Pea green manure management affects organic winter wheat yield and quality in semiarid Montana

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Miller, P. R., Lighthiser, E. J., Jones, C. A., Holmes, J. A., Rick, T. L. and Wraith, J. M. 2011. **Pea green manure management affects organic winter wheat yield and quality in semiarid Montana**. Can. J. Plant Sci. **91**: 497–508. Organic farmers in semiarid Montana desire green manures that supply sufficient soil nitrate-N (NO_3-N) to subsequent crops with minimal soil water depletion. Spring and winter pea (*Pisum sativum* L.) green manures were compared at the bloom and pod stages for soil NO_3-N contribution and water use, and subsequent winter wheat (*Triticum aestivum* L.) grain yield and quality in a long-term organic farm in northern Montana. Winter wheat was managed with three additional variables (cultivar, row spacing, and seeding rate). Winter pea had 15–33 kg ha^{-1} greater shoot N content (at pod stage only), contributed 14–20 kg ha^{-1} greater soil NO_3-N, used 26–31 mm less soil water, and increased winter wheat grain yield by 13–39% and protein by 1.5 percentage units (2007 only), compared with spring pea. Pea green manure type was of primary importance, pea manure termination timing and wheat cultivar generally were of secondary importance, and row spacing and seeding rate were relatively unimportant to wheat yield and quality. Although wheat yield and quality were superior following winter pea green manure in this study, grain protein concentrations were inadequate to meet organic milling industry standards following both green manure types. This suggests that a long-term organic farmer in semiarid northern Montana may not solely rely upon annual legume green manures to sufficiently condition soil NO_3-N for milling wheat production.

Key words: Green manure, organic, pea, semiarid montana, wheat

Miller, P. R., Lighthiser, E. J., Jones, C. A., Holmes, J. A., Rick, T. L. et Wraith, J. M. 2011. **La gestion de l'engrais vert de pois affecte le rendement et la qualité du blé d'hiver biologique dans la région semi-aride du Montana**. Can. J. Plant Sci. **91**: 497–508. Les producteurs de la région semi-aride du Montana qui pratiquent la culture organique aimeraient avoir des engrais verts qui enrichiront suffisamment le sol en N-nitrate (N-NO_3) pour les cultures subséquentes, sans pour autant épuiser les réserves d'eau. Les auteurs ont comparé l'engrais vert de pois de printemps et de pois d'hiver (*Pisum sativum* L.) aux stades de la floraison et de la production des gousses pour vérifier leur apport en N-NO_3 au sol et la quantité d'eau employée. Ils ont ensuite comparé le rendement grainier et la qualité du blé d'hiver (*Triticum aestivum* L.) cultivé subséquemment dans une exploitation pratiquant la culture biologique de longue durée dans le nord du Montana. Trois variables se sont ajoutées à la gestion du blé (cultivar, espacement des rangs et densité des semis). Le pois d'hiver renfermait 15 à 33 kg de N de plus par hectare dans ses pousses que le pois de printemps (stade de la gousse seulement), apportait 14 à 20 kg de N-NO_3 de plus au sol par hectare, utilisait 26 à 31 mm moins d'eau, et a accru le rendement grainier du blé d'hiver de 13 à 39 % de plus et la teneur en protéines du grain de 1,5 % d'unités (en 2007 seulement). La nature de l'engrais vert de pois revêt une importance primordiale, le moment où l'on enfouit l'engrais vert et le cultivar de blé n'ayant généralement qu'une importance secondaire, tandis que l'espacement des rangs et la densité des semis ont relativement peu d'incidence sur le rendement et la qualité du blé. Bien qu'on ait obtenu un meilleur rendement et du blé de meilleure qualité avec l'engrais vert de pois d'hiver dans le cadre de cette étude, la concentration de protéines dans le grain ne satisfait pas aux normes de l'industrie de la farine biologique, quel que soit le type d'engrais vert employé. On en déduit qu'un agriculteur qui pratique la culture organique à long terme dans la région semi-aride du nord du Montana ne devra pas uniquement se fier aux apports annuel de l'engrais vert pour que le sol contienne assez de N-NO_3 pour la culture du blé destiné à la mouture.

Mots clés: Engrais vert, biologique, pois, régions semi-aride du Montana, blé

Although US retail sales of organic foods increased from \$3.6 billion to \$21.1 billion between 1997 and 2008, organic farm production has struggled to keep up with the rapid growth in demand (USDA 2009). Maintaining soil fertility is one of the major challenges facing organic farmers in the northern Great Plains (Entz et al. 2001; Miller et al. 2008a). Although animal manures can be an excellent organic fertilizer source for N and P, cropland in the northern Great Plains generally is too distant from feedlots and too extensive to rely on animal manures.

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Abbreviation: **ALGM**, annual legume green manure

Nitrogen fertility in organic systems of this region is most often achieved through inclusion of leguminous green manures, often sweet clover (*Melilotus officinalis* L.) or alfalfa (*Medicago sativa* L.). One predicament with this approach is that biennial and perennial legumes that maximize N_2 fixation also maximize soil water use (Nielsen et al. 2005). This is particularly important in the northern Great Plains, where yield is typically constrained by water availability (Cochran et al. 2006). Based on findings on the semiarid Canadian prairies, annual legume species such as pea or lentil (*Lens culinaris* Medik.) may provide a better trade-off between N_2 fixation and water use than biennial or perennial legume green manures (Biederbeck et al. 1993; Zentner et al. 2004). Further, due to early spring growth habit, winter-seeded varieties of pea may better optimize N_2 fixation with soil water use than spring-seeded legume green manures (Chen et al. 2006; Miller et al. 2008b).

It is often assumed that as annual legume green manure (ALGM) biomass increases, soil available N will be increased for subsequent crops. In a Montana study by Pikul et al. (1997), researchers terminated lentil growth with different timings in separate years. Delaying termination until shortly after pods were set in the lower portion of the plant averaged 100 kg ha^{-1} more N in lentil biomass than when terminated at bloom. However, despite the increases in lentil shoot N, spring soil NO_3-N was 1 to 23 kg ha^{-1} lower than fallow, and subsequent spring wheat yield averaged 25% lower than fallow. As ALGM matures, the carbon to nitrogen (C:N) ratio increases, potentially slowing decomposition. Because of the large size and dynamic nature of the soil organic N pool, N added or removed by ALGM crops can be difficult to quantify.

