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Legume Cover Crops with Winter Cereals in Southern Manitoba: Establishment, Productivity, and Microclimate Effects

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ABSTRACT

The opportunity to include late-season cover crops in northern cropping systems has been enhanced with the adoption of winter cereal production; however, cover crop feasibility has not been evaluated in these regions. Field experiments were conducted at two sites in Manitoba in 1998 and 1999 to (i) assess establishment and dry matter (DM) production of legume cover crops that were relay-cropped [alfalfa (*Medicago sativa* L.) and red clover (*Trifolium pratense* L.)] or double-cropped [chickling vetch (*Lathyrus sativus* L.) and black lentil (*Lens culinaris* Medik. subsp. *culinaris*)] with winter cereals [winter wheat (*Triticum aestivum* L.) and fall rye (*Secale cereale* L.)], (ii) assess the effect of relay cover crops on cereal grain yield, and (iii) characterize the effects of a red clover cover crop on the microclimate after winter wheat harvest. Establishment and midseason DM of the relay crops were not affected consistently by cereal crop type. Legume DM at freeze-up was similar in winter wheat and fall rye systems and ranged from 190 to 1800 kg ha^{-1}, with moisture availability being the critical factor. Across all site-years, final DM for red clover, alfalfa, chickling vetch, and lentil averaged 1157, 690, 746, and 634 kg ha^{-1}. Relay crops did not affect main-crop grain yield but did significantly reduce main-crop DM production in some cases. The red clover cover crop created a moderating effect on late summer and fall surface (5-cm height) air temperatures and decreased soil moisture availability. Including relay and double crops in winter cereal-based cropping systems appears feasible in southern Manitoba.

INCREASING INTEREST in the sustainability of agricultural systems has led to significant developments in cropping practices over the past number of years. A great deal of emphasis has been placed on the prevention of soil erosion and degradation, with major movements toward minimum and zero tillage systems in many parts of the Canadian prairies and northern U.S. Great Plains and significant reduction in the practice of summer fallow. There is also increasing interest in alternative forms of nutrient management, particularly the role of legumes in supplying N to nonleguminous crops through rotation and intercropping.

The role of forage legume crops in improving agricultural sustainability is well recognized. Benefits include higher grain protein levels, higher yields, weed suppression, increased soil N, and improved soil properties (Spratt, 1966; Hesterman, 1988; Campbell et al., 1991; Entz et al., 1995; Hoyt and Leitch, 1983). Many of the above benefits can also be realized with single-season green manure or forage crops (McGill et al., 1986; Badaruddin and Meyer, 1989; Bremer and van Kessel, 1992; Biederbeck et al., 1996; Kelner and Vessey, 1995). However, the use of single-year systems may not be an attractive option to many producers who have found continuous grain cropping to be feasible in their climate and soil type.

Relay and double cropping represent an option for incorporating legume crops into annual cropping systems without sacrificing a season of grain production. These systems have been shown to have potential in longer growing season areas such as the southern USA (e.g., Parsch et al., 1991) but have been adapted to areas with somewhat shorter growing seasons as well. A number of cover-cropping studies have been conducted in shorter growing season areas such as the north-central USA and south-central Canada in conjunction with corn (*Zea mays* L.) production (Bruulsema and Christie, 1987; De Haan et al., 1997; Adbin et al., 1998), and a few studies were conducted in the

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Abbreviations: DM, dry matter.

north-central USA in conjunction with other crops (Moomaw and Powell, 1990; Hesterman et al., 1992; Stute and Posner, 1993; Mallory et al., 1998). No research has been published on relay and double cropping systems that fit the production systems of the Canadian prairies and the northern U.S. Great Plains.

The dry matter (DM) accumulation of legume cover crops is perhaps the most important factor to consider in determining the feasibility of relay and double cropping systems in short growing season areas because much of their value is based on the amount of N they are able to supply to the following crop. The amounts of thermal time and moisture available after harvest of the primary crop and the adaptation of legume species to particular conditions are important considerations in determining late-season DM production. In a Wisconsin study, satisfactory amounts of DM were produced by double-cropped legumes with 175 mm of rainfall during August, September, and October (Stute and Posner, 1993). In Saskatchewan, spring-seeded green manure chickling vetch and black lentil produced 1418 and 1311 kg ha^{-1} DM, respectively, in 6 to 7 wk with only 100 mm of precipitation (Biederbeck et al., 1993).

Although crop production in western Canada has traditionally been dominated by spring-seeded small grains, winter wheat has recently gained popularity due to the use of improved cultivars and no-till seeding systems. For example, winter wheat production in 2000 was more than 51 000 ha in Manitoba (Winter Cereals Canada, Yorkton, SK). Fall rye is less popular due to less favorable markets. Based on an analysis of long-term climate data, many areas of southern Manitoba, North Dakota, and southern Saskatchewan have sufficient late-season heat and water resources to support growth of late-season cover crops after winter wheat harvest (Thiessen Martens and Entz, 2001).

Legume crops have been found to perform differently on different soil types. Hesterman et al. (1992) found that alfalfa establishment was better on finer textured soils while red clover was unaffected by soil type. Mallory et al. (1998) reported higher DM yields for cover crops grown on silt loam soils compared with sandy loam soils. In the same study, double-cropped hairy vetch (*Vicia villosa* L.) outperformed relay-cropped red clover on silt loam soils while the reverse was true on the sandy loam soils.

The success of a relay or double cropping system also depends on the ability of the second crop to become established under the canopy of the first crop in the case of relay cropping or in variable midsummer conditions in the case of double cropping. Forage establishment studies have found that legume establishment is affected negatively when interseeded with cereals or grasses due to light and moisture competition (Smith, 1975). Simmons et al. (1995) observed that DM production of alfalfa interseeded with oat (*Avena sativa* L.) and barley (*Hordeum vulgare* L.) companion crops was reduced to 16 to 25% of direct-seeded alfalfa and was lower when grown with conventional-height cultivars compared with semidwarf cultivars. Moisture conditions at legume seeding can limit legume establishment and growth in both relay and double cropping systems (Stute and Posner, 1993; Keeling et al., 1996).

Interseeding with cover crops has varying effects on the yield of the main crop, with the relative stages of the two crops appearing to be one of the more important factors. Both De Haan et al. (1997) and Adbin et al. (1998) observed that cover crops seeded at the same time as corn reduced corn yield while corn yield was not affected when cover crop seeding was delayed until corn was well established. Kandel et al. (1997) obtained similar results with sunflower (*Helianthus annuus* L.) as the main crop. Spring-seeding forage legumes into established winter cereals has little effect on cereal yield (Hesterman et al., 1992; Ngalla and Eckert, 1987).

