Use of Selenium-enriched Mustard and Canola Seed Meals as Potential Bioherbicides and Green Fertilizer in Strawberry Production

Gary S. Bañuelos¹

USDA-ARS Water Management Research Unit, 9611 S. Riverbend, Parlier, CA 93648

Bradley D. Hanson

University of California, Davis, Davis, CA 95616

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Abstract. New plant-based products can be produced from seed harvested from Brassica species used for phytomanaging selenium (Se) in the west side of central California. Se-enriched seed meals produced from canola (*Brassica napus*) and mustard (*Sinapis alba*) plants were tested as potential bioherbicides and green fertilizers in strawberry production under controlled and field conditions for two seasons. Treatments consisted of adding each meal (containing 2.2 mg Se/kg dry mass) to the soil at rates equivalent to 0, 2, and 6 t/acre, respectively, 7 days before planting. In growth chamber studies, the highest rates of either meal lowered berry yields by a high of 30% compared with no application (control). Among the nutrient accumulation, berry Se, calcium (Ca), manganese (Mn), and zinc consistently increased with most Brassica meal treatments and most significantly with the mustard meal. In the field studies, mustard treatments lowered the emergence of summer-germinating and resident winter annual weeds more than canola and control treatments. Strawberry fruit yields increased with all Brassica treatments, except a 42% fruit yield reduction was observed at a 6 t/acre rate of mustard meal. Increases in fruit Se concentrations and increases in Ca, phosphorus, and Mn were often observed for all Brassica treatments. Amending soils with Brassica seed meals may have more practical viability in organic agriculture as a potential bioherbicide and green fertilizer.

In the west side of California's San Joaquin Valley (SJV), researchers and growers are using a phytobased strategy to manage selenium (Se) from naturally contaminated soils (Bañuelos, 2009). In its broadest sense, this strategy uses plants to manage soluble Se by accumulating, volatilizing, stabilizing, and transforming Se in contaminated water and soils (Pilon-Smits, 2005). Effective phytomanagement requires that plants produce relatively large amounts of biomass and volatilize and absorb more Se from the soil. Once absorbed by plant roots, Se translocated to the shoot and other plant parts may be harvested and removed from the site. Bañuelos (2002) reported that Brassica crops, e.g., canola (*B. napus*), Indian mustard (*B. juncea*), can be practically used for the management of Se in central California.

Bañuelos (2009) has suggested that Brassica seed harvested from plants used for phytomanaging Se may also have an economic importance for the grower. For example, oil extracted from canola and mustard seeds from plants grown in the SJV produced biofuel blends that were used for operating diesel-powered equipment. He subsequently tested the residual mustard seed meal as a potential biofumigant for inhibiting weeds in greenhouse studies (unpublished data). This preliminary research and earlier biofumigation work by Ascard and Jonasson (1991), Brown et al. (2006), Morra (2004), Snyder et al. (2009) and Stapleton and Bañuelos (2009) prompted Bañuelos and Hanson to evaluate the potential bioherbicidal effects of Brassica seed meals. Some Brassica seed meals contain nitrogen- and sulfur-containing compounds called glucosinolates (GLS), which can be hydrolyzed into a number of bioactive compounds, including isothiocyanates (Morra, 2004) and may be useful for preventing weed emergence under organic agriculture production. Although another Brassica species, canola, has a different and lower GLS profile than mustard meal, both canola and mustard seed meal may have additional benefits as a soil amendment because of their high nutrient content (Balesh et al., 2005). These Brassica seed meals with

6% nitrogen (N) by weight and C:N ratios of 8:1 (Gale et al., 2006) may serve as an organic source of N in agricultural production systems. Moreover, the seed meals are also rich in crude protein (30%) and contain essential nutrients such as phosphorus (P) (0.7% to 0.8%), potassium (K) (0.8% to 1.1%), calcium (Ca) (0.7%), magnesium (Mg) (0.6%), sulfur (0.8% to 1.7%), zinc (Zn) [72 mg·kg⁻¹ dry matter (DM)], manganese (Mn) (37 to 80 mg·kg⁻¹ DM), and Cu (7 to 10 mg·kg⁻¹ DM) (Balesh and Salema, 2000). Snyder et al. (2009) evaluated Brassica seed meals as organic sources of nutrients for increasing plant-available inorganic N to carrots and also investigated the impact of GLS degradation products on microbial N uptake.

