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Suppression of Powell Amaranth (*Amaranthus powellii*) by Buckwheat Residues: Role of Allelopathy

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

Previous studies have demonstrated that emergence and growth of Powell amaranth is inhibited in soils where buckwheat has been grown and incorporated. The primary objectives of this research were to (1) evaluate the possible role of allelopathy in explaining that suppression; (2) distinguish between suppression caused by incorporation of fresh buckwheat residues from suppression caused by changes in soil during buckwheat growth; and (3) quantify the relative importance of buckwheat root vs. shoot tissues in suppression. When all buckwheat plant parts were removed from soil in which buckwheat was grown, Powell amaranth emergence was not suppressed, but growth was reduced 70% compared to bare soil. Addition of buckwheat shoots, but not roots to these soils reduced emergence by 80%, and contributed to additional reduction in growth. Addition of chemically activated carbon did not increase emergence or growth in buckwheat-amended soil. However, thermally activated carbon resulted in greater adsorption of phenolics than chemically activated carbon and alleviated suppression of Powell amaranth in buckwheat-amended, high organic-matter soils. However, suppression was not overcome on mineral soils. In addition to adsorbing phenolics, activated carbon changed the nitrogen (N) content and electrical conductivity of soil extracts. Aqueous shoot extracts of buckwheat stimulated Powell amaranth germination slightly, but inhibited radicle growth. Aqueous soil extracts from buckwheat-amended soil inhibited germination of Powell amaranth compared with extracts from unamended soil. Results suggest that emergence suppression of Powell amaranth by buckwheat residues might be due to allelopathic compounds concentrated in the shoot tissues. However, these inhibitory effects appear to depend on interactions of buckwheat residues with soils. In contrast, suppression of growth of Powell amaranth appears to be associated primarily with lower N availability in buckwheat-grown soils.

Nomenclature: Powell amaranth (= green pigweed), *Amaranthus powellii* S. Wats. AMAPO; buckwheat, *Fagopyrum esculentum* Moench.

Key words: Emergence, growth, cover crop, residue effects, green manure, activated carbon.

Weed suppressive effects of cover crop residues have been explained by different mechanisms, including initial low nitrogen (N) availability following cover crop incorporation (Dyck and Liebman 1994; Kumar et al. 2008; Samson 1991), mulch effects (Mohler 1996; Mohler and Callaway 1991; Mohler and Teasdale 1993), stimulation of pathogens or predators of weed seeds (Carmona and Landis 1999; Conklin et al. 2002; Davis and Liebman 2003; Gallandt et al. 2005; Kremer 1993), and allelopathy (Chou 1999; Weston 1996).

In a previous study, we observed that freshly incorporated buckwheat residue can provide weed control (Kumar et al. 2008). Our results indicate that initial low soil N availability following buckwheat incorporation played a major role in the suppression of shepherd's-purse [*Capsella bursa-pastoris* (L.) Medic.] emergence because it was totally overcome with the addition of N fertilizer. However, reduced emergence of Powell amaranth (*Amaranthus powellii* S. Wats.) in buckwheat-amended soil was not overcome with the addition of N or by treating seeds with fungicides, which suggest that reduced emergence was not due to lack of N availability or higher levels of fungal pathogenicity. This suggests a role for allelopathic effects of buckwheat residue in suppression of Powell amaranth emergence (Kumar et al. 2008).

Allelopathy is a well-known mechanism of weed suppression attributed to many plant species (Barnes and Putnum 1986; Putnum 1994; Weston 1996). Allelopathic compounds released from cover crop residues during decomposition can reduce both emergence and growth of weeds. Allelochemicals can be released either through leaching, decomposition of residues, volatilization, or root exudation (Chou 1999). To achieve consistent results in the field from the use of cover crop residues, it is important to understand the mechanism of allelopathy (Diab and Sullivan 2003).

One approach to understanding the allelopathic effects of cover crop residues is to separate soil effects occurring during the growth of cover crops from residue effects occurring after incorporation. Studies that separate these effects of buckwheat cover crops on weed emergence and growth are lacking. Another approach is to determine which parts of the cover crop—root, shoot, or root plus shoot—has the most suppressive effects on emergence and growth. Machado (2007) evaluated the allelopathic potential of root and shoot extracts of 42 plant species on emergence and growth of downy brome (*Bromus tectorum* L.), a major weed of wheat (*Triticum aestivum* L.). For most plant species, shoot extracts were more effective in inhibiting seed germination and growth of downy broom than root extracts. Butcko and Jensen (2002) found that shoot extracts of two goldenrod species [*Euthamia graminifolia* L. (Nutt.) and *Solidago canadensis* L.] had inhibitory effects on both germination and growth of radish (*Raphanus sativus* L.) and lettuce (*Lactuca sativa* L.). In contrast, root extracts had no inhibitory effects on germination of these two species, but suppressed root growth. On the other hand, rye (*Secale cereale* L.) root residues were found to be more suppressive than shoot tissues on growth and emergence of barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] and growth of sicklepod [*Senna obtusifolia* (L.) Irwin & Barneby] (Brecke and Shilling 1996; Hoffman et al. 1996).