Soil temperature and moisture are affected by the amount, nature, and placement of crop residue on the soil surface. It follows that late-season cover crops may affect the microclimate. Others have observed that microclimatic differences due to plant material affect crop and weed emergence (Blackshaw, 1991; Fortin, 1993; Teasdale and Mohler, 1993), N dynamics (Power and Zachariassen, 1993), crop water use (Wraith and Ferguson, 1994), and insect populations (Orr et al., 1997). Water use by cover crops may increase the drought risk in following crops. In northern areas, maximizing snow water capture through no-till crop production (de Jong and Steppuhn, 1983) should reduce the severity of this problem. On the other hand, late-season cover crop evapotranspiration may provide important dewatering benefits in more moist climates or in those parts of the landscape where adequate or excess water exists.

The objectives of this study were to assess establishment success of relay and double crops, evaluate the effects of relay crops on main-crop productivity, determine potential of cover crop DM production, and characterize the effects of a red clover cover crop on the microclimate within a winter-cereal cropping system. Benefits (i.e., N and non-N benefits and weed suppression) of including legume cover crops in the rotation are being investigated in a follow-up study.

MATERIALS AND METHODS

Experimental Design

Relay and double cropping trials were conducted at two sites: the University of Manitoba research station situated at Winnipeg, Manitoba (49°88′ N, 97°14′ W) on a Black Lake clay soil (fine, clay, frigid Mollic Udifluvent) and the University of Manitoba research station located at Carman, Manitoba (49°49′ N, 98°00′ W) on a Hochfeld fine sandy loam soil (coarse, loamy, mixed Udic Haplocryoll). A total of four separate trials were conducted in 1997–1998 and 1998–1999 at Carman and Winnipeg. The experimental design was a split-plot with four replications.

Main plots were winter cereal type, either fall rye (cv. Prima) or winter wheat (cv. CDC Kestrel). Subplots were relay- or double-cropped legumes seeded either in spring (when winter cereals resumed growth after winter dormancy period) or immediately after winter-cereal grain harvest. Relay-cropped legumes included red clover and alfalfa (cv. Nitro). Double-cropped legumes included chickling vetch (cv. AC Greenfix) and black lentil (cv. Indianhead). Subplots were

2 by 6 m at Winnipeg and 2 by 8 m at Carman. In the 1998–1999 trial, a fifth treatment was added in which plots were passed over with an empty drill (discs penetrating soil), allowing the effects of the cover crop's presence to be distinguished from the effects of the soil disturbance caused by seeding into the winter cereal.

Field Management

All crops in the experiment were seeded using a Fabro (Swift Machinery Co., Swift Current, SK, Canada) no-till offset disc drill. Row width in all cases was 15 cm. In preparation for the 1997–1998 trial, winter cereals were no-till planted into barley stubble in Winnipeg on 4 Sept. 1997 and in Carman on 8 Sept. 1997 at a rate of 98 kg ha^{-1} for winter wheat and 93 kg ha^{-1} for fall rye. Fertilizer was placed with the winter cereal seed at a rate of 20 kg P ha^{-1} and 4 kg N ha^{-1}. In the 1998–1999 trials, winter cereals were no-till seeded into barley stubble at Winnipeg on 3 Sept. 1998 and at Carman on 4 Sept. 1998 at rates of 100 and 80 kg ha^{-1} for winter wheat and fall rye, respectively. Fertilizer was placed with the seed at rates of 20 and 4 kg ha^{-1} P and N, respectively, in this year.

Main crops were fertilized with 80 and 82 kg N ha^{-1} at Carman and Winnipeg, respectively, in late April 1998 and with 99 and 93 kg N ha^{-1} at Winnipeg and Carman, respectively, in mid-April 1999. All fertilizer was applied according to soil test recommendations, and N was applied as broadcast ammonium nitrate (NH_4NO_3) in early spring. In the relay cropping systems, red clover and alfalfa were no-till seeded into the winter cereals on 1 May 1998 and 23 Apr. 1999 at Winnipeg and on 8 May 1998 and 27 Apr. 1999 at Carman. In both years, alfalfa and red clover were seeded at rates of 10 and 12 kg ha^{-1}, respectively. Both were inoculated with Nitragin Gold *Rhizobium* inoculant (LiphaTech, Milwaukee, WI).

On 8 June 1998, propiconazole {1-[[2-(2,4-dichlorophenyl)-4-propyl-1,3-dioxolan-2-yl]methyl]-1H-1,2,4-triazole} was applied to wheat at Winnipeg at the recommended rate of 0.5 L ha^{-1} to control leaf diseases. In 1999, wheat was sprayed with 0.5 L ha^{-1} propiconazole at Winnipeg and Carman on 7 and 8 June, respectively.

Grain yield was determined by harvesting 5 m^2 (Winnipeg) or 7 m^2 (Carman) using a small-plot combine. In 1999, severe lodging of rye at both locations required that the crop be cut by hand and threshed with a stationary machine. Rye was harvested on 27 July at both locations in 1998 and on 4 and 5 August at Carman and Winnipeg, respectively, in 1999. Wheat was harvested on 5 August at both locations in 1998 and on 4 and 10 August at Winnipeg and Carman, respectively, in 1999. Cereal cutting height was approximately 20 cm, and straw was removed from the plot immediately after harvest. After threshing, grain samples were cleaned, weighed, and yield per hectare was calculated.

In 1998, double crops (black lentil and chickling vetch) were no-till seeded into the harvested rye plots on 29 July at Carman and on 31 July at Winnipeg and into harvested wheat plots on 6 August at both sites. Seeding rates were 43 and 93 kg ha^{-1} for black lentil and chickling vetch, respectively. Legumes were inoculated with Soil Implant + *Rhizobium* inoculant (LiphaTech, Milwaukee, WI). Double crop plots in Carman and Winnipeg were sprayed with 5 L ha^{-1} glyphosate [isopropylamine salt of *N*-(phosphonomethyl)glycine] on 31 July to control weeds. On 15 September, all legume relay and double crop plots at Carman were sprayed with 2.7 L ha^{-1} sethoxydim {2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexe 1-one} to control grassy weeds.

In 1999, double crops were no-till seeded into rye plots at Carman and both rye and wheat plots at Winnipeg on 6 August and into wheat plots at Carman on 10 August at the same seeding rates as in 1998. Legumes were inoculated with Nitragin Cell-tech C liquid inoculant. All relay and double crop plots at both Winnipeg and Carman were sprayed with 1.11 L ha^{-1} sethoxydim on 30 and 31 August 1999, respectively. Black lentil and chickling vetch emergence was 70 to 80% in both years.