In addition to meeting crop nutrient demands, dryland organic farmers in the semiarid northern Great Plains must manage ALGM crops to avoid excessive soil water use. One previous study in the northern Great Plains indicated no change in cereal crop yields following ALGM compared with summerfallow (Brandt 1999), while another reported 25% reduced wheat yield because the legume reduced available spring soil water by 50 mm (Zentner et al. 1996). To reduce water use by ALGM crops, one approach is to terminate the crop at or before bloom (Pikul et al. 1997; Zentner et al. 2004). A long-term economic assessment of ALGM at Swift Current, SK, concluded that terminating plant growth at bud stage, just prior to first bloom, provided the best balance of soil water use and NO_3-N contribution (Zentner et al. 2004). One implication from this green manure research for organic growers in the northern Great Plains is to choose early-maturing ALGMs that can be terminated early to conserve soil water, even if it limits N_2 fixation. Differences in green manure crop species and termination timing will likely result in variable soil NO_3-N contribution and water use, two aspects that must be balanced to sustain organic farm viability. The objectives of this study were to compare the effects of legume green manure crops on soil NO_3-N and water, and subsequent winter wheat growth.

MATERIALS AND METHODS

Field Site

The dryland field site at Big Sandy selected for this study is located in north-central Montana, the primary wheat growing region in the state, in Agroecoregion 12 of the northern Great Plains (Padbury et al. 2002). Since 1989 the field site has been certified organic by OCIA International, and, since 2003, also by USDA organic certification standards. A crop rotation was used that consisted of various annual crops grown for grain, annual legume green fallow, or alfalfa harvested for forage one year and terminated as green fallow the following year. Site characteristics for this 3-yr study are summarized in Table 1. Growing season precipitation (Table 2) at the field site was recorded redundantly by both an automated tipping bucket rain gauge and a manual gauge. Over-winter precipitation and average monthly mean temperatures (Table 2) were obtained from the nearest meteorological station located 19 km from the field site. Annual rainfall totals were similar to the 30-yr average of 350 mm in all years. The precipitation pattern in 2005 was highly abnormal, with June rainfall accounting for 52% of the annual total and 270% of the 30-yr average of 66 mm. Mean annual temperatures were 1.0 to 2.3°C warmer than the 1971–2000 average, and 2.0 to 5.3°C warmer in the critical wheat growing month of July. Thus, the context of this research was generally drier and warmer than the 1971–2000 ‘‘normal’’ weather period.

Experimental Design

Experiments were established in Khorasan (aka ‘kamut’) wheat (*Triticum turigidum* L. ssp. *turanicum*) stubble. The experimental design was a randomized complete block, with a strip split-plot treatment arrangement and four replications, modified to include a single subplot of fallow randomized in each rep. The main plot factor was green manure species, subplot treatment factors were

Table 1. General site and soil characteristics at Big Sandy, MT. Soil characteristics for 0–0.3 m unless stated otherwise

Location	48°9′N, 110°4′W
Elevation (m)	834
Soil taxonomy	Telstad-Joplin loam (fine loamy, mixed, Aridic Argiboroll)
Soil texture (USDA Soil Survey)	Sandy loam (2005–2006) Loamy sand (2006–2007)
Soil organic matter (%)	1.9–2.3
Soil pH	7.9–8.2
Initial soil NO_3-N (kg ha^{-1} to 0.6 m depth)	27 (2004 Sep.)[z] 14 (Sep 2005)[z]†
Crop stubble	Khorasan wheat (*T. turigidum*)

[z]Analysis based on composite of 12 and 16 cores per site in 2004 and 2005, respectively.

Table 2. Precipitation and temperature data at Big Sandy, MT, 2005–2007

	2005	2006	2007	LTA[z]	2005	2006	2007	LTA[z]
	(mm)				(Mean temperature °C)			
Sep.–Mar.[y]	99	103	138	*118*	1.9	2.6	2.0	*0.3*
Apr.	17	45	61	*29*	8.4	10.0	6.2	*7.3*
May	18	53	79	*62*	11.6	13.9	13.2	*12.6*
Jun.	178	76	31	*66*	16.2	18.6	17.8	*16.9*
Jul.	8	20	20	*42*	22.2	24.4	25.5	*20.2*
Aug.	22	33	16	*34*	19.8	21.5	20.9	*19.6*
Crop year	342	330	345	*351*	7.6	8.9	8.1	*6.6*

[z]LTA = long-term average at Big Sandy, 1971–2000 average annual precipitation and mean temperature reported by Western Regional Climate Center, Desert Research Institute, Reno, NV.
[y]Over-winter precipitation and mean temperature preceding the growing season.

two green manure termination timings, and eight subsubplot treatments in year 2 were randomized as a 2 × 2 × 2 factorial. Subplot size was 4.9 × 18.2 m in 2005 and 5.5 × 18.2 m in 2006 while subsubplot size was 4.9 and 5.5 m × 1.8 m, respectively. Plot width varied to accommodate the different seeders available in 2004 and 2005.

The green manure species were spring (cv. Arvika) and winter (cv. Melrose) pea, and two non-legume control crops, buckwheat [*Fagopyrum esculentum* (L.) cv. Mancan] and yellow mustard [*Sinapis alba* (L.) cv. AC Base], with spring phenological development similar to spring and winter pea, respectively. Winter pea was sown 2004 Sep. 15 and 2005 Sep 06, and spring crops were sown 2005 Apr. 21 and 2006 Apr. 12. Seeding rates were 120 live seeds m^{-2} for pea and 200 live seeds m^{-2} for mustard and buckwheat. A lentil/pea peat-based granular inoculant (Nitragin Soil Implant Milwaukee, WI) was added in the seed row at a rate of 5 kg ha^{-1} to provide rhizobia for pea. A tilled bare fallow control subplot was randomized within each block (Table 3).

Termination timings were targeted ‘‘early’’ at bloom (visual estimate that at least half of plants have one open flower) or ‘‘late’’ at pod (visual estimate that at least half of plants have one full-length pod) stages for winter and spring pea. These corresponded to BBCH stages 60–61 and 70–71, respectively (Lancashire et al. 1991). Yellow mustard flowering and pod development corresponded most closely with winter pea, and so mustard termination timings were matched to winter pea. Similarly, buckwheat termination dates were matched to spring pea. Pod stage for winter pea and mustard coincided with the flower stage for spring pea and buckwheat, and therefore all these treatments were terminated on the same day.

