Effects of Spring-sown Cover Crops on Establishment and Growth of Hairy Galinsoga (*Galinsoga ciliata*) and Four Vegetable Crops

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Abstract. Hairy galinsoga [*Galinsoga ciliata* (Raf.) Blake] has become a troublesome weed in vegetable crops. Field studies were conducted in 2006 and 2007 in central New York to determine the effects of: 1) spring-sown cover crops on hairy galinsoga growth and seed production during cover crop growth grown before subsequent short duration vegetable crops; and 2) cover crop residues on establishment of hairy galinsoga and four short-duration vegetable crops planted after cover crop incorporation. The cover crops [buckwheat (*Fagopyrum esculentum* Moench), brown mustard (*Brassica juncea* L.), yellow mustard (*Sinapis alba* L.), and oats (*Avena sativa* L.)] were planted in May and incorporated in early July. Lettuce (*Lactuca sativa* L.) and Swiss chard [*Beta vulgaris* var. *cicla* (L.) K. Koch] were transplanted and pea (*Pisum sativum* L.) and snap bean (*Phaseolus vulgaris* L.) were sown directly into freshly incorporated residues. Above-ground dry biomass produced by the cover crops was 4.2, 6.4, 6.8, and 9.7 mg·ha⁻¹ for buckwheat, brown mustard, yellow mustard, and oats, respectively. Cover crops alone reduced the dry weight (90% to 99%) and seed production of hairy galinsoga (98%) during the cover crop-growing season compared with weedy controls. In 2006, only yellow mustard residue suppressed hairy galinsoga emergence (53%). However, in 2007, all cover crop residues reduced hairy galinsoga emergence (38% to 62%) and biomass production (25% to 60%) compared with bare soil, with yellow mustard providing the greatest suppression. Cover crop residues did not affect snap bean emergence, but reduced pea emergence 25% to 75%. All vegetable crops were suppressed by all cover crop residues with crops ranked as: pea > Swiss chard ≥ lettuce > snap bean in terms of sensitivity. The C:N ratios were 8.5, 18.3, 22.9, and 24.8 for buckwheat, brown mustard, yellow mustard, and oat residues, respectively. Decomposition rate and nitrogen release of brown mustard and buckwheat residues was rapid; it was slow for oats and yellow mustard residues. Spring-sown cover crops can contribute to weed management by reducing seed production, emergence, and growth of hairy galinsoga in subsequent crops, but crop emergence and growth may be compromised. Yellow mustard and buckwheat sown before late-planted snap beans deserve further testing as part of an integrated strategy for managing weeds while building soil health.

Cover crops improve soil health and can be beneficial for weed management by suppressing weeds at different stages. During the cover crop growth period, cover crops can reduce weed growth and seed production through direct competition or allelopathic effects (Chou, 1999; Liebman and Davis, 2000). Live cover crops such as red clover may also provide a beneficial habitat for

weed seed predators such as crickets or carabid beetles, which can increase weed seed mortality (Davis and Liebman, 2003). After incorporation into soil, cover crop residues may suppress weeds by inhibiting weed emergence and growth through allelopathy (Kumar et al., 2008b; Weston, 1996), immobilizing nitrogen (Dyck and Liebman, 1994; Kumar et al., 2008a; Samson, 1991), mulch effects (Teasdale, 1998; Teasdale and Mohler, 1993, 2000), or through interactions with pathogens (Conklin et al., 2002). In many northern states of the United States, short-duration cover crops such as buckwheat, yellow and brown mustard, and oats can be planted in spring before short-duration, late-planted vegetable crops for weed management in vegetable cropping system.

Brassica cover crops can suppress weeds (Al-Khatib et al., 1997; Boydston and Al-Khatib, 1994; Haramoto and Gallandt, 2004; Krishnan et al., 1998), nematodes (Mojtahedi et al., 1993), insects (Blau et al., 1978; Williams et al., 1993), and diseases (Angus

et al., 1994; Sarwar et al., 1998). Brassica plants contain glucosinolates that are further hydrolyzed by the enzyme myrosinase to form isothiocyanates (ITCs), compounds toxic to a variety of soilborne plant pests, including weeds (Brown and Morra, 1997; Morra and Kirkegaard, 2002). Reports have described the role of ITC in inhibition of plant growth and seed germination (Petersen et al., 2001; Teasdale and Taylorson, 1986). Greenhouse and field studies have reported the role of brassica cover crop residues in reducing emergence and growth of weeds (Al-Khatib et al., 1997; Boydston and Hang, 1995; Haramoto and Gallandt, 2004; Krishnan et al., 1998). Among mustard cover crops, brown and yellow mustard are readily available, inexpensive, and thought to have good weed-suppressive potential. For example, Shuler et al. (2005) found that brown mustard residue was effective at reducing weeds in a subsequent snap bean crop. Yellow mustard (var. Idagold) has high glucosinolate content and is therefore thought to have good weed-suppression potential (Haramoto and Gallandt, 2005b).

Buckwheat (*Fagopyrum esculentum* Moench) is commonly used in organic vegetable production and has potential as a short-duration cover crop in both organic and conventional systems. Its fast growth and short life cycle make it an ideal choice for niches where the soil would otherwise be left bare during short periods in the late spring or summer. Studies have demonstrated the strong weed-suppressive abilities of buckwheat during crop growth (Creamer and Baldwin, 2000; Golisz et al., 2002; Iqbal et al., 2003; Tominaga and Uezu, 1995). Buckwheat residues may also contribute to weed management by inhibiting emergence and growth of weeds (Haramoto and Gallandt, 2005b; Xuan and Tsuzuki, 2004). Freshly incorporated buckwheat residues reduced and delayed the emergence of red-root pigweed (*Amaranthus retroflexus* L.) and lambsquarters (*Chenopodium album* L.) (Haramoto and Gallandt, 2005b). Pellets made of buckwheat shoots reduced the dry weight (60%) and density (75% to 80%) of weeds in paddy rice (*Oryza sativa* L.) (Xuan and Tsuzuki, 2004). Like with mustard cover crops, chemicals isolated from buckwheat have inhibitory effects on weeds (Golisiz et al., 2007; Iqbal et al., 2002, 2003; Xuan and Tsuzuki, 2004). In field and growth chamber studies, soil amended with buckwheat residues reduced emergence of various weeds, including Powell amaranth (*Amaranthus powellii* S. Wats) (Kumar, 2008). For some weed species (e.g., *Capsella bursa-pastoris*), this suppression was the result of immobilization of nitrogen, whereas for Powell amaranth, allelochemicals concentrated in shoot tissue appear to have played an important role (Kumar et al., 2008a, 2008b).

