Green Manure Comparison between Winter Wheat and Corn: Weeds, Yields, and Economics

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ABSTRACT
Red clover (Trifolium pratense L.) and hairy vetch (Vicia villosa Roth) are leguminous crops (“green manure” hereafter), widely studied for their N2-fixing contributions to cropping systems. Under certain circumstances they can provide weed control in cash crops. This study compared weed control, crop yields, herbicide use, and economic performance of these green manures in a no-till winter cereal–green manure–corn (Zea mays L.) silage cropping sequence in central Pennsylvania. Red clover was interseeded into winter wheat (Triticum aestivum L.) or rye (Secale cereale L.), while hairy vetch and triticale (X Triticosecale) were planted after winter cereal harvest. Compared to hairy vetch, red clover provided continuous soil cover between the winter cereal and corn and two herbicide applications could not be applied (one in wheat and one prior to seeding hairy vetch) to the red clover, reducing herbicide active ingredient use by 28%. Weed infestation in wheat and corn did not differ between green manure systems, but corn yield following red clover averaged 3320 kg ha⁻¹ more, and 2012 wheat yield was 180 kg ha⁻¹ greater in the red clover sequence. Corn after hairy vetch–triticale had lower corn plant population in 2012–2013. Yield differences in corn in 2012 probably resulted from population differences. Primarily because of red clover forage value, the red clover system resulted in greater net returns to management by US$1360 ha⁻¹, and even without the forage harvest, the red clover system would have been more profitable due to lower production costs.

Core Ideas
• As a green manure, red clover provided multiple benefits over hairy vetch and triticale.
• Red clover underseeded in winter grain, produced continuous cover, forage, and higher corn yield.
• Compared to hairy vetch and triticale, red clover controlled weeds with less herbicide.
• Red clover was more profitable than hairy vetch.

THE BENEFITS of no-till cropping are widely accepted for their positive impact on soil health, and reduction in fuel use and labor (Uri, 2000), and in 2014 more land area in Pennsylvania was managed with no-till or conservation tillage practices than was conventionally tilled (USDA NASS, 2014). Herbicides dominate weed management in no-till production systems and this has been facilitated by the introduction and adoption of herbicide-resistant (HR) crops (Gianessi, 2008; Perez-Jones and Mallory-Smith, 2010). Herbicide-resistant crops have enabled more simplified herbicide programs (Young, 2006) that increase selection pressure for HR weeds (VanGessel, 2001). Concerns regarding the negative impacts of HR weeds (Peterson, 1999; Sosnoskie and Culpepper, 2014), herbicide pollution (Smith et al., 1996; Hill et al., 2002; Gilliom, 2007), and non-target toxicity of herbicides (Marrs et al., 1989; Hayes et al., 2002), provide impetus for research that explores weed management methods less reliant on herbicides.

Incorporating cover crops into weed management could help delay the evolution of HR weeds by reducing the need for herbicides used on the cash crop, and in some cases by requiring more diverse herbicide selection to avoid damage to the cover crop by previously used cash crop herbicides. Cover crops can contribute to weed control by creating dead or living mulches (Davis, 2010; Nord et al., 2011; Ryan et al., 2011) or by interfering with weed life cycles (Kegode et al., 1999; Smith and Gross, 2007). In addition, cover crops can provide habitat for weed seed predators such as Carabidae beetles (Shearin et al., 2008; Ward et al., 2011). Cover crops protect soil when a cash crop is not present, reduce potential runoff of soil and nutrients (Clark, 2007), scavenge nutrients not used by the cash crop (Shipley et al., 1992), and green manures can add N to the soil (Dou and Fox, 1994; Liebman et al., 2012). Cover crop adoption is increasing in Pennsylvania (Hively et al., 2015); in some areas cover cropping is subsidized and farmers can receive payments for no-till planting cover crops for the first time, or for planting multi-species cover crop mixtures instead.

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Abbreviations: BM, broadcast manure treatment; GM, green manure; HR, herbicide resistant; HV, hairy vetch treatment; IM, inject manure treatment; POST, postemergence; PSNT, pre-sidedress soil nitrate test; RC, red clover treatment; UAN, urea ammonium nitrate; WAP, weeks after planting.
Red clover and hairy vetch are two legume species used as cover crops or sometimes hay in the mid-Atlantic region. Red clover forage is grown alone or in mixture and is used by some farmers in the mid-Atlantic region in a sequence between winter wheat and the following year’s corn crop. Interseeding red clover into wheat in spring can avoid the need for herbicide use during the post-wheat fallow period since red clover is already established, and the competitive cover can help suppress mid- and late summer weeds, and volunteer cereals (Swanton et al., 1996; Fisk et al., 2001). Hairy vetch is mostly used as a winter annual cover crop that is established in late summer in central Pennsylvania and usually requires some weed control (tillage or herbicide) prior to seeding. When corn follows wheat, both red clover and hairy vetch must be controlled for the following spring prior to no-till corn emergence, and while hairy vetch can be terminated mechanically with a roller-crimper at flowering, control with herbicides is more common to ensure timely planting of the corn crop (Mischler et al., 2010). Grower concerns regarding hard seed and the potential of hairy vetch to become a weed in subsequent crops has also influenced hairy vetch adoption rates (Jacobsen et al., 2010).

While high levels of cover crop biomass are desired to create a weed-suppressive mulch (Fisk et al., 2001; Mischler et al., 2010; Mirsky et al., 2011), a dense cover crop canopy at planting may interfere with effectiveness of burndown and residual herbicides applied before a corn crop (Swanton et al., 1996). Dying red clover has also been shown to have phytotoxic effects due to secretion of phenolic acids, which can inhibit weed growth (Ohno et al., 2000). Red clover reduced winter annual weed density prior to corn planting, and also reduced soil temperatures, potentially making germination conditions for summer annual seedlings less favorable in a subsequent corn crop (Fisk et al., 2001). Hairy vetch has allelopathic properties (White et al., 1989); however weed suppression by hairy vetch residue is mostly governed by light quality and soil temperature (Teasdale and Daughtry, 1993). Hairy vetch can reduce weed density and biomass compared to no-cover crop (Mischler et al., 2010), but its effectiveness depends on the amount of hairy vetch residue remaining on the soil surface (Teasdale and Mohler, 2000).