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Very few studies have examined the relative importance of different plant tissues in the suppression of weeds by buckwheat residue.

The allelopathic potential of chemicals isolated from buckwheat has been demonstrated by many studies (Golisz et al. 2007; Iqbal et al. 2002, 2003; Kalinovà et al. 2005; Tsuzuki and Dong 2003; Xuan and Tsuzuki 2004). Alkaloids such as fagomine, 4-piperidone, and 2-piperidinemethanol isolated from buckwheat shoots caused 50% inhibition of radicle elongation in lettuce seedlings at concentrations less than 100 ppm (Iqbal et al. 2002). The phenolic compounds gallic acid and (+)-catechin isolated from buckwheat foliage have been shown to inhibit root and shoot elongation of common amaranth (*Amaranthus palmeri* S. Wats.), Indian mustard [*Brassica juncea* (L.) Czern.], white clover (*Trifolium repens* L.), lettuce, and Italian ryegrass (*Lolium multiflorum* Lam.) (Iqbal et al. 2003). Other compounds that have been isolated from buckwheat and have shown allelopathic effects are quercetin and its derivatives rutin, epicatechin, and chlorogenic acid (Golisz et al. 2007; Kalinovà et al. 2005). Kalinová et al. (2005) found inhibitory effects on lettuce seedlings of aqueous extracts from buckwheat shoots. They did not find an inhibitory effect of soil extract (1:1) on lettuce growth, but lettuce growth was reduced in the buckwheat-grown soil. Golisz et al. (2007) found that aqueous extracts of buckwheat leaves and inflorescences had higher growth inhibitory effects than stem extracts. Most of these studies examined effects of these identified compounds or buckwheat extract on the lettuce seedling growth (radicle and hypocotyl). Studies related to effects on germination in general and on weed species in particular are lacking.

Allelopathic bioassay studies are often considered unreliable for their artificial nature and for their poor correlation with the outcome in field settings (Harper 1977; Inderjit and Weston 2000). Most allelopathic studies do not involve soil in their bioassays (Inderjit and Dakshini 1995). Soil physical (texture, moisture), chemical (inorganic ions, organic matter), and biological (microorganisms) properties can influence the effects of allelochemicals (Inderjit 2001). To better assess potential allelopathic effects under field conditions, activated carbon can be added to soil. Phenolic compounds such as those isolated from buckwheat residues are adsorbed by carbon, facilitating assessment of their role in inhibiting weeds (Callaway and Aschehoug 2000; Ridenour and Callaway 2001). Activated carbon has a strong affinity for organic compounds (putative allelochemicals) and a weak affinity for inorganic compounds such as nutrients (Cheremisinoff and Ellerbusch 1978). In addition, field conditions can be better simulated through use of aqueous media as opposed to organic compounds in the preparation of cover crop extracts (Inderjit and Dakshini 1995; Schmidt 1990).

Therefore, the primary objectives of this research were to (1) evaluate the possible role of allelopathy in explaining suppression of Powell amaranth, a weed used as a model here, following buckwheat incorporation; (2) distinguish between suppression caused by incorporation of fresh buckwheat residues from suppression caused by changes in soil during buckwheat growth; and (3) quantify the relative importance of buckwheat root vs. shoot tissues in suppression. A secondary objective was to evaluate the effect of different forms of activated carbon on adsorption of phenolics and on other soil properties that might influence emergence and growth, including available N and electrical conductivity.

