

# 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

Virender Kumar, Daniel C. Brainard, and Robin R. Bellinder\*

Buckwheat residues can suppress both emergence and growth of weeds, but the mechanisms of this suppression are not well understood. The main objectives of this research were to evaluate the possible role of (1) low initial nitrogen (N) availability and (2) fungal pathogens in this suppression for three sensitive weed species: Powell amaranth, shepherd's-purse, and corn chamomile. Growth chamber experiments were conducted comparing weed emergence and growth in bare soil or soil with freshly incorporated buckwheat residue at multiple rates of N fertilization with or without fungicide seed treatment. In the absence of N or fungicide addition, emergence of all weed species was reduced 40 to 70%, and dry weight was reduced 85% in buckwheat residue compared with bare soil. For all three weed species, suppression of growth by buckwheat residue was completely overcome with the addition of N. For shepherd's-purse and corn chamomile (2005 only), suppression of emergence was also overcome with the addition of N. In 2006, treatment of corn chamomile seeds with fungicide resulted in a higher emergence in buckwheat residue than in bare soil. In contrast, suppression of Powell amaranth emergence was not overcome with N fertilization or fungicide treatment. The results suggest that buckwheat-mediated changes in N dynamics account entirely for suppression of weed growth but that the mechanisms responsible for suppression of emergence by buckwheat residue vary by species. Fungal and N effects account for suppression of emergence of corn chamomile and shepherd's-purse, but the mechanism of suppression for Powell amaranth remains obscure.

**Nomenclature:** Corn chamomile, *Anthemis arvensis* L. ANTA; Powell amaranth = green pigweed, *Amaranthus powellii* S. Wats. AMAPO; shepherd's-purse, *Capsella bursa-pastoris* (L.) Medicus CAPBP; buckwheat, *Fagopyrum esculentum* Moench.

**Key words:** Emergence, growth, N fertilizer, immobilization, green manure, cover crop, residue effects, allelopathy.

Herbicides are cost-effective and efficient tools for weed control in modern agriculture. However, sole reliance on herbicides has resulted in problems, including evolution of herbicide resistance in weeds (Heap 2007), contamination of surface and groundwater resources (Guzzella et al. 2006; Spalding et al. 2003), and growing public concerns with human health risks (EPA 2007). Such concerns have resulted in an increasing need for alternative weed management strategies, including cover crops.

Cover crops can be integrated into cropping systems for a range of benefits, including reduction of soil erosion (Flach 1990; Hargrove et al. 1984); supply of nitrogen to subsequent crops (Peoples et al. 1995); and improvements in nutrient cycling (Stivers-Young 1998; Weinert et al. 2002), soil quality (Barber and Navarro 1994; MacRae and McDole 1985), and pest management (Haramoto and Gallandt 2004; Sarrantonio and Gallandt 2003). Cover crops also have the potential to reduce weed populations and herbicide use as part of an integrated weed management (IWM) program (Liebman and Gallandt 1997; Williams et al. 1998; Worsham 1991).

Buckwheat, a short-duration broadleaved annual cover crop, has a number of desirable characteristics for use as a summer cover crop. It grows rapidly, establishes canopy faster than most weeds, and hence provides very effective weed suppression during establishment (Creamer and Baldwin 2000; Fitzgerald et al. 2003). Other benefits of buckwheat cover cropping include attraction of beneficial insects (Buggs and Ellis 1990) and sequestration and release of phosphorus to subsequent crops (Annan and Amberger 1989). Because

buckwheat has few insect and disease pests, managing buckwheat as a cover crop is easy and economical.

During buckwheat growth (in-season), buckwheat is effective in suppressing many weeds, including quackgrass (*Agropyron repens* L.; Golisz et al. 2002). Weed biomass during buckwheat growth has been reduced by 75% (Iqbal et al. 2003; Tominaga and Uezu 1995), 86% (Creamer and Baldwin 2000), and 75 to 99% (Kumar et al., unpublished data) compared with weedy controls. Such reductions in weed biomass help prevent establishment of perennial weeds, as well as reduce the risk of seed production by summer annuals. In the absence of buckwheat, weeds that produce seeds rapidly (e.g., hairy galinsoga [*Galinsoga ciliata* (Raf.) Blake]) can add large quantities of seeds to the soil (Kumar et al., unpublished data). Even weeds that produce seeds more slowly are easier to kill after buckwheat cover cropping than they would be in the absence of buckwheat.

Incorporated buckwheat residue might suppress weeds by inhibiting their emergence and growth. Buckwheat residues have the potential to suppress many summer annual weeds (Haramoto and Gallandt 2005; Iqbal et al. 2002, 2003; Xuan and Tsuzuki 2004). Buckwheat pellets (2 tonnes/ha) significantly reduced the dry weight (60%) and density (75 to 80%) of weeds in paddy rice (*Oryza sativa* L.; Xuan and Tsuzuki 2004). Very little published field data is available on the weed-suppressive ability of buckwheat residue in general and on winter annual weed species in particular. To our knowledge, only one field study (Haramoto and Gallandt 2005) has evaluated the effects of incorporated buckwheat residue on selected weeds and crop species. They demonstrated that fresh buckwheat residues delayed as well as suppressed the emergence of redroot pigweed (*Amaranthus retroflexus* L.) and common lambsquarters (*Chenopodium album* L.). However, effects on their subsequent growth were not measured.

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\* First and third authors: Department of Horticulture, Cornell University, Ithaca, NY 14853; second author: Department of Horticulture, Michigan State University, East Lansing, MI 48824. Corresponding author's E-mail: brainar9@msu.edu

In a previous study (Kumar et al., unpublished data) assessing the effects of incorporated buckwheat residue on eight weeds, fresh buckwheat residue significantly reduced emergence and biomass of all tested weed species except barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.]. However, buckwheat residue allowed to decompose for 15 d reduced emergence of only one weed species: Powell amaranth. Powell amaranth, shepherd's-purse, and corn chamomile were the three most sensitive species. Hence, these three weed species were used in this study to identify the mechanism(s) by which buckwheat residues suppressed their emergence and early growth.