Both red clover and hairy vetch can provide N for the subsequent cash crop (Cook et al., 2010; Liebman et al., 2012). These green manures planted in and after a small grain, respectively, produced significantly more N than alfalfa (Medicago sativa L.) and sweetclover (Melilotus officinalis Lam.) (Stute and Posner, 1995). Two studies in the mid-Atlantic demonstrated that hairy vetch planted in fall and terminated in spring before cash crop planting can contribute 65 to 164 kg N ha⁻¹, depending on length of cover crop growth and geography (Dou and Fox, 1994; Clark et al., 1997). Red clover seeded into established winter wheat during spring contributed up to 134 kg N ha⁻¹ approximately 1 yr later; shorter growing periods can result in lower N contributions (Dou and Fox, 1994; Vyn et al., 2000). Companion-planted red clover in oat (Avena sativa L.) and hairy vetch planted after oat can contribute equivalent amounts of N to a subsequent corn crop (Stute and Posner, 1995). Decker et al. (1994) found that legume cover crops used ahead of no-till corn can increase corn yield regardless of N contribution where N is not limited.

The objective of this study was to compare red clover and hairy vetch green manures in a winter wheat–green manure–corn cropping sequence, for their ability to suppress weeds and influence cash crop yield and economic performance. We hypothesized that interseeding red clover into a winter cereal the year prior to corn would reduce herbicide inputs and costs by controlling winter annual weeds in wheat and summer annuals that emerge following wheat harvest, compared to planting a hairy vetch cover crop following wheat harvest. In addition, the red clover system could have an economic advantage due to lower seed costs and by offering an opportunity for forage harvest.

**MATERIALS AND METHODS**

The Sustainable Dairy Cropping Systems Project (hereafter NESARE DCS) is an interdisciplinary experiment that includes crop rotations designed to produce much of the feed, forage, and fuel to sustain an average-sized Pennsylvania dairy herd. The experiment was initiated in 2010 at the Russell E. Larson Agricultural Research Station in Pennsylvania Furnace, PA (40.72° N 77.92° W). The soil at this location was primarily Murnr channery silt loam (fine-loamy, mixed, mesic Typic Hapludult) with small areas of Buchanan channery silt loam (fine-loamy, mixed, semiactive, mesic Aquic Fragiudult) and average annual precipitation of 98 cm. The rotation of interest consisted of a 3-yr alfalfa and orchardgrass (Dactylis glomerata L.) forage crop, followed by corn grown for silage, winter wheat, a green manure crop of either red clover or hairy vetch and triticale, a second corn silage crop, and winter canola (Brassica napus L.). This paper focused on the winter cereal–green manure–corn silage section of the rotation (Fig. 1). This crop rotation featured a nested dairy manure management comparison, in which a manure injection treatment (IM) and broadcast manure treatment (BM) were compared for nutrient supply to the corn crop. The experiment was a full crop entry experiment with a split-split plot design and four replications, with every crop phase of the rotation planted each year. The main plot factor (27 by 36 m) was the rotational crop (e.g., wheat, green manure, corn), the split-plot factor (27 by 18 m) was dairy manures, and the split-split plots, which were half were sown to hairy vetch and triticale following cereal harvest. Both green manures, red clover and hairy vetch, were terminated with herbicides prior to corn planting. Winter cereals with interseeded red clover did not receive herbicide in spring, whereas wheat that was not interseeded received a spring herbicide application. Following cereal harvest, no herbicide was used on red clover plots, but herbicide was used to control late summer weeds prior to hairy vetch and triticale planting.

![Fig. 1. Winter cereal–green manure–corn sequence repeated 2010 to 2013. Rye was planted in fall 2009; wheat was used in subsequent years. The winter cereal was planted in fall, one-half of the cereal plots were interseeded with red clover in spring, and the other half were sown to hairy vetch and triticale following cereal harvest. Both green manures, red clover and hairy vetch, were terminated with herbicides prior to corn planting. Winter cereals with interseeded red clover did not receive herbicide in spring, whereas wheat that was not interseeded received a spring herbicide application. Following cereal harvest, no herbicide was used on red clover plots, but herbicide was used to control late summer weeds prior to hairy vetch and triticale planting.](image-url)
plot (27 by 9 m) factor was green manure species (red clover, RC, or hairy vetch and triticale, HV). Weed management differed at the split-split plot level in the cereal–green manure–corn sequence, according to green manure species. We reported results for wheat crops in 2011 and 2012, green manure crops following winter cereals, and the subsequent corn crops in 2011, 2012, and 2013. We do not report 2010 wheat data as cereal rye was used in place of wheat.

**NESARE DCS Green Manure Crop Experiment**

**Winter Cereals and Green Manures.** On 17 Oct. 2010 and 2011, cultivar FS-8001 soft red winter wheat (Growmark FS, Milford, DE) was no-till drilled seeded in 19 cm rows with a no-till drill (Great Plains 1005 solid-stand, Great Plains Manufacturing, Inc., Salina, KS) at 134 kg ha⁻¹ following a burndown herbicide application (Table 1). Cultivar Aroostook winter rye (Tallman Family Farms, Tower City, PA) managed similarly to wheat was planted on 10 Nov. 2009. In 2011, 202 kg ha⁻¹ K₀ (0–0–60) was spring-applied to the wheat as recommended by the Penn State Analytical Services Lab (University Park, PA). Wheat plots also received 94 and 82 kg ha⁻¹ N (21–0–0–24) in 2011 and 2012, respectively, as a spring top dress. No fertilizer was applied to rye in 2010.

Red clover cultivar Freedom (King’s Agri Seeds, Inc., Ronks, PA) was no-till drilled (see equipment description in wheat) at 13 kg ha⁻¹ into half of each winter cereal plot on 15 Apr. 2010, 21 Apr. 2011, and 14 Mar. 2012. In the half not seeded to RC (HV treatment plot), thifensulfuron [methyl 2-[[[N-(4-methoxy-6-methyl-1,3,5-triazin-2-yl) methylenimino]carbonyl][amino]carbonyl][amino]sulfonylebenzate] plus tribenuron [methyl 2-[[[4-methoxy-6-methyl-1,3,5-triazin-2-yl) methylenimino]carbonyl][amino]sulfonylebenzate] were applied post-emergence (POST) (Table 1) to the wheat on 3 May 2011 and 21 Mar. 2012 (herbicide not applied to rye in 2010) to control emerged winter annual weeds which consisted primarily of common chickweed [Stellaria media (L.) Vill.] and horseweed [Conyza canadensis (L.) Cronquist]. Warm and dry spring conditions in 2012 compared to 2011 (Fig. 2) resulted in the need for earlier weed control, and allowed for earlier red clover seeding. The RC treatment prevented and precluded spring herbicide application in wheat.