Materials and Methods

Role of Buckwheat Parts. To evaluate which buckwheat part was the most effective in suppressing weeds and to separate residue-mediated effects and soil effects on weed suppression, pot bioassays were conducted in 2006 and 2007. Two buckwheat rows 17.5 cm apart were sown in flats that measured 35 by 50 by 9 cm with 25 seeds per row (equivalent to a field rate of 60 kg ha^{-1}) in a greenhouse set to day/night temperatures of 24/19 C and a 16-h photoperiod. Soil used for this study was an 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 soil-less media (1:1 peat moss–vermiculite mixture) (Boodley and Shedrake 1977) to create a 3 : 1 mixture of field soil : soil-less media. The soil-less media was added to minimize soil crusting. Plants were watered as required and did not receive any fertilization. Bare soil flats were also included as a control. Thirty-five d after planting (DAP), buckwheat shoots were clipped and cut into 5-cm pieces. Roots were separated from soil using a sieve with 4.75-mm openings. Bare soil was also sieved through the same sieve size. The experiment was a 2 by 4 factorial arranged in a completely randomized design with four replications. Factors included soil types (buckwheat-grown soil vs. bare soil) and buckwheat parts added (none, root, shoot, and root plus shoot). Total fresh shoot and root biomass was weighed and 25.8 and 47.6 g of shoot and 4.7 and 6.3 g of root tissue were obtained for each 11-cm-diam by 11.5-cm-deep pot in 2006 and 2007, respectively. The quantity of tissue added was intended to mimic concentrations found in field soil following incorporation. Both buckwheat-grown and bare soil either not amended or amended with root, shoot, or root plus shoot were placed in pots. Fifty (2006) or 75 (2007) seeds of Powell amaranth were sown per pot. Pots were placed in growth chambers set to day/night temperatures of 25/20 C and 16-h photoperiod. Pots received water by subirrigation whenever necessary to keep the soil surface wet. Powell amaranth emergence was monitored for 20 d. All but the earliest-emerged five plants were removed at the cotyledon stage. These five plants were harvested at 20 d after seeding, dried, and weighed.

Effect of Chemically Activated Carbon. To investigate the role of allelopathy in weed suppression by buckwheat residue, a pot bioassay was conducted in 2005 and 2006. For this study, buckwheat was grown in the greenhouse as described in the previous experiment. Thirty-five DAP, buckwheat shoots were clipped and cut into 5- to 7-cm pieces and uniformly incorporated in the soil. The experiment was a 2 by 2 factorial arranged in a completely randomized design with four replications. Factors included cover crop (buckwheat-amended vs. unamended soil) and activated carbon (with and without). Pots 11-cm-diam by 11.5-cm deep were filled with buckwheat-amended and unamended soils. Chemically activated granular carbon[1] (50 ml L^{-1} soil; particle size 12 to 20 mesh) was thoroughly mixed with soil in half of the pots of each soil type. Fifty (2005) or 75 (2006) seeds of Powell amaranth were sown per pot. Pots were placed in growth chambers and emergence and early growth were monitored as described in the previous experiment.

Effect of Aqueous Extracts of Buckwheat Shoots. This bioassay was conducted to test if buckwheat residue contained

water-soluble phytotoxic compounds. Buckwheat was grown in the greenhouse as described for previous experiments. After 35 d, shoots of two buckwheat flats were harvested (total area 0.35 m^2) and weighed. Half of the total fresh weight was used for aqueous extract and the other half dried to estimate the equivalent dry weight. The fresh buckwheat shoots (750 g) were then chopped into 1- to 2-cm pieces (but not blended), submerged in 500 ml distilled water, and agitated for 24 h on an orbit shaker[2] (150 rpm) at room temperature. The ratio of buckwheat fresh weight to water was chosen to mimic field conditions assuming a soil water content of approximately one-half field capacity (39 L per cubic meter) (Hill et al. 2006). The buckwheat extract was filtered through cheesecloth and then centrifuged (Beckman J2-MC[3]) at 10,000 rpm for 10 min at 3 C. The resulting supernatant was used for Petri dish experiments. This full-strength extract had a concentration two times the concentration found in field soils based on the amount of extract retrieved per unit area harvested and the water content of field soil (39 L m^{-3} soil). Four rates of buckwheat aqueous extract were used: full strength (1,500 g fresh weight L^{-1} or 113 g dry weight L^{-1}), half strength (diluted once), one fourth strength (diluted twice), and distilled water. At 5 d after initiation, radicle length of five plants in each Petri dish was recorded. The pH and electrical conductivity (EC) (using pHTestr 30 and ECTestr, respectively)[4] and nitrate content (using a nitrate ion meter)[5] of the aqueous extract were measured. Fifty seeds of Powell amaranth were placed in 9-cm Petri dishes with two sheets of filter paper and then saturated with 5 ml extract or distilled water. Petri dishes were sealed with Parafilm and placed in a growth chamber set to 25/20 C day/night temperature and a 16-h photoperiod. Only fluorescent lights were used in this experiment. Germinated seeds (radicle $>$ 2 mm) were counted and removed for 20 d.