Uniquely, seed harvested from Brassica plants used for the phytomanagement of Se in the SJV contain measureable amounts of trace element Se, i.e., 2 to 3 mg·kg⁻¹ DM. Hence, meals produced from these seeds may be potentially useful as a green fertilizer for biofortifying food crops with Se (Bañuelos and Lin, 2009). Coupling the process of phytomanagement of Se in the west side of the SJV with the creation of new byproducts from Brassica spp., e.g., biofuel, biofumigants, and even Se-enriched green fertilizers, may provide central California growers new opportunities to sustain their crop production and create unique Se-enriched products. The use of Brassica seed meal (after oil extraction) may attract more attention with high-value organically grown crops, e.g., strawberries, if it is found to be effective as a biofumigant and/or as a green fertilizer. Because conventional strawberry growers in the United States depend heavily on synthetic fertilizers (May and Pritts, 1990), identifying additional organic sources of nutrients is imperative for successful organic strawberry production in growing regions like central California. For this study, Se-enriched seed meals produced from canola and mustard plants grown for the phytomanagement of Se in the west side of central California were tested as potential bioherbicides and as green fertilizer sources in strawberry production. Two different Se-enriched Brassica seed meals were examined as potential weed inhibitors when added to soil (surface-applied versus incorporated), and the accumulation of macro- and micro-nutrients, including Se, in strawberries was monitored under both controlled and field conditions.

Methods and Materials

Growth chamber studies

Two environmental growth chambers (Conviron; E16, Winnipeg, Manitoba, Canada) were used for growing strawberry (*Fragaria* sp. var. *Camarosa*) under controlled conditions. Treatments consisted of amending potted soils with various rates of Se-enriched canola seed meal or yellow mustard (*Sinapis alba*) seed meal produced from plants grown in a Se phytomanagement/biofuel project in the west side of the SJV (Bañuelos, 2009). Seeds were cold-processed for their oil on

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¹To whom reprint requests should be addressed; e-mail gary.banuelos@ars.usda.gov.

Red Rock Ranch, Five Points, CA, and the residual meal was stored at 12 °C until onset of the study. The Se-enriched seed meals [containing ≈ 2.2 mg Se/kg DM and other nutrients (see Table 1)] were applied as a dry granulated meal at rates equivalent to 0, 2, and 6 t/acre (0, 8.2, and 24.5 g/4-L pot) directly to the soil surface or incorporated into the top 4 cm of soil. Each pot contained 2 kg Hanford sandy loam (coarse-loamy, mixed, superactive, non-acid, thermic Typic Xerothents) field soil with a sand/silt/clay distribution of 60%, 30%, and 10%, respectively, collected near Parlier, CA. No synthetic fertilizers were applied to any treatment. The experiment was set up as a completely randomized design with a minimum of six replicates per treatment. Plastic cups (10 $\times$ 4 $\times$ 4 cm) with small holes surrounding the base were placed 4 cm into the soil in the middle of each pot and used as receptacles for irrigation water to achieve a more equal distribution of water into the soil. Before planting, water was applied every 2 d (up to 1 week) to promote breakdown of the seed meal and encourage glucosinolate hydrolysis and the production of bioicidal products (Morra, 2004).

Growth chambers were maintained at 21°/17 °C at 240 μ E·s⁻¹ with 16/8 h daylight/night. Seven d after amending soils with seed meal, three strawberry slips were planted in each pot. Irrigation rates were determined by measuring weight loss of selected pots from each treatment and then adding water to maintain 70% soil moisture content. When berries first appeared (≈ 5 months after planting), red fruit were picked for a 6-week period, weighed, washed, and immediately frozen at -20 °C for future nutrient analyses (described subsequently). The experiment was conducted in 2005 (January through August) and repeated in 2005–2006 (August through April).

Field studies

Microplot layout. The bioherbicide and strawberry production field trials were simultaneously conducted at the USDA-ARS, San Joaquin Valley Agricultural Science Center, Parlier, CA (each experiment is described subsequently). In Sept. 2006 and Nov. 2007, planting beds (35-m long $\times$ 0.9-m wide $\times$ 20 cm high) were created in the same Hanford sandy loam soil used in the growth chamber experiments. Each bed contained nine microplots (3 $\times$ 0.9 m in size). Se-enriched seed meal amendment treatments were made using the same canola and mustard seed meal used in the growth chamber experiments. In the first field experiment (Sept. 2006 to June 2007), both canola and mustard seed meal were applied evenly to the soil surface at rates equivalent to 0, 1, 2, and 6 t/acre and either

incorporated into the top 10 cm of the soil with a rototiller or left undisturbed on the soil surface. In the second field experiment (Nov. 2007 to June 2008), the surface application of seed meal was removed as a treatment as a result of the high occurrence of soil surface-growing fungi and meal runoff observed in first field experiment. Additionally, incorporated seed meal rates in the second experiment were adjusted, and mustard meal was applied as 0, 1, 2, and 6 t/acre and canola meal at 0, 2, and 6 t/acre and incorporated with a rototiller.