Plant Sampling Procedures

In 1998, measurements included cereal and legume plant population and DM production and light interception by the cereal canopy. In 1999, measurements included cereal and legume crop height and DM production and crop (cereal and cover crop) light interception.

Percent canopy light interception was determined using a LICOR Model LI-185B quantum meter with a line quantum sensor (1 m long). Measurements were taken at approximately solar noon. The quantum flux was determined by placing the sensor at ground level beneath the crop canopy between the crop rows. A second reading was taken above the crop canopy at the same orientation to the sun, and percentage light interception by the crop canopy was then calculated. Measurements were taken in control plots and treatments containing alfalfa (1998 only) and red clover approximately every 2 wk for the first part of the growing season, beginning on 25 May and ending on 9 July 1998 and beginning on 18 May and continuing to 26 and 27 July 1999. A final set of readings was collected in all relay and double crops at the Winnipeg site on 5 Oct. 1999.

Legume plant density was measured by counting the number of plants in two 1-m lengths of row within each plot. Measurements were taken at approximate 2-wk intervals between 19 May and 13 July 1998.

In 1998, legume DM was measured by hand-clipping (at ground level) three 1-m lengths of row at cereal harvest (late July) and on 16 October (Winnipeg) and 24 and 26 October (Carman), approximately corresponding to the end of the growing season, or freeze-up. During the 1999 winter-cereal growing season, relay-crop DM samples (one 1-m length of row) were taken only in the red clover treatment every 2 to 3 wk beginning in mid-June and continuing until cereal harvest, at which time alfalfa DM was also measured. Samples of all four cover crops were taken from one 1-m length of row in late September and again in early November 1999 (freeze-up).

Main-crop (cereal) DM samples (1 m^2) were taken just before harvest in 1998. In 1999, cereal DM was monitored during the growing season by collecting samples from 1-m lengths of row four times between mid-May and cereal harvest. All DM samples were dried at 70°C for 48 h and then weighed. Rye height at maturity was 130 to 145 cm, and wheat height was 100 to 115 cm.

Average daily growth for legumes was calculated for the period from main-crop harvest to freeze-up. For relay crops, DM accumulation after main-crop harvest was divided by the number of days from main-crop harvest to the date of final DM sampling. For double crops, final DM production was divided by the number of days from seeding to the date of final DM sampling.

Soil and Environment Sampling Procedures

In 1999, at Carman and Winnipeg, samples were taken for gravimetric soil moisture determination four times during the growing season in two treatments—wheat with and without a relay crop of red clover. Using a Dutch auger, samples were taken at the following depths: 0 to 20, 20 to 50, 50 to 80, and

80 to 110 cm. Samples were taken 4 May, 16 June, 11 August, and 4 October at Winnipeg and 17 May, 17 June, 12 August, and 5 October at Carman. On the first Winnipeg sampling date, soil moisture samples were taken in wheat plots only, and the wheat–red clover treatment was assumed to be the same.

Soil and air temperatures were monitored from 1 May 1999 throughout the growing season and the following winter using a Campbell-Scientific CR10 data logger. Temperature sensors (Model 107 thermistors, Campbell Scientific, Chatham, ON, Canada) were placed at five levels (50, 15, and 5 cm above the soil and 2 and 15 cm below the soil) in the wheat–red clover treatment and the winter wheat control at the Winnipeg site. Hourly readings and daily averages were collected, and from these, thermal time and daily temperature fluctuations were calculated. Thermal time was calculated as growing degree days, using a base temperature of 5°C, and was summed for the summer growing season (1 May to 5 August, the harvest date of the wheat) and the fall (6 August to 31 October). Monitoring stations were placed in only one replicate, and so data derived from these measurements are purely observational. Precipitation and air temperature (1.5 m above soil) data were collected at a weather station located approximately 100 m from the plot site at Winnipeg and 500 m from the plot site at Carman.

Statistical Analysis

Factorial analysis-of-variance tests were carried out on early and late-season light interception, plant density, DM production, daily growth rate of legumes, and yield data to detect main-crop and cover crop effects and interactions. Combined site-year analysis was done on cereal yield and final legume DM production after a Bartlett's test confirmed homogeneity of error variances. Soil moisture data was analyzed using a one-way analysis of variance. A Fisher's LSD test was used to detect significant differences between treatments for all analysis-of-variance tests, with $\alpha = 0.05$.

RESULTS AND DISCUSSION

Establishment and Competition Factors

Measurements of canopy light interception were initiated after full ground cover by the winter cereals, and as a result, average values were very high (>70%) at the first measurement time. Percent light interception by the crop canopy was affected more strongly and consistently by the main-crop type than by the relay crop treatments (Table 1). Early season (mid- to late May) light interception was lower in wheat than in rye in all site-years. Light interception later in the season (9 July 1998 and 26–27 July 1999) tended to be lower in rye than in wheat although these differences were significant in only two of the four site-years. These seasonal differences reflect the more rapid development of rye. Similar observations were reported by Klebesadel and Smith (1959).

Early season light interception was affected by cover crop only at Carman in 1998. In this case, light interception in the alfalfa treatment was significantly lower than in the control. The mean of the red clover treatment was not different from the other treatments (Table 1). A main crop × cover crop interaction was observed for early season light interception in this site-year; the presence of a relay crop had no effect on light interception in rye while in wheat, light interception in the alfalfa treatment was lower than in the red clover or control. Because legumes and companion crops compete strongly for light (Smith, 1975), the greater light penetration through the wheat canopy at this sampling time may have provided conditions more conducive to legume growth, which in turn, may have caused the legume to put more competitive pressure on wheat. In other site-years, the percent interception tended to be somewhat lower in treatments containing cover crops compared with the control, suggesting greater competition of legume with main-crop cereal. However, these differences were not statistically significant, and no further interactions were observed.

Light interception, measured in July, was not consistently affected by a cover crop. A strong effect was observed in only one instance (Winnipeg 1999) where the red clover cover crop resulted in greater interception

Table 1. Effect of main- and relay-crop type on early and late-season canopy light interception, relay-crop density, and relay-crop dry matter (DM) production at the time of main-crop harvest at Carman and Winnipeg (Wpg), Canada in 1998 and 1999.