Effect of Aqueous Soil Extract from Buckwheat-Amended and Unamended Soil with and without Two Forms of Activated Carbon. For this study buckwheat was sown in the field on a Howard gravel loam soil (loamy-skeletal mixed mesic Glosoboric Hapludalf) and Eel silt loam soil (fine loamy, nonacid mixed, mesic Fluvaquentic Eutrudepts) on May 25, 2007 and July 25, 2007, respectively at the H. C. Thompson Vegetable Research Farm in Freeville, NY. Buckwheat was seeded at 60 kg ha^{-1}. A bare soil treatment was included as control. Buckwheat plots were mowed and incorporated 38 DAP in both fields. Soil samples were collected 1 d after incorporation for aqueous soil extraction (1 : 1 v/v) from both buckwheat-amended and unamended (bare soil) plots. The experiment was a 2 by 3 factorial arranged in a completely randomized design with four replications. Factors included cover crop (buckwheat-amended vs. unamended soil) and activated carbon (no carbon, chemically-activated carbon in granular form[2], and thermally-activated in powder form[6]). Sixty ml soil (buckwheat-amended or unamended soil) was placed in 120 ml plastic cups. One-third of these cups received chemically activated granular C, one-third received thermally activated powder, and other one third were without activated carbon. Activated carbon (50 ml L^{-1}) was thoroughly mixed and then 60 ml distilled water was added to each cup. For extraction, these cups were agitated for 24 h on an orbit shaker (150 rpm) at room temperature. Extract was filtered through Whatman filter paper #42. The resultant extract was used immediately for Petri dish bioassays. The remaining extract was frozen until it could be analyzed for total phenolic content. The number of Powell amaranth seeds, Petri dish setup, addition of treatment solutions, growing conditions, and data measurement were as described in the previous experiment. These soil extracts were analyzed in November 2007 for total phenolics (using Folin-Ciocalteau reagent) and results are expressed in equivalent of gallic acid (Waterhouse 2008).

Table 1. Emergence and growth of Powell amaranth in buckwheat-grown and bare soil amended with different buckwheat parts (none = no residue, root only, shoot only, and root + shoot) in 2006 and 2007.

Buckwheat parts added	Emergence		Growth	
	2006	2007	2006	2007
	%		DW (g)[a]	
Buckwheat-grown soil				
None	36 a[b]	23 a	0.015 b	0.005 b
Root	48 a	16 a	0.008 b	0.002 bc
Shoot	39 a	5 b	0.002 c	0.001 c
Root + shoot	41 a	5 b	0.001 c	0.001 c
Bare soil				
None	38 a	24 a	0.063 a	0.022 a
Root	36 a	21 a	0.061 a	0.007 b
Shoot	18 b	5 b	0.014 b	0.003 b
Root + shoot	35 a	4 b	0.015 b	0.004 b

[a] Dry weight (DW) per plant 20 d after seeding.
[b] Means within a column followed by same letter are not significantly different at the 0.05 level according to Fisher's Protected LSD test.

Statistical Analysis. The data were subjected to analysis of variance (ANOVA) and analyzed using the general linear model procedures of the Statistical Analysis System (SAS 2001). Data were either not transformed or log- or square root-transformed as needed to improve assumptions of normality and equal variance of population distributions. Emergence data for Powell amaranth in the activated carbon study were combined for all the trials because there was no treatment by trial interaction. However, growth data are presented separately for each trial. Treatment mean values were separated by Fisher's Protected LSD test at $P = 0.05$. Radicle length data also was combined for both trials because there was no treatment by trial interaction. The effects of soil type, parts added to soil on final emergence (cumulative emergence at 20 d after seeding), and growth (dry weight) were assessed using two-way ANOVA. Similarly, effects of cover crops and activated carbon on final emergence and growth and soil extracts on germination of Powell amaranth were assessed using two-way ANOVA.

Results and Discussion

Role of Buckwheat Parts. *Effects on Emergence*. In 2006, Powell amaranth emergence was suppressed only by the addition of shoots to bare soil (Table 1). In 2007, irrespective of soil type, emergence was reduced when soils were amended with shoot or shoot plus root tissues, when compared with soils that received no amendment. During both years, emergence was not inhibited in either soil type when amended with root tissues and in buckwheat-grown soil when no buckwheat tissue was added. These results suggest that root

exudates released during buckwheat growth had no inhibitory effect on emergence of Powell amaranth.