Inhibitory effects of cover crop residues are often selective and weeds can be suppressed by different mechanisms. Knowledge of the mechanisms involved in weed suppression by buckwheat residue could be useful in designing strategies for managing weeds successfully. For example, if weed emergence and growth is inhibited by nitrogen tie-up, residue-mediated effects would be less likely in a highly fertilized system; therefore, manipulation of crop fertilization would play an important role in maximizing weed control benefits. On the other hand, if allelopathy were the primary mechanism of weed suppression by cover crop residue, then weed suppression would more likely be species specific and independent of fertility management. To our knowledge, no studies have previously assessed the mechanisms of weed suppression by buckwheat residue other than allelopathy. The allelopathic potential of chemicals isolated from buckwheat has been demonstrated by several studies (Golisz et al. 2007; Iqbal et al. 2002, 2003; Xuan and Tsuzuki 2004). The allelopathic compounds that have been isolated from buckwheat and have shown allelopathic effects are gallic acid, (+)-catechin, (-)-epicatechin quercetin, and rutin (Golisz et al. 2007; Iqbal et al. 2002, 2003). Although allelopathy is a possible mechanism of weed suppression by buckwheat residue, the potential role of nitrogen and fungal pathogen in inhibiting emergence and growth of weeds by buckwheat residues has not been evaluated.

Initial low nitrogen (N) availability after cover crop incorporation is one possible mechanism of weed suppression (Dyck and Liebman 1994; Samson 1991). Cover crops take up N during growth, thereby reducing soil N. In addition, cover crop residues incorporated into soil undergo a process of decomposition by soil microbes, and if the N present in the residue is less than that required by microbes, soil inorganic N will be immobilized temporarily to complete the process of decomposition (Corbeels et al. 1999). Generally, a carbon to nitrogen (C:N) ratio of 20 is the threshold between net mineralization and immobilization of N in soil by microbes (Harmsen and Van Schreven 1955; Iritani and Arnold 1960). Buckwheat residue with a C:N ratio of 34 (Creamer and Baldwin 2000) has the potential to immobilize soil N and hence decrease N availability in the soil initially after buckwheat incorporation.

Initial low N availability during the early stages of plant development might affect the growth of weeds more negatively than crops because weeds are adapted to early rapid growth and N uptake (Haynes et al. 1991; Seibert and Pearce 1993). Large-seeded crops have lower initial relative growth rate than most weeds. Shipley and Keddy (1988) showed that plants with the highest relative growth rate ( $RGR_{max}$ ) under optimal nutrient condition suffered the largest decline in  $RGR_{max}$  under nutrient stress conditions.

Large-seeded species (e.g., most crops) are generally more tolerant of low soil nutrients than small-seeded species (e.g., most weeds) because they can draw on seed nutrient resources (Westoby et al. 1996). This suggests that cover crop incorporation that reduces nutrient availability early in the growing season can provide selective disadvantage to small-seeded weeds compared with large-seeded crops. Several studies have suggested that low early season N levels can selectively suppress weeds (Davis and Liebman 2001; Dyck et al. 1995; Liebman and Davis 2000). Delayed fertilization of a maize crop accounted for a 50% reduction in weed biomass and 70% increase in crop biomass (Alkämper et al. 1979). Angonin et al. (1996) obtained a similar result by delaying N fertilization in winter wheat (*Triticum aestivum* L.).

In addition, nitrogenous compounds are known to stimulate the germination and emergence of many weed species (Baskin and Baskin 1998; Karssen and Hilhorst 1992), including Powell amaranth (Brainard et al. 2006) and shepherd's-purse (Popay and Roberts 1970; Roberts and Benjamin 1979). Conversely, initial low soil N levels after buckwheat incorporated could inhibit weed emergence. Therefore, we hypothesized that weed emergence and growth would be suppressed after buckwheat incorporation and that addition of N fertilizer would overcome at least some of the observed suppression.

An increased incidence in pathogens of weeds might be another possible mechanism of weed suppression by cover crop residues (Conklin et al. 2002). Fresh plant residues provide a substrate for fungal growth, thereby stimulating fungal attack (Toussoun and Patrick 1963). Higher populations of *Pythium*, *Rhizoctonia solani*, *Fusarium*, and *Thielaviopsis* spp. have been found after incorporation of cover crops (Dabney et al. 1996; Rothrock and Kirkpatrick 1995; Toussoun and Patrick 1963). Cover crop residues could also affect fungal pathogens of weeds indirectly through their effects on soil N. For example, the activity of *Rhizoctonia* (Jackson 1940) and *Fusarium* (Tint 1945) in soil can be stimulated by N. So N immobilization after buckwheat incorporation could reduce fungal effects on weeds. To our knowledge, no study has evaluated the role of fungal pathogens in suppression of weeds after incorporation of buckwheat residue. We hypothesized that (1) seed treatment with fungicide would improve the emergence and growth of test weed species more in soil with buckwheat residue than in bare-soil treatments and (2) the effect of fungicide treatment would be greater at higher levels of soil N. Thus, the specific objectives of this research were to evaluate the relative importance of N tie-up and fungal pathogen on the suppression of Powell amaranth, shepherd's-purse, and corn chamomile by buckwheat residue.

## Materials and Methods

**Seed Source.** Two populations of Powell amaranth, AMAPO (2000) and AMAPO (2003); one population of shepherd's-purse, CAPBP (2002); and two populations of corn chamomile, ANTA (2005) and ANTA (2006), were used in this study. Detailed information about their year and site of collection is given in Table 1. Corn chamomile seeds were sorted by size, and only the smallest seeds (0.84 to 1.00 mm) were used in this study because large seeds are highly dormant shortly after collection (Ellis and Illnicks 1968).

Table 1. Summary of timing and site of seed collection of seed lots used in this study and their germination response to ammonium nitrate ( $\text{NH}_4\text{NO}_3$ ) concentrations of 0.0, 0.002, and 0.02 M.

Species	Seed lot	Year collected	Collection site	Date tested <sup>a</sup>	Germination <sup>b,c</sup>		
					0.0 M	0.002 M	0.02 M
					%		
Powell amaranth	AMAPO (2000)	2000	Freeville, NY	2005	75 a	78 a	80 a
	AMAPO (2003)	2003	Myres, NY	2006	50 b	52 b	76 a
Shepherd's-purse	CAPBP (2002)	2002	Illinois <sup>d</sup>	2005	51 b	87 a	98 a
	CAPBP (2002)	2002	Illinois <sup>d</sup>	2006	40 b	44 b	66 a
Corn chamomile	ANTAR (2005)	2005	Ithaca, NY	2005	26 b	73 a	60 a
	ANTAR (2006)	2006	Batavia, NY	2006	7 b	25 a	28 a

<sup>a</sup> Seed lots were tested for their response to nitrogen in the both years just after their use in pot studies each year.

<sup>b</sup> Germination response to different concentrations of ammonium nitrate (34–0–0 N–P–K).

<sup>c</sup> Means within a row followed by the same letter are not significantly different at the 0.05 level according to Fisher's Protected LSD test.

