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Hairy Vetch Varieties and Bi-Cultures Influence Cover Crop Services in Strip-Tilled Sweet Corn

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ABSTRACT

Hairy vetch (*Vicia villosa* Roth) cover crops provide a wide array of ecosystem services including erosion protection, weed suppression, and N fixation. However, adoption has been hindered by risks including overwinter mortality and regrowth following mowing or crimping. Early-flowering vetch varieties and mixed stands of vetch and cereal rye (*Secale cereale* L.) have the potential to reduce these risks, but little is known about their impact on N fixation. In field trials in Central Michigan, two early-flowering hairy vetch varieties (Purple Bounty and Purple Prosperity) and one later-flowering variety ('Oregon') were grown alone and in mixtures with cereal rye, prior to strip-tilled sweet corn (*Zea mays* L. var. *rugosa*). Vetches grown in mixture with rye had equal or greater overwinter survival and earlier flowering than vetches grown in monoculture. Nitrogen fixation of early-flowering varieties was not affected by mixture with rye. However, N fixation of Oregon was lower when grown in monoculture than when grown in mixture in 2009. Purple Bounty and Purple Prosperity flowered earlier than Oregon, exhibited comparable survival, and had equal or greater levels of N fixation. Despite differences in the timing of flowering, there were no differences in regrowth of hairy vetch following mowing. Nor were any differences in sweet corn yield or quality detected. These results demonstrate that rye–vetch mixtures can increase overwinter survival, accelerate flowering, and increase N fixation relative to vetch monocultures. Observed varietal differences in flowering time, N fixation, and response to bicultures may be exploited to optimize cover crop use in agroecosystems.

Hairy vetch is a vining legume native to Eurasia. Of all the species in the genus *Vicia* (150+), hairy vetch is reported as the only one that can survive moderate to harsh winter conditions when sown in the fall (Undersander et al., 1990). Because of its winter hardiness and its ability to provide large amounts of N to subsequent crops through biological nitrogen fixation (BNF), hairy vetch has received much attention as a potentially valuable cover crop in many cropping systems. Depending on planting density and climate, hairy vetch may fix up to 300 kg N ha^{-1} (Ledgard, 2001) with typical rates in the northern United States ranging from 50 and 190 kg N ha^{-1} (Teasdale et al., 2004). As a winter cover crop, hairy vetch also provides: (i) a C source to build soil organic matter and improve soil physical properties; (ii) ground cover during a time period when fields are without crops and are prone to soil erosion; and (iii) suppression of weed growth through allelopathy and mulch effects (Clark, 2007; Hill et al., 2006; Teasdale and Mohler, 2000). Crop yields following hairy vetch and rye–vetch mixtures have generally been comparable or greater than bare soil, although results vary depending on factors including the level of N fertilization as well as tillage and weed management practices used in bare soil controls (Carrera et al., 2004; Hanson et al., 1993; Miguez and Bollero 2005).

Despite these potential benefits, widespread adoption of hairy vetch has been limited by several management challenges. Problems associated with hairy vetch include overwinter mortality (Jannink et al., 1997), regrowth following mechanical termination resulting in competition with subsequent crops (Aarssen et al., 1986; Teasdale and Shirley, 1998) and rapid mineralization of residues resulting in N losses prior to crop N uptake (Rosecrance et al., 2000). Cover crop competition with cash crops due to regrowth is a well-established potential problem in cropping systems (Moschler et al., 1967). Indeed, hairy vetch is considered a problematic weed especially in winter annual crops like wheat (*Triticum aestivum* L.) and in perennial tree fruit (Aarssen et al., 1986). Hairy vetch regrowth can be particularly problematic in reduced tillage systems in which mechanical means of termination including mowing or roller crimping are used. For example, Boydston and Williams (2011) report that yields in reduced tillage dry bean (*Phaseolus vulgaris* L.) production were lower where hairy vetch was roller crimped due to competition from vetch that regrew. Hairy vetch regrowth in subsequent grain crops may necessitate extra herbicide applications (Hanson et al., 1993).

Since regrowth of vetch following mowing or roller crimping is reported to be minimized when vetch has reached full flowering and early pod set (Mischler et al., 2010), early-flowering varieties may be terminated earlier in the spring with reduced risk of regrowth. Estimates in the literature regarding the appropriate time to mechanically terminate (e.g. flail mow)

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Abbreviations: BNF, biological nitrogen fixation; CNF, cost of nitrogen fixed; %Ndfa, percentage of nitrogen derived from the atmosphere; TNF, total nitrogen fixed.

hairy vetch range from 50 to 100% flowering (Clark et al., 1997; Hoffman et al., 1993; Moncada and Sheaffer, 2011). Since early planting of crops like sweet corn often results in greater profits due to early price premiums (Beale, 2008), the ability to successfully kill hairy vetch 2 to 3 wk earlier may mean the difference between using this cover crop or not. If cover crops fit the needs of the farmer's crop management system, then there is a greater likelihood for adoption (Anderson-Wilk, 2008).

Mixtures of legumes with cereals often have synergistic beneficial effects for both plant populations (Vandermeer, 1989) and may alleviate some of the constraints to successful adoption of hairy vetch. Specifically, documented benefits of grass legume mixtures relative to monocultures include improved legume growth due to more diverse plant architecture for vine climbing (Keating and Carberry, 1993), transfer of biologically fixed N to the cereal species via root interaction (Dakora et al., 2008), more efficient N fixation of the legume (Izaurralde et al., 1992; Jensen, 1996), improved overwinter survival (Jannink et al., 1997), improved weed suppression (Brainard et al., 2011; Burgos and Talbert, 1996; Liebman and Dyck, 1993), and slower N mineralization rates following termination, resulting in better synchrony of N supply and crop N demand (Rosecrance et al., 2000). In a meta-analysis of winter cover crop effects on corn yields, Miguez and Bollero (2005) found that grass–legume bicultures improved subsequent corn yields by 22% on average. On the other hand, in some cases, grass cover crops may suppress legume growth and nodulation (Brainard et al., 2011), or interfere with successful establishment of subsequent crops (Carrera et al., 2004).

