred because soil water reserves were depleted during the 2-yr legume phase preceding the wheat phase, as expected. Forage legumes depleted soil water reserves compared with fallow in rotations with wheat in eastern North Dakota (Badaruddin and Meyer, 1989), particularly when legume growth was unrestricted. Legume growth was not controlled until the fall of the second year in our study because we believed that terminating growth earlier could reduce seed production and subsequently the soil seed bank. Work is needed to determine when legume species must be terminated so soil water recharge can occur while also allowing adequate seed production to maintain the soil seed bank. Herbicide treatments sometimes failed to kill established birdsfoot trefoil, kura clover, and red clover plants before seeding wheat in this study. Wheat growth and grain yield were suppressed in plots where persisting legume plants occurred. Alfalfa was controlled by applications of clopyralid, glyphosate, and other herbicides before seeding wheat in a sub-humid region (Bullied et al., 1999), but these same treatments did not control alfalfa consistently in western North Dakota (Carr, unpublished data, 2004). The efficacy of many herbicides declines when hot and dry conditions develop, as commonly occurs in late summer in much of the northern Great Plains. Research is needed to identify the herbicides and the timing of application that result in consistent termination of birdsfoot trefoil and other persisting legumes in western North Dakota and similar semiarid regions.

A 2-yr legume phase preceded the wheat phase in our study so that species with an ability to regenerate from the soil seed bank could be identified. We hypothesize that the soil seed bank created by the initial 2-yr phase could be maintained by subsequently rotating legume pasture on an annual basis with wheat in alternate years. Birdsfoot trefoil and sweetclover are tap rooted (McGraw and Nelson, 2003), and limiting stand persistence to a single growing season could reduce root development and soil water depletion compared with soil water removal when 2-yr legume stands are maintained. However, the ability of a single year of birdsfoot trefoil and possibly annual sweetclover to produce adequate seed to maintain the soil seed bank and forage to support grazing has not been determined. Additional research is necessary to determine if soil water is conserved and adequate forage DM and seed production is maintained

when birdsfoot trefoil and annual sweetclover pastures are limited to a single growing season.

Crop–fallow is being replaced by rotations that include various crops in addition to wheat across the northern Great Plains. The increased complexity of cropping systems suggests that rotating legume pasture with wheat in alternate years may not be attractive to commercial producers interested in expanding grain and seed crop choices. Research is needed to determine if birdsfoot trefoil and other legume species can regenerate from the soil seed bank following other cereal crops besides wheat and particularly broadleaf crops. Specifically, work is needed to determine the maximum interval between successive pasture phases that still allows regeneration of forage legume seedlings from the soil seed bank in diverse rotations.

An important determinant in the success at regenerating legume pasture in ley farming is the amount of crop residue that remains on the soil surface following a wheat crop. Research in Australia indicates that density of regenerated medic seedlings was inversely related to surface residue cover and that crop residue in excess of 4 Mg ha<sup>-1</sup> creates a surface mulch that may inhibit natural reseeding by medic seedlings (Reeves, 1987). Wheat residue production sometimes exceeded 4 Mg ha<sup>-1</sup> following selected legume treatments in 2001 and 2003 in our study, based on crop residue/grain ratios for spring wheat reported by Engel et al. (2003). A possible strategy to reduce crop residue on the soil surface is to allow ruminants to graze crop residue following wheat harvest. Grazing crop aftermath would not only result in a decrease in wheat stubble through consumption by livestock but would also bury some residue through the hoof action of animals. Shallow burial of legume seeds produced during the previous pasture phase might also occur. Research is needed to determine if grazing crop aftermath following wheat harvest improves regeneration of legume pasture from the soil seed bank in no-tillage systems and if postharvest grazing contributes to soil compaction.

The grazing of legume pasture is an important component contributing to the economic and environmental sustainability of ley farming. Birdsfoot trefoil is non-bloating and produces high quality forage. However, no cropping system investigation has incorporated the grazing of birdsfoot trefoil or other legume species in the northern Great Plains. Unfortunately, many of the benefits attributed to ley farming occur because legume species are grazed and not hayed or plowed under as green manures. The grazing of legume species during the pasture phase should be included in future studies of ley farming to learn if the benefits resulting from this farming method in Australia can be transferred to the northern Great Plains region of North America.

## CONCLUSIONS

Results of this investigation suggest that pasture–wheat rotations patterned after Australian ley farming can be adopted in the northern Great Plains. Birdsfoot trefoil will regenerate from the soil seed bank and pro-

duce adequate amounts of forage DM to support grazing following wheat, and biennial sweetclover also has potential as a regenerating pasture species. Incorporating these two and perhaps other regenerating legume species as pasture crops into wheat production systems presents an opportunity to enhance the economic and environmental sustainability of agricultural cropping systems in the region.

Spring wheat generally cannot be grown profitably in western North Dakota without government subsidy payments. A majority of the wheat presently is grown in a continuous monoculture, and this production system requires relatively high inputs of N fertilizer. Incorporating grazed legume pasture into rotations with wheat by ley farming should reduce or even eliminate the need for N fertilizer during the cereal grain phase. Wheat production could become more sustainable economically by ley farming compared with continuous wheat monoculture if grain yield was maintained but N fertilizer inputs were reduced.

Crop–fallow once dominated wheat production methods in the northern Great Plains, and preceding spring wheat with fallow still is a popular practice. Bare soil is susceptible to both water and wind erosion, and sometimes even untilled soils can erode because of the limited amount of crop residue that remains after grain harvest. Incorporating legume forages into rotations with wheat provides vegetative cover for the soil surface during the pasture phase, thereby reducing or eliminating soil erosion and enhancing the environmental sustainability of wheat production systems in the region.

The growing popularity of reduced- and no-till systems along with the development of diverse rotations are important in sustaining crop production viability in western North Dakota and throughout the northern Great Plains. Many emerging strategies and technologies for cropping systems rely heavily on fossil fuels to power planting and harvesting equipment. Costs of fossil fuels continually increase, and less expensive alternative fuels or decreases in consumption are needed to counter the price increases. Grazing regenerating pasture is an alternative to harvesting forages mechanically that should reduce fossil fuel use directly by eliminating mechanized planting and harvesting operations. Incorporating legume pasture into rotations with wheat also may reduce fertilizer N needs in the cereal crop, thereby reducing natural gas consumption that occurs when manufacturing most N fertilizers.

## ACKNOWLEDGMENTS

Appreciation is extended to Glenn Martin and Burt Melchior, agricultural specialists at the Dickinson Research Extension Center, for assistance in establishing the field experiments. The work reported in this manuscript was supported by the Cooperative State Research, Education, and Extension Service, USDA, under Agreement no. 2001-34216-10563. All opinions, findings, conclusions, or recommendations expressed in this manuscript are those of the authors and do not necessarily reflect the view of the USDA.

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