<sup>d</sup> Seeds were purchased from a weed seed company.<sup>2</sup>

**Germination Testing.** The effect of ammonium nitrate ( $\text{NH}_4\text{NO}_3$ ) concentration on germination of weed seed lots of three weed species used in this study was tested in petri dishes in growth chambers in the same year the seed lots were used in the pot studies to determine their response to N in the absence of soil. Fifty randomly selected seeds from each seed lot were placed in 9-cm petri dishes with two sheets of filter paper saturated with 5-ml solutions of 0, 0.002, or 0.02 M ammonium nitrate. Four replicates of each seed lot by fertilizer combination were placed randomly in a single growth chamber set at 25/20 C day/night temperatures with a 16-h day length. Germinated seeds (radicle > 2 mm) were counted daily and removed for 20 d.

**Experiment 1: Role of N.** To explore whether weed suppressive effects of buckwheat residue were due to initial low N availability (because of N taken up by buckwheat plus N immobilization after residue incorporation), a growth chamber pot bioassay was conducted in 2005 and 2006, in which incorporated buckwheat residue soil and bare soil were supplemented with N fertilizer. The experiment was a 2 by 4 by 3 factorial arranged in a randomized complete block design with four replications. Factors included cover crop residue (bare soil vs. incorporated buckwheat residue), N level applied (0, 40, 80, and 160 kg N ha<sup>-1</sup>), and weed species (Powell amaranth, corn chamomile, and shepherd's-purse). For this study, buckwheat was grown in the field on a Howard gravel loam soil (loamy-skeletal mixed mesic Glosoboric Hapludalf) at the H. C. Thompson Vegetable Research Farm in Freeville, NY, in 2005 and 2006. Buckwheat was seeded at 50 and 60 kg ha<sup>-1</sup> on August 3, 2005 and 2006, respectively, with a Great Plains no-till drill<sup>1</sup> with 17.8-cm row spacing. A bare-soil treatment was included as a control. The experimental design was a randomized complete block with four replications. Buckwheat was mowed and incorporated with disking approximately 10 d after anthesis (40 d after planting). To estimate aboveground biomass produced by buckwheat, immediately before mowing, shoots of buckwheat were harvested from two 0.25-m<sup>2</sup> permanent quadrats per plot, oven dried for 7 d at 65 C, and weighed. The bare-soil treatment was kept weed free by repeated harrowing at 10- to 14-d intervals. Immediately after buckwheat incorporation, soil samples were collected from both incorporated buckwheat as well as bare-soil plots by randomly taking 8 to 10 soil samples at a depth of 5 to 10 cm within each plot. Soil obtained from each plot was sieved to remove large stones; plant residues were cut into 5- to 7-cm pieces, and soil and

residue were mixed thoroughly and placed in 11-cm-diam by 11.5-cm-deep pots. Fifty seeds of Powell amaranth, 75 seeds of corn chamomile, and 50 (2005) or 75 (2006) seeds of shepherd's-purse were sown in separate pots. Ammonium nitrate fertilizer (34–0–0, N–P–K) was used as a source of N. Fertilizer was dissolved in water, and 40 ml of ammonium nitrate solution containing the equivalent of 0, 40, 80, and 160 kg N ha<sup>-1</sup> was added to each pot. Pots were placed in growth chambers in a randomized complete block design set at day/night temperatures of 25/20 C and a 16-h day length. Pots received water by subirrigation whenever necessary to keep the soil surface wet. Weed emergence was monitored daily for 20 d. In addition, five plants per pot were left for biomass sampling. These plants were harvested 20 d after seeding, dried, and weighed. Immediately after incorporation, soil samples from both buckwheat residue and bare-soil plots were submitted to Cornell Nutrient Analysis Lab for analysis of pH; organic matter (by the loss on ignition [LOI] method); and Morgan-extractable P, K, Ca, Mg, Mn, Fe, Zn, and nitrate ( $\text{NO}_3$ ).

**Experiment 2: Role of N and Fungal Pathogens.** Another growth chamber pot bioassay was conducted in 2005 and 2006 to evaluate the interactive effects of fungi and N on weeds. The experiment was a 2 by 2 by 2 by 3 factorial arranged in a randomized complete block design with four replications. Factors included cover crop residue (bare soil and incorporated buckwheat residue), N fertilization (0 and 160 kg N ha<sup>-1</sup>), weed seed treatment (fungicide treated and untreated), and weed species (Powell amaranth, corn chamomile, and shepherd's-purse).

For this study, two buckwheat rows 17.5 cm apart per flat were sown in flats of dimension 35 by 50 by 9 cm with 25 seeds per row (equivalent to a field rate of 60 kg ha<sup>-1</sup>) in a greenhouse at a day/night temperature of 24/19 C with a 16-h day length. Soil used for this study was Eel silt loam (fine loamy, nonacid mixed, mesic Fluvaquentic Eutrudepts) collected from the H. C. Thompson Vegetable Research Farm in Freeville, NY, and mixed with a soilless medium (1 : 1 peat moss : vermiculite) to create a 3 : 1 mixture of field soil : soilless medium. Field soil was mixed with the soilless medium to improve soil physical properties. Plants were watered as required and did not receive fertilization. Bare-soil flats were also included as a control treatment. Thirty-five days after planting, buckwheat shoots were cut with a hedge trimmer into 5- to 7-cm segments and uniformly incorporated into the soil.

Table 2. Monthly rainfall and average monthly temperature in 2005 and 2006.

Month	Precipitation		Air temperature	
	2005	2006	2005	2006
	mm		C	
May	28	69	9.5	10.5
June	84	197	19.0	16.1
July	73	192	19.5	19.5
August	74	128	18.3	16.7
September	66	63	12.5	12.0
Total	325	649		
Average			15.8	15.0

Fungicide solution was prepared by mixing captan<sup>3</sup> at 1,900 µg g<sup>-1</sup> seed, trifloxystrobin<sup>3</sup> at 450 µg g<sup>-1</sup>, metalaxyl<sup>3</sup> at 540 µg g<sup>-1</sup>, and PSF 1003<sup>3</sup> binder at 2,000 µg g<sup>-1</sup> in 2 ml of water. This fungicide solution was applied to the weed seeds at 200 µl g<sup>-1</sup> of seeds and dried. This combination of fungicides (both systemic and protectant) was selected to protect against multiple seed and soilborne fungal pathogens. This combination is used in treatment of crop seeds for protection against pre- and postemergence damping-off of seedlings caused by *Pythium*, *Phytophthora*, and other seed-rotting fungi (*Rhizoctonia*, *Fusarium*) (Jeff 1986; Koepsell and Pscheidt 1995; Schwinn and Urech 1986). Germination assays with these three weed species were conducted in petri dishes to demonstrate that the fungicide cocktail used in this study was not phytotoxic to seeds.