Hairy galinsoga [*Galinsoga ciliata* (Raf.) Blake], a summer annual broadleaf weed with worldwide distribution, can reduce yields from 10% to 50% in a wide range of

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vegetable crops (Warwick and Sweet, 1983). Chemical weed control options for this species are limited within many vegetable crops because many registered herbicides have limited efficacy against this weed. Moreover, hairy galinsoga can produce up to 1.3 million seeds/m² in unmanaged fields (Brainard, unpublished data). Hairy galinsoga can also produce viable seeds very rapidly, often within 35 to 40 d of plant emergence (Brainard, 2002; Warwick and Sweet, 1983). Most studies evaluating weed-suppressive ability of cover crops during cover crop growth period estimate only reduction in biomass and do not estimate number of weed seed produced. It is very important to estimate number of seeds produced by hairy galinsoga under cover crop canopies at cover crop termination in the context of a short-season green manure crop followed by a short-season vegetable crop. This is because fresh hairy galinsoga seeds are nondormant, and seed produced during the cover crop growth period will create problems in the succeeding vegetable crops. Competition from a rye cover crop reduced hairy galinsoga seed production and delayed the timing of seed production (Brainard, 2002). Because hairy galinsoga seeds are relatively short-lived (3 to 4 years), practices that prevent seed production can be useful in rapidly reducing hairy galinsoga populations (Warwick and Sweet, 1983). The potential for cover crops to inhibit seed production and emergence of this weed in subsequent vegetable crops has not been examined.

Although cover crop residues can suppress weed emergence and biomass production, crop establishment and yield may be affected. However, large-seeded species (e.g., snap beans, corn) are more tolerant to physical and chemical stresses caused by cover crop residues than are many small-seeded weed species (Westoby et al., 1996). Adverse effects of residues on seed germination are also avoided when transplants are used. However, effects of cover crop residues on transplant growth have not been extensively tested.

Because nitrogen is an important stimulant of weed seeds of many weed species and a critical factor in the growth of both weeds and crops, the C:N ratio and decomposition rates of cover crops can have important effects on weed-crop competition.

The central objectives of this study were to examine the: 1) effects of spring-sown buckwheat, brown mustard (*Brassica juncea* L.), yellow mustard (*Sinapis alba* L.), and oat (*Avena sativa* L.) cover crops on hairy galinsoga growth and seed production during cover crop growth; and 2) residue effects of these cover crops on establishment of hairy galinsoga and four short-duration vegetable crops planted immediately after cover crop incorporation. We hypothesized that cover crops would reduce seed production of hairy galinsoga during cover crop growth and that cover crop residues would suppress hairy galinsoga more than large-seeded [snap bean (*Phaseolus vulgaris* L.) and pea (*Pisum*

sativum L.)] and transplanted [lettuce (*Lactuca sativa* L.) and swiss chard [*Beta vulgaris* var. *cicla* (L.) K. Koch] vegetable crops.

Materials and Methods

Field procedures. Field studies were conducted on an Eel silt loam soil (fine loamy, nonacid mixed, mesic Fluvaquentic Eutrochrepts) at the H. C. Thompson Vegetable Research Farm in Freeville, NY, in 2006 and 2007. Fields were selected that were known to have had high densities of hairy galinsoga the previous year. Different fields were used each year. The fields were moldboard plowed, disked, fertilized, with 392 kg-ha⁻¹ of 13N–13P–13K fertilizer, and cultivated just before planting the cover crops.

In each year, five treatments were arranged in a randomized complete block design with four replications. The treatments included: 1) buckwheat; 2) brown mustard; 3) yellow mustard; 4) oat; and 5) bare soil (weed-free). Brown mustard, var. 'Florida broadleaf', yellow mustard, var. 'Tilney', and oat were sown on 1 May 2006 and 7 May 2007; buckwheat was sown on 25 May 2006 and 2007 using a Great Plains no-till drill in both years. The later planting date for buckwheat was used to avoid frost damage and to ensure that cover crops would be at an appropriate stage for incorporation before establishment of vegetables. Plots measured 3 × 9 m. Yellow mustard, buckwheat, and oats were sown at a seeding rate of 17, 78, and 134 kg-ha⁻¹, respectively, in both years. Brown mustard was sown with a seed rate of 12 kg-ha⁻¹ in 2006 and 17 kg-ha⁻¹ in 2007. Bare soil plots were maintained weed-free with glyphosate applications. Two weedy control (Weedy 1 and Weedy 2 for each planting date) were established within the bare soil plots by allowing weeds to grow in microplots (0.25 m²) to evaluate the effects of cover crops on weed growth and biomass for both cover crop planting dates. For each cover crop planting date, two microplots were established by covering weeds with plastic containers during glyphosate applications. Cover crop treatments were mowed, disked, and rototilled and bare soil plots disked and rototilled on 6 July 2006 and 2 July 2007 and then fertilized with 56 kg-ha⁻¹ of nitrogen as ammonium nitrate.

Immediately after cover crop incorporation, four vegetable crops (pea, snap bean, lettuce, and Swiss chard) were each planted in a single row within each main cover crop plot. Pea, var. 'Bolero', and snap bean, var. 'Hystyle', were drilled simultaneously with a Monosem two-row vacuum planter with 76-cm row spacing. 'Fordhook Giant' Swiss chard and 'Capistrano' Romaine-type lettuce were hand-transplanted at the three- to four-leaf stage at a 30-cm in-row and 38-cm between-row spacing. The location of both direct-seeded and transplanted crops was randomized within main plots. To avoid residue contamination, the outer row of the crop was 60 cm from the plot edge. Swiss chard and lettuce transplants were grown in

200-cell flats in soilless media (1:1 peat:vermiculite) for 4 weeks in a greenhouse before transplanting.

Cover crop sampling and in-season weed suppression. Immediately before mowing cover crops, shoots of both weeds (by species) and cover crops were counted and harvested from the same two permanent quadrats, oven-dried for 7 d at 65 °C and weighed. In addition, seed production by hairy galinsoga was estimated in cover crop and weedy plots just before mowing from the same permanent quadrats. In 2006, only mature flower heads were counted; in 2007, mature and immature flower heads were counted. Seed production per plant was estimated by multiplying flower head number by 29, the approximate number of seeds per flower head (Ivany, 1971).