Bioherbicide trial. To determine the effect of seed meal on weed emergence and productivity, weed seed was planted in 40-cm rows in a 1-m area of each microplot. Weed seed was planted by hand before application of surface-applied seed meals or immediately after shallow incorporation of seed meal (see Fig. 1A for planting scheme). Within each microplot, 10 weed species was seeded by sprinkling dry seed or tubers into shallow furrows spaced 10 cm apart. Weeds included barnyardgrass (*Echinochloa crus-galli*), annual bluegrass (*Poa annua*), common chickweed (*Stellaria media*), large crabgrass (*Digitaria sanguinalis*), horseweed (*Conyza canadensis*), little mallow (*Malva parviflora*), redroot pigweed (*Amaranthus retroflexus*), common purslane (*Portulaca oleracea*), Italian ryegrass (*Lolium multiflorum*), and yellow nut-sedge (*Cyperus esculentus*). Weed emergence data were collected and total above-ground biomass for each planted and native weed species was collected 8 to 10 weeks after seeding from a 0.1-m² area within each microplot.

Strawberry productivity and weed control. Within each microplot, three strawberry slips (*Frageria* sp. var. *Camarosa*) were initially planted 14 d after meal application and then on a weekly basis for 6 weeks. In Week 7, nine slips were planted in the area previously planted to weeds, which had been completely harvested by Week 7 (described in Fig. 1B). The planting scheme for strawberry slips was repeated identically on new growing sites in the second year, except the planting date was 43 d later (26 Nov. 2007) compared with the first planting date (13 Oct. 2006). Weekly plantings were conducted to provide a diminishing dose of any injurious compounds, i.e., isothiocyanates, to allow assessment of the amount of time required before safe transplanting could occur. Each respective strawberry field experiment was arranged as a randomized complete block with each treatment replicated on four planting beds. Microplots were initially irrigated with micro-sprayers (Bow-Smith Fan Jet R SP, 22.8 L·h⁻¹ at 138 K/Pa; Bow-Smith, Inc., Exeter, CA) to

promote breakdown of the seed meal and facilitate release of bioactive compounds into the soil. For irrigation after planting of the strawberry slips, a single 1.9-L·hr⁻¹ drip tape was installed on each bed. Irrigation rates were based on evapotranspiration losses recorded by the CIMIS weather station at the University of California Kearney Research Station located 2 km from the field site in Parlier, CA. The only source of nutrients applied to the plots was the respective seed meal treatments.

After 5 months of growth, strawberry plants were checked on a daily basis for fruit production during the prime fruit producing season (April through mid-June) for each field experiment. Fruit were collected, weighed, washed, and frozen at -20 °C for nutrient analysis (described subsequently). As a result of the large number of fruit produced, only strawberries collected during the month of May in each season were analyzed for nutrient content for both testing years.

Fruit nutrient analysis. In preparation for analysis, frozen fruit samples from all growth chamber and field studies were sliced into smaller pieces, placed into petri dish-like plates, and oven-dried for 3 to 5 d. A low drying temperature of 50 °C was used to reduce potential loss of Se through volatilization during dehydration. Total Se and the essential nutrients (i.e., Ca, Mg, K, P, Mn, Cu, Zn, and iron) were determined in a 500-mg fruit sample after digestion with nitric acid, hydrogen peroxide, and hydrochloric acid as described by Bañuelos and Akohoue (1994). Se and other nutrients were analyzed by an inductively coupled plasma spectrometer-mass spectroscopy (Agilent 7500ex, Santa Clara, CA). The statistical analysis system (Version 6.03; SAS Institute, Cary, NC) was used for the data analysis (SAS Institute, 1988), and Duncan's multiple range test was applied to determine significant differences between treatment means at the $P < 0.05$ level of significance for yield and nutrient concentrations. Fisher's least significant difference test ($P < 0.05$) was used to evaluate weed data.