	Early season light interception				Late-season light interception				Relay-crop plant density		Relay-crop DM at main-crop harvest			
	1998		1999		1998		1999		1998		1998		1999	
Main effect	Carman 25 May	Wpg 26 May	Carman 18 May	Wpg 18 May	Carman 9 July	Wpg 9 July	Carman 27 July	Wpg 26 July	Carman 13 July	Wpg 13 July	Carman	Wpg	Carman	Wpg
	%								plants m^{-2}		kg ha^{-1}			
Relay crop														
Red clover	80ab†	73a	71a	58a	84b	82a	89a	90a	89a	250a	40a	220a	82a	144a
Alfalfa	78b	75a	–	–	86a	83a	–	–	55a	112b	16b	107a	27b	190a
Control	83a	81a	71a	64a	85ab	85a	90a	83b	–	–	–	–	–	–
LSD (0.05)	4	8	10	13	2	5	5	4	37	66	21	190	34	133
Main crop														
Winter wheat	74b	72b	60b	47b	84a	86a	93a	89a	75a	198a	47a	274a	32a	116a
Fall rye	87a	81a	82a	75a	85a	8b	86b	83a	69a	164a	9a	53a	77a	218a
LSD (0.05)	6	6	7	14	4	1	6	7	61	133	53	350	48	108
							ANOVA ($P > F$)							
Source of variation														
Relay crop (RC)	0.018	0.123	0.958	0.311	0.113	0.434	0.697	0.006	0.006	0.002	0.030	0.196	0.008	0.432
Main crop (MC)	0.008	0.015	0.002	0.008	0.610	0.001	0.024	0.086	0.798	0.481	0.107	0.139	0.058	0.057
MC × RC	0.002	0.356	0.383	0.813	0.061	0.949	0.478	0.011	0.591	0.624	0.064	0.320	0.039	0.236

† Means within the same column followed by the same letter are not significantly different according to Fisher's LSD test ($P < 0.05$).

compared with the control (Table 1). A main crop × cover crop interaction indicated that main crops responded differently to cover crops at this site. The cover crop had no effect on light interception in wheat while interception was increased by the presence of red clover in rye compared with rye alone. This increased interception was possibly caused by the red clover crop itself, which produced somewhat more DM, and thus, a denser canopy in the rye crop (160 kg ha^{-1}) than in the wheat (129 kg ha^{-1}) in this site-year. A weak main crop × cover crop interaction ($P = 0.061$) was observed in the July measurements at Carman in 1998. Levels of light interception were lowered slightly by the presence of a cover crop in rye while they were increased slightly by the cover crop treatments in wheat.

The only significant effect of the legume plant population was observed at Winnipeg in 1998 where the stand of red clover (250 plants m^{-2}) was higher than that of alfalfa (112 plants m^{-2}). This pattern was observed weakly at Carman as well (Table 1). In Michigan relay-cropping trials, Hesterman et al. (1992) observed that Nitro alfalfa tended to have lower plant populations than other alfalfa cultivars and red clover when intercropped with a cereal. In the present study, legume plant stands were higher at Winnipeg than at Carman. Hesterman et al. (1992) also found better legume establishment on finer textured soils vs. sandy loam soils. Relay crop stands were consistently, though not significantly, higher in wheat than in rye. This is likely related to lower early season light interception and shorter stature of wheat at this time. This would create conditions that are more conducive to legume establishment (Smith, 1975; Simmons et al., 1995; Springer, 1997). There were no interactions between main crop and cover crop for legume plant stand, indicating that both cover crops responded to main-crop competition in a similar manner. Although variation in legume establishment was observed, legume stands were considered adequate in all cases.

Relay-crop DM production at main-crop harvest was not affected consistently by main-crop type. In 1998, no difference in relay-crop DM accumulation at the time of cereal harvest was observed between wheat and rye. The opposite trend was observed in 1999, with higher relay-crop DM in rye than in wheat at both sites ($P = 0.058$ and 0.057, respectively). More relay-crop growth in rye than wheat in 1999 could be related to the different growth phases and resource use patterns of the two cereals. The earlier maturing rye allowed for slightly better light penetration in the later part of the season than wheat (Table 1). This supports Simmons et al. (1995), who found that reductions in legume DM production under the canopy of a companion crop were related to light interception by the companion crop. Water requirements for rye also decline earlier in the season than for wheat (Klebesadel and Smith, 1959), which increases the moisture available to the relay crop.

Dry matter accumulation of relay crops at main-crop harvest was higher at Winnipeg than at Carman in both years (Table 1), likely due to higher moisture-holding capacity of the clay soil (Table 2) and slightly greater precipitation in May, June, and July at Winnipeg (Table 3). At Winnipeg, differences in DM production between relay crops were not significant or consistent. However, with the lower moisture availability at the Carman site, red clover produced significantly more DM than alfalfa in both years. Peterson et al. (1992) found alfalfa to be more drought tolerant than red clover when grown in pure stands. Gist and Mott (1957) observed that root growth of alfalfa seedling was reduced significantly by shading, reducing drought tolerance. In the same study, red clover was generally found to produce more DM in low-light conditions than alfalfa.

Table 2. Effect of a red clover relay crop on gravimetric soil moisture content throughout the growing season in winter wheat at two locations in 1999.

	Carman				Winnipeg			
Soil depth	**17 May**	**17 June**	**12 Aug.**	**5 Oct.**	**4 May**	**16 June**	**11 Aug.**	**4 Oct.**
	g water/g soil							
0–20 cm								
Winter wheat	0.28a†	0.16a	0.20a	0.19a	0.29‡	0.25a	0.30a	0.36a
Winter wheat–red clover	0.27a	0.14a	0.17a	0.12b	–	0.25a	0.28a	0.28b
LSD (0.05)	0.04	0.04	0.04	0.03	–	0.02	0.04	0.02
ANOVA ($P > F$)	0.570	0.217	0.198	0.006	–	0.645	0.168	<0.001
20–50 cm								
Winter wheat	0.25a	0.16a	0.12b	0.14a	0.29	0.26a	0.29a	0.34a
Winter wheat–red clover	0.24a	0.15a	0.15a	0.13a	–	0.26a	0.28a	0.26b
LSD (0.05)	0.04	0.04	0.02	0.06	–	0.01	0.05	0.02
ANOVA ($P > F$)	0.542	0.319	0.017	0.587	–	0.135	0.498	0.001
50–80 cm								
Winter wheat	0.22a	0.16a	0.12a	0.15a	0.28	0.27a	0.23a	0.27a
Winter wheat–red clover	0.22a	0.16a	0.12a	0.13a	–	0.26a	0.24a	0.24b
LSD (0.05)	0.03	0.02	0.04	0.05	–	0.02	0.02	0.03
ANOVA ($P > F$)	0.811	0.771	0.968	0.378	–	0.656	0.539	0.035
80–110 cm								
Winter wheat	0.25a	0.21a	0.16a	0.18a	0.25	0.28a	0.23a	0.24a
Winter wheat–red clover	0.24a	0.22a	0.16a	0.17a	–	0.28a	0.24a	0.24a
LSD (0.05)	0.06	0.04	0.03	0.02	–	0.02	0.02	0.02
ANOVA ($P > F$)	0.721	0.291	0.687	0.363	–	0.889	0.360	0.917

† Means within columns followed by the same letter are not significantly different according to Fisher's LSD test ($P < 0.05$).