Subsubplot treatment factors for the year 2 winter wheat test crop included two cultivars (Norstar and Pryor), two row spacings (standard = 26 to 30 cm and narrow = ½ standard), and two seeding rates (200 and 400 seeds m^{-2}). These factors were laid out in a randomized strip plot manner, in a complete factorial arrangement, perpendicular to the green manure treatments. Cultivars were chosen to contrast genetically. Norstar was released in 1977 and is a very winter-hardy cultivar characterized by maximum winter dormancy, tall stem height, and relatively low yield potential (Grant 1980). Pryor was released in 2003 and is a semidwarf wheat well adapted to traditional winter wheat regions in Montana, and has high yield potential (McVay 2009). Norstar was expected to compete well with weeds due to its greater height and tillering. Narrow row spacing (i.e., 13–15 cm) to enhance crop competitiveness is commonly used by organic growers in Montana.

Field Operations

In 2004/2005, green manure seeding was done using a 2.4-m-wide hoe drill with 18-cm row spacing. In 2005/2006, a 1.8-m-wide no-till plot-scale disk seeder with 15-cm row spacing was used. Winter pea was sown directly into standing wheat stubble, whereas spring pea, mustard, and buckwheat were sown into tilled wheat stubble. In 2005, a high-speed 3-pt hitch mounted rotary tiller was used on Apr. 21 to prepare a tilled seedbed for spring green manures. In 2006, a 4-m heavy duty tandem disk was used on Apr. 12 followed immediately by a cultivator with rear-mounted spring tine harrows to prepare a seedbed for spring-sown green manures. Termination dates and all other tillage operations are summarized in Table 3. In 2006, buckwheat was frost-killed, and so was omitted from 2006 analyses.

Winter wheat test crops were sown 2005 Sep. 06 and 2006 Sep. 28. The winter wheat test crop was used to determine the cropping sequence effect on grain yield, seed weight and density, grain protein concentration, and grain N yield. Both years winter wheat was sown with the no-till disk seeder described above. Narrow row spacing was achieved by using banding disks positioned midway between seed disks without on-row packing. This configuration limited wheat emergence of unpacked rows to approximately 50% of the packed seed rows.

Table 3. Green manure tillage operations for Big Sandy, MT, summer 2005 and 2006

Green manure	Timing	2005			2006		
Winter pea	Bloom	*16*	*Jun.*[z]	Rotary tiller	*01*	*Jun.*	Tandem disk
		01	Jul.	Rotary tiller	10	Jul.	Chisel plough
		12	Jul.	Rotary tiller	18	Jul.	Tandem disk
		05	Aug.	Tandem disk	04	Sep.	Tandem disk, cultivator[y]
		25	Aug.	Tandem disk[x]			
	Pod	*01*	*Jul.*	Rotary tiller	*20*	*Jun.*	Tandem disk[w]
		12	Jul.	Rotary tiller	18	Jul.	Tandem disk
		05	Aug.	Tandem disk	04	Sep.	Tandem disk, cultivator[z]
		25	Aug.	Tandem disk[y]			
Mustard	Bloom	*16*	*Jun.*	Rotary tiller	*01*	*Jun.*	Tandem disk
		01	Jul.	Rotary tiller	10	Jul.	Chisel plough
		12	Jul.	Rotary tiller	18	Jul.	Tandem disk
		05	Aug.	Tandem disk	04	Sep.	Tandem disk, cultivator[z]
		25	Aug.	Tandem disk[y]			
	Pod	*01*	*Jul.*	Rotary tiller	*20*	*Jun.*	Tandem disk
		12	Jul.	Rotary tiller	18	Jul.	Tandem disk
		05	Aug.	Tandem disk	04	Sep.	Tandem disk, cultivator[z]
		25	Aug.	Tandem disk[y]			
Spring pea	Bloom	*01*	*Jul.*	Rotary tiller	*20*	*Jun.*	Tandem disk
		12	Jul.	Rotary tiller	18	Jul.	Tandem disk
		05	Aug.	Tandem disk	04	Sep.	Tandem disk, cultivator[z]
		25	Aug.	Tandem disk[y]			
	Pod	*12*	*Jul.*	Rotary tiller	*10*	*Jul.*	Tandem disk
		05	Aug.	Tandem disk	18	Jul.	Tandem disk
		25	Aug.	Tandem disk[y]	04	Sep.	Tandem disk, cultivator[z]
Buckwheat[x]	Bloom	*01*	*Jul.*	Rotary tiller			
		05	Aug.	Tandem disk			
		25	Aug.	Tandem disk[y]			
	Pod	*12*	*Jul.*	Rotary tiller			
		05	Aug.	Tandem disk			
		25	Aug.	Tandem disk[y]			
Fallow		21	Apr.	Rotary tiller	12	Apr.	Tandem disk, cultivator[z]
		16	Jun.	Rotary tiller	10	Jul.	Tandem disk
		01	Jul.	Rotary tiller	18	Jul.	Tandem disk
		12	Jul.	Rotary tiller	04	Sep.	Tandem disk, cultivator[z]
		05	Aug.	Tandem disk			
		25	Aug.	Tandem disk[y]			

[z] *Italicized dates indicate green manure termination date.*
[y] Cultivator equipped with spring tine harrows.
[x] Tillage performed on 25 Aug 2005 and 4 Sept 2006 was perpendicular to plots with a tandem disk. Buckwheat plots omitted from 2006 analysis due to frost kill.
[w] Winter pea –pod plots were disked twice at termination.