In addition to these potential biological effects, grass–legume mixtures may reduce costs relative to legume monocultures since grass seeds are generally less expensive than legume seeds and recommended legume seeding rates are usually lower in mixtures (Brainard et al., 2011). Partial budget analyses have demonstrated increased profitability of tomato (*Lycopersicon esculentum* L.) cropping systems when mulch from hairy vetch monocultures was used compared to black plastic mulch (Kelly et al., 1995). Similarly, use of hairy vetch improved profitability relative to grass cover crops in no-till corn (Hanson et al., 1993; Ott and Hargrove, 1989). In no-till corn, higher profitability of a hairy vetch cover crop was attributed primarily to N fertilizer savings (N fertilizer replacement value) that exceeded the extra costs associated with hairy vetch seeds (Hanson et al., 1993). To our knowledge, no studies have evaluated the relative profitability of hairy vetch and rye–vetch mixtures, or of different varieties of hairy vetch.

Despite the potential benefits of growing vetch with rye, little information is available on the compatibility of different vetch varieties with rye in mixtures. Most breeding programs and variety trials involving hairy vetch have selected varieties based on their performance in monoculture (e.g. Teasdale et al., 2004). However, plant traits that may result in optimal performance in mixture may be quite different from optimal traits in monoculture. For example, shade avoidance response can vary within species and may play an important role in determining the outcome of competitive interactions (Weinig, 2000). Similarly, N-fixation inhibition under high soil inorganic N can vary with legume variety (Buttery and Dirks, 1987), and may be an important determinant of N-fixation efficiency in mixture relative to monoculture.

With increasing interest in cover crops, plant breeders have begun selecting for locally appropriate cultivars of hairy vetch. Wilke and Snapp (2008) argue for selection within the hairy vetch genome to produce cultivars with traits that include: (i) better winter survival; (ii) lower soil water depletion; (iii) morphology suited to no-till practices; (iv) greater residual N uptake; (v) better potential as forage; and (vi) greater resistance to temperature and drought stress. Yeater et al. (2004) found substantial intraspecific variation across hairy vetch accessions in a number of plant traits including seed germination, leaf morphology, overwinter survival and C/N ratio, and suggested that this information could be useful for efficiently focusing plant breeding efforts to improve hairy vetch performance as a cover crop. Other traits that are likely to be valuable for successful integration of hairy vetch varieties in production systems include: (i) early flowering, (ii) compatibility with cereal rye in mixtures, and (iii) greater capacity to fix N. Teasdale et al. (2004) evaluated early flowering hairy vetch varieties (e.g., AU Early Cover, Population 8, Population 26) in Maryland and New York and found that despite flowering earlier than a common variety, the new varieties were not winter hardy in New York. Subsequent breeding efforts by the same group resulted in the release of two new varieties, Purple Bounty and Purple Prosperity, that are reported to have improved winter hardiness while retaining the early-flowering characteristic (Comis, 2008). However, these varieties have not been evaluated for N-fixation ability, performance in rye–vetch bicultures, or influence on subsequent crops.

With these issues in mind, we evaluated the performance of the early-flowering varieties, Purple Bounty and Purple Prosperity, alongside a common "variety not stated" (VNS) vetch from Oregon to determine their potential usefulness for cropping systems in northern climates. These two recently released varieties may alleviate some of the problems identified by researchers and farmers, including high rates of winterkill and late spring flowering. This research expands on trials done at the USDA-ARS Sustainable Agricultural Systems Laboratory in Beltsville, MD, and addresses the concerns regarding adaptation to climate and latitude addressed by prior research (Brandsaeter et al., 2008; Wilke and Snapp, 2008). Additionally, combining these new varieties with cereal rye may be of further benefit through reductions of overall costs and potential improvements in the efficiency of N fixation (Ranells and Wagger, 1996). The objectives of this study were to evaluate hairy vetch function when grown alone and in combination with cereal rye based on: (i) overwinter survival; (ii) biomass production and BNF; (iii) time of flowering; (iv) regrowth following mowing; and (v) effect on the yield and quality of the following crop of sweet corn grown in a strip-till system.

MATERIALS AND METHODS

Site Description

This study was conducted from September 2008 through August 2010 near East Lansing, MI, (42°44″ N, 84°29″ W), on two adjacent fields at the Michigan State University Horticulture Teaching and Research Center on a Spinks loamy sand soil (sandy, mixed, mesic Lamellic Hapludalf). Soil chemical characteristics included a pH of 7.9, CEC of 18.9 cmol kg^{-1}; and initial P, K, and Mg levels of 71, 83, and 266 g kg^{-1}, respectively. Both fields had a summer sorghum sudangrass (*Sorghum bicolor* × *S. bicolor* var. sudanese) cover crop prior to seeding hairy vetch and rye in the fall.

Experimental Design

Two factors, variety and cropping system, were arranged as a 3 × 2 factorial in a randomized complete block design with four replications. Hairy vetch varieties included a "variety not stated" from Oregon, and the early flowering varieties Purple Bounty and Purple Prosperity. The cropping system factor consisted of two levels: hairy vetch grown in monoculture or hairy vetch grown in biculture with cereal rye. Hairy vetch seeding rates were 45 kg ha^{-1} in monoculture and 22.5 kg ha^{-1} (50% of monoculture rate) in mixture with cereal rye sown at 62.5 kg ha^{-1} (50% of typical recommended monoculture rate). In addition, a rye monoculture treatment was sown at 125 kg ha^{-1} in randomized plots within each block for use as a reference plant for N fixation estimation. In 2008–2009 the plot size was 3.8 by 18.3 m with five rows of corn. In 2009–2010 the plot size was reduced to 3.0 by 12.2 m with four rows of corn due to shortage of Purple Bounty seeds.

Cover Crop Management

The timing of key field operations and data collection is presented in Table 1. The previous sorghum sudangrass cover crops were flail mowed and incorporated in late August in both 2008 and 2009. Fall fertilizer applications prior to planting winter cover crops included 224 kg ha^{-1} of 19–19–19 (N–P–K) in 2008 and 45 kg ha^{-1} urea plus 67 kg ha^{-1}potash in 2009. In addition, 336 kg ha^{-1} of elemental S was applied prior to cover crop planting in both years to lower soil pH. Fall-applied fertilizers were broadcast and incorporated with a harrow. In 2008, cover crops were drilled using a Moore UniDrill no-till seeder (County Antrim, Northern Ireland) on 2 September. In 2009, a John Deere 750 no-till grain drill (Deere and Company, Moline, IL) was used to plant the rye and a Jang push seeder (JP-3, Chungbuk, South Korea) was used to plant the hairy vetch varieties on 4 September. The vetch seeds were inoculated with N-Dure *Rhizobium* inoculant prior to seeding.