‡ Soil water content in winter wheat and winter wheat–red clover treatments were assumed to be equal at this sampling date.

Table 3. Average temperatures and precipitation for the growing season months at Carman and Winnipeg.

	Temperature				Precipitation						
Month	1997	1998	1999	Avg.†	1997		1998		1999		Avg.†
	°C				mm	%‡	mm	%	mm	%	mm
					Carman						
Apr.	−0.5	8.3	5.8	4.2	67.8	250	53.4	197	15.4	57	27.1
May	9.0	12.9	11.8	12.5	25.0	47	43.2	81	142.0	266	53.4
June	18.6	15.1	16.0	16.9	59.0	71	94.6	114	74.0	89	82.8
July	19.0	18.7	18.8	19.4	117.8	159	33.4	45	83.2	112	74.1
Aug.	18.1	20.2	18.1	18.2	50.4	80	45.4	72	31.0	49	62.8
Sept.	14.4	14.4	11.3	12.2	32.6	65	13.3	27	36.6	73	49.9
Oct.	5.2	6.4	5.0	5.5	48.4	130	55.6	149	15.4	41	37.2
Avg/total	12.0	13.7	12.4	12.7	401	104	338.9	88	397.6	103	387.3
					Winnipeg						
Apr.	0.4	9.0	7.5	3.9	35.1	129	36.3	134	29.2	108	23.5
May	9.8	14.0	13.0	11.9	36.3	68	118.6	222	102.9	193	57.8
June	20.3	16.7	17.5	17.0	53.1	64	71.2	86	95.5	115	89.0
July	20.8	21.0	20.8	19.5	93.2	126	67.8	92	72.4	98	71.6
Aug.	19.4	21.6	19.5	18.5	73.4	117	15.0	24	35.3	56	75.0
Sept.	15.1	15.6	12.4	12.4	50.5	101	14.2	29	58.4	117	55.6
Oct.	5.9	6.6	5.4	5.2	74.4	200	59.2	159	22.9	61	28.5
Avg/total	13.1	14.9	13.7	12.6	416.1	107	382.4	99	416.5	108	401

† 30-yr average.
‡ Percent relative to 30-yr average.

Main-Crop Dry Matter Production and Grain Yield

An important question in interseeding systems regards the main-crop yield penalty, which might result from relay-crop competition.

Main-crop DM production in 1998 was approximately half that of 1999 (Table 4), and under these conditions, DM production of the cereals was also more sensitive to the relay crop. For example, significant relay-crop effects were observed at both sites in 1998, and red clover tended to decrease main-crop DM more than alfalfa (Table 4). No significant effects of relay crop on main-crop DM production were observed in 1999. This data suggests that relay crops have the potential to decrease main-crop yields, especially where main-crop yield potential is already low due to other factors. Similar trends have been observed in recent weed competition studies in Manitoba (Ross and Van Acker, personal communication, 2000). Because DM production is a measure of yield, these results suggest that interseeded

Table 4. Effect of relay-crop type and site-year on dry matter (DM) production at crop maturity and grain yield of winter wheat and fall rye.

	Main-crop production				Main-crop grain yield				
	1998		1999		1998		1999		
Main effect	Carman	Wpg†	Carman	Wpg	Carman	Wpg	Carman	Wpg	Combined site-years
	kg ha^{-1}								
Relay crop									
Red clover	7 785b‡	6 295c	13 145b	15 061a	4 217a	3 078a	5 456a	5 199a	4 432a
Alfalfa	8 827b	7 654b	16 756a	15 381a	4 076a	2 990a	5 419a	5 300a	4 446a
Control	10 381a	8 885a	15 323ab	14 449a	4 426a	3 287a	5 816a	5 047a	4 606a
LSD (0.05)	1 184	1 130	3 509	4 045	951	408	420	722	311
Main crop									
Winter wheat	7 783b	7 612a	14 775a	15 561a	3 159b	2 257b	5 401a	5 544a	4 030b
Fall rye	10 213a	7 611a	15 375a	14 366a	5 321a	3 979a	5 713a	4 849b	4 950a
LSD (0.05)	1 670	2 153	5 940	5 940	954	516	2 439	542	457
Site-year									
Carman 1998	–	–	–	–	–	–	–	–	4 240b
Wpg 1998	–	–	–	–	–	–	–	–	3 118c
Carman 1999	–	–	–	–	–	–	–	–	5 557a
Wpg 1999	–	–	–	–	–	–	–	–	5 181a
LSD (0.05)	–	–	–	–	–	–	–	–	673
	ANOVA ($P > F$)								
Source of variation									
Relay crop (RC)	0.002	0.001	0.120	0.879	0.728	0.302	0.115	0.737	0.396
Main crop (MC)	0.019	0.999	0.583	0.568	0.006	0.002	0.757	0.032	0.002
Site-year (SY)	–	–	–	–	–	–	–	–	<0.001
MC × RC	0.035	0.278	0.859	0.969	0.248	0.947	0.068	0.559	0.506
SY × RC	–	–	–	–	–	–	–	–	0.782
SY × MC	–	–	–	–	–	–	–	–	0.002
SY × MC × RC	–	–	–	–	–	–	–	–	0.210

† Wpg, Winnipeg.
‡ Means within columns followed by the same letter are not significantly different according to Fisher's LSD test ($P < 0.05$).

legumes did reduce main-crop yield in several instances.

Dry matter production varied significantly between main crops in 1998 at the Carman site; rye produced more DM than wheat (Table 4). The significant main crop × cover crop interaction at this site-year was attributed to the negative effect of the alfalfa treatment on the DM production of wheat compared with rye.

Main-crop grain yield was not affected by the presence of the alfalfa or red clover relay crops; however, slight yield reductions were observed in three out of four site-years (Table 4). Effects of interseeded legumes on grain yield gave mixed results. This has been reported by others (Hesterman et al., 1992; Moynihan et al., 1996; De Haan et al., 1997; Jeranyama et al., 1998; Adbin et al., 1998). At both sites in 1998, rye yielded more than wheat while in 1999, wheat yielded more than rye at Winnipeg and similarly at Carman. No main crop × cover crop interactions were observed in any trials, indicating that cover crops affected both main-crop yields in a similar manner.