Soil and Plant Data Collection

Soil cores were taken from each plot at fall or spring seeding, immediately prior to green manure termination, and in all plots at the end of the fallow period prior to seeding winter wheat. The tilled fallow control was sampled at all dates to provide a comparative time series of soil water and N status throughout the green manure phase. Soil cores (diam. 30.3 mm) were extracted to a depth of 1.2 m and split into four 0.3-m increments. Two cores were taken per subplot at each sampling date, duplicates for each depth composited in plastic-lined paper sample bags or in plastic freezer bags, and placed in storage coolers for transport from the field to the laboratory. Bags were weighed ‘‘wet’’, opened, and placed upright in a drying oven at 50°C. When the drying oven was not available, bags were placed in a freezer −20°C) after obtaining wet weights, and dry weights were obtained at a later date. Gravimetric water content was determined by taking a subsample from each of the 0- to 0.3-m and 0.3- to 0.6-m increments, and the entire core sample from the 0.6- to 0.9-m and 0.9- to 1.2-m increments, and weighing before and after drying in an oven for at least 72 h at 105°C. The remaining samples from the 0- to 0.3-m and 0.3- to 0.6-m increments were dried at 50°C, ground to pass a 2-mm sieve, and analyzed for NO_3-N using the cadmium reduction method (Huffman and Barbarick 1981). Bulk density values for the sampling depths were determined by dividing the oven-dried soil mass values by volumes of soil cores. Site bulk densities, by depth, were determined by averaging all values for each block and used to calculate equivalent depth (mm) of soil water (Or and Wraith 1999). Soil NO_3-N (kg ha^{-1}) was determined similarly.

Shoot biomass samples were collected prior to each green manure termination by removing a representative 2-m^2 sample by hand with a rice sickle cutting the plants at the soil surface. Weed and green manure biomass were separated and dried at 50°C for at least 96 h before weighing to determine crop and weed biomass per unit area. After weighing, weed and green manure biomass were recombined, milled, and analyzed for total N using a LECO CNS combustion analyzer (LECO Corporation, St. Joseph, MO) to estimate the amount of shoot biomass N returned to plots. Root biomass was not measured.

Winter wheat was harvested 2006 Jul. 18 and 2007 Jul. 25 with a plot combine with a 1.5-m cutting width. In 2006, winter wheat was severely infested with wheat stem sawfly (*Cephus cinctus* Norton) with $>50\%$ of wheat stems estimated cut and with most cut wheat stems nearly horizontal. It was not possible to obtain an accurate m-row hand sample amid this tangle of stems, but the plot combine was equipped with vine lifters, which proved very effective at collecting wheat stems. Visual observations showed that only a small fraction of stems were not retrieved within the harvest swath (estimated $<1\%$) and that no obvious differences in harvestability existed between wheat cultivars, row spacings, or seeding rates. In 2007, cutting by sawfly was relatively minor (estimated $<5\%$) and so 2 m of row were obtained from the center of each wheat plot with wide row spacing, and 4 m of row from plots with narrow row spacing 2007 Jul. 10. From these hand samples the total number of reproductive tillers per meter-row was determined along with wheat and weed shoot biomass. After subsequent threshing of the biomass samples (using same plot combine), wheat harvest index and kernel weight were also determined, which, in turn, permitted calculation of the total number of kernels per wheat spike. Additionally, the combined wheat samples were cleaned, weighed, and moisture content determined. Protein content of the combined wheat samples was determined via whole-grain NIR with an Infratec 1225 instrument (FOSS Analytical A/S, Hillerød, Denmark).

Statistical Analyses

Analysis of variance (ANOVA) was performed to examine treatment differences using JMP statistical software (SAS Institute, Inc. 2005). Year 1 green manure treatment means were evaluated using the Protected LSD test (Steel and Torrie 1980). Years and sites were considered fixed, blocks (= replicates) were considered a random effect, and all treatment variables were considered fixed. In the split-plot analysis (i.e., year 1 green manure phase) and strip split-plot analyses (i.e., year 2 winter wheat phase) block × crop or timing interaction terms, when significant ($P<0.10$), were used to test green manure (and/or termination timing effects in year 2 analysis), otherwise residual error was used to test significance among crop and termination timing effects. For soil water and N analyses, tilled bare fallow treatments were used to calculate "marginal" values by subtracting soil water and N values under tilled fallow from green manure treatments obtained on the same dates. Both the green manure and winter wheat phases were analyzed separately by year due mainly to strong climatic differences between years. For the winter wheat phase, the non-legume green manures were omitted from further analysis owing to their inadequate growth in this N-limited environment.

The ANOVA for winter wheat analysis contained six treatment factors, each implemented at two levels: (1) year, (2) winter pea or spring pea manure, (3) bloom or pod termination timing, (4) Norstar or Pryor wheat cultivar, (5) standard (26 to 30 cm) or narrow (½ standard) row spacing, and (6) 200 or 400 seeds m^{-2}. Blocks nested within years were used to test the year effect. "Block × pea manure" and "block × termination timing" interactions were compared against "block × pea manure × termination timing" using an *F*-test and were determined not to be significant (i.e., $P>0.10$) in any instance. Thus, variance from these three interactions with "block" was pooled to constitute Error B. Expected mean squares were computed for variances measured significant ($P<0.10$) for each of the six winter wheat treatment factors, and for all interactions among these six factors. Variance associated with significant treatment interactions was apportioned equally to all terms in the interactions; the proportion of treatment variance associated with each of the six agronomic factors was the sum of its main effect from ANOVA plus its equal proportional variance from all involved interaction terms. This variance component analysis was used to compare the relative magnitude of each agronomic factor on five wheat grain yield or quality parameters.

RESULTS AND DISCUSSION

Green Manure Productivity

The shoot biomass of the non-legume control crops, buckwheat and mustard varied from 17 to 45% of spring pea, illustrating how strongly low soil available N limited crop growth at this location and raising serious concern about their use as control treatments for pea (Table 4). In 2005, the mean biomass of winter pea was 19% greater than spring pea ($P=0.02$), but did not differ in 2006 (Table 4). Initial green manure termination in 2005 was delayed 7–10 d after first bloom due to excessively wet soil conditions in early June. As a result, the biomass present at early termination was approximately 75% of that present at late termination. In 2006, a more typical precipitation pattern permitted timely early termination, resulting in winter pea biomass that was 43% of the late terminated biomass, and 62% in the case of spring pea, which was consistent with an earlier 2-yr Montana study under conventional no-till management (Miller et al. 2008b).