Pots of 11 cm diameter by 11.5 cm depth were filled with the incorporated buckwheat and bare soil immediately after buckwheat incorporation. Each pot was sown separately with 50, 75, and 50 seeds of Powell amaranth, shepherd's-purse, and corn chamomile, respectively, in 2005 and with 75, 100, and 50 seeds in 2006. Immediately after sowing, pots were watered by subirrigation and placed in the growth chamber with day/night temperatures of 25/20 C and a 16-h day length. Each pot received a 40-ml solution of ammonium nitrate (34-0-0, N-P-K) of concentration equivalent to either 0 or 160 kg N ha<sup>-1</sup>. Seedlings were counted and removed daily for 20 d, and five plants per pot were left for biomass sampling. Available nitrate and ammonium N were assessed via KCl extraction at 1, 4, 13, and 16 d or 1, 5, and 13 d after buckwheat incorporation in 2005 or 2006, respectively. Extracts were analyzed with a Bran and Luebbe Autoanalyzer 3.<sup>4</sup>

**Statistical Analysis.** The data were subjected to analysis of variance (ANOVA) and analyzed with the general linear model procedures of the Statistical Analysis System (SAS 2001). The effects of cover crop and N fertilization on

emergence (cumulative emergence at 20 d after seeding) and early growth (dry weight) were assessed with a two-way ANOVA, whereas effects of cover crop, N fertilization, and fungicide treatment were assessed by three-way ANOVA for each species. Emergence data were either not transformed, log transformed, or square root transformed, and biomass data were either not transformed, log transformed, or inverse square root transformed as needed to improve assumptions of normality and equal variance of population distributions. Treatment mean values were separated by Fisher's Protected LSD test.

## Results and Discussions

**Experiment 1: Response to N. Buckwheat Biomass and Soil Characteristics at Buckwheat Incorporation.** Buckwheat biomass production in 2005 was 1.8 times higher than in 2006 (3,650 and 2,011 kg ha<sup>-1</sup>, respectively). The lower biomass in 2006 was due in part to poor cover crop establishment (130 plants m<sup>-2</sup> in 2005 and 110 plants m<sup>-2</sup> in 2006) and in part to the very wet conditions in 2006 (Table 2). In 2005, immediately after buckwheat incorporation, bare-soil plots had higher soil nitrate levels (7.4 mg kg<sup>-1</sup>) than buckwheat residue plots (0 kg kg<sup>-1</sup>) (Table 3). In contrast, in 2006, both bare-soil and buckwheat plots had very low nitrate levels (0 to 1.2 mg kg<sup>-1</sup>) and were not different (Table 3). The lower nitrate in bare soil in 2006 compared with 2005 could have been due to abundant rainfall in 2006 (Table 2), which caused leaching of N. Potassium was significantly higher in buckwheat residue soil than bare soil controls in both years. In 2005, zinc was lower in buckwheat residue and organic matter was higher than in bare soil (Table 3).

**Effects of N on Germination in Petri Dishes.** Germination of all seed lots in petri dishes was significantly influenced by N except seed lot AMAPO (2000) of Powell amaranth, which did not respond to N (P = 0.43; Table 2). Germination of AMAPO (2003) seed lot of Powell amaranth increased from 50 to 76% with the addition of a 0.02 M concentration of ammonium nitrate (Table 1). Germination of the shepherd's-purse seed lot (CAPBP 2002) increased with the addition of ammonium nitrate from 51 to 98% in 2005 and from 40 to 66% in 2006. Lower germination of shepherd's-purse seeds in 2006 was probably due to loss of seed viability during storage. In 2005, germination of freshly collected seeds of corn chamomile (ANTAR 2005), increased from 26 to 73% with the addition of a 0.002 M concentration of ammonium nitrate and did not respond to further addition of ammonium nitrate. In 2006, freshly collected seeds had lower germination

Table 3. Characteristics of soils from buckwheat residue or bare-soil plots immediately after buckwheat incorporation.<sup>a</sup>

Treatment	pH	NO <sub>3</sub> -N	P	K	Ca	Mg	Fe	Mn	Zn	OM
	mg kg <sup>-1</sup> soil <sup>b</sup>									%
2005										
Bare soil	6.5 a	7.4 a	20.7 a	114.8 b	1074.2 a	103.0 a	2.5 a	10.0 a	0.2 a	3.1 b
Buckwheat	6.5 a	0.0 b	23.0 a	183.4 a	1029.3 a	105.2 a	2.1 a	17.2 a	0.0 b	3.3 a
2006										
Bare soil	5.9 a	1.2 a	12.7 a	171.5 b	948.5 a	76.7 a	3.8 a	11.9 b	0.5 a	4.0 a
Buckwheat	6.0 a	0.0 a	14.2 a	208.8 a	889.5 a	81.5 a	3.9 a	15.2 a	0.5 a	4.1 a

<sup>a</sup> Abbreviations: OM, Organic matter; NO<sub>3</sub>-N, nitrate nitrogen.

<sup>b</sup> Within columns and year, means followed by the same letter are not significantly different at the 0.05 level according to Fisher's Protected LSD test.

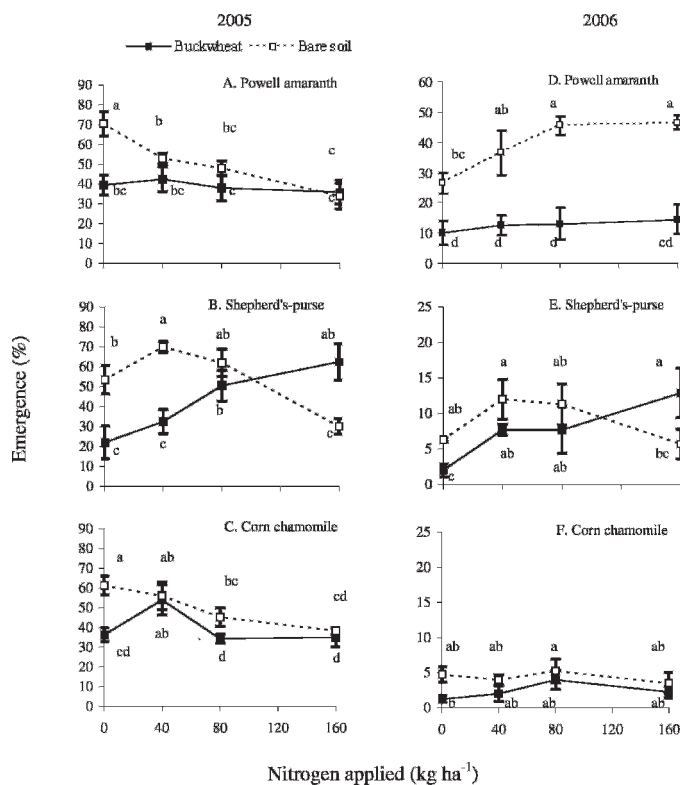


Figure 1. Emergence (mean  $\pm$  SE) of Powell amaranth, shepherd's-purse, and corn chamomile in 2005 (A, B, C) and 2006 (D, E, F) in buckwheat residue (■) and bare-soil (□) treatment at different levels of nitrogen applied immediately after buckwheat incorporation. Different letters indicate significant differences among treatments. Means were separated by Fisher's Protected LSD<sub>0.05</sub>.