The reason for lack of suppressive effects of buckwheat residue in 2006 could be attributed to several factors. First, buckwheat dry weight was lower in 2006; therefore, the amount of root and shoot tissue added per pot in 2006 was also lower compared to 2007 (25.8 g vs. 47.6 g). Al-Khatib et al. (1997) reported that emergence suppression of common chickweed [*Stellaria media* (L.) Vill.] increased as the amount of brassica cover crop foliage incorporated into soil increased. Teasdale and Mohler (2000) found that weed emergence declined at an exponential rate as a function of cover crop residue biomass. It is likely that the concentration of phytotoxin released during decomposition of residues was lower in 2006 because of lower buckwheat residues added to soil.

Differential effects of plant tissues on seed emergence have been documented in several other studies. Butcko and Jensen (2002) found inhibitory effects of shoot extracts of goldenrod species (*E. graminifolia* and *S. canadensis*) but not of root extracts on germination of lettuce and radish. In contrast, Hoffman et al. (1996) found that rye root residues had more suppressive effects on both emergence and growth of barnyardgrass than did shoot tissues. Inhibitory effects of both root and shoot extracts of buckwheat on germination of downy brome, although low, (17 to 22%) were similar (Machado 2007).

Effects on Growth. In both years, growth of Powell amaranth was reduced in buckwheat-grown soil compared to bare soil control regardless of buckwheat parts added (Table 1). Without any buckwheat tissue, Powell amaranth biomass was reduced by 76 and 77% in 2006 and 2007, respectively, in buckwheat-grown soil compared with bare soil. The addition of shoot or shoot plus root to buckwheat-grown soil resulted in further suppression of Powell amaranth growth in both years. In buckwheat-grown soil, Powell amaranth biomass was reduced by 82 to 93% with the addition of shoot or shoot plus root tissues compared to buckwheat-soil without residue. In contrast, addition of root to buckwheat-grown soil had no additional negative effects on growth of Powell amaranth.

In bare soil, addition of root tissue did not suppress the growth of Powell amaranth in 2006 but significantly suppressed growth in 2007 (Table 1). With the addition of shoot or shoot plus root in bare soil, growth of Powell amaranth was reduced by 76 to 78% in 2006 and 82 to 86% in 2007 compared with bare soil without residue. The reason for differences across years might be due to the fact that more root tissues were incorporated in 2007 than in 2006, 6.25 and 4.7 g, respectively. Inhibitory effects of aqueous extracts and compounds isolated from buckwheat shoots have been reported (Iqbal et al. 2002, 2003; Kalinová et al. 2005; Tsuzuki and Dong 2003; Xuan and Tsuzuki 2003). These results are consistent with the earlier reports that shoot tissues had higher growth inhibitory effects than root tissues (Bonanomi et al. 2006; Machado 2007).

Suppression of Powell amaranth growth in buckwheat-grown soil in the absence of any buckwheat residue might be attributed to changes in soil characteristics that occurred during the growth of buckwheat. Among the most likely changes are (1) release of inhibitory exudates from the buckwheat roots, or (2) removal of available nutrients during buckwheat growth. The second possibility is supported by a previous study (Kalinová et al. 2005) where lettuce growth was suppressed in buckwheat soil, but not by aqueous extracts from that soil.

Table 2. Emergence and growth of Powell amaranth in buckwheat-amended and unamended soil with and without chemically activated carbon.

Treatment	Emergence	Growth		
		Trial 1	Trial 2	Trial 3
	%	Dry weight (g)[a]		
Without carbon				
Buckwheat	21 b[b]	0.0026 b	0.0020 c	0.0009 b
Bare soil	34 a	0.0918 a	0.0167 b	0.0379 a
With carbon				
Buckwheat	27 ab	0.0014 b	0.0021 c	0.0011 b
Bare soil	38 a	0.0760 a	0.0392 a	0.0510 a
ANOVA				
Cover crop[c]	***	***	***	***
Carbon[d]	*	NS	*	NS
Cover*carbon	NS	NS	*	NS

[a] Dry weight per plant 20 d after seeding.
[b] Means within a column followed by same letter are not significantly different at the 0.05 level according to Fisher's Protected LSD test.
[c] Cover crop (buckwheat vs. bare soil control).
[d] Half pots received chemically activated granular form of carbon and other half without carbon.
+ $P < 0.10$; * $P < 0.05$; ** $P < 0.01$.

Suppression of both emergence and growth caused by shoot or shoot plus root tissues added to buckwheat-grown soil and bare soil might have been due to either N immobilization, allelochemicals released by residues during decomposition, or interaction between buckwheat tissues and fungal pathogens of weed seedlings. In our earlier studies, we found that fungal pathogens are not responsible for suppression of emergence and growth of Powell amaranth (Kumar et al. 2008) and N fertilization did not overcome the suppressed emergence of Powell amaranth. However, reduced growth was totally overcome by N fertilization. These results suggest that suppression of emergence of Powell amaranth was most likely caused by allelopathic effects of shoots and growth by low N availability.