The drill pass treatment was found to have no effect on grain yield (data not shown), indicating that the spring seeding operation to establish relay crops in this study was not detrimental to main-crop yield. Therefore, this treatment was excluded from further analysis.

When the four site-years were combined, rye yielded more than wheat, and 1999 yields were considerably higher than 1998 (Table 4), reflecting the poorer performance of winter cereals in 1998. Analysis of yields across all site-years indicated that the relay crops did not reduce yield although means were slightly lower (3.4 to 3.8%) in relay-cropped treatments compared with the control. Similar yield losses due to relay cover crops were observed by Ngalla and Eckert (1987). Hesterman et al. (1992) reported no yield penalty due to a relay crop because the DM production of the legume at the time of main-crop harvest was not sufficient to cause competition. The absence of significant main crop × cover crop or site-year × main crop × cover crop interactions indicates that the two relay cover crops affected main-crop yield in a similar manner and that this trend was consistent across environments sampled.

Final Legume Dry Matter Production and Growth Rate

Dry matter production by the four legumes at the end of the growing season ranged from 190 to 1800 kg ha^{-1}, and average daily growth rates ranged from 2 to 18 kg ha^{-1} d^{-1} (Table 5). Red clover produced the most DM and had the highest average daily growth. Black lentil tended to produce the least DM although its differences from alfalfa and chickling vetch were generally not significant. Chickling vetch growth rates were generally higher than those of alfalfa while final DM production was similar. Hesterman et al. (1992) observed that red clover produced >1600 kg ha^{-1} more DM than alfalfa when relay-cropped with winter wheat. Biederbeck et al. (1993) found that black lentil produced significantly less DM (1478 kg ha^{-1}) than chickling vetch (1790 kg

Table 5. Effect of legume cover crop type, main-crop type, and site-year on final dry matter (DM) production and daily growth rates (after main-crop harvest) of legume cover crops.

	Cover crop growth rate				Cover crop final DM				
	1998		1999		1998		1999		Combined site-years
Main effect	Carman	Wpg†	Carman	Wpg	Carman	Wpg	Carman	Wpg	
	kg ha^{-1} d^{-1}				kg ha^{-1}				
Cover crop									
Red clover	6.66a‡	17.2a	5.85a	18.0a	605a	1542a	607a	1804a	1157a
Alfalfa	2.04c	11.9b	4.14b	10.9c	189c	1021b	398b	1193b	690bc
Chickling vetch	4.50b	13.4ab	3.81b	14.2b	367b	1004b	339b	1276b	746b
Black lentil	2.34c	12.8ab	3.60b	11.7bc	190c	977b	319b	1051b	634c
LSD (0.05)	1.85	4.6	1.52	3.0	158	315	142	271	110
Main crop									
Winter wheat	4.08a	12.7a	4.33a	13.3a	348a	1042a	393a	1267a	762a
Fall rye	3.49a	15.2a	4.37a	14.1a	309a	1244a	439a	1395a	849a
LSD (0.05)	2.89	5.1	0.72	7.2	238	381	68	651	136
Site-year									
Carman 1998	–	–	–	–	–	–	–	–	329b
Wpg 1998	–	–	–	–	–	–	–	–	1140a
Carman 1999	–	–	–	–	–	–	–	–	416b
Wpg 1999	–	–	–	–	–	–	–	–	1331a
LSD (0.05)	–	–	–	–	–	–	–	–	244
	ANOVA ($P > F$)								
Source of variation									
Cover crop (CC)	<0.001	0.152	0.024	<0.001	<0.001	0.004	0.002	<0.001	<0.001
Main crop (MC)	0.816	0.189	0.862	0.729	0.816	0.176	0.117	0.576	0.169
Site-year (SY)	–	–	–	–	–	–	–	–	<0.001
MC × CC	0.688	0.427	0.278	0.154	0.688	0.175	0.094	0.112	0.652
SY × CC	–	–	–	–	–	–	–	–	0.110
SY × MC	–	–	–	–	–	–	–	–	0.610
SY × MC × CC	–	–	–	–	–	–	–	–	0.025

† Wpg, Winnipeg.

‡ Means within columns followed by the same letter are not significantly different according to Fisher's LSD test ($P < 0.05$).

ha^{-1}) as a spring-seeded green manure crop. In the present study, main-crop type did not affect the final DM accumulation or growth rate of the cover crops in any case, indicating that there were no deleterious effects of fall rye, which is known to have allelopathic properties (Weston, 1996).

Combined site analysis for total cover crop DM revealed significant cover crop and site-year effects. Cover crop DM accumulation and average growth rates were higher at Winnipeg than at Carman in both years, again reflecting the higher soil moisture availability at the Winnipeg site. This suggests that, under Manitoba conditions, relay and double cropping systems may be best suited to areas with high rainfall and/or heavy soils with a high water-holding capacity. Mallory et al. (1998) and Hesterman et al. (1992) also found that cover crop DM yields were lower on coarser textured soils. Over all sites, red clover produced the most DM ($P < 0.05$), followed by chickling vetch, alfalfa, and then black lentil. It was interesting to observe a similar DM yield for chickling vetch and alfalfa (Table 5) because alfalfa was relay-cropped and had the advantage of being established at the time of main-crop harvest. This reflects the higher aboveground growth rate of chickling vetch compared with alfalfa in three out of four site-years (Table 5). The relatively fast growth rate of annual legumes compared with perennials has been observed in cover crop research by Stute and Posner (1993) and could be related to greater seed mass in annuals compared with perennial plants.

Late-season moisture conditions tended to be drier than average at both sites and in both years of the study, with monthly averages often below 75% of the long-term average in August, September, and October and falling below 30% of the long-term average at Winnipeg in August and September 1998 (Table 3). Total precipitation during August, September, and October for both sites in both years was approximately equal to or lower than the rainfall expected during this time in southern Manitoba for 3 out of 4 yr (approximately100 mm) and was considerably lower than the average precipitation during this time (approximately 150 mm; Thiessen Martens and Entz, 2001).

The significant site-year × main crop × cover crop interaction (Table 5) indicates that the effect of the main crop on total cover crop DM was different for different site-years. However, no clear trends were established.

Based on a typical legume N content of 30 g kg^{-1}, N contributions by the aboveground biomass of these legumes can be estimated at 29 to 54 kg ha^{-1} for the Winnipeg site and 6 to 18 kg ha^{-1} for the Carman site. Because it is well established that root/shoot ratios tend to be higher for perennials than for annuals, aboveground biomass may not be a true measure of the total DM production and N contributions of these legumes. This considered, it appears that relay cropping with perennial legumes may provide more benefits to the system than double cropping with annual legumes. The benefits of either system may be limited in locations with sandy soils or low late-season precipitation.