| Crop               | Application time | Active ingredient | Trade name          | Herbicide rate RC kg a.i. or a.e. ha⁻¹ | Herbicide rate HV kg a.i. or a.e. ha⁻¹ | Percent reduction in a.i. or a.e. in RC%
|--------------------|------------------|-------------------|---------------------|----------------------------------------|----------------------------------------|----------------------------------
| Wheat              | Pre-plant        | glyphosate†        | Roundup WeatherMax  | 1.05                                   | 1.05                                   | –15.00%
|                    |                  | 2,4-D†             | 2,4-D Ester          | 0.28                                   | 0.28                                   | –13.00%
|                    | POST             | thifensulfuron‡   | Harmony Extra        | –                                      | 16                                     | –15.00%
|                    |                  | + tribenuron§      | –                    | –                                      | 8                                      | –15.00%
|                    | Total¶¶          |                   |                     | 1.33                                   | 1.57                                   | –15.00%
| Green manure       | Pre-plant        | glyphosate        | Roundup WeatherMax  | –                                      | 0.84                                   | –100.00%
|                    |                  | 2,4-D             | 2,4-D Ester          | –                                      | 0.56                                   | –100.00%
|                    | Total            |                   |                     | 1.40                                   |                                       | –100.00%
| Corn               | Pre-plant        | glyphosate#        | Roundup WeatherMax  | 0.98                                   | 0.98                                   | 0.00%
|                    |                  | 2,4-D             | 2,4-D Ester          | 0.56                                   | 0.56                                   | 0.00%
|                    |                  | dicamba††          | Bankel               | 0.47                                   | 0.47                                   | 0.00%
|                    | POST             | glufosinate‡‡      | Liberty              | 0.6                                    | 0.60                                   | –28.00%
|                    |                  | halosulfuron§§     | Permit               | 4.33                                   | 4.33                                   | –28.00%
|                    |                  | nicosulfuron¶¶     | Accent               | 4.33                                   | 4.33                                   | –28.00%
|                    |                  | dicamba +          | Distinct             | 0.05                                   | 0.05                                   | –28.00%
|                    | Total            |                   |                     | 2.68                                   | 2.68                                   | –28.00%
| Total active ingredient use |                   |                   |                     | 4.06                                   | 5.70                                   | –28.00%

† N-(phosphonomethyl) glycine (Monsanto Company, St. Louis, MO). Rates were 0.84 and 1.26 kg ha⁻¹ in 2011 and 2012, respectively. Rates differed at burndown to control high levels of alfalfa in fields before wheat planting in 2012.
‡ 2,4-dichlorophenoxyacetic acid. (WinField Solutions, LLC. St. Paul, MN): applied at 0.56 kg ha⁻¹ in 2012 only to control volunteer canola.
§ (methyl 2-[[[4-methoxy-6-methyl-1,3,5-triazin-2-yl) methylenimino]carbonyl][amino]carbonyl][amino]sulfonylebenzate] + (methyl 2-[[[4-methoxy-6-methyl-1,3,5-triazin-2-yl] methylenimino]carbonyl][amino]sulfonylebenzate], (DuPont Pioneer, Wilmington, DE). Rates reported in g ha⁻¹.
¶¶ Totals are sums of all active ingredient or acid equivalent rates in kg ha⁻¹.
†† No. 84 kg ha⁻¹ in 2011 and 2012; 1.26 kg ha⁻¹ in 2012.
‡‡ 3,6-dichloro-2-methoxybenzoic acid (BASF Corp., Research Triangle Park, NC), applied at 0.56 kg ha⁻¹ in 2011 and 0.42 kg ha⁻¹ in 2012 and 2013.
§§ (RS)-2-amino-4-(hydroxy(methyl)phosphinyl)butanoic acid, (Bayer CropScience LP. Research Triangle Park, NC).
|| (methyl 3-chloro-5-(4,6-dimethoxypyrimidin-2-ylcarbamoylsulfonyl)-1-methylpyrazole-4-carboxylate (Gowan Company, Yuma, Arizona); 13 g ha⁻¹ applied in 2011 only to control volunteer orchardgrass (Dactylis glomerata L.) and yellow nutsedge (Cyperus esculentus L.) in the corn.
||| (3-pyrindin-carboxamide, 2-[[[4,6-dimethoxypyrimidin-2-yl)methylenimino]carbonyl]amino]sulfonylebenzate]–N,N-dimethyl (DuPont Pioneer, Wilmington, DE); applied at 13 g ha⁻¹ in 2011 only to control volunteer orchardgrass and yellow nutsedge in corn.
### Sodium salt of 3,6-dichloro-0-anisic acid + 2-[[[[3,5-difluoro-phenylamino]carbonyl]hydrazono]methyl]-3-pyridinecarboxylic acid sodium salt (BASF Corp., Research Triangle Park, NC). Applied at 0.14 and 0.06 kg ha⁻¹, respectively, in 2013 only for additional control of perennial broadleaf weeds.
Aboveground weed biomass was collected from two 0.8 m² quadrats in each treatment plot in early July, just prior to wheat harvest (“in wheat”); weed biomass not collected in rye, and again in early August, prior to hairy vetch planting (“after wheat”). Different locations within plots were sampled each time, so that earlier sampling would not influence later sampling that occurred in the same growing season. A mid-August application of glyphosate [(N-phosphonomethyl)glycine] plus 2,4-D [(2,4-dichlorophenoxy)acetic acid] (Table 1) was made in HV plots to control emerged volunteer wheat and broadleaf weeds prior to hairy vetch planting.

Winter cereals were mechanically harvested for yield removing a center 4 by 30 m strip from each treatment plot with a small plot combine (Massey Ferguson 550, AGCO Corporation, Duluth, GA) on 16 July 2010, 14 July 2011, and 6 July 2012. Cereals were weighed and adjusted to 13.5% moisture for yield calculation.

Following cereal harvest, HV plots received an herbicide application to terminate germinated weeds on 17 Aug. 2010 and 2011 and 16 Aug. 2012 (Table 1). Hairy vetch cultivar Auburn Early Cover (Cover Crop Solutions LLC, Lititz, PA) and triticale cultivar Trical 815 (King’s Agri Seeds, Inc. Ronks, PA) were no-till drill seeded (see description above) in 19-cm rows in HV plots at 34 kg ha⁻¹ each on 1 Sept. 2010 and 2011, and 30 Aug. 2012. Red clover was harvested for silage from RC plots on 16 Sept. 2010, Oct. 2011, and 22 Aug. 2012; yield was measured from a 1 m strip harvested from the center of each treatment plot with a small plot forage harvester (Carter Mfg. Co., Inc., Brookston, IN); subsamples (approximately 500 g fresh wt.) were dried for 72 h at 60°C and weighed to determine moisture content.