than in 2005, but germination increased from 7.5 to 25% with the addition of a 0.002 M concentration of ammonium nitrate. Our findings for Powell amaranth are consistent with previous studies showing stimulatory effects of N on germination for some seed lots but not others (Brainard et al. 2006). Stimulatory effects of N for shepherd's-purse were also consistent with findings of previous studies (Kleijn and van der Voort 1998; Popay and Roberts 1970; Roberts and Benjamin 1979).

*Effects of N on Emergence in Pots.* At low N, emergence of all three weed species was suppressed significantly in pots with freshly incorporated buckwheat residue compared with bare-soil pots (Figure 1). For example, in 2005, Powell amaranth emergence was 44% lower in buckwheat soil compared with the bare-soil control, whereas shepherd's-purse and corn chamomile emergence was 59 and 41% lower, respectively (Figure 1A–C). In both years, Powell amaranth emergence did not respond to added N in the buckwheat residue treatment, and the observed suppression of emergence at low N was not overcome with N fertilization (Figure 1A and 1D). In 2005, Powell amaranth emergence declined with increasing N fertilization in bare-soil treatments (Figure 1A). In 2006, emergence was 62% lower in the buckwheat residue treatment at 0 kg N ha<sup>-1</sup> compared with the bare-soil treatment, and suppression increased slightly at higher levels of fertilization (Figure 1D).

Several explanations could account for the differential response of Powell amaranth to N in the bare-soil treatment in 2005 compared with 2006. First, the seed lot used in 2005

(AMAPO 2000) was nonresponsive to N, whereas the seed lot used in 2006 (AMAPO 2003) was N-responsive (Table 1). Second, the background level of nitrate N in the bare soil was higher in 2005 (7.4 compared with 1.2 mg kg<sup>-1</sup>; Table 3), and further addition of N might have reduced emergence via an osmotic effect. Sardi and Beres (1996) studied the effect of ammonium nitrate fertilizer on germination of redroot pigweed and found that 10 and 100 ppm concentration stimulated the germination but 1,000 ppm (equivalent to our 160 kg N ha<sup>-1</sup> rate) concentration significantly inhibited germination. A third possible explanation is that the higher level of N indirectly inhibited emergence of Powell amaranth by stimulating fungal pathogens of freshly germinated seeds (Tint 1945).

In 2005, the suppression of shepherd's-purse emergence in buckwheat residue at low N was overcome with the addition of 80 and 160 kg N ha<sup>-1</sup> (Figure 1B). For example, shepherd's-purse emergence increased from 22 to 63% with the addition of 160 kg N ha<sup>-1</sup> in buckwheat residue, which was equivalent to the maximum emergence in bare soil found at 40 or 80 kg N ha<sup>-1</sup>. In 2006, the same emergence pattern was observed in response to N fertilization (Figure 1E); however, total emergence was lower and the suppressive effect of buckwheat residue was less evident compared with 2005. This year-to-year variation could be attributed to several factors. First, the shepherd's-purse seed lot (CAPBP 2002) had reduced viability at the beginning of the 2006 experiment (Table 1). Second, treatment differences in soil N were less pronounced in 2006 compared with 2005 (Table 3); thus, emergence suppression because of N tie-up (low N availability) was not apparent. As with Powell amaranth, reduction in emergence of shepherd's-purse in the bare-soil treatment at the highest N level (160 kg N) could be attributable to either an osmotic effect or the interaction between N and fungal diseases.

For corn chamomile, suppression caused by buckwheat residue at low N was overcome with the addition of 40 kg N ha<sup>-1</sup> in 2005 (Figure 1C). At 40 kg N ha<sup>-1</sup>, emergence in the buckwheat residue treatment was equivalent to the maximum emergence observed in bare soil (Figure 1C). However, in 2006, emergence of corn chamomile was low in all treatments (Figure 1F), so no conclusion can be drawn about the mechanisms of suppression. Low emergence in 2006 was due in part to higher seed dormancy of the 2006 seed lot, ANTA 2006 (Table 1). As with shepherd's-purse, smaller treatment differences in soil N in 2006 (Table 3) also could explain lack of a suppressive effect.

The results are consistent with the hypothesis that for shepherd's-purse and corn chamomile emergence, the inhibitory effect of buckwheat residue was due to changes in soil N dynamics and N immobilization. For these species, suppression of emergence was overcome with N fertilization in 2005, and little suppression was observed in 2006 when treatment differences in soil N were small. In contrast, lack of N availability does not appear to account for the suppression of Powell amaranth emergence. For Powell amaranth, emergence suppression was not overcome with N fertilization in 2005, and strong suppression was observed in 2006, even though soil N differences were minimal. Inhibition of common lambsquarters emergence by crimson clover residues was not overcome by applying N fertilizers (Dyck and Liebman 1994).