Cover crop emergence was evaluated by counting hairy vetch and rye seedlings in two 0.5 m^2 quadrats per plot on 29 Oct. 2008 and 16 Oct. 2009. Hairy vetch survival was evaluated by counting hairy vetch seedlings in two 0.5 m^2 quadrats on 12 May 2009 and 2 Apr. 2010. Percent overwinter survival was estimated as the percentage change in the number of plants between fall and spring counts.

Table 1. Dates of key field operations and data collection.

Operation	Date 2008–2009	Date 2009–2010
Planted cover crops	2 Sept.	4 Sept.
Evaluated cover crop emergence	29 Oct.	16 Oct.
Evaluated cover crop survival	12 May	2 Apr.
Sampled cover crop biomass	29 May	27 May
Evaluated vetch flowering	30 May	28 May
Flail-mowed cover crops	30 May	30 May
Strip-tilled	9 June	14 June
Planted sweet corn	21 June	15 June
Applied sidedress N	21 July	14 July
Harvested sweet corn	11 Sept.	25 Aug.

Hairy vetch flowering was evaluated on 30 May 2009 and 28 May 2010 using two methods: visual estimation of percent flowering (Fp) and counts of the number of flowering racemes per stem (Fn). Visual estimates of flowering are commonly used by plant breeders and agronomists (T. Devine, personal communication, 2006) but no published information is available regarding the consistency of these estimates between observers, nor how visual estimates relate to more easily quantifiable measurements like Fn. Visual estimates of Fp were made on a whole plot basis, by visually contrasting the percentage of purple flowers relative to green vegetative cover and assigning a percentage between 0 and 100 (to the nearest 5%), with 100 representing full flowering (based on previous experience with hairy vetch). The Fn was determined by randomly selecting 10 stems from each plot following a W-shaped transect, and counting the number of racemes per stem with at least one open flower (purple color showing).

On 29 May 2009 and 27 May 2010, cover crops were clipped at ground level from two 0.25 m^2 quadrats per plot, placed into paper bags and dried at 60° C. The samples were then ground using a centrifugal mill (Thomas Model 4 Wiley Mill, Swedesboro, NJ) with a 1.0 mm screen and stored in sterile, sealed plastic bags. The ground cover crop biomass was thoroughly mixed and loaded into 5 × 9 mm tin capsules (Costech no. 041061) with 3 μg for vetch and 10 μg for rye. Samples were analyzed at the University of California-Davis Stable Isotope Facility (SIF) for percent total nitrogen (%N) and $\delta^{15}N$ using an elemental analyzer (ANCA-GSL, PDZ Europa, Norwich, Cheshire, UK) interfaced to an isotope ratio mass spectrometer (20-20, Sercon, UK).

Strip-Tilled Sweet Corn Management

On 30 May in both years, cover crops were flail mowed at a target height of 5 to 10 cm and allowed to decompose for 1 to 2 wk prior to strip-tillage (Table 1). Following flail mowing, potash was broadcast at 218 kg ha^{-1}. On 9 June 2009 and 14 June 2010, a Hiniker Model 6000 two-row strip-tiller (equipped with notched trash-cleaning discs, cutting-coulter, shank-point assembly, berming disks, and rolling basket) was used to create 25 by 25 cm deep strips at 76 cm between-strip spacing.

Sweet corn 'Luscious' was planted in tilled strips on 21 June 2009 and 14 June 2010 using a MatterMac Series 8000 two-row vacuum precision planter. Sweet corn was planted in rows 76 cm apart at an estimated population of approximately 65,000 plants ha^{-1}. Fertilization was based on soil tests and recommended nutrient levels for Michigan sweet corn, taking into consideration N credits from the rye and hairy vetch cover crops. In both years, 218 kg ha^{-1} of potash was broadcast before planting and 224 kg ha^{-1} of a 19–19–19 (N–P–K) granular fertilizer was banded at planting. Based on previous work with these cover crops (Snapp, unpublished data, 2008), N credits of 1% of rye shoot biomass and 3% of vetch shoot biomass were assigned to each treatment of which half of that credit was estimated to be available to the subsequent sweet corn crop. In 2009, using this calculation, the N credits for hairy vetch monoculture and mixture treatments (63 kg ha^{-1}) were not significantly different ($p > 0.05$) and were deemed sufficient to avoid additional N fertilization at planting. In 2010, the N credit for hairy vetch monoculture treatments was estimated at 58 kg ha^{-1} compared to 46 kg ha^{-1} in rye–vetch mixture treatments ($p < 0.05$), so an additional 12 kg N ha^{-1} and 24 kg N ha^{-1} (as urea) was broadcast in rye–vetch and vetch treatments, respectively. Soil samples for the pre-sidedress nitrate test (PSNT) were taken on 20 July 2009 and 14 July 2010 to determine side-dress N application rates for each treatment. In both years, PSNT levels were similar in all treatments, suggesting that our cover crop N credits were reasonably accurate. Based on PSNT test results, urea was side-dressed at 56 kg N ha^{-1} in 2009 and 67 kg N ha^{-1} in 2010 in all treatments. Weeds were managed through a combination of the herbicides Fluazifop-P-butyl (butyl(R)-2-[4-(5-trifluoromethyl-2-pyridinyloxy)phenoxy]propionate) and S-metolachlor ((2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-[(1*S*)-2-methoxy-1-methylethyl] acetamide) applied before corn planting at 0.18 kg a.i. ha^{-1} and 1.24 kg a.i. ha^{-1} respectively. Handweeding was done as needed to manage escaped weeds after sweet corn emergence. No fungicide or insecticide applications were made.

Eighteen row-meters of sweet corn were harvested from the interior two rows of each plot and were sorted as marketable or unmarketable based on characteristics including length, width, and tipfill. Ears meeting U.S. no. 2 standards (USDA-Agricultural Marketing Service, 1992) or above were considered marketable. After sorting, ears were weighed and counted and a subsample of 10 randomly selected marketable ears were husked and measured for width and length. The soluble solid content of kernel sap was measured by extracting sap from a composite of kernels from a subsample of five marketable ears per plot and measuring the refractive index (RI) with an Atago PAL-1 digital handheld refractometer. This device reports RI readings in degrees Brix (°Bx) based on the relationship between RI and the sucrose concentration (%ww) of a pure sucrose solution at 20°C. For sweet corn kernel extract, °Bx reflects not only sucrose, but also other sugars including glucose, as well as other soluble solids which have little impact on sweetness (Zhu et al., 1992).