Table 4. Mean crop and weed biomass, C:N ratio of total biomass, and total biomass N yield of four green manure crops terminated early or late at Big Sandy, MT, 2005–2006

Crop	Termination	Crop biomass	Weed biomass	C:N ratio	N yield
		(Mg ha^{-1})			(kg ha^{-1})
			2005		
Buckwheat[z]	Early	0.46	0.42	22.3	16.8
	Late	0.82	0.87	26.7	26.3
Mustard	Early	0.90	0.10	21.1	18.0
	Late	0.88	0.18	29.0	16.2
Spring pea	Early	2.01	0.44	16.3	68.7
	Late	2.74	0.44	21.4	68.0
Winter pea	Early	2.42	0.09	18.2	59.4
	Late	3.24	0.06	17.7	83.2
LSD[y]		0.30	0.27	2.2	11.1
			2006		
Mustard	Early	0.37	0.36	18.1	14.5
	Late	0.96	0.64	27.5	22.2
Spring pea	Early	2.12	0.79	24.5	50.7
	Late	3.41	0.59	27.9	63.5
Winter pea	Early	1.65	0.24	16.6	49.9
	Late	3.87	0.25	19.0	96.9
LSD		0.56	0.23	3.1	13.3

[z]Buckwheat was analyzed in 2005 only.
[y]Fisher's Protected LSD ($P < 0.10$) for comparing means within columns.

The weed community was dominated by dicot species at this long-term organic farm. At the 2005/2006 field site, weeds in the mustard family [e.g., flixweed (*Descurainia sophia* Webb. ex Prantl), tumble mustard (*Sisymbrium altissimum* L.), and pennycress (*Thlaspi arvense* L.)] were most prevalent, while Russian thistle (*Salsola iberica* Sennen) and wild buckwheat (*Polygonum convolvulus* L.) were dominant at the 2006/2007 site. Two observations are noteworthy relative to weed biomass (Table 4). First, for buckwheat and mustard, weed biomass was similar to crop biomass in four of six cases, but was not generally greater than the weed biomass associated with spring pea. Second, the weed biomass associated with winter pea (5% of total shoot biomass) appeared to be much less than that associated with spring pea (18% of total shoot biomass) averaged over both years and termination timings. Superior crop competition with weeds by winter pea was likely due to the lack of soil disturbance associated with seeding directly into standing cereal stubble, N-fixation in a farm soil with very low NO_3-N, and to the benefit of a winter growth habit competing with annual weeds.

The C:N ratio did not differ between termination timings of winter pea, while this ratio was greater for later termination in all other crops in both years (Table 4). This may reflect a superior N_2 fixation ability as has been observed anecdotally in previous comparisons of winter and spring pea root biomass in conventionally managed no-till studies in Montana, and which has manifested in increased seed or forage N content for winter pea (Chen et al. 2006; Miller et al. 2008b). Supporting this contention, the total biomass N yield of winter pea was 29–49% greater at late termination, while no spring crop differed in shoot biomass N yield between early and late termination ($P > 0.10$). This indicates that winter pea growth may have been supported by active N_2 fixation during a greater period of its growth.

Green Manure Effects on Soil Water and Nitrogen

Growing season patterns in soil water storage to a 1.2-m depth under the tilled summerfallow control treatment were similar between years. Stored soil water was maximal by mid-June of the summer fallow period, and declined 22 to 63 mm by winter wheat planting in late summer or early fall, despite more than 30 mm of rainfall in the interim both years (Tables 2 and 5). A similar water storage pattern was observed for the same control treatment during a separate 2-yr organic green manure study at Bozeman, MT (Izard 2007). This highlights a varying degree of ''use it or lose it'' opportunity for crop transpiration since soil water loss due to evaporation occurs during summer. Here, two key points are noteworthy. First, except for spring pea in 2005 where ''early'' termination was delayed due to excessively wet soil conditions, early termination of pea near first bloom resulted in a soil water content to a 1.2-m depth that did not differ from the tilled summerfallow control. This highlights a key aspect of soil water conservation where minimizing drought risk in the subsequent crop is paramount. Second, while in all cases delaying pea manure termination until the plump pod stage resulted in a soil water content that was 29 to 67 mm less than tilled summerfallow, soil under winter

Table 5. Total soil water content measured in bare summerfallow time series at Big Sandy, MT, 2005 and 2006

	Soil water				
	Soil depth increment (m)				
	0–0.3	0.3–0.6	0.6–0.9	0.9–1.2	**0–1.2**
Date	(mm cm^{-3})				
			2004–2005		
Sep. 29	53	38	41	45	**177**
Apr. 21	71	53	42	44	**210**
Jun. 16	77	79	52	49	**257**
Jul. 01	68	70	65	47	**251**
Jul. 12	63	68	62	45	**238**
Aug. 22	57	64	59	55	**235**
LSD[z]	5	9	11	NS	**29**
			2005–2006		
Sep. 02	38	32	37	58	**166**
Apr. 06	79	70	56	56	**262**
Jun. 01	74	76	65	60	**276**
Jun. 20	79	82	79	82	**322**
Jul. 10	45	59	75	71	**249**
Sep. 27	68	62	62	66	**259**
LSD	6	10	12	11	**24**

[z]Fisher's Protected LSD ($P<0.10$) for comparing means within columns and table sections.

pea contained 26 to 31 mm greater water than under spring pea (Table 6). Early-terminated pea has been shown to conserve soil water for subsequent crops in previous studies under conventional crop management in Montana (Miller et al. 2006, 2008b). The interval between bloom and pod stage termination in 2006 was 19 and 20 d, respectively, for winter and spring pea (Table 3). During this brief but rapid growth phase, spring pea depleted soil water a further 53 mm compared with 34 mm in winter pea.

Under tilled summerfallow, soil NO_3-N increased by 14 and 11 kg NO_3-N ha^{-1} in 2005 and 2006, respectively, indicative of limited N mineralization from indigenous soil organic matter. Marginal soil NO_3-N status under pea manures at winter wheat planting was practically significant only in the top 0.3 m of soil (Table 6). In 2005, spring pea manure decreased available soil N and only early-terminated winter pea manure showed a positive N status compared with the tilled summerfallow control; in 2006 the NO_3-N levels in all but late-terminated spring pea manure were greater than in the summerfallow control ($P<0.10$). Plant biomass decomposition is partially a function of soil water and temperature, though water would typically be the most limiting factor in semiarid regions such as north-central Montana. The ALGM/wheat crop sequence during the 2006–2007 period followed much more closely the long-term average precipitation pattern at Big Sandy. In particular, the September through May period of green manure decomposition received 117 mm greater precipitation in the 2006–2007 period, compared with