Effects of cover crop residues on emergence and growth of hairy galinsoga and vegetable crops. Emergence of hairy galinsoga in-row was counted in four 0.15-m² rectangular frames (one from each crop row) per plot at 14 and 17 d after cover crop incorporation (DAI) in 2006 and 2007, respectively. In 2007, within each plot, hairy galinsoga emergence was also monitored in two 0.25-m² quadrats between rows (one between pea and snap bean and the other between lettuce and Swiss chard) at 34 DAI. In addition, hairy galinsoga plants were clipped at the soil surface from these quadrats, bagged, and dried at 65 °C for 7 d and weighed.

Emergence of snap bean and pea was estimated by counting numbers of plants/m of row at two random locations in each plot 20 d after planting (DAP) in 2006 and 10 DAP in 2007. To examine effects of cover crop residues on growth of lettuce and Swiss chard, five plants of each crop were harvested from each plot 20 d after transplanting (DATP) and fresh weight recorded in both years. In addition, in 2007, all lettuce and Swiss chard plants were harvested 31 DATP from each plot and fresh weight recorded. Effects of cover crop residues on snap bean dry weight were evaluated only in 2007 because in 2006, as a result of severe flooding, pea and snap bean died and dry weights were not able to be estimated. Five and 10 randomly chosen plants were clipped at the soil surface at 20 and 31 DAP, oven-dried for 7 d at 65 °C, and weighed.

Litterbag decomposition. Cover crop residue decomposition was evaluated using litterbag techniques described by Swift and Anderson (1989), which is considered the most used technique for estimating decomposition and nutrient release from plant materials in the field for its simplicity, reliability, replicability, and ability to exclude class of soil fauna (Vanlauwe et al., 1997a, b). Cover crop shoots were collected just before mowing on 2 July 2007 and cut into 4- to 5-cm pieces to simulate mowing. Rubberized nylon litterbags (0.30 × 0.30 m, 1-mm mesh size) were filled with 200 g of fresh residues of individual cover crops and buried at 5- to 10-cm depth in their respective plots to

simulate field condition of cover crop incorporation. The mesh size of the litterbags used in this study (1 mm) was small enough to prevent loss of litter as a result of breakage but sufficiently small to permit the access of decomposers (Sundarapandian and Swamy, 1999). Five litterbags of each cover crop residue were buried in each plot (total of 80 bags) and marked with flags. A subsample of each cover crop residue was oven-dried for 7 d at 65 °C to determine initial dry weight. Litterbags were retrieved 6, 10, 20, 30, and 34 d after burial. The residues recovered from each bag at each sampling time were cleaned carefully with a paint brush, oven-dried, weighed, and then ground using a Wiley mill to pass a 2-mm screen. Ground litter at each sampling date was analyzed for nitrogen using a LECO CN-2000 (St. Joseph, MI).

Statistical analysis. Data were subjected to analysis of variance and analyzed using the general linear model (GLM) procedures of the Statistical Analysis System (SAS Institute, 2001). Data were not transformed or log or square root transformed as needed to improve assumptions of normality and equal variance of population distributions. The year $\times$ treatment interactions were nonsignificant for any of the cover crop aboveground dry weights. Cover crop biomass was pooled over years. Other data were presented separately by years as a result of significant year $\times$ treatment interactions. Treatment mean values were separated by Fisher's protected least significant difference test at $P < 0.05$. For estimating weed suppression by cover crops during cover crop growth period, separate analysis was done for each planting date. Residue decomposition was analyzed by fitting a first-order exponential model: $Y_t = 100 \cdot \exp(-k \cdot t)$, where Y is percent dry weight or N remaining in the residue at time t (day) and k is decomposition rate constant (d^{-1}). The NLIN procedure of SAS was used to estimate the rate constant for each cover crop residue and then rate constants were analyzed using GLM procedures. The relationship of N release to time (days after incorporation/burial) of different cover crop residues was analyzed by fitting to a rectangular hyperbola model: $Y = ax/b + x$, where a is maximum N release with the constraint that maximum N release could not exceed 100% and b represents days after incorporation/burial when N release was equal to $a/2$, i.e., 50%. Curve fitting and parameter estimation was done using statistical package SigmaPlot 8.0 (SPSS Inc., Chicago, IL).

Results and Discussion

The amount of rainfall was higher in 2006 than in 2007 (Table 1). Higher rainfall after incorporation of cover crop residues occurred in July 2006 compared with 2007. In 2006, high precipitation led to overflowing of an adjacent creek, which flooded the trial 15 d after planting the vegetable crops. When the water drained away, emergence counts of pea and snap bean were taken; however, substantial and uneven moisture damage to

Table 1. Monthly rainfall and average monthly temperature in 2006 and 2007 at Freeville, NY.

Month	Precipitation			Air temperature		
	2006	2007	30-year avg	2006	2007	30-year avg
	(mm)			(°C)		
May	69	42	86	12.5	13.0	12.3
June	197	105	103	18.0	18.7	18.5
July	192	139	102	21.5	17.2	20.3
Total	458	286	291			
Average				17.3	16.3	17.0

Fig. 1. Mean ($\pm$ SE) aboveground dry weight ($mg \cdot ha^{-1}$) of spring-sown cover crops at Freeville, NY, at the time of incorporation into soil. Results did not vary by year, so data were combined for 2006 and 2007. Different letters indicate significant differences among treatments. Means were separated by Fisher's protected least significant difference (0.05).

the plants made biomass estimates unreliable. Fresh weights of lettuce and Swiss chard were taken. Flooding made evaluation of pea and bean dry weight impossible and added substantially to the variability of lettuce and Swiss chard dry weight estimates.

Cover crop biomass

Biomass production by the cover crops was consistent across years and was greatest for oats followed by yellow mustard and brown mustard and least for buckwheat (Fig. 1). Averaged over 2 years, aboveground dry weight produced by buckwheat, brown mustard, yellow mustard, and oats was 4.2, 6.4, 6.8, and 9.6 $mg \cdot ha^{-1}$, respectively.