Biological Nitrogen Fixation Estimation

The percentage of hairy vetch N derived from the atmosphere (%Ndfa) was estimated using the ^{15}N natural abundance technique (Boddey et al., 2000; Shearer and Kohl, 1986). This technique takes advantage of the fact that soil N sources usually have a higher percentage of rare ^{15}N atoms than atmospheric N. Therefore, plants like cereal rye which derive N from the soil N usually have a higher percentage of ^{15}N than plants like hairy vetch which derive some of their N from atmospheric sources through BNF. Small differences between ^{15}N composition in plant tissue relative to atmospheric ^{15}N composition are expressed as δ^{15}N in parts per thousand (‰) (Shearer and Kohl, 1986). Values of δ^{15}N generally range from –30‰ to +30‰ with higher values indicating greater enrichment in ^{15}N (Robinson 2001). The percentage of legume tissue N derived from the atmosphere is approximated using the following equation (Boddey et al., 2000; Shearer and Kohl, 1986).

$$\%\text{Ndfa} = (\delta^{15}\text{N}_{\text{ref}} - \delta^{15}\text{N}_{\text{leg}})/(\delta^{15}\text{N}_{\text{ref}} - B) \times 100 \qquad [1]$$

where $\delta^{15}\text{N}_{\text{ref}}$ is the δ^{15}N value for cereal rye in monoculture (used as reference plant) grown in the field study, $\delta^{15}\text{N}_{\text{leg}}$ is the δ^{15}N value for hairy vetch grown in the field study, and B is the estimated δ^{15}N value for hairy vetch when the plant is totally dependent on BNF for growth (Peoples et al., 2002). Following Mariotti et al. (1982) and Evans et al (1996), the most negative $\delta^{15}\text{N}_{\text{leg}}$ value for each vetch variety was used to approximate B. This approach assumes that the lowest value of $\delta^{15}\text{N}_{\text{leg}}$ has a corresponding %Ndfa close to 100%, and results in conservative estimates of %Ndfa. Cereal rye grown in monoculture was chosen as the reference plant because (i) of its convenience as a common companion of hairy vetch, (ii) it has a similar growth pattern and root architecture to hairy vetch, and (iii) no non-nodulating hairy vetch varieties were available. When non-nodulating varieties of the study legume are not available, cereal grains or naturally occurring weed species are often used as reference plants (Dakora et al., 2008; Nyemba and Dakora, 2010; Rochester and Peoples, 2005).

Following Rochester and Peoples (2005), the amount of shoot N derived from N fixation by each variety was estimated using these formulas:

$$\text{Shoot N} = (\text{shoot dry weight}) \times (\%\text{N}) \qquad [2]$$

$$\text{Shoot N fixed} = (\text{shoot N}) \times (\%\text{Ndfa}) \qquad [3]$$

$$\text{TNF} = \text{Total N fixed} = \text{shoot N fixed} \times 1.20 \qquad [4]$$

where %N is total N weight as a percentage of total dry weight of shoot tissue from the tissue subsample submitted to UC-Davis SIF and legume dry weight is from the cover crop harvest prior to mowing. The estimate of total N fixed (Eq. [4]) is based on the assumption that root N accounts for an additional 20% of N derived from N fixation.

Cost of Nitrogen Fixed

To provide additional insight into the costs that growers would incur to obtain N from hairy vetch through BNF, the cost of nitrogen fixed (CNF) was estimated for each treatment by dividing the seed costs of each treatment by TNF according to:

$$\text{CNF} = [(P_v \times Q_v) + (P_r \times Q_r) - (P_r \times 125)]/\text{TNF} \qquad [5]$$

where P_v and P_r are the prices ($ ha^{-1}) of hairy vetch and rye seed, respectively; Q_v and Q_r are the seeding rates (kg ha^{-1}) of hairy vetch and rye, respectively, and TNF is the estimated total N fixed (kg ha^{-1}) from Eq. [4]. The CNF reflects costs for fixed N that would be incurred by a grower who already uses cereal rye at a seeding rate of 125 kg ha^{-1} as a cover crop, and simply substitutes hairy vetch or rye–vetch seeds in the grain drill. Since use of cereal rye is common in sweet corn production systems in the Upper Midwest, CNF is an estimate of additional costs that most sweet corn growers would incur to gain fixed N in their cropping system.

Statistical Analysis

The fixed effects of hairy vetch variety, cropping system (monoculture vs. mixture) and their interactions on hairy vetch overwinter survival, biomass, flowering, N fixation, the CNF, and subsequent sweet corn yield and quality were determined using Proc MIXED procedures in SAS with block (replicate) and interactions of block as random effects (SAS Institute, 2001). Year was initially included as a fixed effect in the model, but because interactions between year and either variety or cropping system were significant ($p < 0.05$) for all responses (except for Brix and cob length), analysis was conducted separately by year. For Brix and cob length, interactions between year and variety and cropping system were not significant ($p > 0.05$), so data was combined. Normal probability and residual plots were examined for violations of assumptions of normality and constant variance. To improve model assumptions, rye and vetch shoot dry weight was square root transformed and TNF and CNF were log transformed. Treatment means were separated using Fisher's protected LSD test at $p < 0.05$. The relationship between visual estimates of Fp and the number of flowering racemes per stem Fn was examined using the REG procedures in SAS (SAS Institute 2001).

RESULTS AND DISCUSSION

Temperature and Rainfall

Growing degree days (GDD; base 4°C) during the period of hairy vetch establishment (September–November) were similar in both years of the study (Table 2). However, GDD were much lower in the spring of 2009 compared to 2010, particularly during the month of April. Warmer temperatures in spring 2010 compared to 2009, resulted in accumulation of 123 more GDD at the time of vetch mowing in preparation for sweet corn planting. Rainfall during vetch growth was higher in 2008–2009 compared to 2009–2010. During the summer months from June to August, 231 more GDD accumulated in 2009–2010 compared to 2008–2009. In 2009–2010, 31 fewer mm of rainfall fell during this period. The combine effect of warmer temperatures and less rainfall during the 2009–2010 growing season may have contributed to increased drought stress relative to 2008–2009.