Prior to green manure termination in spring of 2011, 2012, and 2013, green manure biomass was collected from two 0.5 m² quadrats per treatment plot. Samples were separated by cover crop and weed species, then dried for a minimum of 48 h at 60°C before weighing. In addition to the separated samples, a small sample of green manure crop (approximately 500 g fresh wt.) from each treatment plot was removed prior to termination; these were pooled by manure treatment (IM or BM), and a subsample of approximately 100 g was submitted for tissue analysis (%N) to the Penn State Analytical Services Laboratory (University Park, PA). Green manure tissue analysis results and aboveground dry matter were multiplied to estimate the aboveground N contribution of the green manures.

Green manures were terminated with herbicides on 12 May in 2011 and 2012 and 14 May 2013 (Table 1). The HV treatment was rolled down with a 3.0 m wide roller-crimper described by Mischler et al. (2010) 2 to 5 d after herbicide application to create a weed suppressive mulch. The roller-crimper was not used in red clover because previous research showed that the roller-crimper does not enhance the red clover mulching effect (Curran et al., 2010). While the roller-crimper can control hairy vetch without an herbicide, the vetch must be rolled at late bloom to early pod set to be successfully terminated (Mischler et al., 2010). In central Pennsylvania, this would generally delay corn planting until early June, which was beyond the desired timing for producing corn silage in this cropping system. The combination of herbicide and rolling ensured timely corn planting and the successful control of both HV and emerged weeds and the desired mulching effect.

Corn. Corn plots were fertilized with 168 kg ha⁻¹ K₂O (0–0–60) on 25 and 26 May in 2011 and 2012, respectively, and 67 kg ha⁻¹ K₂O (0–0–60) was applied on 6 June 2013, as recommended by the Penn State Analytical Services Lab (University Park, PA). Liquid dairy manure was applied at 46 Mg ha⁻¹ either broadcast or injected in 76 cm rows on 1 June 2011 and 10 Apr. 2012; in 2013 41 or 47 Mg ha⁻¹ was broadcast or injected, respectively, on 22 May. Dairman manure application rates were based on Pennsylvania Nutrient Management Program guidelines (State Conservation Commission, Pennsylvania Department of Agriculture, Penn State University, National Resources Conservation Service, and Pennsylvania Department of Environmental Protection, 2015). In 2012, the dairman was applied before cover crop termination and earlier than in other years due to logistical constraints at the research site. Corn cultivar TA 290-08 (89 CRM; T.A. Seeds, Avis, PA) Liberty Link (Bayer CropScience, Research Triangle Park, RTP, NC) was planted at 87,500 seeds ha⁻¹ in 76 cm rows with a no-till planter (John Deere 1780, Deere & Company, Moline, IL) on 3 June 2011, 18 May 2012, and 23 May 2013. In 2011, 19 kg ha⁻¹ N as 13–25–8–8, plus 34 kg ha⁻¹ N as 0–0–60 was applied with the corn planter; in 2012, 19 kg ha⁻¹ N as 13–25–8–8 was applied, and in 2013, 6 kg ha⁻¹ N as 7–21–7 was applied. Preseeded soil nitrate tests (PSNT; Fox et al., 1989; Beegle et al., 1999) were performed at the V5 or V6 stage of corn maturity to determine the need for additional N in 2011 and 2012; due to frequent rain in June PSNT sampling was not conducted in 2013. Samples submitted to the Penn State Analytical Services Laboratory (University Park, PA) in 2011 and 2012 indicated that the corn following both green manures did not require additional N (data not shown). Since PSNT samples were not collected in 2013, available N was estimated from manure and legumes based on the Penn State nutrient management planning estimates (Beegle, 2013), and 50 kg ha⁻¹ N or 84 kg ha⁻¹ N as UAN were applied to IM and BM plots, respectively, on 3 July.

Weed density was collected from two 0.8 m² quadrats in each treatment plot at 4 wk after corn planting (WAP) in 2011, and at 4 and 8 WAP in 2012 and 2013. Herbicide (POST) was applied

![Fig. 2. Monthly precipitation and average temperatures at the Russell E. Larson Agricultural Research Station, Pennsylvania Furnace, PA, in March to October of 2011 to 2013.](image-url)
on 29 June 2011, 14 June 2012, and 26 June 2012 when corn was in the V3–V4 stage of growth (Table 1). Aboveground weed biomass was collected 12 WAP from two 0.8 m² quadrats in 2011 and 2013, and two 3 m² (0.76 by 4 m) areas in 2012. All samples were dried for a minimum of 48 h at 60°C before weighing. Insect pest and slug (Deroceras reticulatum, D. laeve, and Arion fasciatum) damage was measured in corn at stages V2 and V5 by counting the number of plants out of two 3 m rows in each treatment plot, and estimating the percent of plant tissue damaged by each species on a scale of 1 to 4 (1 = 0–25% of tissue damaged; 2 = 25–50% damaged, etc.). Corn population was measured simultaneously with insect and slug monitoring at V5.

Corn silage was mechanically harvested using a silage harvester with two-row head (Kemper Champion C1200, Champion Danmark A/S Christiansfeld 6070, Denmark) equipped with an automated weigh scale, mounted onto a tractor (McCormick MTX 135, McCormick International USA, Duluth, GA) on 13 Sept. 2011, 7 Sept. 2012, and 6 Sept. 2013. Yield was harvested from the two center rows in each treatment plot. Silage weight was adjusted to 65% moisture for yield calculation.

**Statistical Analysis.** Weed biomass and crop yield data were analyzed using the PROC Mixed in SAS for Windows v. 9.1.3 (SAS Institute, Inc., Cary, NC) for a split-split plot design, with four replications with “block” and its interaction terms as random factors. Fixed factors included dairy manure management (BM or IM) as split-plot main management within crop entry, and green manure treatment (RC or HV) as the split-split plot factor. Where data collection was repeated across years, a two-sided F test (a = 0.01) was performed to compare variances between years. When variances did not differ, data were pooled across year, and year was included in the model as a fixed effect. For data collected at two or more dates from the same plots (weed density or biomass), repeated measures were applied with date as a fixed effect. All statistical analyses performed on the data compared the dependent variable within a crop and weed type, and partitioned effects were tested using the “slice” statement to perform a single degree-of-freedom F test between green manure treatments, by date and/or year, and to derive least-squares means (lsmeans). Differences were considered significant when P < 0.05. Weed biomass and density data were transformed (log10(y + 1)) to meet the assumptions of ANOVA; reported lsmeans were back-transformed. Where density was sampled within a plot at two dates (before and after POST), data were analyzed with repeated measures, with sampling date (“Date”) and its four interactions as additional fixed effects. Least-squares means were generated for pre-planned contrasts that compared the weed treatments at each date using the “slice” command. The Satterthwaite degrees of freedom approximation was used in all analyses, except those using repeated measures, which used the Kenward–Roger approximation (Kowalchuk et al., 2004).