Weed suppression during cover cropping

Initial weed density in weedy microplots and cover crop plots were similar at 15 d after cover crop sowing (data not shown). In 2007, cover crops had no effect on final density of hairy galinsoga during the cover crop growth period compared with weedy microplots. However, in 2006, final density of hairy galinsoga was 91%, 63%, and 30% lower in oats, brown mustard, and yellow mustard plots, respectively, compared with the Weedy 1 treatment (data not shown). High hairy galinsoga mortality in 2006 in oat and mustard plots was likely attributable in part to competition from dense canopy of these cover crops. Heavy flooding during cover crop growth in 2006 may have also contributed to death of plants weakened by competition.

All cover crops were very effective in reducing weed biomass. Reduction in bio-

mass in the cover crop plots compared with weedy controls ranged from 90% (buckwheat) to 99% (mustards and oats) (Table 2). Because Weedy 1 plots had longer duration of weed growth (24 d in 2006 and 18 d in 2007), weed biomass was higher in the Weedy 1 compared with the Weedy 2 microplots. In both years, final hairy galinsoga dry weight was higher in buckwheat plots compared with other cover crop plots despite the shorter duration of hairy galinsoga growth (Table 2). In both years, seed production per plant was reduced in all cover crop plots by at least 98% compared with weedy controls (Table 2). In the absence of cover crops, hairy galinsoga individuals produced almost 400 mature seeds/plant in 2006 and 44 mature seeds/plant in 2007. Given final hairy galinsoga density, these levels of fecundity correspond to 98,900 and 9,485 seeds/ m^2 , respectively. The year-to-year difference may be attributable, in part, to the shorter duration of weed growth in 2007 compared with 2006 (10 and 4 d shorter for Weedy 1 and Weedy 2, respectively). Hairy galinsoga seed production increases exponentially over time. In previous studies, hairy galinsoga seed production increased from 100 to over 10,000 seeds per plant over a 2-week period (Brainard, 2002).

Effects of cover crop residues on emergence of hairy galinsoga

In 2006, hairy galinsoga emergence was unaffected by cover crop residues other than yellow mustard (Table 3). Hairy galinsoga emergence at 14 DAI was 53% lower in

Table 2. Hairy galinsoga mean dry weight and seed production (per plant) in different cover crop treatments in 2006 and 2007 at the termination of cover crops at Freeville, NY.^z

Cover crop ^y	2006			2007			
	DW (g·m ⁻²)	Weed suppression (%)	Seed production ^x (no./plant)	DW (g·m ⁻²)	Weed suppression (%)	Seed production	
						Mature (no./plant)	Total
Brown mustard	5.6 c ^z	99	0.53 b	5.5 b	98	0.8 b	2.9 b
Yellow mustard	9.2 b	98	0.08 b	2.1 c	99	0.0 b	0.0 b
Oat	1.2 d	100	0.00 b	8.7 b	96	0.2 b	1.4 b
Weedy 1	405.0 a	—	391.50 a	231.4 a	—	43.9 a	341.1 a
ANOVA ^w	***	—	***	***	—	*	*
Buckwheat	13.6 b	90	0.38 b	7.8 b	89	0	0
Weedy 2	129.8 a	—	17.17 a	71.5 a	—	0	0.5
ANOVA	***	—	**	***	—	NS	NS

^zAfter termination of cover crops, short-duration vegetable crops were planted into freshly incorporated cover crop residues.

^yAs a result of the difference in cover crops planting dates, two controls were used: Weedy 1 was a comparison for brown mustard, yellow mustard, and oats and Weedy 2 was a comparison for buckwheat.

^xSeed production per plant was estimated by multiplying flower head number by 29, the approximate number of seeds per flower head (Ivany, 1971).

^wSignificant at * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; NS = nonsignificant ($P > 0.10$).

^zMeans within a column followed by the same letter are not significantly different at the 0.05 level according to Fisher's protected least significant difference. DW = dry weight; ANOVA = analysis of variance.

Table 3. Mean early emergence and growth of hairy galinsoga in freshly incorporated spring-sown cover crop residues in 2006 and 2007 at Freeville, NY.

Cover crop	Emergence			DW
	2006	2007		2007
	14 DAI ^z	17 DAI ^z	34 DAI ^y	34 DAI ^y
		(no./m ²)		(g·m ⁻²)
Buckwheat	162 ab ^x	285 b	414 b	164 b
Brown mustard	235 a	270 cb	343 b	126 bc
Yellow mustard	118 b	215 c	320 b	92 c
Oat	197 ab	345 b	362 b	126 bc
Bare soil	252 a	560 a	718 a	219 a

^zWeed emergence measured in-row.

^yWeed emergence and dry weight measured between-row.

^xMeans within a column followed by the same letter are not significantly different at the 0.05 level according to Fisher's protected least significant difference.

DW = dry weight; DAI = days after incorporation.

yellow mustard residues compared with bare soil plots. In 2007, residues of all the cover crops were effective in reducing hairy galinsoga emergence with yellow mustard again providing the most effective suppression. At 17 DAI, hairy galinsoga emergence was 38%, 49%, 52%, and 62% lower in oats, buckwheat, brown mustard, and yellow mustard plots, respectively, compared with bare soil plots. By 34 DAI, residues of all cover crops were equally effective in reducing hairy galinsoga emergence from 42% to 55%.

In 2007, hairy galinsoga dry weight was lower in all cover crop residue treatments compared with bare soil (Table 3). Hairy galinsoga biomass production was most inhibited by yellow mustard residues. Dry weight of hairy galinsoga was 25%, 42%, 42%, and 60% lower in buckwheat, brown mustard, oats, and yellow mustard residues, respectively, compared with bare soil.

Lower cover crop suppression of hairy galinsoga in 2006 compared with 2007 may have been attributable, in part, to leaching of allelochemicals as a result of heavy rainfall in 2006. Within 10 d of incorporation of cover crop residues, 81 mm of precipitation occurred in 2006 compared with 49 mm in 2007.

Our results are consistent with studies examining effects of mustard cover crops

on weeds. Residues of both spring- and fall-sown brassicas have shown weed-suppressive effects resulting from release of glucosinolate allelochemicals (Al-Khatib et al., 1997; Haramoto and Gallandt, 2005a; Norsworthy et al., 2005, 2007). In pot bioassays, incorporated yellow mustard residues suppressed emergence of several weed species from 49% to 97% (Al-Khatib et al., 1997). In field studies, lower weed densities were observed after incorporation of various brassica cover crops (Boydston and Hang, 1995; Haramoto and Gallandt, 2005a; Krishnan et al., 1998).