Table 6. Green manure crop and termination timing effects on marginal[z] soil water and nitrate-N measured prior to winter wheat sowing at Big Sandy, MT, 2005 and 2006

		Soil water					Soil nitrate-N	
		Soil depth increment (m)						
		0–0.3	0.3–0.6	0.6–0.9	0.9–1.2	0–1.2	0–0.3	0.3–0.6
Crop	Timing	(mm cm^{-3})					(kg ha^{-1})	
					1st study: soil sampled 2005 Aug. 22			
Buckwheat[y]	Early	0	−4	2	−3	−6	−11	−6
	Late	−12	−18	−12	−13	−56	−16	−7
Mustard	Early	0	−4	−8	−10	−22	0	−3
	Late	−7	−14	−16	−15	−52	−11	−6
Spring pea	Early	−10	−11	−15	−14	−50	−9	−6
	Late	−13	−21	−12	−14	−60	−11	−4
Winter pea	Early	0	1	0	2	2	9	−3
	Late	−13	−14	−1	−1	−29	3	−5
LSD[x]		5	11	9	6	19	7	NS
					2nd study: soil sampled 2006 Sep. 27			
Mustard	Early	2	4	2	−6	3	8	0
	Late	−1	0	−5	−8	−14	3	−1
Spring pea	Early	−2	−2	−5	−4	−14	15	0
	Late	−10	−26	−18	−13	−67	−3	−4
Winter pea	Early	2	0	−4	−4	−7	29	1
	Late	−5	−14	−15	−7	−41	17	−2
LSD[x]		4	4	6	NS	15	13	2

[z]Green manure treatment minus the fallow control on same date. Fallow nitrate-N content in the 0–0.3 m and 0.3–0.6 m soil depth increments was 30 and 11 kg ha^{-1}, respectively, on 2005 Aug. 22; and 19 and 6 kg ha^{-1}, respectively, on 2006 Sep. 27.
[y]Buckwheat froze out in 2006.
[x]Fisher's Protected LSD ($P<0.10$) for comparing means within columns.

the 2005–2006 period. The only notable difference in temperature between green manure-winter wheat crop cycles was that Apr. 2007 was 3.8°C colder than Apr. 2006, which may affect plant biomass decomposition. However, Magid et al. (2001) showed that N mineralization from legume residues was not strongly retarded by temperatures as low as 3°C in a greenhouse experiment. Maximum soil NO_3-N at winter wheat planting occurred under early terminated winter pea manure, 29 kg ha^{-1} greater than tilled fallow control. In both years and both termination timings, soil NO_3-N ranged from 14 to 20 kg ha^{-1} greater under winter pea manure than spring pea manure. The difference could be due to more time for winter pea residue to mineralize, higher soil water content at termination, or differences in C:N ratios.

Except for the bloom stage in 2005, biomass C:N ratios were narrower for winter pea compared with spring pea biomass (Table 4), and this difference may have caused a difference in N mineralization. Vigil and Kissel (1991) conducted a meta-analysis study of N release from crop residues of varying C:N ratios that illustrated the rapid change in potential N mineralization between C:N ratios of 30 to 15. Magid et al. (2001) showed that C:N ratios of different green manure species varying from 13 (legume) to 22 (non-legume) caused large differences in soil N mineralization across a range of temperatures in a controlled environment study. It is noteworthy that among the four spring pea treatment samples in this study, only spring pea terminated at early bloom in 2006 increased soil NO_3-N compared with summer fallow (Table 6). The C:N ratio of that spring pea biomass sample was 24.5 (Table 4). Conversely, in 2005 the C:N ratio of spring pea terminated at bloom was 16.3 and it did not increase soil NO_3-N relative to the bare fallow control. A review of regionally relevant legume green manure literature revealed no reports with C:N ratio examined in field studies *per se*, but some reports included biomass N concentration which would be expected to vary inversely with C:N ratio. Although Janzen et al. (1990) did not discuss the relationship of biomass N concentration with soil N mineralization, it was noteworthy that the N concentration in two legume green manures was 4.2–4.3% in the first year of their study, and 2.4–2.7% in the second year. Nitrogen recovery measured in a subsequent wheat crop averaged 20% in the first case, and 12% in the second, indicating a possible positive relationship between the narrow C:N (i.e., greater N concentration) legume biomass and N mineralization. In another field study also conducted in the northern Great Plains, Tanaka et al. (1997) showed that biomass N concentration did not differ between the flowering and pod formation stages of two legumes, pea and Tangier flatpea (*Lathyrus tingitanus* L.), unlike in our study. However, also unlike our study, legume green manure terminated prior to maturity did not increase soil NO_3-N concentration compared with tilled summer fallow in any treatment over 4 yr. Perhaps the effects of small differences in biomass C:N ratio, or more simply, biomass N concentration, in conditioning soil NO_3-N response merit further investigation.

Additional N_2 is fixed by allowing pea to grow later in the green fallow period (Pikul et al. 1997). However, subsequent fall-sown crops have been shown to recover a lesser percentage of plant-derived N when termination is delayed (Jensen 1994). Therefore, we hypothesized that soil NO_3-N at the end of the green fallow period would be greatest for early-terminated legume green manures, based on a longer effective period for biomass decomposition, as was observed in 2006 only. Pod-terminated pea began decomposing 2+ wk later than bloom-stage pea, under warmer and drier soil conditions, and therefore the measurement of soil NO_3-N taken at the end of the green fallow period likely did not fully account for N_2 fixation potential. Superior N_2 fixation may ultimately contribute greater N to the soil organic N pool, and thus sustain crop yields over the long-term, so it is an important consideration in choosing when to terminate green manure growth. Over both years, winter pea N uptake was 40 and 94% greater when allowed to grow to the pod stage compared with bloom, while soil NO_3-N at wheat planting did not differ in either year. This suggests that the amount of fixed N was substantially greater when winter pea was allowed to grow to pod, in agreement with others who have found that the amount of fixed N increases throughout the pea growing season (Jensen 1987; Salon et al. 2001). Organic producers in nutrient-constrained systems should terminate annual green manures at pod to maximize N fertility in the long-term. If only the next year's crop is being considered, results of this study demonstrate that early termination is more beneficial than late termination.