**Partial Budget Analysis.** Revenue, operational, and ownership costs were used to generate enterprise budgets (Kay et al., 2004) for each crop in the entire cropping sequence under each green manure crop treatment. Experimental yields and costs were averaged over the 3 yr of the experiment (or 2 yr of wheat; rye not used in analysis) to generate these values for the budgets. Costs and revenue that differed between manure management were averaged within a green manure crop treatment. Yearly ownership costs and operational costs, such as soil testing and lime application, were assumed for 3 yr, since this is the length of time covered by this cropping sequence. Equipment ownership, maintenance and repair costs, and land ownership costs were obtained from the Penn State Agronomy Guide (Harper, 2013), or were estimated using actual equipment prices, estimated use, and depreciation (Kay et al., 2004).

The red clover forage was assumed to be wet wrapped for silage by a custom operator, and the per bale wrapping cost was based on local prices (S. Munrick and V. Ishler, personal communication, 2013). Revenue from red clover silage was based on experimental yield and a 5-yr (2010–2014) average price received for alfalfa hay and haylage in six states (Iowa, Illinois, Michigan, New York, Ohio, Pennsylvania; USDA-NASS, 2016), adjusted for moisture. Corn silage was calculated with experimental yield and the Pennsylvania annual average market price (Ishler, 2013). Wheat revenue was calculated by multiplying experimental yield with a 5-yr average price of soft red winter wheat in Pennsylvania from 2008 to 2012 (USDA-NASS, 2016). The N contribution of the green manure crops was assigned a conservative estimate of 67 kg ha⁻¹ N, based on values obtained in the literature (Dou and Fox, 1994). The dollar value for this N was calculated by multiplying the estimate with the cost of N as liquid UAN, which is commonly used as a side-dress fertilizer. While the dollar value attributed to the green manure crop was minimal, it was included to acknowledge the potential N contribution and reduction in costs from these green manure crops. Finally, a partial budget analysis was conducted for managing these crops through the entire sequence, to compare net returns to management under each green manure crop treatment (Kay et al., 2004).

**RESULTS AND DISCUSSION**

**Weather.** Precipitation in March to October was highest in 2011 (95 cm) compared to 2012 (67 cm) and 2013 (59 cm), though much of this precipitation fell in the early and late parts of the season (Fig. 2). March and April of 2012 were much warmer (avg. temperature of 9°C) than in 2011 and 2013 (4° and 5°C, respectively) (Fig. 2), which likely encouraged greater cover crop biomass accumulation.

**Wheat.** The main effect of manure management did not impact weed biomass (data not shown). The year × green manure × date interaction was not significant for weed biomass (Table 2); however, year × green manure and year × date interactions were significant (Table 2) as weed biomass was on average greater in 2011 in RC than in HV but the opposite was true in 2012. Also, in 2011 weed biomass was greater in wheat than after wheat, but the opposite was true in 2012. March–April of 2011 had higher rainfall compared to 2012 (Fig. 2), which may have stimulated more weed germination in wheat and particularly in red clover where no herbicide was applied (Table 1).

In 2011, weed biomass sampled in early July prior to wheat harvest did not differ between green manure treatments (Table 2), though this was likely due to variable weed populations throughout the experiment. Horseweed was commonplace in part of the experiment and contributed to some of the weed biomass in the RC plots in wheat in 2011 (Table 2), whereas the thifensulfuron plus tribenuron application in HV wheat
(Table 1) should have provided some control. Interseeded red clover into wheat should help suppress winter annual weeds, but severe infestations would likely dictate additional control measures, which may not be possible with interseeded red clover. In 2012, low weed biomass in both RC and HV wheat plots indicates that winter annual weed populations were sufficiently managed with both interseeded red clover and herbicide application (Table 2). Wheat yield did not differ between green manure treatments in 2011, but RC wheat yield was 182 kg ha⁻¹ greater than HV yields in 2012 (Table 3). Though it is unclear why yield varied, weed competition was not responsible for the differences observed. Rye yield in 2010 was 1639 and 1431 kg ha⁻¹ in RC and HV, respectively \((P = 0.07)\).

**Green Manure.** In 2012, weed biomass after wheat harvest in mid-August (“after wheat”) was greater in HV (Table 2), indicating that red clover suppressed weed growth compared

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<th>Green manure crop</th>
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<td>In wheat</td>
<td>After wheat</td>
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<tr>
<td></td>
<td>g m⁻²</td>
<td></td>
</tr>
<tr>
<td>RC</td>
<td>29.5a</td>
<td>3.6a</td>
</tr>
<tr>
<td>HV + thifensulfuron/tribenuron</td>
<td>14.1a</td>
<td>4.9a</td>
</tr>
</tbody>
</table>

**Significance of fixed effects**

<table>
<thead>
<tr>
<th>Year</th>
<th>GM‡</th>
<th>Year × GM</th>
<th>Date</th>
<th>Year × Date</th>
<th>GM × Date</th>
<th>Year × GM × Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>*</td>
<td>ns‡</td>
<td>*</td>
<td>ns</td>
<td>***</td>
<td>**</td>
</tr>
</tbody>
</table>

* Significant at the \(P < 0.05\) level.
** Significant at the \(P < 0.01\) level.
*** Significant at the \(P < 0.001\) level.
† GM refers to green manure treatment, red clover (RC) or hairy vetch (HV).
‡ ns, nonsignificant.

Table 2. Weed biomass in wheat prior to harvest and after harvest, in two green manure management programs: red clover (RC) or hairy vetch and triticale (HV). “In Wheat” collection point just before wheat harvest; “After Wheat” collection occurred approximately 1 mo after harvest, before herbicide application and hairy vetch and triticale planting. Analysis performed using repeated measures within a year, with year in the model. Nonsignificant effects not reported. Values within a year and date are significantly different \((P < 0.05)\) between green manure treatments if followed by different letters (a, b).

Table 3. Wheat population and yield, biomass and estimated N contribution of the green manure crops red clover (RC) or hairy vetch (HV), and corn population and yield in 2 yr of wheat–green manure–corn cropping sequence. Wheat was harvested for grain and corn harvested for silage. Green manure biomass was measured just prior to termination and corn planting. Data was pooled across years where variances did not differ significantly between years. Values (lsmeans) within a year and column are significantly different \((P < 0.05)\) if followed by different letters.