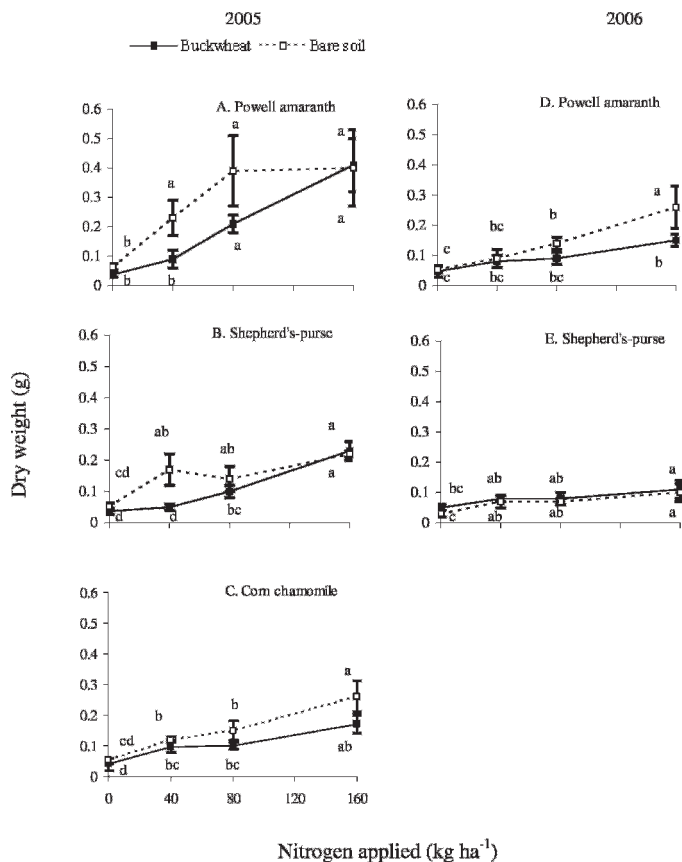


Figure 2. Aboveground dry weight per plant (mean  $\pm$  SE) of Powell amaranth (A, D), shepherd's-purse (B, E), and corn chamomile (C) in 2005 (A, B, C) and 2006 (D, E) in buckwheat residue (■) and bare-soil (□) treatment at different levels of nitrogen applied immediately after buckwheat incorporation. Note that corn chamomile data for 2006 was not available because of low emergence and high mortality. Different letters indicate significant differences among treatments. Means were separated by Fisher's Protected LSD<sub>0.05</sub>.

**Effects of N on Growth in Pots.** In 2005, growth of shepherd's-purse and Powell amaranth was suppressed by buckwheat residue compared with the bare-soil treatment at intermediate (40 or 80 kg N ha<sup>-1</sup>) rates of N fertilization (Figure 2A and 2B). Maximum suppression by buckwheat residue was observed at 40 kg N ha<sup>-1</sup> rather than 0 kg N ha<sup>-1</sup>. This increased suppression of weed growth in buckwheat residue treatment at 40 kg N ha<sup>-1</sup> compared with 0 kg N ha<sup>-1</sup> might have occurred because of lower response to added N in buckwheat residue soil than bare soil, in that some of the added N could have been used by microbes (N tie-up) in buckwheat treatments. This suppression was overcome with the addition of 160 kg N ha<sup>-1</sup> (Figure 2A and 2B). For corn chamomile, no significant suppression was detected at any N level (Figure 2C). In both years, all three species responded to N in both buckwheat residue and bare-soil treatments (Figure 2).

In 2006, buckwheat had little or no effect on growth of Powell amaranth and shepherd's-purse (Figure 2D and 2E). Because of low emergence in the corn chamomile pots in 2006, insufficient plants were available to assess biomass effects. At low N rates, no suppression was observed for any species. However, at high N, Powell amaranth grown in buckwheat soil had 40% lower biomass than that grown in bare soil (Figure 2D). The reason for Powell amaranth suppression by buckwheat at high N is unclear. Lack of

suppression of weed growth by buckwheat residue in 2006 was probably due to small soil nitrate differences in buckwheat residue and bare-soil treatments in that year (Table 3).

As with emergence, the results demonstrate that N dynamics play an important role in mediating the effects of buckwheat residue on weed growth. In 2005, our results suggest that the growth of all tested weed species was suppressed because incorporated buckwheat residue soil had lower background soil N than bare soil (Table 3). This suppression was not seen in 2006 soils, which did not have low N levels in buckwheat residue soil. These results are consistent with previous studies that showed that suppression in growth in residue-amended soil or plant debris is the result of changes in soil N dynamics and N immobilization rather than a direct effect of phytotoxins released from residues (Castells et al. 2004, 2005; Michelsen et al. 1995; Schmidt et al. 1997). However, we cannot rule out the possibility that addition of N had an indirect effect on weed suppression through its influence on allelochemical fate. For example, it is possible that addition of N in buckwheat residue soil stimulated microbial breakdown of allelochemicals released from buckwheat residue (Blum 1998).

**Experiment 2: Role of N and Fungal Pathogens.** *Nitrate, Ammonium Nitrogen in Pots.* In both years at low N, nitrate N was lower in buckwheat residue soil compared with bare soil after buckwheat incorporation (Table 4). Similarly, at high N, NO<sub>3</sub>-N was lower in pots with buckwheat residue soil than bare soil in both years (with the exception of 13 d after buckwheat incorporation in 2006). In contrast to NO<sub>3</sub>-N, NH<sub>4</sub>-N levels were similar in pots with buckwheat residue and bare soil at low N in both years (Table 4). In both years at high N, buckwheat residue and bare soil were not different in NH<sub>4</sub>-N immediately after buckwheat incorporation. However, NH<sub>4</sub>-N levels were higher in bare soil than buckwheat residue soil 5 and 16 d, and 4 and 13 d after buckwheat incorporation in 2005 and 2006, respectively. In 2005, pots with buckwheat residue soil at high N and bare-soil pots at low N were equivalent in NO<sub>3</sub>-N. Similarly, in 2006, buckwheat residue soil at high N and bare soil at low N were equivalent in NO<sub>3</sub>-N except 1 d after incorporation (Table 4).

The lower N in buckwheat residue soil compared with bare soil could be the result of N uptake by buckwheat during its growth and N immobilization after its incorporation. Lower N initially after cover crop incorporation compared with bare soil has been reported by many studies, especially in cover crops with high C:N ratios (Baggs et al. 2000; Rayns and Lennartson 1995).

**Effects of N and Fungicide Seed Treatment on Emergence.** Powell amaranth emergence was significantly suppressed by buckwheat residue at low N in 2006 but not in 2005 (Table 5). In 2006, Powell amaranth emergence at 0 kg N ha<sup>-1</sup> was 63% lower in the buckwheat residue treatment than in the bare-soil treatment. This suppression was not overcome by either fungicide seed treatment or addition of N. As in experiment 1, these results suggest that suppression of Powell amaranth emergence caused by buckwheat residue is not due to lack of N availability. Results from 2006 also suggest that suppression was not due to higher

Table 4. Nitrate (NO<sub>3</sub>), ammonium (NH<sub>4</sub>) nitrogen in buckwheat and bare soil 1, 4, 13, and 16 d and 1, 5, and 13 d after buckwheat incorporation (DAI) in 2005 and 2006, respectively.<sup>a</sup>