Results and Discussion

Growth chamber trials

No yield benefits from seed meal amendments were observed in the two environmental chamber experiments. In fact, the highest application rates of either mustard or canola seed meal applied to the soil significantly lowered berry yields compared with berry yields measured from control treatments (Tables 2 and 3). Berry Se concentration was two- to 10-fold higher when soil was amended with either Se-enriched canola or mustard seed meals irrespective of mode and

Table 1. Mean nutrient content of canola and mustard and seed meals added to soils as green fertilizer.

Meal type ^z	Nitrogen (%)	Phosphorus	Potassium	Sulfur	Calcium	Magnesium	Iron	Manganese	Zinc	Copper	Boron
		(mg·kg ⁻¹ dry matter)									
Canola	5.1 ^v (0.4)	6,635 (582)	7,752 (595)	4,741 (365)	6,437 (541)	2,896 (541)	186 (19)	41 (4)	31 (3)	5 (0.5)	36 (4)
Mustard	4.9 (0.3)	9,621 (369)	10,857 (856)	12,682 (582)	7,700 (588)	3,716 (246)	313 (25)	32 (3)	49 (5)	9 (0.9)	49 (5)

^zSelenium concentrations were on the average 2.2 mg·kg⁻¹ dry matter for both seed meals.

^vValues represent the mean with sd in parentheses from five meal samples.

rate of meal application (Tables 2 and 3). In the second growth chamber study, mustard seed meal treatments increased concentrations of all nutrients to a greater degree than canola meal treatments in both first and second growth chamber trials (Tables 2 and 3). Among the nutrients, fruit Ca concentrations increased significantly with mustard seed meal treatments and with canola seed

meal treatments (except with the surface-applied treatment at a low rate) (Tables 2 and 3), whereas the addition of mustard seed meal consistently increased Mn and Zn concentrations in the berries irrespective of mode of meal application for both chamber trials. In addition, slight burning-like symptoms were sometimes observed on leaf edges in plants exposed to equivalent to mustard meal

at 6 t/acre. Nutrient analyses did not identify any elements' concentrations in excess (data not reported). Hence, the observed effects may have been the effects induced by bioactive compounds released by glucosinolate hydrolysis of the seed meals.

Field trials

Bioherbicides for weed control. The role of Se as a bioherbicide has been discounted as a result of the lack of supporting literature reporting on its potential involvement in plant phytotoxicity. Dhillon and Dhillon (2009) have even reported that perennial weeds can be used for the phytoremediation of seleniferous soils because of their ability to accumulate Se. As previously described, surface-applied canola and mustard meal treatments were only used in the first field experiment as a result of excessive accumulation and formation of fungi observed on the soil surface (note that this phenomena was also observed with all higher-rate meal treatments in the growth chamber studies). In the first field trial, established in the fall, summer annual weed emergence was significantly affected by seed meal treatments (Table 4). In general, emergence of summer germinating weeds was somewhat lower in microplots treated with the high rate of mustard meal irrespective of mode of meal application. Mustard meal also appeared to be slightly

Fig. 1. Planting scheme for weeds and strawberries in the first through the eighth week (A) and for strawberries in the ninth week (B).

Table 2. Yield and nutrient concentrations in strawberry fruit grown in soils amended with Brassica seed meals in first growing season under growth chamber conditions.^z

Brassica treatment ^y (t/acre)	Total fresh yield (g/pot)	Calcium	Magnesium	Potassium	Phosphorus	Manganese	Copper	Zinc	Selenium
					(mg·kg ⁻¹)				(ug·kg ⁻¹)
Control (0)	95 ^{bxw} (1)	1,429 ^f (57)	927 ^e (24)	11,697 ^d (209)	1,703 ^c (33)	21 ^c (33)	3 ^a (0)	13 ^c (1)	53 ^f (2)
Canola-S-(2)	110 ^a (2)	1,535 ^c (64)	1,009 ^{de} (28)	11,909 ^{cd} (205)	1,775 ^c (34)	22 ^c (1)	3 ^a (0)	15 ^c (0)	143 ^d (3)
Canola-I-(2)	78 ^c (2)	1,874 ^c (76)	1,084 ^d (30)	13,822 ^{ab} (225)	1,700 ^c (32)	20 ^c (1)	4 ^a (0)	16 ^{bc} (1)	148 ^d (3)
Canola-S-(6)	56 ^d (1)	1,985 ^b (78)	1,023 ^d (30)	13,943 ^{ab} (227)	1,795 ^c (32)	22 ^c (1)	4 ^a (0)	14 ^c (0)	178 ^{bc} (4)
Canola-I-(6)	32 ^c (1)	2,269 ^a (82)	1,652 ^a (37)	14,667 ^a (247)	2,406 ^a (37)	35 ^b (1)	4 ^a (0)	21 ^a (1)	202 ^a (4)
Mustard-S-(2)	98 ^{ab} (2)	2,289 ^a (81)	1,261 ^c (22)	12,605 ^{bc} (237)	1,764 ^c (33)	32 ^b (1)	4 ^a (0)	18 ^{ab} (0)	186 ^{ab} (4)
Mustard-I-(2)	62 ^d (1)	2,203 ^a (84)	1,407 ^b (36)	12,806 ^{bc} (218)	2,001 ^{ab} (38)	40 ^b (1)	4 ^a (0)	15 ^c (1)	103 ^c (2)
Mustard-S-(6)	32 ^e (1)	1,725 ^d (53)	962 ^e (20)	12,524 ^{bc} (231)	1,861 ^b (35)	55 ^a (2)	4 ^a (0)	19 ^{ab} (1)	159 ^{cd} (3)
Mustard-I-(6)	50 ^d (1)	1,509 ^{ef} (42)	953 ^e (20)	13,024 ^b (247)	2,314 ^a (40)	56 ^a (2)	4 ^a (0)	21 ^a (0)	170 ^{bc} (2)