Fewer field studies have compared the effects of multiple cover crops on weeds. Haramoto and Gallandt (2005b) evaluated effects of spring-sown brassica and nonbrassica cover crops on subsequent emergence of several weeds, including hairy galinsoga and crop species, and found that both brassica and nonbrassica cover crops were equally suppressive. In contrast, suppression of hairy galinsoga was higher for mustard cover crops than by oat in 2007 (Table 3). Residue-mediated effects of spring-planted green manure crops on hairy galinsoga establishment, although not offering levels of weed control satisfactory to growers, will contribute to a lower initial seedling density and thus support their cultivation efforts, i.e., a lower

Table 4. Mean emergence of pea and snap bean in different cover crop treatments in 2006 and 2007 at Freeville, NY.^z

Cover crops	Pea ^y		Snap bean ^y	
	2006	2007	2006	2007
	(plants/m row)			
Buckwheat	5 b	4 c	15 a	22 a
Brown mustard	9 b	3 c	16 a	20 a
Yellow mustard	8 b	5 c	16 a	21 a
Oat	7 b	15 b	13 a	20 a
Bare soil	17 a	20 a	16 a	22 a

^zMeans within a column followed by the same letter are not significantly different at the 0.05 level according to Fisher's protected least significant difference.

^yPea and snap bean emergence was measured 20 d after sowing (DAS) in 2006, whereas in 2007, it was measured 10 DAS in 2007.

final population after cultivation kills a fixed proportion.

Effects of cover crop residues on vegetable crops

Effects on emergence of pea and snap bean. Pea emergence was inhibited by all cover crop residues compared with bare soil in both years (Table 4). In 2006, cover crops suppressed emergence equally with a 57% average reduction. In 2007, buckwheat and mustard cover crops reduced pea emergence by 80% on average, and oat reduced emergence by 25%. In contrast, snap bean emergence was unaffected by cover crop residues in either year.

Suppression of pea by yellow mustard and oat cover crop residues was previously reported by Jaakkola (2005), who found that pea emergence was reduced by 55% to 60% when planted 1 d after incorporation. In contrast, Al-Khatib et al. (1997) found that pea emergence was not inhibited in yellow mustard residue when planted 2 to 3 weeks after its incorporation. Our results also differ from those of Haramoto and Gallandt (2005b), who observed delayed and/or reduced emergence of snap beans planted 2

Table 5. Mean fresh weight of lettuce and Swiss chard and dry weight (DW) of snap bean at 20 and 31 d after sowing (DAS)/transplanting (DATP) in 2006 and 2007 at Freeville, NY.^z

Cover crop	Lettuce			Swiss chard			Snap beans	
	20 DATP		31 DATP	20 DATP		31 DATP	20 DAS	31 DAS
	2006	2007	2007	2006	2007	2007	2007	
	(fresh wt; g)			(fresh wt; g)			(DW; g)	
Buckwheat	42 a	25 b	181 b	32 b	24 b	169 b	0.60 b	1.98 ab
Brown mustard	34 a	20 cd	157 bc	24 b	21 b	160 b	0.58 b	1.93 ab
Yellow mustard	37 a	17 d	128 c	42 ab	23 b	136 b	0.52 b	2.10 ab
Oat	37 a	23 bc	153 bc	39 ab	22 b	147 b	0.60 b	1.87 b
Bare soil	56 a	46 a	249 a	55 a	48 a	261 a	0.86 a	2.40 a

^zMeans within a column followed by the same letter are not significantly different at the 0.05 level according to Fisher's protected least significant difference test.

weeks after incorporation of several mustard cover crops and buckwheat.

Effects on crop growth. In 2006, no differences in fresh weight of lettuce were detected in cover crop residues compared with bare soil (Table 5). However, Swiss chard fresh weight was reduced by ~50% in buckwheat and brown mustard residues compared with bare soil plots (Table 5). In 2006, fresh weight of lettuce was not different from other cover crop treatments as a result of large variability, which may be attributed to flooding that had occurred before biomass sampling in that year.

In 2007, growth of lettuce and Swiss chard was reduced in all cover crop treatments compared with bare soil at both 20 and 31 DATP (Table 5). However, reduction in fresh weight was lower at 31 DATP (27% to 48% in lettuce and 35% to 48% in Swiss Chard) compared with 20 DATP (46% to 63% in lettuce and 50% to 56% in Swiss chard). Lettuce fresh weight was reduced more in mustard residues than in buckwheat and oat residues at 20 DATP, whereas at 31 DATP, reduction in fresh weight was similar in all cover crop treatments. Growth of Swiss chard was reduced similarly in all cover crop treatments compared with bare soil at both 20 and 31 DATP.

In 2007, at 20 DAP, dry weight of snap bean was reduced by 30% to 40% in plots with cover crop compared with bare soil (Table 5). However, negative effects of cover crops were no longer detectable by 31 DAP, except in oat residues, which reduced snap bean dry weight by 22%. Haramoto and Gallandt (2005a) reported reductions in growth of green beans (*Phaseolus vulgaris* L.) after yellow mustard even when they were

planted 2 weeks after incorporation. Soybean [*Glycine max* (L.) Merr] biomass was reduced in plots with brown and yellow mustard residues when planted immediately after incorporation compared with no cover crop treatment (Krishnan et al., 1998).

Cover crop C:N ratio and decomposition

Initial residue quality. Nitrogen content of cover crops ranged from 4.3% for buckwheat to 1.8% for oats (Table 6). The C:N ratio ranged from 8.5 in buckwheat to 24.8 in oats. Because a C:N ratio of 20 is generally considered the threshold between net mineralization and immobilization of N in the soil by microbes (Harmsen and Van Schreven, 1955; Iritani and Arnold, 1960), buckwheat and brown mustard cover crops were unlikely to have tied up significant N after incorporation, whereas yellow mustard and oats may have contributed to N tieup.

Dry matter loss. Decomposition rates of buckwheat and brown mustard residues were rapid compared with yellow mustard and oat residues (Table 7). The decomposition rate estimates (k) of buckwheat and brown mustard (0.0488 and 0.0564/d, respectively) did not differ but were higher than those of yellow mustard and oat residues (0.0303 and 0.0214/d, respectively). Within 20 d, buckwheat and brown mustard residues lost 65% and 71% of their initial weight, respectively, compared with 41% for yellow mustard and 21% for oats.