<table>
<thead>
<tr>
<th>Year</th>
<th>Wheat yield †</th>
<th>Green manure biomass ‡</th>
<th>Green manure N contribution</th>
<th>Corn population</th>
<th>Corn yield §</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg ha⁻¹</td>
<td>kg ha⁻¹</td>
<td>kg ha⁻¹</td>
<td>plants ha⁻¹</td>
<td>kg ha⁻¹</td>
</tr>
<tr>
<td>2011</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RC</td>
<td>3614a</td>
<td>3403a</td>
<td>136a</td>
<td>76,627a</td>
<td>36,652a</td>
</tr>
<tr>
<td>HV</td>
<td>3937a</td>
<td>3163a</td>
<td>129a</td>
<td>75,283a</td>
<td>35,770b</td>
</tr>
<tr>
<td>2012</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RC</td>
<td>5225a</td>
<td>3849a</td>
<td>156a</td>
<td>60,243a</td>
<td>42,666a</td>
</tr>
<tr>
<td>HV</td>
<td>5043b</td>
<td>4220a</td>
<td>157a</td>
<td>45,453b</td>
<td>36,915b</td>
</tr>
<tr>
<td>2013</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RC</td>
<td>–</td>
<td>4165a</td>
<td>191a</td>
<td>72,567a</td>
<td>40,309a</td>
</tr>
<tr>
<td>HV</td>
<td>–</td>
<td>2874b</td>
<td>157b</td>
<td>56,131b</td>
<td>36,979b</td>
</tr>
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</table>

**Significance of fixed effects**

<table>
<thead>
<tr>
<th>Effect</th>
<th>Year</th>
<th>GM†</th>
<th>Year × GM</th>
<th>Date</th>
<th>Year × Date</th>
<th>GM × Date</th>
<th>Year × GM × Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>–</td>
<td>ns‡</td>
<td>*</td>
<td>*</td>
<td>ns</td>
<td>***</td>
<td>**</td>
</tr>
</tbody>
</table>

* Significant at the \(P < 0.05\) level.
** Significant at the \(P < 0.01\) level.
*** Significant at the \(P < 0.001\) level.
† Wheat grain yield reported at 13.5% moisture. Data not pooled across years.
‡ Green manure biomass reported as dry matter, not including red clover forage harvest in fall. 2011 and 2012 data were pooled; 2013 data analyzed separately.
§ Corn yield as silage reported at 65% moisture.
¶ ns, nonsignificant. Reporting for pooled 2011 and 2012 data only.
# GM refers to green manure treatment, RC vs. HV.
†† Pre-planned contrasts indicated a significant difference in 2013 \((P = 0.01)\).
to no green manure crop. Although soil nitrate levels can stimulate weed seed germination and growth (Sweeney et al., 2008), this and previous studies (Swanton et al., 1996) did not observe more weeds in RC after wheat. The weeds that emerged following wheat harvest were predominately volunteer wheat, lady’s thumb (Polygonum persicaria S.F. Gray), dandelion (Taraxacum officinale F.H. Wigg), smooth pigweed (Amaranthus hybridus L.), and giant foxtail (Setaria faberi Herrm.). Ultimately, the HV plots were treated with herbicide in mid-August prior to hairy vetch establishment and RC plots were harvested in early September, so both treatments were managed to reduce weed maturation and potential seed rain.

Green manure biomass in spring ranged from about 2800 to 4200 kg ha⁻¹ and there was no difference in biomass production between green manure treatments in 2011–2012; but in 2013, RC spring biomass was significantly greater than HV (Table 3). The biomass levels achieved in this study are similar to those reported by others (Clark, 2007; Mischler et al., 2010). Red clover produced equal or more biomass in the spring than hairy vetch–triticale despite having removed over 18 Mg ha⁻¹ red clover for forage the previous fall (data not reported). Triticale was mixed with hairy vetch at planting in a 1:1 ratio by weight, though in 2011 it only accounted for 20% of dry matter at termination, 16% in 2012, and 24% in 2013. The amount of green manure N estimated from the plant tissue % N samples did not differ between green manure crops in 2011 and 2012 (Table 3), but average N contribution from the green manures was higher in 2013 and 2012 than in 2011.

Corn. In 2011, weed density was only collected at 4 WAP, and density did not differ between green manure treatments (Table 4) or dairy manure treatments (data not shown). In 2012 and 2013, repeated measures were used to analyze weed density at 4 and 8 WAP, and years were pooled. No interaction terms were significant for weed density in corn, but average weed density was greater (but still relatively low) in the broadcast manure treatment (BM, eight plants m⁻²) than in the inject manure (IM; four plants m⁻²). Weed density was also greater in 2012 (11 plants m⁻²) than in 2013 (three plants m⁻²), and greater in June (nine plants m⁻²) than in July (four plants m⁻²). The latter was expected as herbicides were applied between the sampling dates for POST control in corn (Table 1).

There was no residual herbicide applied pre-emergence to corn in any year and though not analyzed statistically, weed density in 2011 corn was numerically higher at 4 WAP than in 2012 or 2013. Previous research suggests that these cover crop biomass levels (Table 3) were below the amount necessary to provide consistent weed suppression (Teasdale and Mohler, 2000; Teasdale et al., 2012). The greater number of weed seedlings observed in 2011 was likely due to the wet spring (Fig. 2) which delayed corn planting for almost 3 wk after green manure termination likely allowing residue decay and subsequent weed emergence prior to corn planting.

Weed biomass in corn at 12 WAP did not differ between green manure treatments, though biomass was significantly greater in 2012 than in either 2011 or 2013 (Table 4). This may have resulted from additional herbicides utilized in 2011 and 2013, targeting yellow nutsedge (Cyperus esculentus L.) and orchardgrass in 2011 and broadleaf weeds in 2013 (Table 1). However, weed biomass was below 10 g m⁻² every year, and year was not a significant factor in predicting corn yield (Tables 3 and 4). We did not actively monitor persistence of green manure mulch, but observed that the red clover residue appeared to persist longer on the soil surface than hairy vetch. Previous research showed RC residue dissipated more slowly than HV residue (Teasdale and Daughtry, 1993), but this did not impact weed biomass in corn in this experiment, where POST herbicides were used.

For corn population, year, green manure and year × green manure were all significant. Corn populations were similar between RC and HV treatments in 2011, but corn population in RC was 25 and 22% higher than in HV in 2012 and 2013, respectively (Fig. 2).

### Table 4. Weed density and biomass in corn following one of two green manure crops (GM): red clover (RC) or hairy vetch and triticale (HV) averaged over the dairy cattle manure treatments. Weed density was sampled at 4 or 8 wk after planting (WAP), and weed biomass was collected 12 WAP. Repeated measures used to analyze weed density data in corn, before and after postemergence weed control for 2012 and 2013; year included as a fixed effect for these and weed biomass data. Values (lsmeans) within a year are significantly different (P < 0.05) if followed by different letters.