Table 2. Monthly growing degree days (GDD) and rainfall totals at East Lansing, MI, 2008–2010.

Month	GDD†		Rainfall	
	2008–2009	2009–2010	2008–2009	2009–2010
			mm	
September‡	347	345	189	24
October	172	161	41	92
November	67	64	32	24
March	53	57	76	16
April	150	218	165	74
May	315	365	109	129
June§	126	187	6	42
July	283	394	61	64
August	316	375	105	34
Sept. to Nov.‡	586	570	261	141
March to May	518	641	351	218
June to August§	725	956	171	140

† The GDD calculated with base 4° C for period of vetch growth (September to May) and base 10° C for period of sweet corn growth (June to August).

‡ Beginning after vetch planting (4 Sept. 2008; 5 Sept. 2009).

§ Beginning after sweet corn planting (21 June 2009; 14 June 2010).

Overwinter Survival of Hairy Vetch

The presence of a rye intercrop was associated with greater winter survival of hairy vetch in 2009–2010 ($p < 0.05$) but not 2008–2009. Averaged over variety, overwinter survival in vetch monoculture in 2009–2010 was 75%, compared to 100% for hairy vetch grown in mixture. Greater overwinter survival of hairy vetch growing in mixture with rye is consistent with Jannink et al. (1997) who reported an increase in hairy vetch overwinter survival from 68% in monoculture to 80% in mixture with rye in 1 yr in Maine. The mechanism responsible for this effect is not clear, but there are several possibilities. First, rye may improve retention of snow through changes in microclimate (e.g., reduced temperature through shading), or by acting as a windbreak. Greater snow retention is known to improve overwinter survival of many plants (Brandsaeter et al., 2008; Clark et al., 1997; Guldan and Martin, 2003; Jannink et al., 1997). Second, the fibrous roots of rye may reduce the extent of frost-heaving, which is also known to increase overwinter mortality (Clark, 2007). Third, the presence of rye may indirectly improve hairy vetch survival by providing a less favorable environment for pathogens or predators of hairy vetch. Studies in other cropping systems have demonstrated benefits of intercropping for pest suppression (reviewed in Vandermeer, 1989, p. 93–103).

Overwinter survival did not differ ($p > 0.05$) by variety in either year (Fig. 1). This result is consistent with previous

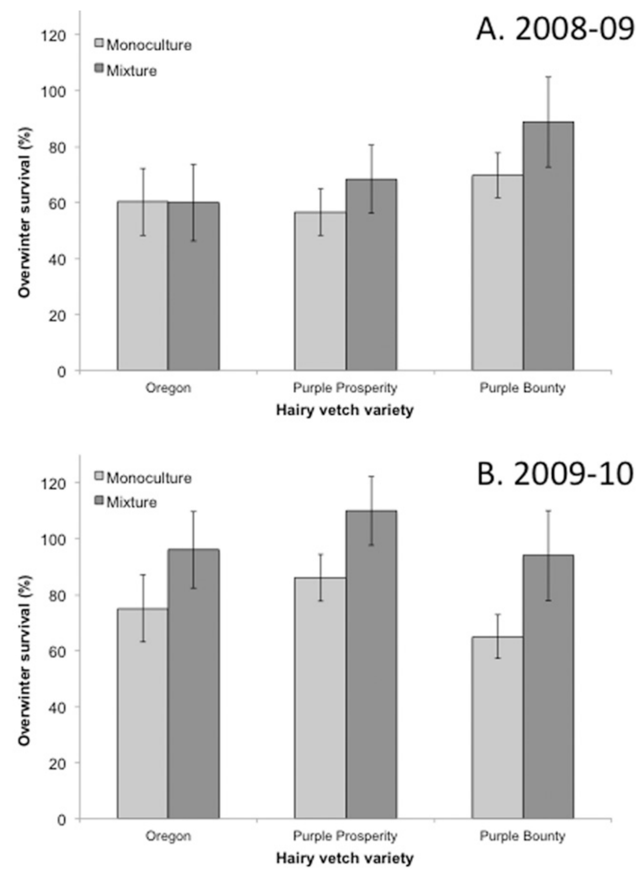

Fig. 1. Mean (± SEM) percent overwinter survival of three hairy vetch varieties grown in monoculture or in mixture with cereal rye, (A) 2008–2009 and (B) 2009–2010. Neither variety nor cropping system effects were significant (0.05) in 2008–2009. In 2009–2010, cropping system effects were significant ($p < 0.05$), but neither variety nor variety × cropping system interactions were significant (0.05).

reports that Purple Bounty and Purple Prosperity—in contrast with previously selected early-flowering lines—have comparable winter hardiness to commonly used, later-flowering varieties (Comis, 2008). However, it should be noted that in 2009–2010, estimated overwinter-mortality for Purple Prosperity grown in mixture exceeded 100% (Fig. 1). The most likely explanation for this overestimation of winter survival of Purple Prosperity is that some emergence occurred between fall and spring seedling counts. Such delayed germination and emergence is not uncommon with hairy vetch seed, which has physical dormancy characterized by a thick seed coat (Aarssen et al., 1986; Baskin et al., 2000).

Flowering Time and Regrowth

A close linear relationship between visual ratings of flowering time (Fp) and the number of flowering racemes per stem (Fn) was observed (Fig. 2). Using parameter estimates from this regression, the estimated Fn corresponding to 50% flowering was 6.32. In subsequent analysis, Fn was used as the response variable because it is a more objective and less variable measure of the extent of flowering.

In both years, cropping system (monoculture vs. mixture) and hairy vetch variety influenced Fn (Fig. 3a and 3b). As expected, Purple Bounty and Purple Prosperity had greater Fn then Oregon at the time of mowing. For example, averaged over cropping system, Fn at the time of mowing in 2009 was 1.7 for Oregon, 4.2 for Purple Prosperity and 6.0 for Purple Bounty. The earlier flowering of Purple Prosperity and Purple Bounty compared to Oregon is consistent with previous reports for these varieties, which were bred specifically for this characteristic (Comis, 2008).