Effects of Integrated Crop Management on Winter Wheat

Treatment Means

"Year" affected all wheat parameters as a model main effect for all but grain protein, where it interacted significantly with pea manure type and wheat cultivar (Table 7). Notably, test weight and seed weight were higher in 2006 than 2007, evidence of drought stress during the grain fill period in 2007. Winter pea manure increased wheat grain yield by 25%, grain protein by 10.7 g kg^{-1}, and grain N yield by 38%, compared with spring pea manure, averaged for both years. Pea manure type was involved in highly significant interactions with year for wheat test weight and seed weight. Winter pea increased wheat test weight and seed weight in 2006 and decreased them in 2007 (data not shown, $P<0.01$). Yield components were only measured in 2007 due to extensive sawfly wheat stem cutting in 2006 that made it impossible to trace stems back to specific row areas;

Table 7. The ANOVA mean squares and treatment means for grain yield and quality of winter wheat test crops at Big Sandy, M T, 2006–2007

Source	df	Grain yield	Test weight	Seed weight	Grain protein	Grain N yield
		(Mg ha^{-1})	(lb bu^{-1})	(mg seed^{-1})	(g kg^{-1})	(kg ha^{-1})
Year (Y)	1	4.003*	293.49**	382.5**	0.00	1533*
Block(Y)-Error A	6	0.898	3.94	10.6	1.90	229
Pea manure type (PMT)	1	14.860**	2.05	5.1	23.20**	9855**
Y × PMT	1	2.280	15.22**	128.0**	4.25*	110
Manure term. time (MTT)	1	4.691**	3.40	7.4	5.07	1066*
Y × MTT	1	0.488	2.13	0.3	13.33	531*
Error B (pooled)	18	0.522	1.72	7.5	3.09	169
Wheat Cultivar (WC)	1	4.709**	0.14	37.5**	1.38*	1146**
Row Space (RS)	1	0.001	1.54*	5.7*	3.49**	56*
Seed Rate (SR)	1	0.160*	1.82**	9.9**	3.39**	0
Y × WC	1	2.930**	13.38**	7.3*	4.19**	635**
Y × SR	1	0.109	0.10	2.7	0.04	59*
PMT × WC	1	0.443**	0.30	0.2	0.45	195**
WC × RS	1	0.250*	0.01	4.0*	0.62	50
WC × SR	1	0.387**	0.01	7.7**	0.22	85*
RS × SR	1	0.336*	0.05	2.3	0.75 2.18**	48
PMT × MTT × RS	1 GMT × RS	0.011	0.01	0.2	1.17*	24
Y × WC × SR	1	0.104	0.10	23.0**	1.65*	2
Y × RS × SR	1	0.031	0.03	1.0	1.34*	3
WC × RS × SR	1	0.323*	0.32	4.3*	1.19*	180**
Y × PMT × MTT × WC WC	1	0.177	0.09	1.5	0.04	98*
Y × PMT × MTT × SR	1	0.131	0.02	0.1	1.27*	117*
Y × MTT × WC × SR	1	0.016	1.63**	1.8	0.14	0
Residual error[z]	165	0.051	0.26	1.2	0.30	20
				Treatment means		
		Mg ha^{-1}	lb bu^{-1}	mg seed^{-1}	g kg^{-1}	kg ha^{-1}
				Year		
2006		2.06	**62.0**[y]	**30.1**	103.5	37.1
2007		**2.31**	59.9	27.7	103.4	**42.0**
				Green manure pea		
Spring pea		1.94	61.1	29.1	98.1	33.3
Winter pea		**2.42**	60.9	28.8	**108.8**	45.8
				Green manure termination timing		
Early (bloom)		**2.32**	61.1	29.1	102.0	41.6
Late (pod)		2.05	60.9	28.7	104.9	37.5
				Winter wheat cultivar		
Norstar (tall)		2.05	61.0	28.5	104.2	37.4
Pryor (short)		2.32	60.9	**29.3**	102.7	41.7
				Winter wheat row spacing		
Narrow (13–15 cm)		2.18	60.9	28.8	102.3	39.1
Wide (26–30 cm)		2.18	**61.0**	29.1	104.6	40.0
				Winter wheat seeding rate		
200 m^{-2}		2.16	60.9	29.1	104.6	39.6
400 m^{-2}		2.21	**61.1**	28.7	102.3	39.5
(Fallow control[y])		(2.30)	(61.4)	(30.7)	(87.5)	(35.1)

Note that only interactions that were significant ($P > 0.1$) for at least one wheat parameter were reported in the interest of space.
[z]Residual error accounts only for df and variance associated with interactions with "Block".
[y]Mean values in bold text are greater than unbolded counterpart ($P < 0.10$).
[x]Excluded from analyses, included for reference.
*, ** Significant at $P < 0.1$ and $P < 0.01$, respectively.

the 13% grain yield increase in 2007 was the result of 9% increased tiller density, 18% increased seeds per tiller, and 6% reduced seed weight (data not shown, all differences significant at $P < 0.10$). Since seed weight is determined last during wheat yield formation, this suggests that winter pea provided a superior growth environment until seed number was determined but could not fully sustain this effect until final grain yield formation. This was consistent with visual observations at the site when on 2007 Jun. 12 a Field Day was held at this location and the amount and greenness of biomass of winter wheat on winter pea manure plots was judged far superior to that on spring pea plots. However, when mature biomass samples were collected on Jul. 09, winter wheat on the winter pea manure plots was heavily scorched from drought stress, indicating "haying off''. Concurring with this was the observation that the mean harvest index was 0.365 for wheat on winter pea manure and 0.400 for wheat on spring pea manure (data not shown, $P<0.01$). We concluded in this study superiority of winter pea over spring pea when used as a green manure crop.

It is important to note that winter pea rarely has been grown as a fall-seeded crop on Montana farms due to uncertainty of winter survival. In addition to this study, winter pea has been grown successfully in experimental plots in the mild winter environments associated with relatively high elevation in the Montana Rocky Mountain foothills (Chen et al. 2006). Although winter pea should be considered experimental by organic farmers in Montana, relative to the green manure merits of spring pea, it appears that it would be worthwhile for growers to learn the limits of winter pea in their systems.