^zOnly fruit from 30 Jan. 2007 through 22 Mar. 2007 were analyzed from three plants per pot.

^yS (meal applied to surface) and I (meal incorporated).

^xValues represented the means with SE in parentheses from all fruit picked from a minimum of five replications for the designed growing season.

^wMeans followed by the same letter within each column are not significantly different ($P < 0.05$) according to Duncan's multiple range test for each respective parameter.

Table 3. Yield and nutrient concentrations in strawberry fruit grown in soils amended with Brassica seed meals in the second growing season under growth chamber conditions.^z

Brassica treatment ^y (t/acre)	Total fresh yield (g/pot)	Calcium	Magnesium	Phosphorus	Potassium	Manganese	Copper	Zinc	Selenium
					(mg·kg ⁻¹)				(ug·kg ⁻¹)
Control (0)	95 ^{ax} (1)	2,400 ^d (45)	1,494 ^c (28)	10,076 ^d (222)	1,781 ^c (31)	34 ^d (1)	2 ^b (0)	15 ^b (1)	42 ^c (2)
Canola-S-(2)	92 ^a (2)	3,625 ^b (57)	1,512 ^c (29)	16,747 ^{ab} (265)	2,592 ^c (44)	34 ^d (1)	3 ^b (0)	17 ^b (1)	221 ^b (5)
Canola-I-(2)	56 ^b (2)	2,825 ^c (51)	1,374 ^d (28)	12,451 ^c (240)	1,727 ^c (32)	45 ^d (2)	3 ^b (0)	14 ^b (1)	108 ^d (3)
Canola-S-(6)	59 ^b (2)	2,518 ^d (47)	1,506 ^c (28)	12,641 ^c (249)	2,207 ^d (43)	36 ^d (1)	3 ^b (0)	17 ^b (1)	162 ^c (5)
Canola-I-(6)	32 ^c (1)	2,520 ^d (48)	1,544 ^c (32)	12,533 ^c (270)	2,301 ^d (46)	35 ^d (1)	3 ^b (0)	18 ^b (1)	192 ^b (5)
Mustard-S-(2)	87 ^a (2)	3,362 ^b (60)	1,842 ^b (34)	15,760 ^b (298)	2,875 ^b (53)	67 ^c (3)	3 ^b (0)	15 ^b (1)	93 ^d (3)
Mustard-I-(2)	59 ^b (2)	3,250 ^b (64)	1,934 ^b (36)	17,208 ^a (318)	3,233 ^a (59)	68 ^c (3)	3 ^b (0)	16 ^b (1)	92 ^d (3)
Mustard-S-(6)	62 ^b (2)	4,542 ^a (74)	2,294 ^a (38)	17,258 ^a (300)	3,684 ^a (62)	133 ^a (4)	7 ^a (0)	22 ^a (1)	321 ^a (8)
Mustard-I-(6)	32 ^d (1)	4,666 ^a (75)	1,938 ^b (35)	15,560 ^b (27)	3,355 ^d (58)	115 ^b (3)	6 ^a (0)	18 ^b (1)	396 ^a (5)

^zOnly fruit from 20 Apr. 2007 through 12 June 2007 were analyzed from three plants per pot.

^yS (meal applied to surface) and I (meal incorporated).