Effects of Chemically Activated Carbon. *Effect on Emergence*. Powell amaranth emergence was reduced (36%) in buckwheat-amended soil compared with unamended soil in the absence of chemically activated carbon (Table 2). No significant reduction in the suppression of Powell amaranth emergence was detected with addition of activated carbon. Activated carbon had a significant effect on emergence of Powell amaranth but the effect did not vary with the cover crop.

The role of activated carbon in reducing the allelopathic effects in the soil has been reported previously (Callaway and Aschehoug 2000; Prati and Bossdorf 2004; Ridenour and Callaway 2001). The lack of response to chemically activated carbon suggests that either (1) factors other than allelopathy (resource competition, N immobilization) play a primary role in suppression of emergence; or (2) chemically activated carbon is ineffective in adsorbing potentially allelopathic compounds. The latter explanation is more likely because the chemically activated carbon used in this study only partially adsorbed the allelochemicals present in the buckwheat-amended soil (discussed in a later section). Özgür and Ferhan

Table 3. Germination and radicle length of Powell amaranth in aqueous shoot extracts of buckwheat.

Strength of original extract	Germination		Radicle length
	Trial 1	Trial 2	
	%		cm[a]
0.00 (distilled water)	29 b[b]	50 b	1.37 a
0.25 (one-fourth)	26 b	73 a	1.18 b
0.50 (one-half)	33 ab	78 a	1.19 b
1.00 (full)	42 a	73 a	0.87 c

[a] Results did not vary by trial so data were combined.
[b] Means within a column followed by same letter are not significantly different at the 0.05 level according to Fisher's Protected LSD test.

(2006) observed that thermally-activated and powder forms of carbon are more effective in adsorbing phenolics than chemically activated and granular forms. The type of activated carbon used in this experiment was an acid-washed granular type. In addition, previous experiments (Kumar et al. 2008) have demonstrated suppressive effects of buckwheat residue on emergence of Powell amaranth in spite of N fertilization and seed treatment with fungicide.

Effect on Growth. Growth of Powell amaranth was suppressed 88 to 99% in buckwheat-amended compared with unamended soil (Table 2). Addition of chemically activated carbon did not ameliorate the suppressive effect of buckwheat residue on growth. As with emergence, this result implies that either allelopathic effects of buckwheat are small or chemically activated carbon did not adequately adsorb allelochemicals, or both.

Effect of Aqueous Extracts of Buckwheat Shoots. *Germination and Radicle Length*. In the first trial, germination of Powell amaranth was stimulated by full-strength aqueous shoot extract of buckwheat (Table 3) being 46% higher in full strength aqueous extract than in distilled water control. Lower concentrations of the extract had no effect on germination. In the second trial, germination was stimulated by all the extract concentrations. Germination was 44 to 55% higher in extracts than in distilled water. Radicle length of Powell amaranth was inhibited (13 to 37%) by buckwheat shoot extracts.

Previous studies have reported that aqueous extracts of buckwheat are less effective in inhibition of germination and growth of plants than organic solvent extracts (Eom et al. 1999; Iqbal et al. 2003). Our findings are consistent with previous studies showing no phytotoxic effects of buckwheat aqueous extracts on germination of livid amaranth (*Amaranthus lividus* L.). (Eom et al. 1999; Iqbal et al. 2003). However, in contrast to our results, they found no effect of these extracts on root elongation of livid amaranth. Similar to our results, other researchers have found inhibitory effects of buckwheat shoot extracts on root elongation of lettuce (Iqbal et al. 2003; Kalinová et al. 2005).

Although extracts did not inhibit germination in Petri dishes, inhibitory effects on germination from these extracts might occur in soils, because allelochemicals are transformed by soil microbes to more phytotoxic forms. It has been reported that microbially produced transformation products of 2 (3H)-benzoxazalinone (BOA) were more phytotoxic than BOA released by rye residues (Chase et al. 1991; Gagliardo and Chilton 1992). Stimulation of Powell amaranth germination in shoot extracts was probably due to lower pH (4.58 and 4.72 in trial 1 and trial 2, respectively) and higher NO_3 levels (17 and 20 ppm in trial 1 and 2, respectively) in buckwheat shoot extracts than distilled water. Thomas et al. (2006) found that germination of slender amaranth (*Amaranthus viridis* L.) was greater under acidic than basic pH conditions. N compounds are also known to stimulate germination of many weed species (Baskin and Baskin 1998; Karssen and Hilhorst 1992), including Powell amaranth (Brainard et al. 2006). Our results suggest that suppression of radicle elongation might account for some of the reduced emergence observed in previous trials; reduced radicle elongation might increase pre-emergence mortality by reducing the ability of freshly germinated seeds to obtain moisture or nutrients and reducing their capacity to emerge from greater depths or through crusted soils.