In both years, hairy vetch grown in mixture with rye had more extensive flowering at the time of mowing than hairy vetch grown alone (Fig. 3a and 3b; system effect $p < 0.001$ in 2009 and 2010). In 2009, Purple Bounty and Purple Prosperity had 51% greater Fn when grown in mixture than when grown alone, although no effect of cropping system on the Fn of Oregon was detected. In 2010, hairy vetch averaged 38% more Fn when grown in mixture compared to monoculture. More extensive flowering of hairy vetch grown in mixture compared with monoculture may be related to changes in light quality perceived by hairy vetch when grown with rye. Accelerated flowering has been observed among plants subjected to shade, and is considered one of the suite of phytochrome-mediated shade avoidance responses of some plant species (Ballaré et al., 1990). Although changes in light quality were not measured in this experiment, the presence of a taller cereal rye cover crop in mixtures may have reduced the ratio of red to far-red light perceived by the developing hairy vetch cover crop. Alternatively, cereal rye may have reduced nutrient or water availability, both of which can induce accelerated flowering in some plants (Kolar and Senkova, 2008).

The greater extent of flowering of vetch at the time of mowing in 2010 compared to 2009 was likely due to warmer spring temperatures in 2010, especially during the month of April (Table 2). At the time of mowing, 123 more GDD had accumulated in 2010 compared to 2009. Hairy vetch growth and development is more sensitive to spring temperatures than fall temperatures because the spring is when most biomass production occurs (Brandsaeter et al., 2008; Clark, 2007; Guldan and Martin, 2003; Teasdale et al., 2004).

Contrary to expectations, regrowth of vetch after mowing did not occur for any of the varieties studied in either year (data not shown). Minor vetch regrowth was noticed only in unlevel areas of the field where the mower did not cut the vetch at the target height of approximately 5 to 10 cm. The risk of hairy vetch regrowth is generally considered to be greatest when mowing or crimping occurs before plants are at the 50 to 100% flowering stage (Clark et al., 1997; Moncada and

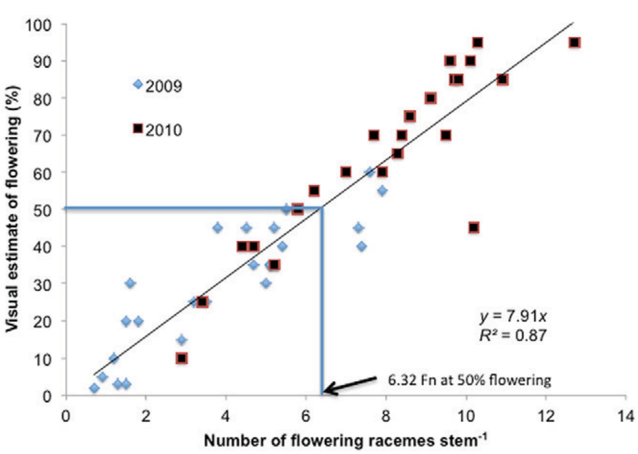

Fig. 2. Relationship between the number of flowering racemes per stem (Fn) and visual estimates of flowering percentage, 2009 and 2010.

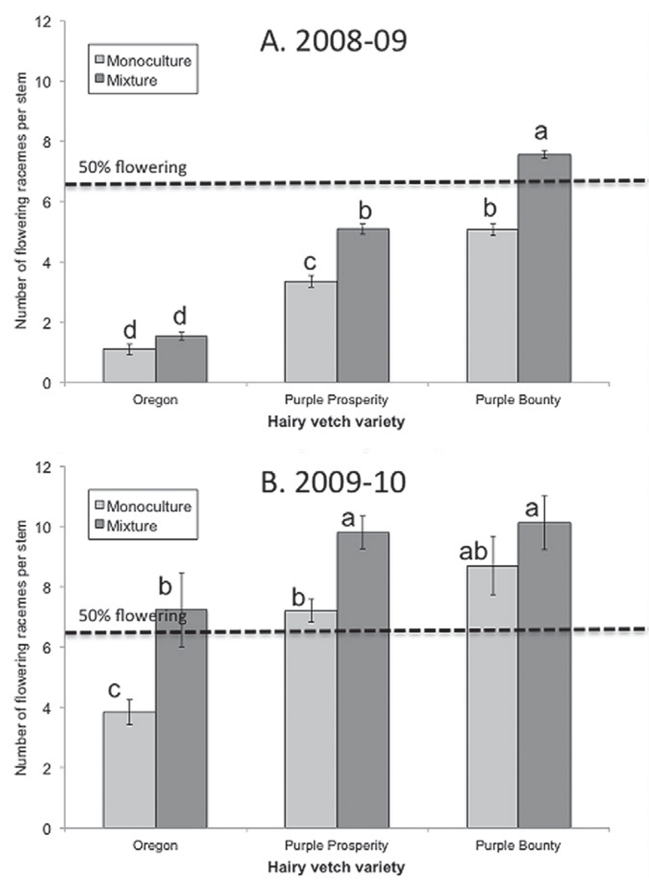

Fig. 3. Mean (± SEM) number of flowering racemes per stem (Fn) of three hairy vetch varieties grown in monoculture or in mixture with cereal rye, 2008–2009 (A) and 2009–2010 (B).

Sheaffer, 2011). Based on this information, in 2009 we would have expected regrowth for all hairy vetch varieties except Purple Bounty grown in mixture with cereal rye, since this was the only treatment exceeding 50% flowering (Fig. 3a). In contrast, in 2010, we would have expected potential regrowth *only* in Oregon grown in monoculture, since this was the only treatment with *less* than 50% flowering in that year (Fig. 3b). The fact that no regrowth occurred in any treatment in either year demonstrates that 50% flowering is not always required to successfully terminate hairy vetch with a flail mower. Although no advantage of early flowering for prevention of regrowth was observed in this study, it is likely that the early flowering varieties and mixtures of vetch with rye can reduce regrowth risk when less aggressive forms of mechanical kill such as roller crimping are used.

Cover Crop Biomass and Nitrogen Content

No differences in shoot dry weight were detected between hairy vetch varieties (data not shown). However, both hairy vetch dry weight and total cover crop dry weight were affected by cropping system (Fig. 4). In both years, hairy vetch biomass was greater when grown in monoculture than mixture, while total cover crop biomass was greatest in rye–vetch mixtures. Greater total hairy vetch biomass in monoculture compared to mixture is not surprising given that the seeding rate in mixture was half of the monoculture seeding rate. Total cover crop biomass in mixture was approximately 7000 kg ha^{-1} in 2009 and 6000 kg ha^{-1} in 2010, compared to approximately 4000 kg ha^{-1} for hairy vetch monocultures. Higher cover crop biomass in mixture was due to the large contribution of rye to total biomass.