<table>
<thead>
<tr>
<th>Green manure</th>
<th>2011 Weed density</th>
<th>2012 Weed density</th>
<th>2013 Weed density</th>
<th>Repeated measures contrasts†</th>
<th>Significance of fixed effects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4 WAP</td>
<td>4 WAP</td>
<td>8 WAP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RC</td>
<td>239.7</td>
<td>21.2</td>
<td>5.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HV</td>
<td>266.9</td>
<td>15.8</td>
<td>6.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weed density</th>
<th>Year</th>
<th>Date</th>
<th>Manure‡</th>
<th>GM§</th>
<th>P &gt; F</th>
<th>ns‡‡</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2011</td>
<td>2012</td>
<td>2013</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RC</td>
<td>0.3</td>
<td>9.8</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HV</td>
<td>0.8</td>
<td>8.2</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Significant at the P < 0.05 level.
** Significant at the P < 0.01 level.
*** Significant at the P < 0.001 level.
†† Apply to 2012 and 2013 data only as weed density was only measured at 4 wk after planting in 2011.
‡‡ Manure refers to the dairy cattle manure management comparison (broadcast vs. inject manure).
§ GM refers to green manure treatment, red clover (RC) vs. hairy vetch (HV).
¶¶ ns, nonsignificant.
Corn yield after red clover was also significantly 16 and 9% higher than after hairy vetch in 2012 and 2013, respectively (Table 3). The yield reduction corresponds to predictions for yield loss associated with this degree of loss in corn plant population (Roth and Beegle, 2013). Regional research suggests that optimal yield is achieved with populations between 61,750 and 74,100 plants ha\(^{-1}\), and that lower populations, such as the 45,453 and 56,131 achieved in HV in 2012 and 2013, respectively, results in lower yield (Cox and Atkins, 2011).

It is not clear what reduced corn population in HV in 2012, but slug and insect pest herbivory were particularly problematic in this year, in both treatments. In 2011, corn injury from slugs was more frequent and severe after hairy vetch compared to red clover (Table 5), and, the percentage of herbivore (slugs and insect) damaged corn plants was statistically higher following HV compared to RC at both the V2 and V5 corn stage. In 2012, slug damaged plants was higher than in 2011 or 2013, and one possibility is that slugs consumed seeds and/or seedlings before corn plant damage and plant populations asessment at V2 and V5. In 2012 and other warm and wet springs, we observed that green manure residues retained soil moisture and contributed to poor planter seed closure, leaving seeds and seedlings more exposed to herbivory. Insect damage ratings were also higher at V2 compared to V5, likely due to an outbreak of true armyworm \(Pseudaleta unipuncta\) (Haworth). Previous research suggests that true armyworm infestations are more severe following small grain cover crops (Willson and Eisley, 1992), but in this experiment true armyworm damage was greater in corn following RC \((P = 0.04; \text{data not shown})\). True armyworm damage in 2012 did not reach the economic threshold of 10% of plants damaged (Calvin and Tooker, 2009) in either treatment, so control measures were not implemented.

In addition to pest problems, corn yield may have been affected by differing green manure N contribution. The PSNTs were averaged across the two green manure treatments and although they revealed no need for additional N-fertilizer, possible differences between the green manure crops in 2011 and 2012 would not have been detected (see Methods). Sidedress fertilizer was added in 2013 at two different rates to IM and BM split-plots, and was also averaged across treatment (RC or HV). While aboveground N contribution estimates did not differ between treatments in 2011 and 2012, in 2013, aboveground red clover N was 22% higher than HV (Table 3). Further, red clover grew more than 4 m longer than HV, so RC may have contributed more N to the soil (Dou and Fox, 1994; Vyn et al., 2000).

### Economic Analysis

Partial budget analysis demonstrated a $1355 ha\(^{-1}\) advantage in net returns to management from including red clover in this cropping sequence compared to hairy vetch and triticale (Table 6). Herbicide, labor, and fuel costs in wheat were higher under HV management due to the herbicide application (Table 6); however since red clover is planted into wheat, the actual number of field passes in wheat would be similar between treatments. If postemergence herbicide were not applied in wheat because of low winter annual weed infestations, wheat management costs would be the same in HV and RC, so net returns in wheat would be equivalent or slightly higher in HV than RC in this study owing to slugs, though not significantly, higher yield in HV (Table 3). However, total net returns in RC would still be $1294 higher than in HV, even without the herbicide application in wheat.

The bulk of the advantage from the RC treatment comes in form of revenue from the red clover forage (Table 6). According to 5-yr price averages, revenue from red clover would range from $1185 to $1367 ha\(^{-1}\) (USDA NASS, 2016), and result in a $1309

### Table 5. Percent of corn plants damaged by slugs and average herbivore damage rating recorded in corn at V2 and V5, and following red clover (RC) or hairy vetch and triticale (HV), in 2011 through 2013. Data from 2012 and 2013 were pooled for analysis; 2011 data was analyzed separately. Different letters (a, b) indicate a statistical significance at \(P < 0.05\) between treatments within a year, or between growth stages within a year.

<table>
<thead>
<tr>
<th>Green manure</th>
<th>Percent slug damaged plants</th>
<th>Average damage rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC</td>
<td>53b</td>
<td>97a</td>
</tr>
<tr>
<td>HV</td>
<td>72a</td>
<td>99a</td>
</tr>
<tr>
<td><strong>Stage</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V2</td>
<td>53b</td>
<td>99a</td>
</tr>
<tr>
<td>V5</td>
<td>72a</td>
<td>98a</td>
</tr>
<tr>
<td><strong>Effect</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green manure</td>
<td>*</td>
<td>ns‡</td>
</tr>
<tr>
<td>Year</td>
<td>–</td>
<td>***</td>
</tr>
<tr>
<td>Stage</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>Green manure × Stage</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Year × Stage</td>
<td>–</td>
<td>***</td>
</tr>
</tbody>
</table>

* Significant at the \(P < 0.05\) level.  
** Significant at the \(P < 0.01\) level.  
*** Significant at the \(P < 0.001\) level.  
† Severity of damage: 0–1: up to 25% of plant area damaged; 1–2: 25 to 50% plant area damaged; 2–3: 50 to 75% plant area damaged; 3–4: 75 to 100% plant area damaged.  
‡ ns, nonsignificant.
to $1490 ha⁻¹ advantage of the RC system over HV under experimental management. However, the price of hay and silage fluctuates with supply and demand, so in times of high demand for legume forages, the revenue potential may be higher. In years with drought or low yield, the prices may be driven even higher. Conversely, in excellent forage production years or areas where there is little demand for legume forages (i.e., areas without cattle production), the income potential for red clover would be lower. If red clover is only mowed but not harvested for forage, managing red clover costs $86 ha⁻¹ less than hairy vetch and triticale because of the higher seed and herbicide costs for hairy vetch, and the ownership and repair costs of the roller-crimper (Snyder, 2013). This study used a high-quality forage red clover seed (cultivar Freedom; see Materials and Methods) that is more expensive than many other red clover varieties. The slightly different costs and returns for corn management are for the cost of custom silage chopping, hauling, and silo filling, and are attributable to corn yield differences (Table 3). Thus, even if red clover is not harvested for storage, net returns to management for the RC treatment are $123 ha⁻¹ greater than in the HV treatment.