Effect of Aqueous Soil Extract from Buckwheat-Amended and Bare Soil with and without Two Forms of Activated Carbon. *Characteristics of Aqueous Soil Extracts*. The pH of the aqueous soil extract from buckwheat-amended soil was higher than from unamended soil (Table 4). Addition of activated carbon had no effect on the pH of soil extract.

In trial 1, the electrical conductivity (EC) of soil extracts from buckwheat-amended and unamended soil was similar when no activated carbon was added (Table 4). Addition of thermally activated carbon in powder form in both buckwheat-amended and unamended soil had no effect on EC of the soil extract. In contrast, chemically activated carbon in granular form increased the EC of aqueous extracts of both buckwheat-amended and unamended soils. In trial 2, soil extract from buckwheat-amended soil had higher EC than

Table 4. The characteristics of aqueous soil extract from buckwheat-amended and unamended soil with and without activated carbon.[a]

Treatment	Trial 1 (Eel silt loam soil)			Trial 2 (Gravel loam soil)		
	pH	EC[b]	$NO_3 + NH_4$–N	pH	EC	$NO_3 + NH_4$–N
		μS	ppm		μS	ppm
Buckwheat-amended soil						
No carbon	7.5 a	663 c	14 c	7.5 a	601 b	0.03 c
Chemically activated granular	7.5 a	842 a	10 c	7.5 a	745 a	0.02 c
Thermally activated powder	7.6 a	700 bc	9 c	7.4 a	394 c	0.02 c
Unamended soil						
No carbon	6.9 b	688 c	84 a	7.1 b	188 d	15.38 a
Chemically activated granular	6.9 b	817 ab	60 b	7.0 b	354 c	2.44 b
Thermally activated powder	7.0 b	657 c	67 ab	7.1 b	121 d	1.91 b

[a] Means within a column followed by same letter are not significantly different at the 0.05 level according to Fisher's Protected LSD test.
[b] Abbreviations: EC, electrical conductivity; μS, micro Siemens.

Table 5. Total phenolics in aqueous soil extracts of buckwheat-amended and unamended soil with different types of activated carbon.[a]

Treatment	Trial 1	Trial 2
	mg L^{-1}	
Buckwheat-amended soil		
No carbon	2.47 a	4.56 a
Chemically active granular carbon	1.90 ab	1.72 a
Thermally active powder carbon	1.18 bc	0.19 c
Unamended soil		
No carbon	1.11 bc	0.53 b
Chemically active granular carbon	0.92 c	0.30 bc
Thermally active powder carbon	1.05 c	0.20 c

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

Table 6. Germination of Powell amaranth in aqueous soil extract of buckwheat-amended and unamended soil with and without two different types of activated carbon.

Treatment	Trial 1 (Eel silt loam soil)	Trial 2 (Gravel loam soil)
	%[a]	
Buckwheat-amended soil		
No Carbon	50 bc	22 b
Carbon (Chemically activated granular form)	42 c	22 b
Carbon (Thermally activated powder form)	60 ab	24 b
Unamended soil		
No Carbon	73 a	33 a
Carbon (Chemically active granular form)	70 a	29 ab
Carbon (Thermally active powder form)	68 a	36 a

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

unamended soil. Addition of thermally activated carbon in powder form either reduced (buckwheat-amended) or had no effect (unamended soil) on the EC of the soil extract. Similar to trial 1, chemically activated carbon increased the EC of soil extracts from both buckwheat-amended and unamended soil. Nitrogen levels (NO_3 + NH_4) in aqueous soil extracts from buckwheat-amended soil were lower than unamended soil in both trials (Table 4). Nitrogen levels were similar in soil extracts from buckwheat-amended soil with or without carbon. However, activated carbon in unamended soil reduced the N levels in the soil extract.

Total phenolics were higher in buckwheat-amended soil compared with unamended soil when activated carbon was not added (Table 5). Chemically activated carbon in granular form did not reduce the phenolics levels in either buckwheat-amended or unamended soil. In contrast, thermally activated carbon in powdered form reduced the phenolics levels in both soils and total phenolics in buckwheat-amended soil with this carbon were either similar or lower than unamended soil without carbon.