Release of nitrogen. Nitrogen release was also more rapid from buckwheat and brown mustard residues than from oats and yellow mustard (Fig. 2). Buckwheat and brown mustard residue released 50% of their initial N within 5 d, whereas yellow mustard and oats took 20 and 24 d, respectively (see parameter *b* value; Table 8).

Rapid decomposition of buckwheat and brown mustard compared with yellow mustard and oat residues may be explained in part by initial higher N and lower C:N ratios of their residues than for yellow mustard and oat residues (Table 6). Rapid release of N by buckwheat and brown mustard residues compared with yellow mustard and oats residues may also be explained by higher initial N level and lower C:N ratios in their residues. The C:N ratio of the residue is most widely used as an index to predict decomposition rate and nutrient release (Gupta and Singh, 1981; Heal et al., 1997; Swift et al., 1979). However, initial decomposition rate of brown mustard was more rapid than buckwheat residues although its residues had higher C:N (two times) and lower N content than buckwheat residues (Tables 6 and 7). The N release pattern for buckwheat and brown mustard residues was similar, although both varied in N concentration and C:N ratio. This suggests that factors other than N and C:N ratio play important roles in residue decomposition and nutrient release from decomposing residues. Residue weight loss and nutrient release are also influenced by structural plant compounds such as lignin (L), polyphenols (PP), and L:N ratio and PP:N ratios (Fox et al., 1990; Oglesby and Fownes, 1992; Palm and Sanchez, 1991; Tian et al., 1992), which may have varied across cover crops in this study.

The mechanisms by which cover crop residues in this study suppressed weeds and crops are unclear. In the case of oats and yellow mustard, relatively high C:N ratios and slow decomposition suggest that N tieup may have played an important role in reducing vigor and dry weight of weeds and crops. Tying up of N after incorporation of these cover crops may have reduced germination of hairy galinsoga. Allelopathy or interactions with fungal pathogens may also have played a suppressive role in some cases. Previous research on the suppressive effects of buckwheat residues suggests that N tieup, allelochemicals, and interactions with fungal pathogens can all play a role in suppressing weeds and that the most important mechanism can vary with weed species and life stage (Kumar, 2008).

The results demonstrate that use of buckwheat, yellow and brown mustard, and oats as spring-sown cover crops before late-planted vegetable crops can contribute to management of hairy galinsoga by direct

Table 6. Some chemical characteristics of buckwheat, brown mustard, yellow mustard, and oat residues at cover crop termination in 2007 at Freeville, NY.^z

Cover crop residues	N	C	C:N
	----- (%) -----	----- (%) -----	
Buckwheat	4.3 a	36.9 c	8.5 c
Brown mustard	2.3 b	41.5 b	18.3 b
Yellow mustard	1.9 c	43.4 a	22.9 a
Oats	1.8 c	44.5 a	24.8 a

^zMeans within a column followed by the same letter are not significantly different at the 0.05 level according to Fisher's protected least significant difference.

Table 7. Decomposition rate (k) for dry weight (DW) loss and DW remaining of buckwheat, brown and yellow mustard, and oat residues in a litterbag experiment at 6, 10, 20, 30, and 34 d after burial at Freeville, NY.^z

	k	Days after burial				
		6	10	20	30	34
	(d ⁻¹)	(DW remaining; % of initial wt)				
Buckwheat	0.0488 c	85 bc	75 b	35 c	20 c	16 c
Brown mustard	0.0564 c	79 c	45 c	29 c	23 c	20 c
Yellow mustard	0.0303 b	93 ab	85 ab	59 b	37 b	37 b
Oats	0.0214 a	97 a	95 a	79 a	51 a	45 a

^zMeans within a column followed by the same letter are not significantly different at the 0.05 level according to Fisher's protected least significant difference.

Fig. 2. Predicted nitrogen (N) release from buckwheat, brown mustard, yellow mustard, and oats residues as a function of days after their incorporation. Rectangular hyperbola model was used with the constraints that maximum N release (a) could not exceed 100%. Initial N (kg ha⁻¹) in different cover crops was calculated by multiplying cover crop biomass with their respective N content at cover crop termination.

Table 8. Parameter (a, b) estimates ($\pm$ SE) and R^2 for the rectangular hyperbola model of different cover crops describing nitrogen release (%) from decomposing residue as a function of days after incorporation.²

Cover crops	Parameters of hyperbola		R^2
	a	b	
Buckwheat	100	4.5 $\pm$ 0.7	0.96
Brown mustard	100	6.2 $\pm$ 0.8	0.98
Yellow mustard	100	16.7 $\pm$ 5.1	0.91
Oats	100	23.0 $\pm$ 8.5	0.88

²Equation of rectangular hyperbola model: $Y = ax / (b + x)$, where parameter a is maximum N release with the constraint that maximum N release could not exceed 100% and parameter b represent days after incorporation/burial when N release was equal to a/2, i.e., 50%.

interference with its growth and seed production and through residue-mediated effects on its emergence and growth in subsequent crops. Cover crops sown in early May reduced seed production from $\approx 100,000$ seeds/m² in untreated plots to near zero. Emergence of hairy galinsoga after cover crop incorporation was reduced from 0% to 53% in 2006 and 42% to 55% in 2007 compared with bare soil. Among cover crops, yellow mustard residues were found most effective in reducing hairy galinsoga emergence and growth in both years. However, cover crop residues can also adversely affect crops. Snap bean emergence was unaffected, but pea emergence was drastically reduced in all the cover crop residues. Growth of all the vegetables was reduced in all cover crop residues and their growth inhibition varied

in the following order: pea > Swiss chard $\geq$ lettuce > snap bean. Although snap bean growth was suppressed initially, by 31 d after sowing, snap bean dry weight was not significantly reduced in buckwheat and mustard cover crop treatments.

Successful adoption of cover crops for weed management depends on identifying cover crops that suppress weeds without suppressing the crop. Results of this study suggest the potential of including yellow mustard or buckwheat before late-planted snap beans as part of integrated strategies for managing hairy galinsoga while building soil health. However, more research is needed to understand the mechanisms by which these cover crops suppress weeds and crops. With this type of information, cover crop systems may be optimized for selective management of weeds in horticultural crops.