Treatment	2005								2006					
	NO <sub>3</sub>				NH <sub>4</sub>				NO <sub>3</sub>			NH <sub>4</sub>		
	1 DAI	4 DAI	13 DAI	16 DAI	1 DAI	4 DAI	13 DAI	16 DAI	1 DAI	5 DAI	13 DAI	1 DAI	5 DAI	13 DAI
	mg kg <sup>-1</sup> soil													
Low N														
Buckwheat	0.3 c	2.2 c	1.4 c	2.2 c	7.7 b	4.9 c	5.0 b	5.4 c	1.0 d	1.3 c	1.1 b	8.5 b	5.2 c	1.4 c
Bare soil	199.4 ab	397.5 b	234.5 b	61.7 b	9.4 b	5.4 c	4.7 b	6.0 c	33.4 c	36.5 b	22.6 a	7.7 b	5.8 c	1.8 c
High N														
Buckwheat	67.3 b	317.8 b	297.0 b	51.9 b	300.2 a	227.1 b	67.6 a	14.6 b	285.7 b	116.3 b	65.1 a	250.9 a	63.8 b	16.4 b
Bare soil	669.0 a	1768.2 a	838.7 a	987.2 a	418.9 a	463.0 a	173.4 a	68.8 a	443.5 a	985.0 a	121.7 a	327.4 a	283.3 a	52.1 a
ANOVA <sup>b</sup>														
Cover crop <sup>c</sup>	***	***	***	***	NS	**	NS	***	***	***	*	NS	**	**
Nitrogen <sup>d</sup>	***	***	***	***	***	***	***	***	***	***	***	***	***	***
Cover × nitrogen	**	***	***	NS	NS	**	NS	***	***	NS	*	NS	**	*

<sup>a</sup> Means within a column followed by the same letter are not significantly different at the 0.05 level according to Fisher's Protected LSD test.

<sup>b</sup> Significant at + P < 0.10; \* P < 0.05; \*\* P < 0.01; \*\*\* P < 0.001. NS, not significant (P > 0.10).

<sup>c</sup> Cover crop (buckwheat vs. bare-soil control).

<sup>d</sup> Pots were supplemented with two rates of nitrogen: 0 and 160 kg N ha<sup>-1</sup>.

levels of fungal pathogenicity in the incorporated buckwheat residue. However, in 2005, fungicide treatment increased Powell amaranth emergence at high N in buckwheat residue, but not in bare-soil pots. This suggests that in 2005, fungal pathogens were higher in buckwheat residue soil at high N and might have inhibited Powell amaranth emergence. The fungicide mixture used for seed treatment did not influence Powell amaranth emergence in petri dishes (data not shown).

In both years, as with experiment 1, shepherd's-purse emergence was suppressed by buckwheat residue at low N, but

that suppression was overcome by addition of N (Table 5). For example, emergence in buckwheat residue increased from 8 to 32% with the addition of 160 kg N ha<sup>-1</sup> in 2005 and from 3 to 10% in 2006. As in experiment 1, emergence declined or did not respond to higher N rate (160 kg N ha<sup>-1</sup>) in bare soil. In 2005, fungicide-treated shepherd's-purse seeds had higher emergence than untreated seeds, suggesting that fungal pathogens can play an important role in suppressing emergence. However, this effect did not vary with buckwheat or N treatments (interaction not

Table 5. Effects of cover crops, nitrogen, and fungicide seed treatment on emergence of Powell amaranth, shepherd's-purse, and corn chamomile in 2005 and 2006.

Treatment	Final emergence <sup>a,b</sup>					
	Powell amaranth		Shepherd's-purse		Corn chamomile	
	2005	2006	2005	2006	2005	2006
	%					
Low N (0 kg N ha <sup>-1</sup> )						
Buckwheat						
Untreated	51 ab	13 b	8 d	3 c	24 c	15 e
Treated	45 ab	14 b	19 bcd	4 bc	32 bc	28 bc
Bare soil						
Untreated	46 ab	33 a	17 bcd	9 a	48 ab	38 ab
Treated	53 a	38 a	27 ab	7 ab	56 a	48 a
High N (160 kg N ha <sup>-1</sup> )						
Buckwheat						
Untreated	36 bc	20 b	32 a	10 a	35 bc	16 de
Treated	53 a	16 b	31 a	11 a	41 abc	23 cd
Bare soil						
Untreated	24 c	37 a	12 cd	9 a	28 c	35 abc
Treated	26 c	33 a	24 abc	10 a	35 bc	37 ab
ANOVA <sup>c</sup>						
Cover crop <sup>d</sup>	*	***	NS	*	+	***
Nitrogen <sup>e</sup>	**	NS	*	***	NS	NS
Fungicide <sup>f</sup>	NS	NS	*	NS	NS	**
Cover × nitrogen	*	NS	***	**	**	NS
Cover × fungicide	NS	NS	NS	NS	NS	+
Nitrogen × fungicide	NS	NS	NS	NS	NS	NS
Cover × nitrogen × fungicide	+	NS	NS	NS	NS	NS

<sup>a</sup> Emergence 20 d after seeding.

<sup>b</sup> Means within a column followed by the same letter are not significantly different at the 0.05 level according to Fisher's Protected LSD test.

<sup>c</sup> Significant at + P < 0.10; \* P < 0.05; \*\* P < 0.01; \*\*\* P < 0.001, NS, not significant (P > 0.10).

<sup>d</sup> Cover crop (buckwheat vs. bare soil control).

<sup>e</sup> Pots were supplemented with two rates of nitrogen: 0 and 160 kg N ha<sup>-1</sup>.

<sup>f</sup> Weed seed either treated with fungicide or not treated.

Table 6. Effects of cover crops, nitrogen, and fungicide seed treatment on early growth of Powell amaranth, shepherd's-purse, and corn chamomile in 2005 and 2006.

Treatment	Dry weight <sup>a,b</sup>					
	Powell amaranth		Shepherd's-purse		Corn chamomile	
	2005	2006	2005	2006	2005	2006
gm						
Low N (0 kg N ha <sup>-1</sup> )						
Buckwheat						
Untreated	0.027 c	0.044 d	0.003 c	0.001 c	0.008 c	0.001 d
Treated	0.008 c	0.049 d	0.004 c	0.001 c	0.010 c	0.002 d
Bare soil						
Untreated	0.312 b	0.349 bc	0.105 b	0.051 b	0.134 b	0.059 bc
Treated	0.289 b	0.287 c	0.312 a	0.055 b	0.101 b	0.051 c
High N (160 kg N ha <sup>-1</sup> )						
Buckwheat						
Untreated	0.306 b	0.530 ab	0.244 a	0.191 a	0.174 ab	0.065 bc
Treated	0.482 ab	0.520 ab	0.278 a	0.164 a	0.282 a	0.099 ab
Bare soil						
Untreated	0.336 b	0.675 a	0.430 a	0.133 a	0.291 a	0.150 a
Treated	0.762 a	0.494 ab	0.398 a	0.175 a	0.251 a	0.147 a
ANOVA <sup>c</sup>						
Cover crop <sup>d</sup>	***	***	***	***	***	***
Nitrogen <sup>e</sup>	***	***	***	***	***	***
Fungicide <sup>f</sup>	NS	NS	NS	NS	NS	NS
Cover × nitrogen	NS	***	*	***	***	***
Cover × fungicide	NS	NS	NS	NS	+	NS
Nitrogen × fungicide	**	NS	NS	NS	NS	NS
Cover × nitrogen × fungicide	NS	NS	+	NS	NS	NS

<sup>a</sup> Dry weight per five plants 20 d after seeding.