Pea manure termination timing is an important consideration because it represents a management balance between total biological N_2 fixation and soil water use, both crucial soil management aspects. Early pea manure termination increased wheat yield by 0.27 Mg ha^{-1} (13%), but did not affect any other wheat parameter consistently (Table 7). Pea manure termination timing interacted with year for grain N yield where timing did not differ in 2006, but in 2007 early termination resulted in 7 kg ha^{-1} greater N yield. It is not possible to draw firm conclusions about pea manure termination timing from these results, but it appears in the short term greater N may be cycled to the subsequent crop by terminating pea manure at first bloom. Pea termination timing had been previously shown to affect soil water use in Montana, both by spring and winter pea, increasing grain N yield in conventionally managed no-till systems (Miller et al. 2006, 2008b). However in organic systems, the balance between N contributions from ALGM's and water use must be tilted in favor of soil available N, unlike in conventional systems augmented by nitrogen fertilizer.

Cultivar effects interacted strongly with year. In 2006, Norstar and Pryor grain yields did not differ ($P>0.1$), while in 2007, Pryor yielded 0.49 Mg ha^{-1} (24%) greater ($P<0.0001$). The yield advantage of Pryor was due mainly to a greater mean harvest index than Norstar (0.44 vs. 0.33; $P<0.01$), consistent with genetic advancement for improved harvest index in wheat. It is possible that the more sudden onset of summer drought in 2007 favored the development of Pryor over Norstar. The most important wheat pest present at this site was wheat stem sawfly. Infestation was high in both years, but delayed harvest in 2006 resulted in a high proportion of physically cut stems (assessed visually to be >50%) with no visually apparent differences among treatments. Wheat stem sawfly is known to show wheat cultivar preference for oviposition (Holmes and Peterson 1960) and Norstar is a cultivar known to be preferred by wheat stem sawfly (Buteler 2008). Regardless, since wheat stem sawfly infestation was high in both years, this pest is unlikely to explain the difference in cultivar response between the 2006 and 2007 trials. The 2007 yield results were consistent with a previous report comparing spring wheat cultivars in North Dakota that concluded modern high-yielding wheat cultivars retained their yield advantage under organic management (Carr et al. 2006). The cultivar $\times$ year interaction for grain N yield followed a similar pattern as for grain yield. However, seed weight was 3% greater for Pryor than Norstar since the interaction with year was of a non-crossover type (i.e., change in slope only). No informative conclusions could be drawn about wide vs. narrow row spacing or seeding rate in this study. Test weight was greater for the wide row spacing and the high seeding rate, but the differences were so small as to be practically irrelevant.

Previous study of the interaction of wheat cultivar, row spacing, and density has not been reported in organic management systems to the authors' knowledge. A conventionally managed study from Great Britain assessing integrated weed management reported that the effects of similarly strongly contrasting winter wheat cultivars on grain yield and quality were much greater than the effects of seeding rate or row spacing (Champion et al. 1998). Although the present study was conducted in a long-term organic field, weed biomass abundance was very low in winter pea plots (Table 4), and was trivial during the winter wheat phase of this trial (overall mean weed biomass was 2.2% of total wheat shoot biomass). Thus the greater height (estimated visually to be 0.2–0.3 m greater) and tiller density (406 vs. 341 tillers m^{-2}; data not shown) of Norstar compared with Pryor may not have been an advantage as reported in weedier situations (Lemerle et al. 1996; Mason et al. 2007).

A goal of this study was to examine the relative influence of five integrated crop management factors (previous pea manure crop, previous pea manure termination timing, cultivar, row spacing, and seeding rate) on grain yield or quality parameters of winter wheat. The distribution of ANOVA treatment variance indicated that ''year'', a factor not in a producer's control, had the greatest effect on grain test weight and seed weight, likely owing to the sudden terminal summer drought which occurred in 2007 and not in 2006 (Table 8). The type of pea green manure (winter or spring) was the most important crop management factor in this study, accounting for 46, 66, and 66% of total model variance for grain yield, grain protein, and grain N yield, respectively (Table 8). Green manure termination timing and wheat cultivar accounted for secondary variance for grain yield and grain N yield, while all management factors other than the type of pea green manure accounted for approximately equal variance for grain protein. For management of organic winter wheat in this study, we concluded that the previous pea green manure crop was of primary importance, previous pea green manure termination timing and wheat cultivar were of secondary

Table 8. Significant ($P<0.10$) ANOVA variance contributed by year, previous green manure crop and termination timing, and cultivar, row spacing, and seeding rate of winter wheat grown organically at Big Sandy, MT, 2006 and 2007

Source	Grain yield	Test weight	Seed weight	Grain protein	Grain N yield
	(%)				
Year	16.2	92.8	74.6	11.6	12.5
GM pea	46.1	0.2	10.2	65.6	66.0
GM timing	12.5	0.7	0.0	6.7	7.5
Cultivar	19.9	2.1	8.0	3.3	10.9
Row space	0.6	0.4	1.2	3.7	0.6
Seed rate	1.5	0.6	3.4	3.9	0.9

importance, and wheat row spacing and seeding rate were comparatively unimportant management factors.

CONCLUSIONS

In a long-term organic farm field in semiarid north-central Montana, early-seeded non-legume green manure species proved inadequate due to severely N-constrained growth. Winter pea growth was superior to spring pea, producing equal or greater shoot biomass and less weedy biomass, narrower C:N ratio biomass, and equal or greater shoot biomass N content. Winter pea used equal or less soil water to a 1.2-m depth compared with spring pea, ranging from 7 to 52 mm less water use at coincident plant growth stages, and contributed greater soil NO_3-N to a 0.3-m depth by winter wheat planting, ranging from 14 to 20 kg ha^{-1} greater NO_3-N. Winter wheat grain yield and quality were affected primarily by previous pea manure crop (i.e., spring vs. winter pea), and secondarily by termination timing (bloom vs. pod) of the previous pea manure crop and by wheat cultivar. Wheat seeding rate and row spacing generally had trivial effects on wheat grain yield and quality. Final grain N yield was 11 to 14 kg ha^{-1} greater following winter pea than for spring pea; nevertheless, wheat grain protein values were generally unacceptably low for all pea manure treatments, ranging from 8.7 to 10.1% (10% grain moisture basis). Among these treatments, winter pea manure best achieved the goal of conserving soil water, while contributing greater soil NO_3-N relative to other green manures. Early termination of pea manure provided greater N to a subsequent winter wheat crop in 1 yr of this 2-yr study. However, over longer-periods, pod-terminated pea may enhance soil N fertility due to greater N_2 fixation potential.

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