The 3 yr of cash crop performance data, in response to the green manure crop treatment, indicate that the cash crops alone can be profitably managed this way, but that the cost of planting and managing a hairy vetch cover crop between these crops may not result in a profitable outcome over the 2 yr of management. However, interseeding red clover into wheat in this sequence, even if not harvested for silage, will result in a profitable outcome. The N contribution from the green manures may offset the need for N fertilizer, and if the cost of fertilizer and/or herbicides were to increase substantially, the economic benefit from these green manures may become more important. In this experiment, we were able to achieve this economic profitability while reducing herbicide use by 28% in the RC treatment (Table 1).

Interseeding red clover in wheat may provide some suppression of winter annual weeds, however it may also preclude the ability to apply herbicide, especially in spring and could increase the risk for certain weed problems in wheat. In choosing to interseed red clover into wheat, farmers should first consider the potential for weed competition that may merit control with herbicide. We can only speculate, but N contribution from red clover in wheat in 2012 may have resulted in a yield benefit; future studies should investigate this phenomenon.

Table 6. Itemized partial budget analysis of using red clover (RC) vs. hairy vetch plus triticale (HV) as cover crops between winter wheat and corn. Only costs or revenue that differed between treatments shown. Costs calculated from experimental operating costs and yield quantified in 2011 and 2012 for wheat, and in 2011 to 2013 for green manure and corn.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Source of difference</th>
<th>RC</th>
<th>HV</th>
<th>RC-HV†</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>Revenue</td>
<td>wheat grain</td>
<td>$948.83</td>
<td>$965.21</td>
<td>$−16.38</td>
</tr>
<tr>
<td></td>
<td>Cost</td>
<td>herbicide</td>
<td>$7.61</td>
<td>$29.65</td>
<td>$−22.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>labor</td>
<td>$41.64</td>
<td>$55.53</td>
<td>$−13.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>fuel</td>
<td>$23.49</td>
<td>$31.32</td>
<td>$−7.83</td>
</tr>
<tr>
<td></td>
<td>Total costs</td>
<td></td>
<td>$865.21</td>
<td>$908.96</td>
<td>$−43.76</td>
</tr>
<tr>
<td></td>
<td>Net returns to manag</td>
<td></td>
<td>$83.62</td>
<td>$56.24</td>
<td>$27.38</td>
</tr>
<tr>
<td>Green manure</td>
<td>Revenue</td>
<td>forage</td>
<td>$1231.96</td>
<td>$0.00</td>
<td>$1231.96</td>
</tr>
<tr>
<td></td>
<td>Cost</td>
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<td>$170.43</td>
<td>$−52.46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>herbicide</td>
<td>$7.61</td>
<td>$29.65</td>
<td>$−22.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>custom wet wrapping</td>
<td>$41.64</td>
<td>$55.53</td>
<td>$−13.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Roller-crimper</td>
<td>$23.49</td>
<td>$31.32</td>
<td>$−7.83</td>
</tr>
<tr>
<td></td>
<td>Total costs</td>
<td></td>
<td>$406.04</td>
<td>$319.56</td>
<td>$86.48</td>
</tr>
<tr>
<td></td>
<td>Net returns to manag</td>
<td></td>
<td>$825.92</td>
<td>$−319.56</td>
<td>$1145.48</td>
</tr>
<tr>
<td>Corn</td>
<td>Revenue</td>
<td>corn silage</td>
<td>$1622.64</td>
<td>$1409.30</td>
<td>$213.34</td>
</tr>
<tr>
<td></td>
<td>Cost</td>
<td>custom silage</td>
<td>$371.08</td>
<td>$340.24</td>
<td>$30.82</td>
</tr>
<tr>
<td></td>
<td></td>
<td>chop, haul, and fill</td>
<td>$172.19</td>
<td>$0.00</td>
<td>$172.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total costs</td>
<td></td>
<td>$1266.33</td>
<td>$1235.51</td>
<td>$30.82</td>
</tr>
<tr>
<td></td>
<td>Net returns to manag</td>
<td></td>
<td>$356.31</td>
<td>$173.79</td>
<td>$182.52</td>
</tr>
<tr>
<td></td>
<td>Total net returns</td>
<td></td>
<td>$1265.85</td>
<td>$−89.53</td>
<td>$1355.38</td>
</tr>
</tbody>
</table>

† Values listed by crop represent the difference in values, calculated by subtracting value for hairy vetch (HV) treatment from red clover (RC) treatment. Thus, positive values indicate greater revenue, costs, and net returns from RC.
‡ USDA NASS (2016).
§ The Pennsylvania State University (2013).
¶ S. Munrick and V. Ishler, personal communication, 2013.
# Ishler, Gap, PA; Kay et al. (2004).
†† Ishler (2013).
Interseeded red clover reduced summer annual weed biomass compared to the wheat–hairy vetch rotation in 1 of 2 yr. These results and other research (Fisk et al., 2001) demonstrate that interseeding red clover is an effective cultural practice for suppressing certain weeds between a winter cereal and subsequent corn. Weed maturation was not monitored in this experiment, but weed seed rain could become a concern in red clover following wheat harvest with certain early maturing species, and early mowing or selective herbicides should be considered to prevent seed rain for those choosing to interseed red clover.

Weed density and biomass in corn did not differ as a result of the preceding green manure in this experiment. It is possible that while green manure residues can reduce early season weed density as compared with no cover, they may result in higher weed density later in the season as crop residues dissipate due to moisture conservation, light penetration (Teasdale and Daugtry, 1993), and the effect of mineralized N from legumes on weed seed germination; these merit further investigation. Establishing corn in hairy vetch and small grain residue with the planter used in this experiment led to low populations and lower yield; research should continue to investigate the effects of cover crop residue on crop establishment, and optimal planting equipment for planting into different residues. Future research should also investigate if green manure residues differentially contribute to enhancing corn herbivory. Regardless of their ability to suppress weeds, any cover crop or green manure whose residue remains on the surface during a summer annual cash crop can conserve moisture, which in years with mid-summer drought could benefit crop yield. Red clover provided soil cover for a full year and flower provisions in the late summer and fall for pollinators. Finally, including red clover in this sequence can be profitable on farms that feed livestock, but even without livestock, this study found red clover to be the more profitable green manure crop.

ACKNOWLEDGMENTS

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REFERENCES