Soil Moisture

Soil moisture data collected in 1999 is shown in Table 2. As expected, negligible differences between the control and the red clover relay crop treatments were observed in May and June, at both the Winnipeg and Carman sites, because the red clover was still in the very early stages of development. The week after wheat harvest (August), soil moisture levels in the two treatments were significantly different only at Carman in the 20- to 50-cm soil zone where the relay-cropped treatment had higher soil moisture than the wheat alone. The opposite trend was observed weakly in the surface layer at this site and in the upper 50 cm of soil at Winnipeg, with red clover treatments having lower soil moisture.

Samples taken near the end of the growing season (early October) indicated lower soil moisture in the red clover treatment compared with wheat alone, reflecting late-season water use by the red clover. At Carman, this difference was only significant near the soil surface (0–20 cm). However, differences were significant to 80 cm at Winnipeg. These results suggest that red clover root activity extended to 80 cm at Winnipeg by the end of the growing season. Assuming a soil bulk density of 1.25 g cm^{-3}, the red clover treatment contained 54 mm less water than the control to a depth of 110 cm at Winnipeg in October. Previous research suggests that soil moisture depletion by the legume may decrease crop yield the following year when moisture levels are low (Hoyt and Leitch, 1983; Hesterman et al., 1992). In wet climates, this moisture depletion may be beneficial to the following crop.

Microclimate

The presence of red clover in the winter wheat canopy had no effect on air temperature at either the 15- or 50-cm height. At 5 cm above the soil surface, differences in thermal time between treatments were negligible for the summer and fall portions of the season (Fig. 1). However, average temperatures appeared to be slightly moderated in the red clover treatment, beginning in August and extending until the first major snowfall, which occurred on 19 December. Diurnal temperature fluctuations (Fig. 2) revealed a strong moderating effect of red clover during the fall, with reduced maximum temperatures and increased minimum temperatures. This moderating effect coincided with clover canopy closure, and was therefore likely caused by a combination of shading, higher humidity due to transpiration, and reduction in heat loss and gain caused by the insulating layer created by the red clover canopy. Calculation of daily temperature changes for the whole season revealed a large reduction in temperature fluctuations in the relay-cropped treatment during the autumn period (Fig. 3). Similar reductions in daily temperature amplitude by a cover crop have been documented by Teasdale and Mohler (1993) and Orr et al. (1997). In the present study, this moderating effect was weakly visible by the

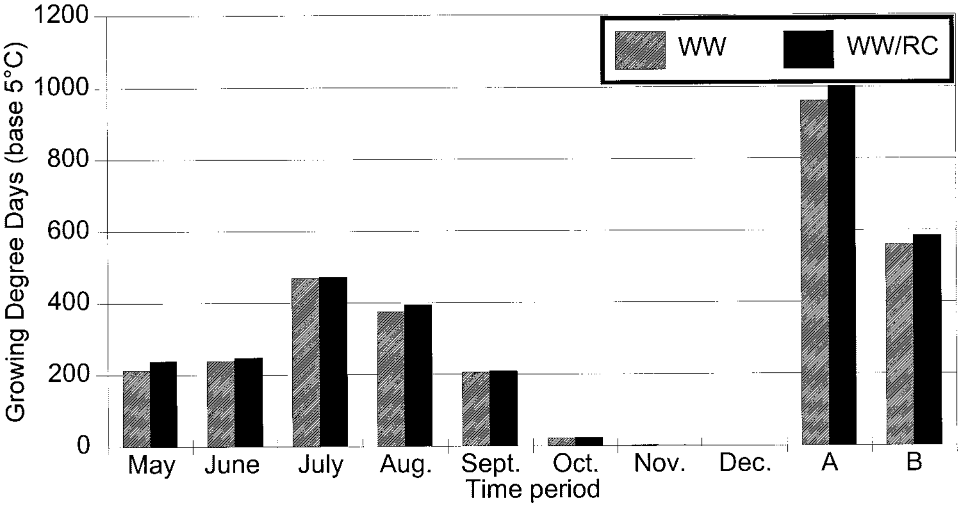

Fig. 1. Accumulated thermal time (base temperature = 5°C) at 5 cm above the soil surface in winter wheat plots with (WW/RC) and without (WW) a red clover relay crop at Winnipeg in 1999. Time Period A is the time from 1 May to 5 August, the date of winter wheat harvest. Time Period B is the time from 5 August until the end of October, the effective end of the growing season.

beginning of July and extended until the first major snowfall (19 December).

Because the late-season accumulation of thermal time was not affected substantially at any aboveground levels (Fig. 1), it appears that length of growing season was not modified by cover crop in this preliminary study. However, occurrence of the first killing fall frost at 5 cm (−3°C; Hall, 1995) was 60 d later in the red clover than in the control. The dense red clover canopy was able to insulate its growing points, thereby extending its growing season.

Comparisons of air temperatures 5 cm above the soil surface in a native grass system and an oat crop system (Thiessen Martens and Entz, unpublished data, 2000) revealed a similar moderating or self-insulating effect in the native grass system during the latter part of the season (after oat harvest). This suggests that relay cropping may emulate the microclimate of native grassland