Literature Cited

- Al-Khatib, K., C. Libbey, and R. Boydston. 1997. Weed suppression with Brassica green manure crops in green pea. *Weed Sci.* 45:439–445.
- Angus, J., P. Gardner, J. Kirkegaard, and J. Desmarchelier. 1994. Biofumigation: Isothiocyanates released from *Brassica* roots inhibit growth of the take-all fungus. *Plant Soil* 162:107–112.
- Blau, P.A., P. Feeny, L. Contardo, and D.S. Robson. 1978. Allylglucosinolate and herbivorous caterpillars: A contrast in toxicity and tolerance. *Science* 200:1296–1298.
- Boydston, R. and A. Hang. 1995. Rapeseed (*Brassica napus*) green manure crop suppresses weeds in potato (*Solanum tuberosum*). *Weed Technol.* 9:669–675.

- Boydston, R.A. and K. Al-Khatib. 1994. Brassica green manure crops suppress weeds. *Proc. West. Weed Sci. Soc.* 47:24–27.
- Brainard, D.C. 2002. Weed management implications of a broccoli-winter rye intercropping system. Cornell Univ., Ithaca, NY, PhD Diss.
- Brown, P.D. and M.J. Morra. 1997. Control of soil-borne plant pests using glucosinolate-containing plants. *Adv. Agron.* 61:167–231.
- Chou, C.H. 1999. Roles of allelopathy in plant biodiversity and sustainable agriculture. *Crit. Rev. Plant Sci.* 18:609–636.
- Conklin, A.E., M.S. Erich, M. Liebman, D. Lambert, E.R. Gallandt, and W.A. Halteman. 2002. Effects of red clover (*Trifolium pratense*) green manure and compost soil amendments on wild mustard (*Brassica kaber*) growth and incidence of disease. *Plant Soil* 238:245–256.
- Creamer, N.G. and K.R. Baldwin. 2000. An evaluation of summer cover crops for use in vegetable production systems in North Carolina. *HortScience* 35:600–603.
- Davis, A.S. and M. Liebman. 2003. Cropping system effects on *Setaria faberi* seed bank dynamics. *Asp. Appl. Biol.* 69:83–91.
- Dyck, E. and M. Liebman. 1994. Soil fertility management as a factor in weed control: The effect of crimson clover residue, synthetic nitrogen fertilizer, and their interaction on emergence and early growth of lambsquarters and sweet corn. *Plant Soil* 167:227–237.
- Fox, R.H., R.J.K. Myers, and I. Vallis. 1990. The nitrogen mineralization rate of legume residues in soil as influenced by their polyphenol, lignin and nitrogen contents. *Plant Soil* 129:251–259.
- Golisz, A., D. Ciarka, and S.W. Gawronski. 2002. Allelopathy activity of buckwheat (*Fagopyrum esculentum* Moench), p. 161. In: Fujii, Y., S. Hidarate, H. Araya (eds.). *Proceedings III World Congress on Allelopathy*. Sato Printing, Tsukuba City, Ibaraki, Japan.
- Golisz, A., B. Lata, S.W. Gawronski, and Y. Fujii. 2007. Specific and total activities of the allelochemicals identified in buckwheat. *Weed Biol. Manage.* 7:164–171.
- Gupta, S.R. and J.S. Singh. 1981. The effect of plant species, weather variables and chemical composition of plant material on decomposition in tropical grassland. *Plant Soil* 59:99–117.
- Haramoto, E.R. and E.R. Gallandt. 2004. Brassica cover cropping for weed management: A review. *Renew. Agr. Food Syst.* 19:187–198.
- Haramoto, E.R. and E.R. Gallandt. 2005a. Brassica cover cropping: II. Effects on growth and interference of green bean (*Phaseolus vulgaris*) and redroot pigweed (*Amaranthus retroflexus*). *Weed Sci.* 53:702–708.
- Haramoto, E.R. and E.R. Gallandt. 2005b. Brassica cover cropping: I. Effects on weed and crop establishment. *Weed Sci.* 53:695–701.
- Harmsen, G.W. and D.A. Van Schreven. 1955. Mineralization of organic nitrogen in soil. *Adv. Agron.* 7:299–395.
- Heal, O.W., J.M. Anderson, and M.J. Swift. 1997. Plant litter quality and decomposition: An historical overview, p. 3–30. In: Cadish, G., and K.E. Giller (eds.). *Driven by nature: Plant litter quality and decomposition*. CAB International, Wallingford, UK.
- Iqbal, Z., S. Hiradate, A. Noda, S. Isojima, and Y. Fuji. 2002. Allelopathy of buckwheat: Assessment of allelopathic potential of extract of aerial parts of buckwheat and identification of fagomine and other related alkaloids as allelochemicals. *Weed Biol. Manage.* 2:110–115.
- Iqbal, Z., S. Hiradate, A. Noda, S. Isojima, and Y. Fuji. 2003. Allelopathic activity of buckwheat:

- Isolation and characterization of phenolics. *Weed Sci.* 51:657–662.
- Iritani, W.M. and C.Y. Arnold. 1960. Nitrogen release of vegetable crop residues during incubation as related to chemical composition. *Soil Sci.* 89:74–82.
- Ivany, J.A. 1971. *Galinsoga ciliata* (Raf.) Blake and *G. parviflora* Cav.: Germination, growth, development and control, Cornell University, Ithaca, NY, PhD Diss.
- Jaakkola, S. 2005. White mustard mulch is ineffective in weed control, p. 227–232. In: Harper, J.D.I., M. An, H. Wu, and J.H. Kent (eds.), *Proc. 4th World Congress on Allelopathy*, International Allelopathy Society, Charles Sturt University, Wagga Wagga, NSW, Australia.
- Krishnan, G., D.L. Holshouser, and S.J. Nissen. 1998. Weed control in soybean (*Glycine max*) with green manure crops. *Weed Technol.* 12: 97–102.
- Kumar, V. 2008. Effects of summer annual cover crops on weed population dynamics. Cornell Univ., Ithaca, NY, PhD Diss.
- Kumar, V., D.C. Brainard, and R.R. Bellinder. 2008a. Suppression of Powell amaranth (*Amaranthus powellii*), shepherd's-purse (*Capsella bursa-pastoris*), and corn chamomile (*Anthemis arvensis*) by buckwheat residues: Role of nitrogen and fungal pathogens. *Weed Sci.* 56:271–280.
- Kumar, V., D.C. Brainard, and R.R. Bellinder. 2008b. Suppression of Powell amaranth (*Amaranthus powellii*) by buckwheat residues: Role of allelopathy. *Weed Sci.* 57:66–73.
- Liebman, M. and A.S. Davis. 2000. Integration of soil, crop and weed management in low-external-input farming systems. *Weed Res.* 40:27–47.
- Mojtahedi, H., G. Santo, J. Wilson, and A.N. Hang. 1993. Managing *Meloidogyne chitwoodi* on potato with rapeseed as green manure. *Plant Dis.* 77:42–46.
- Morra, M.J. and J.A. Kirkegaard. 2002. Isothiocyanate release from soil-incorporated *Brassica* tissues. *Soil Biol. Biochem.* 34:1683–1690.
- Norsworthy, J.K., L. Brandenberger, N.R. Burgos, and M. Riley. 2005. Weed suppression in *Vigna unguiculata* with a spring-seeded brassicaceae green manure. *Crop Prot.* 24:441–447.
- Norsworthy, J.K., M.S. Malik, P. Jha, and M. Riley. 2007. Suppression of *Digitaria sanguinalis* and *Amaranthus palmeri* using autumn-sown glucosinolate-producing cover crops in organically grown bell pepper. *Weed Res.* 47:425–432.
- Oglesby, K.A. and J.H. Fownes. 1992. Effects of chemical composition on nitrogen mineralization from green manures of seven tropical leguminous trees. *Plant Soil* 143:127–132.
- Palm, C.A. and P.A. Sanchez. 1991. Nitrogen release from the leaves of tropical legumes as affected by their lignin and polyphenol contents. *Soil Biol. Biochem.* 23:83–88.
- Petersen, J., R. Belz, F. Walker, and K. Hurler. 2001. Weed suppression by release of isothiocyanates from turnip-rape mulch. *Agron. J.* 93:37–43.
- Samson, R.A. 1991. The weed suppressing effects of cover crops. Fifth Annual Resource Efficient Agricultural Production (REAP) Conference, Macdonald College, Ste-Anne-de-Bellevue, Quebec, Canada.
- Sarwar, M., J. Kirkegaard, P. Wong, and J. Desmarchelier. 1998. Biofumigation potential of brassicas. III. In vitro toxicity of isothiocyanates to soil-borne fungal pathogens. *Plant Soil* 201:103–112.
- SAS Institute. 2001. SAS/STAT user's guide. Version 8-1. SAS Institute, Cary, NC.
- Shuler, J., J.B. Masiunas, and S.F. Vaughn. 2005. Use of mustard green manures for control of weeds in snapbeans (*Phaseolus vulgaris*). *Weed Science Society of America Meeting Abstracts*.
- Sundarapandian, S.M. and P.S. Swamy. 1999. Litter production and leaf litter decomposition of selected tree species in tropical forest at Kodoyar in the Western Ghats, India. *For. Ecol. Mgt.* 123:231–244.
- Swift, M.J. and J.M. Anderson. 1989. Decomposition, p. 547–569. In: Lieth, H. and M.J.A. Werger (eds.), *Tropical rain forest ecosystems. Biogeographical and ecological studies*. Elsevier, Amsterdam, The Netherlands.
- Swift, M.J., O.W. Heal, and J.M. Anderson. 1979. Decomposition in terrestrial ecosystems. Blackwell Scientific, Oxford, UK.
- Teasdale, J.R. 1998. Cover crops, smother plants, and weed management, p. 247–270. In: Hatfield, J.L., D.D. Buhler, and B.A. Stewart (eds.), *Integrated weed and soil management*. Ann Arbor Press, Chelsea, MI.
- Teasdale, J.R. and C.L. Mohler. 1993. Light transmittance, soil temperature and soil moisture under residue of hairy vetch and rye. *Agron. J.* 85:673–680.
- Teasdale, J.R. and C.L. Mohler. 2000. The quantitative relationship between weed emergence and the physical properties of mulches. *Weed Sci.* 48:385–392.
- Teasdale, J.R. and R.B. Taylorson. 1986. Weed seed response to methyl isothiocyanate and metham. *Weed Sci.* 34:520–524.
- Tian, G., B.T. Kang, and L. Brussaard. 1992. Effects of chemical composition on N, Ca and Mg release during incubation of leaves from selected agroforestry and fallow species. *Biogeochem.* 16:103–119.
- Tominaga, T. and T. Uezu. 1995. Weed suppression by buckwheat, p. 693–697. In: Matano, T. and A. Ujihisa (eds.), *Current advances in buckwheat research. Vol. 2. Proc. 6th International Symposium of Buckwheat*. Shinshu University Press, Nagano, Japan.
- Vanlauwe, B., J. Diels, N. Sanginga, and R. Merckx. 1997a. Residue quality and decomposition: an unsteady relationship? p. 157–166. In: Cadisch, G. and K.E. Giller (eds.), *Driven by Nature: Plant Litter Quality and Decomposition*. CAB International, Wallingford, Oxon, U.K.
- Vanlauwe, B., N. Sanginga, and R. Merckx. 1997b. Decomposition of four *Leucaena* and *Senna* prunings in alley cropping systems under sub-humid tropical conditions: the process and its modifiers. *Soil Biol. Biochem.* 29:131–137.
- Warwick, S.I. and R.D. Sweet. 1983. The biology of Canadian weeds. 58. *Galinsoga parviflora* and *G. quadriradiata* (= *G. ciliata*). *Can. J. Plant Sci.* 63:695–709.
- Westoby M., M. Leishman, J. Lord. 1996. Comparative ecology of seed size and dispersal. *Philos. Trans. Roy. Soc. Lond. B.* 351:1309–1318.
- Weston, L.A. 1996. Utilization of allelopathy for weed management in agroecosystems. *Agron. J.* 88:860–866.
- Williams, L., III, M. Morra, P. Brown, and J. McCaffrey. 1993. Toxicity of allyl isothiocyanate-amended soil to *Limonius californicus* (Mann.) Coleoptera:Elateridae) wireworms. *J. Chem. Ecol.* 19:1033–1046.
- Xuan, T.D. and E. Tsuzuki. 2004. Allelopathic plants. Buckwheat. *Allelopathy J.* 13:137–148.