Adsorptive capacity of carbon varies with the type of carbon activation (thermally or chemically activated) and form of carbon (powder vs. granular). Our results are consistent with previous studies in that it was found that thermally activated carbon in powder form was more effective in adsorbing phytotoxins than the chemically activated carbon in granular form (Özgür and Ferhan 2006).

Germination. Aqueous soil extracts of buckwheat-amended soils without carbon from both trials reduced the germination of Powell amaranth by 32% compared to soil extract of unamended soil (Table 6). Addition of a chemically activated granular form of carbon did not ameliorate the phytotoxic effects of the soil extracts in both trials. In trial 1 (on Eel silt loam soil), germination of Powell amaranth increased in soil extracts of buckwheat-amended soil with a thermally activated carbon in powder form and germination in soil extracts from buckwheat-amended soil with this carbon and unamended soil were not different. In trial 2 (on gravel loam), addition of thermally activated carbon had no effect on Powell amaranth germination.

The germination of Powell amaranth was higher in trial 1 than trial 2 due to higher N concentrations in the aqueous soil extract used in trial 1 (Table 4). In the absence of carbon, germination was suppressed by buckwheat-amended soil extracts, but with the thermally activated carbon (powder form), there was no significant reduction in germination in Eel silt loam soil. However, in the gravel loam, inhibition of germination was not overcome with this carbon (Table 6). Thermally activated carbon was effective in adsorbing phenolics from buckwheat-amended soil. This result suggests that inhibition of Powell amaranth germination in this case (on gravel loam soil) was due to something other than phenolics. One possibility is that the very low levels of nitrate in the buckwheat-amended gravel loam soil (Table 4) inhibited germination of Powell amaranth. These results suggest that suppression of Powell amaranth germination was due to a combination of low N and allelopathy. In previous research, addition of N did not overcome the reduced emergence in buckwheat-amended soil (Kumar et al. 2008).

These results suggest that inclusion of buckwheat as a cover crop in a cropping system can contribute to weed management by reducing both emergence and growth of Powell amaranth in the subsequent crops when planted immediately after buckwheat incorporation. In many northern states of the United States, buckwheat can be included in vegetable cropping systems either in the spring before planting late vegetables such as transplanted broccoli (*Brassica oleracea* L.) or snap beans (*Phaseolus vulgaris* L.), or in midsummer after harvest of early vegetables such as snap beans, lettuce, and peas (*Pisum sativum* L.), and subsequent planting of winter grains.

In summary, the above results suggest that neither buckwheat root exudates nor buckwheat root tissues have inhibitory effects on Powell amaranth emergence. Emergence suppression is most likely due to allelochemicals in shoot tissues, although in some cases, changes in soil N also might play a role. Powell amaranth germination is influenced by the interactive effects of allelochemicals and the soil environment; Powell amaranth responded differently to aqueous extracts from buckwheat tissues than it did to buckwheat-amended soil. In contrast with emergence patterns, suppression of Powell amaranth growth in buckwheat-amended soil appears to be largely due to changes in soil characteristics during buckwheat growth; when fresh buckwheat tissue was removed from soil, significant suppression still occurred. Our previous research suggests that this effect is largely the result of reduced N availability where buckwheat was grown (Kumar et al. 2008). This study also demonstrates the potential problems associated with reliance on activated carbon to assess allelopathic effects. Thermally activated powder was more

effective in adsorbing phenolics from soil than a chemically activated granular form. Moreover, activated carbon also influenced EC and N availability, factors that can have a significant effect on germination and growth of many weed species including Powell amaranth.

Sources of Materials

[1] Chemically activated carbon, Darco, granular, 12–20 mesh, Sigma-Aldrich, 3050 Spruce St., St. Louis, MO 63103.

[2] Orbit shaker 3520, Labline Instruments USA, 15th & Bloomingdale Ave., Melrose Park, IL 60160.

[3] Beckman J2-MC Centrifuge, Analytical Instruments, LLC, 1200 Mendelssohn Ave., Suite 50, Golden Valley, MN 55427–4366.

[4] pHTestr 30 and ECTestr, Oakton Instruments, P.O. Box 5136, Vernon Hills, IL 60061.

[5] Cardy Compact Nitrate Ion Meter C-141, Horiba Instruments, 17671 Armstrong Ave., Irvine, CA 92614.

[6] Thermally activated carbon, Darco, powder, -100 mesh size, Sigma-Aldrich, 3050 Spruce St., St. Louis, MO 63103.

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