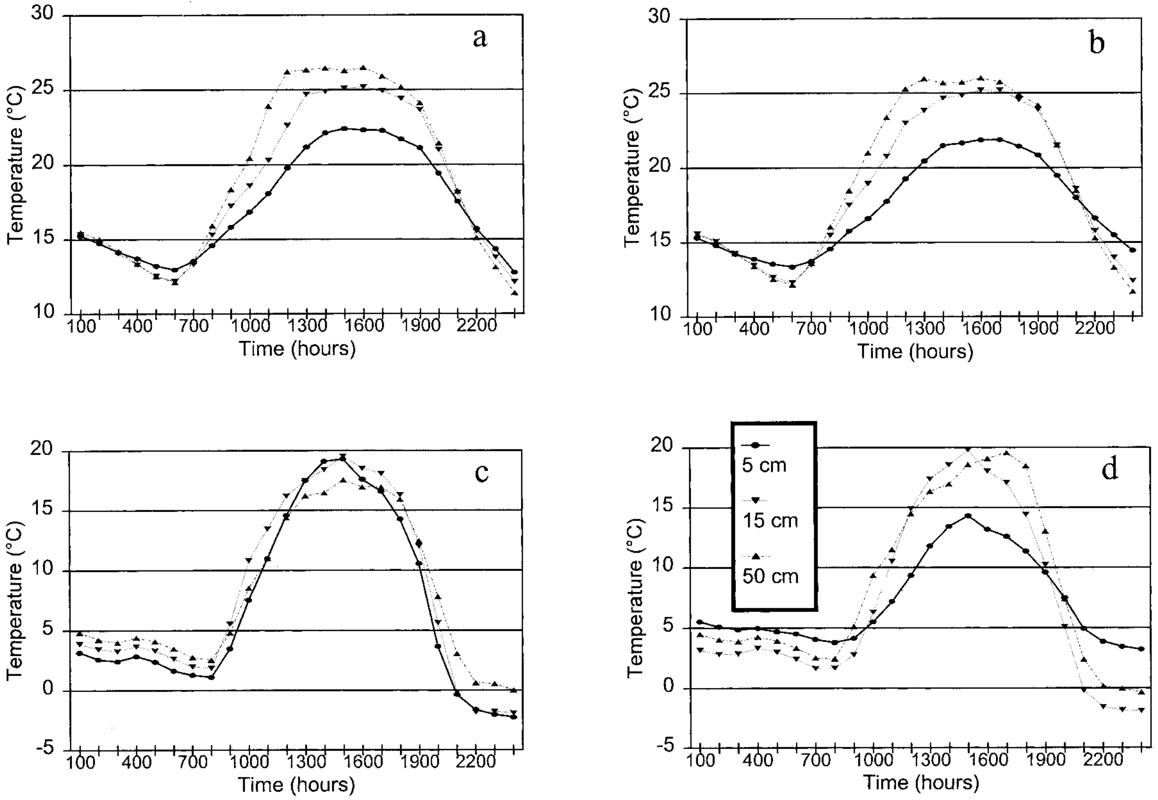

Fig. 2. Diurnal air temperature fluctuations at 5, 15, and 50 cm above the soil surface on 24 June (a) in winter wheat control and (b) in winter wheat with a red clover relay crop and (c) on 10 October in winter wheat stubble and (d) in winter stubble with a red clover relay crop at Winnipeg in 1999.

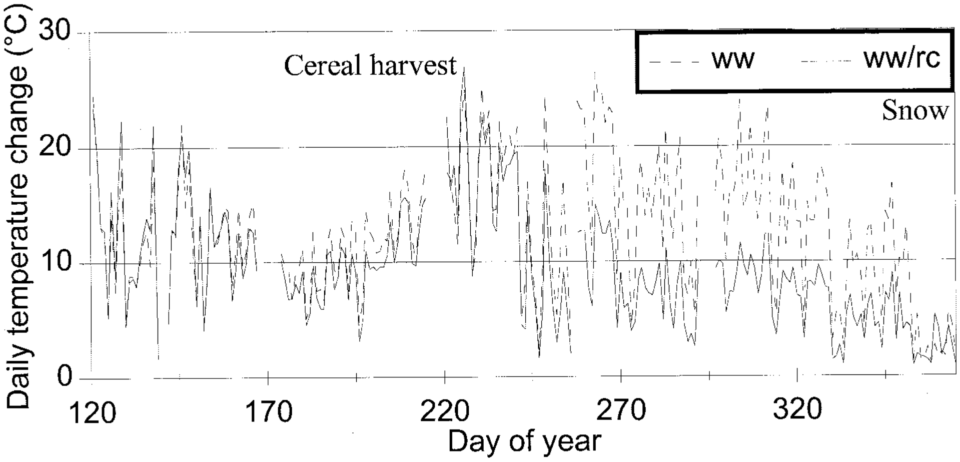

Fig. 3. Daily temperature fluctuations (daily maximum minus daily minimum) at 5 cm above the soil surface in winter wheat plots with (ww/rc) and without (ww) a red clover relay crop at Winnipeg in 1999.

ecosystems more closely than conventional cropping systems.

Drury et al. (1999) found that soil temperatures were not affected by a red clover cover crop. In the present study, cover crop effects were negligible during the main-crop growing season. However, during the fall and winter, temperatures at the 15-cm soil depth tended to be lower in the red clover treatment than in the control (data not shown). This effect became especially strong after the first major, ground-covering snowfall but was gradually reduced over time. Lower temperatures in red clover plots were attributed to lower soil moisture. Others also have determined that crop residue can reduce soil temperature (Fortin, 1993; Teasdale and Mohler, 1993).

Temperature modifications by a cover crop can affect ecological processes such as N utilization by various legumes (Power and Zachariassen, 1993), plant water use (Wraith and Ferguson, 1994), weed emergence and growth (Blackshaw, 1991), and insect populations (Orr et al., 1997). Drury et al. (1999) observed that a red clover cover crop increased the rate of residue decomposition, resulting in higher corn plant emergence the following year. Whether the soil temperature modifications observed in this study were large enough or consistent enough to cause any effects is unclear, and further research is required.

SUMMARY AND CONCLUSIONS

Rye and wheat affected cover crop establishment and understory DM production in a similar manner. Only a few differences caused by main-crop type were observed. Rye, despite tall growth and its well-documented allelopathic properties (Weston, 1996), allowed successful establishment of both red clover and alfalfa relay crops.

Relay cropping provided no significant main-crop yield penalties in any of the environments, indicating that competition from the legume relay crop was relatively low. This means that relay cropping and double cropping systems can be compared equally in terms of their effects on the main crop.

Performance of relay- and double-cropped legumes was affected most by moisture conditions after main-crop harvest. In the present study, cover crop yields were higher in soils with higher water-holding capacity. Greater water-holding capacity of clay soils may make them better suited to late-season plant growth and less reliant on late-season precipitation than sandy soils. The type of cover crop also significantly affected final DM production. Red clover produced the most aboveground DM and had the fastest growth rate of all cover crops studied. In most cases, relay-cropped perennial legumes produced more DM than double-cropped annuals and can thus be expected to provide more N to the following crop. Greater DM of relay crops will, however, increase the potential water penalty to the cropping system.

A preliminary study revealed the presence of microclimate modification when cover crops were grown after winter wheat harvest. The cover crop decreased soil moisture and reduced temperature fluctuations at 5 cm above the soil. The implications of these modifications are unknown and require further research.

The successful establishment of relay and double cropping systems at two sites in 2 yr without grain yield penalties to the main crop indicates that intensification of cropping systems with legume cover crops is agronomically feasible in southern Manitoba. The economic feasibility and the potential for adoption depends on a number of factors, including fertilizer replacement value of these legumes and input costs of cover crop systems. Both of these objectives are currently being investigated by Entz and coworkers.

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