Total hairy vetch shoot N content was affected by cropping system in both years ($p < 0.001$), but not by vetch variety (Fig. 5). Total hairy vetch shoot N content in mixture was 54% of that in monoculture in 2009, and 43% of that in monoculture in 2010. As with hairy vetch biomass, this result is not surprising given that hairy vetch seeding rates in mixture were 50% of those in monoculture. Total N content of cover crops was also affected by system in both years ($p < 0.01$ in 2009; $p < 0.03$ in 2010), but not by vetch variety (Fig. 5). Total cover crop N content in mixture was 77% of that in monoculture in 2009 and 65% of that in monoculture in 2010. Lower total N content in mixtures was due to lower N concentration in rye tissue compared to vetch tissue rather than lower total biomass (Fig. 4). These results also indicate that our calculated N credit was an underestimation of the contribution of N from hairy vetch residue relative to rye–vetch residue.

Nitrogen Fixation

The estimated %Ndfa was affected by cropping system in 2009 but not in 2010 (Table 3). Averaged across all three varieties in 2009, %Ndfa was 70% for hairy vetch grown in mixture vs. 58% for hairy vetch grown in monoculture. In 2010, %Ndfa was 73%, with no detectable differences between systems or varieties. Results from 2009 support the finding by Izaurralde et al. (1992) and Jensen (1996) that increased BNF efficiency can occur within legume–cereal bicultures.

In 2009, the effect of system on %Ndfa was influenced by variety (significant system × variety interaction; Table 3). In particular, the %Ndfa for Purple Prosperity and Purple Bounty was approximately twice that of Oregon when grown in monoculture, but equivalent to Oregon when grown in mixture. Oregon N fixation was apparently inhibited when grown in monoculture, while the early-flowering varieties were not. Although the reasons for such inhibition are unclear, it is possible that soil inorganic N status in monoculture vetch was higher than in mixtures with cereal rye, and may have suppressed N fixation.

The effect of cropping system on fixed N in hairy vetch shoots was marginally influenced by variety in both years (variety × system interaction $p < 0.06$). In 2009, Oregon grown in monoculture fixed about half as much N as the early flowering varieties (48 vs. 92 kg ha^{-1}), due to lower %Ndfa

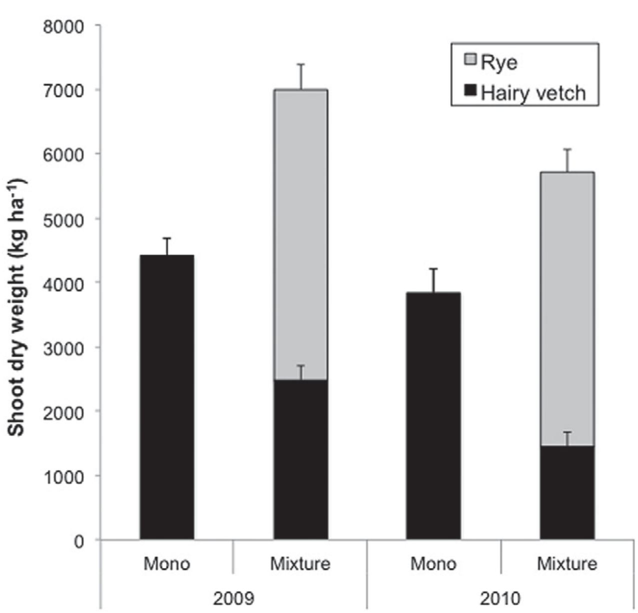

Fig. 4. Mean (± SEM) cover crop shoot dry weight at the time of mowing for hairy vetch monoculture ('mono') or rye–vetch mixtures, 2009 and 2010. Data within each cropping system is mean of all three varieties.

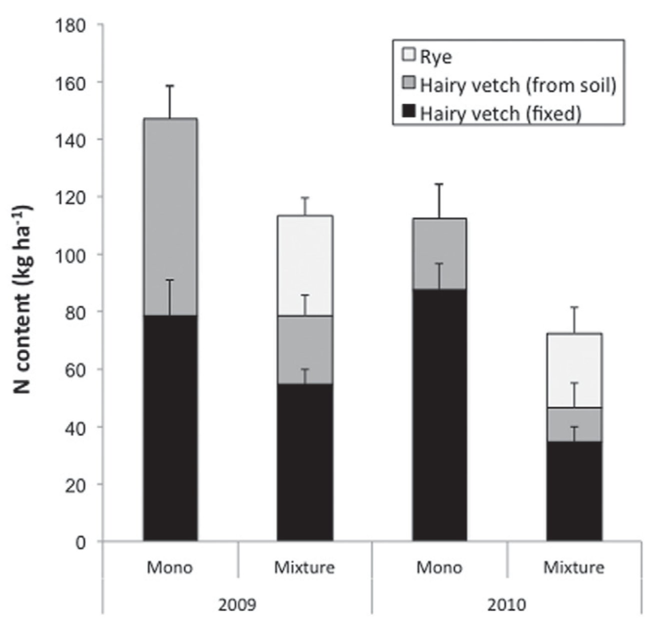

Fig. 5. Mean (± SEM) cover crop shoot N by source at the time of mowing for hairy vetch monoculture ('mono') or rye–vetch mixtures, 2009 and 2010. Data within each cropping system is mean of all three varieties.

Table 3. Estimated shoot N fixation and cost of nitrogen fixed (CNF), 2009 and 2010.

Cropping system and vetch variety	Estimated shoot N fixed†					
	Percentage		kg ha^{-1}		CNF‡	
	2009	2010	2009	2010	2009	2010
	—— % ——		— kg ha^{-1} —		— $ kg^{-1} —	
Monoculture						
Oregon	35a§	79	48a	89a	2.79c	1.19ab
Purple Prosperity	65b	62	93b	68ab	1.26bc	1.87ab
Purple Bounty	65b	71	90b	112a	1.22bc	0.95ab
In mixture with rye						
Oregon	63b	71	62ab	46b	0.90a	1.35a
Purple Prosperity	60b	75	60a	35bc	0.93ab	1.79ab
Purple Bounty	72b	77	42ab	22c	1.45bc	3.12b
Sources of variation	——— Significance of fixed effects ———					
System	+¶	ns#	ns	***	*	ns
Variety	ns	ns	ns	ns	ns	ns
System × variety	*	ns	+_	+	+	+

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† From Eq. [1] and [3].