<sup>b</sup> Means within a column followed by the same letter are not significantly different at the 0.05 level according to Fisher's Protected LSD test.

<sup>c</sup> Significant at + P < 0.10; \* P < 0.05; \*\* P < 0.01; \*\*\* P < 0.001. NS, not significant (P > 0.10).

<sup>d</sup> Cover crop (buckwheat vs. bare-soil control).

<sup>e</sup> Pots were supplemented with two rates of nitrogen: 0 and 160 kg N ha<sup>-1</sup>.

<sup>f</sup> Weed seed either treated with fungicide or not treated.

significant), so fungal pathogen effects do not explain the suppression of emergence by buckwheat residue observed in this study.

Corn chamomile emergence was 50 to 60% lower in buckwheat residue compared with bare soil in low N/untreated treatments (Table 5). However, in contrast with shepherd's-purse, addition of N did not overcome this suppression in either year. In 2005, at high N (160 kg N ha<sup>-1</sup>), total emergence in buckwheat residue was equivalent to the bare-soil treatment. However, this reduced difference in emergence between buckwheat residue and bare-soil treatment at the high N rate was due to a significant decline in emergence in bare soil and a slight increase in emergence in the buckwheat residue treatment. In both the petri dish N response study and experiment 1, maximum germination occurred at intermediate levels of N, and higher levels inhibited corn chamomile emergence. Therefore, it is likely that the high rate of fertilization used in this study masked the compensatory effect of N on suppression of emergence by buckwheat.

In 2006, fungicide-treated corn chamomile seeds had higher emergence than untreated seeds. This effect was greater in buckwheat soils, suggesting that fungal pathogens could have played a role in suppression of corn chamomile emergence in buckwheat (Table 5). The fungicide mixture used for treating corn chamomile seeds also had no effect on germination of corn chamomile in petri dishes (data not shown).

*Effects of N and Fungicide Seed Treatment on Growth.* In contrast with experiment 1, the growth of all the weed species

was suppressed in buckwheat residue treatment compared with bare-soil treatment in both years, provided no N was applied (Table 6). For example, buckwheat residue suppressed the growth of Powell amaranth, shepherd's-purse, and corn chamomile by 94, 98, and 92%, respectively, in 2005 and by 85, 98, and 97%, respectively, in 2006 at the low N level. Nitrogen significantly increased the dry matter accumulation of weeds in both buckwheat residue and bare-soil treatments. However, greater increases were observed in buckwheat residue treatments. With the addition of 160 kg N ha<sup>-1</sup>, suppression of growth of all three weed species was completely overcome, and dry matter accumulation in buckwheat treatments was equivalent to the bare-soil treatments. The fungicide effect on weed growth was not significant for any of the weed species. Results of this experiment are consistent with the hypothesis that initial low N availability is the major cause of suppression in early growth of weed species in buckwheat residues in that nitrate N and total N was much lower in buckwheat residue than bare-soil treatments (Table 4). However, as with experiment 1, we cannot rule out the possibility that added N influenced weed suppression indirectly by stimulating the breakdown of allelochemicals. Ongoing research investigating the effect of activated carbon on the suppression of weeds in buckwheat residue soil should help clarify the possible role of allelochemicals.

Overall, results of this study indicate that fresh, incorporated buckwheat residue suppresses both emergence and growth of Powell amaranth, shepherd's-purse, and corn chamomile. Suppression of growth for all three species appears to be the direct result of low N availability. In contrast, multiple mechanisms are involved for emergence suppression. Initial

low N availability after buckwheat incorporation appears to play a major role in suppression of both shepherd's-purse and corn chamomile emergence by buckwheat residue. For corn chamomile, interactions between buckwheat residue and fungal pathogens appear to also play a role in suppression of emergence. In contrast, suppression of Powell amaranth emergence cannot be explained by either N or fungal effects, suggesting that other mechanisms like allelopathy might be important. Inhibition of early growth of weed species including common amaranth (*Amaranthus palmeri* S. Watson) by compounds derived from buckwheat has been demonstrated under laboratory conditions (Iqbal et al. 2002, 2003).

These results suggest that buckwheat cover cropping can contribute to weed management by reducing both emergence and growth of weeds when crops are planted in fresh residue immediately after its incorporation. Buckwheat can be included in vegetable cropping systems either before late-planted crops, such as transplanted broccoli (*Brassica oleracea* L.) or snap beans (*Phaseolus vulgaris* L.), or after early harvested vegetable crops like peas (*Pisum sativum* L.) and lettuce (*Lactuca sativa* L.). For example, in New York State, land is often left bare after pea harvest in July until planting of winter wheat in late September. Buckwheat can fill this niche, helping to prevent weed seed production in-season while providing a residue that can suppress winter weeds like corn chamomile from becoming established in the subsequent winter wheat crop.

Results from this study suggest that emergence of Powell amaranth will be suppressed by buckwheat residue irrespective of soil fertility levels. In contrast, in a highly fertilized system, it is unlikely that buckwheat residue will have inhibitory effects on the emergence and growth of species like shepherd's-purse. To get maximum benefit from buckwheat cover cropping, delayed fertilizer application after buckwheat incorporation might provide maximum weed control benefits. For large-seeded crops with high N reserves, reduced N availability after buckwheat incorporation might not be detrimental to crops. However, for many crops, this could be a risky strategy. More work is needed to identify circumstances in which buckwheat residue soil suppresses weeds without suppressing crops, regardless of fertility level.

### Sources of Materials

<sup>1</sup> Great Plains Mfg., Inc., 1525 East North Street, Salina, KS 67401.

<sup>2</sup> F. and J. Seed Service, P.O. Box 82, Woodstock, IL 60098.

<sup>3</sup> Bayer Crop Science, 2 T. W. Alexander Drive, Research Triangle Park, NC 27709.

<sup>4</sup> Seal Analytical, Inc., 1492 W. Mequon Rd., Mequon, WI 53092.

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