‡ From Eq. [5].

§ Within columns, means followed by the same letter are not significantly different according to LSD (0.05)

¶ +, significant at the 0.10 probability level.

\# ns, nonsignificant at the 0.10 probability level.

(Table 3). In addition, in 2009, Purple Prosperity fixed more shoot N when grown in monoculture (93 kg ha^{-1}) than when grown in mixture (60 kg ha^{-1}) (Table 3) due to lower overall biomass production when grown in mixture (Fig. 4). In 2010, hairy vetch grown in mixture fixed less shoot N than hairy vetch grown in monoculture. This effect was due to lower shoot biomass production in mixture, not lower %Ndfa (Table 3). Purple Bounty was most sensitive to the system effect in 2010, fixing roughly five times as much shoot N when grown in monoculture compared to mixture.

The estimated CNF by hairy vetch based on seed costs alone ranged from \$0.90 to \$3.12 kg^{-1} (Table 3). In 2009, CNF was affected by cropping system, with the cost in mixtures (\$1.09 kg^{-1}) lower than that for monocultures (\$1.71 kg^{-1}). In contrast, in 2010, no cropping system effect was detected for CNF. In several cases, the effect of cropping system on CNF differed with hairy vetch variety, although these interactions had marginal significance ($p < 0.10$). These estimates of CNF can be compared to the cost of obtaining N from other sources. For example, the cost of N from urea fertilizer ranged from \$0.98 to \$1.24 kg^{-1} over the last 5 yr (USDA-Economic Research Service, 2011). These results suggest that for a grower already using cereal rye, the additional seed costs associated with substitution of hairy vetch or rye–vetch mixtures would be partially offset by N fertilizer savings. Of course this comparison is complicated by the fact that the proportion of N released from organic N sources and available for use by subsequent crops varies with N source (Agehara and Warncke, 2005; Ranells and Wagger, 1996). A second important caveat in comparing hairy vetch CNF estimates with fertilizer prices is that the potential benefits and costs associated with hairy vetch include many elements beyond N fixation including improvements in soil physical properties, erosion protection, and weed suppression (Clark, 2007; Hill et al., 2006; Teasdale and Mohler, 2000).

Sweet Corn Yield

No effects of hairy vetch variety or cropping system on sweet corn yield or quality were detected in either year (Table 4). However, large variability in sweet corn yield, especially in 2010, limited the ability to detect treatment differences. Nonetheless our results demonstrate that differences in N content of cover crops do not necessarily translate into differences in crop yield. For example, in 2010, the amount of fixed N and total N in monoculture was greater than that in mixture (Fig. 5), and the same amount of N fertilizer was applied in both, but no system differences in sweet corn yield were observed. One explanation for this result is that rates of N loss from vetch

Table 4. Mean (± MSE) sweet corn yield and quality characteristics, 2009 and 2010.

Cropping system and vetch variety	Marketable yield		Characteristics of marketable ears			
			Length	Weight		Soluble solids
	2009	2010	2009/2010	2009	2010	2009/2010
	—— thousands of ears ha^{-1} ——		cm ear^{-1}	——— kg ear^{-1} ———		°Bx†
Monoculture						
Oregon	12.9(2.2)	22.4(1.8)	17.1(0.3)	0.37(0.07)	0.25(0.07)	19.9(0.1)
Purple Prosperity	18.7(3.2)	19.5(3.8)	17.4(0.1)	0.36(0.08)	0.26(0.15)	19.2(0.2)
Purple Bounty	17.0(4.6)	20.0(3.4)	17.7(0.2)	0.33(0.07)	0.30(0.17)	19.8(0.2)
Mixture						
Oregon	19.2(2.5)	17.2(2.0)	17.7(0.3)	0.35(0.12)	0.30(0.16)	19.7(0.3)
Purple Prosperity	20.2(1.5)	20.1(0.9)	17.8(0.2)	0.35(0.04)	0.30(0.10)	19.3(0.1)
Purple Bounty	15.2(2.0)	21.3(1.0)	17.8(0.1)	0.37(0.10)	0.28(0.10)	20.5(0.1)
Sources of variation	——— Significance of fixed effects ———					
Cropping system (CS)	ns‡	ns	ns	ns	ns	ns
Variety (V)	ns	ns	ns	ns	ns	ns
CS × V	ns	ns	ns	ns	ns	ns

† Degrees Brix (see methods for definition and interpretation of °Bx obtained from refractometer).

‡ ns, nonsignificant at the 0.05 probability level.

monoculture may exceed those for rye–vetch mixtures due to the higher C/N ratio in mixture (Rosecrance et al., 2000; Wagger et al., 1998). Rosecrance et al. (2000) observed more rapid rates of N mineralization from pure vetch residue compared to rye–vetch mixtures and hence greater potential for N losses due to leaching prior to significant crop N uptake. On the sandy soils of this experiment, N losses due to leaching were potentially more important than on finer-textured soils.

Overall, yields observed in this study (17,000 marketable ears ha^{-1} in 2009 and 20,000 ears ha^{-1} in 2010) were low relative to U.S. averages for conventionally grown fresh market sweet corn. For example, the average yield of fresh market sweet corn in Michigan in 2009 was approximately 26,000 ears ha^{-1} (USDA-Economic Research Service, 2010). Lower than average yields may have been related to i) the sandy soil of the experimental site, which may have resulted in periods of drought stress, or nutrient losses through leaching; and/or (ii) negative effects of strip-tillage on sweet corn establishment and growth. Although strip-tilled sweet corn yields are often equivalent to conventional tillage, strip-tillage can create challenges for crop and pest management that may reduce yields in some years (Luna and Staben, 2003).

CONCLUSION

In summary, our results demonstrate that mixtures of hairy vetch with rye provide several potential advantages compared to vetch monoculture including (i) greater overwinter survival (Fig. 1); (ii) accelerated flowering (Fig. 2), and (iii) improved efficiency of N fixation—for the Oregon variety in 2009 (Table 3). The accelerated flowering response of hairy vetch in mixture is a unique finding, and suggests that more consistent mechanical kill of vetch may occur when mixtures are used. Observed varietal differences in flowering timing and N fixation deserve further investigation by plant breeders, horticulturalists, and agronomists interested in optimized cover crop management.

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