^xValues represent the means from all fruit picked with SE in parentheses from a minimum of five replications. Means followed by the same letter within each column are not significantly different ($P < 0.05$) according to Duncan's multiple range test for each respective parameter.

more effective than canola meal for weed control, although the differences were not always significant. Compared with control plots, emergence of the small-seeded broad-leaf weeds, e.g., common purslane and red-root pigweed, was reduced by all seed meal treatments (Table 4).

A frost between the last emergence rating and biomass collection killed all summer weeds; therefore, above-ground biomass data for the summer weeds were not collected. Biomass production of the winter annual weeds in the first field trial was not statistically different among treatments because of high variability among replicates (Table 4); however, high rates of mustard meal amendment tended to reduce weed biomass production. Biomass production of the resident winter annual weeds (primarily shepherd's purse, Italian ryegrass, desert rock purslane, and annual bluegrass) was reduced by all meal treatments compared with the control. The greatest reductions in resident weed biomass occurred with both mustard meal and high canola meal treatments (surface-applied). In the second field trial, which was established in early winter (43 d later than the first field trial), summer annual weeds emerged poorly or not at all as a result of cool

environmental conditions (data not shown). Emergence of the five winter annual weeds usually was lower in mustard meal treatments than in canola meal treatments (Table 5). Biomass accumulation of the winter weeds was highly variable, possibly as a result of confounding effects of growth inhibition and a positive fertilizer response from meal treatments. Weeds in low seed meal treatments tended to produce more biomass than the control treatment, whereas high rates of meal amendment were often associated with biomass production similar to the control plots (Table 5).

Green fertilizer for use in strawberry production. In both years, visual observations suggested that strawberry plants transplanted shortly after mustard meal incorporation were initially stunted and discolored; however, by early spring, strawberry survival, growth, and productivity were similar among all treatments (data not shown). Compared with the control treatment (without seed meal amendment), strawberry fruit yield increased in the first field trial with all seed meal treatments, except at the high rate of mustard meal application, which caused a 42% reduction in fruit yield (Table 6). Similarly, in the second trial, strawberry yields were reduced

in plots treated with incorporated canola and mustard seed meals at high rates of application (Table 7). For both field trials, significant increases in berry Se concentrations were measured for all canola and mustard seed meal treatments compared with control treatments (Tables 6 and 7). These increases were, however, considerably less dramatic than the Se increases observed in the growth chamber studies (Tables 2 and 3). Berry Ca concentration in field-grown fruit was generally higher for all treatments in Year 2, whereas inconsistent increases in berry Ca concentrations were observed for most of the canola and mustard treatments compared with control treatments in Year 1 (Tables 6 and 7). Berry Mn concentration significantly increased with all meal treatments for both years (except with canola meal surface-applied or incorporated at low rates in Year 1). Effects on berry concentration of other nutrients were not clearly observed for other canola and mustard meal treatments in either field study (Tables 6 and 7).

Similar to results from other studies (e.g., Hoagland et al., 2008; Rice et al., 2006), weed control with Brassica seed meal soil amendments was variable among replicates. In some cases, weed emergence or biomass

Table 4. Emergence of summer annual weeds 1 month after planting and above-ground biomass production of winter annual weeds 2 months after strawberry microplots amended with Brassica seed meal, first year experiment (2006–2007).

Seed meal	Rate (t/acre)	Meal placement	Summer annual weed emergence ^z				Winter annual weed above ground ^y					
			Large crabgrass	Barnyard grass	Common purslane	Redroot pigweed	Annual bluegrass	Annual ryegrass	Common chickweed	Horseweed	Little mallow	Resident weeds
			(no. per 30-cm row)	(no. per 30-cm row)	(no. per 30-cm row)	(no. per 30-cm row)	(g per 30-cm row)	(g per 30-cm row)	(g per 30-cm row)	(g per 30-cm row)	(g per 30-cm row)	(g·m ⁻²)
Control	—	—	5.5	2.5	10.8	12.0	1.70	16.20	0.90	0.80	3.80	53.2
Canola	2	Incorporated ^x	13.8	7.3	0.0	5.8	4.88	29.10	0.63	0.50	5.30	25.6
Canola	2	Surface	4.8	4.5	5.5	3.0	2.75	25.90	1.60	0.65	2.68	27.4
Canola	6	Incorporated	2.3	2.5	0.0	1.0	2.45	26.50	0.15	0.75	2.78	33.9
Canola	6	Surface	1.3	1.0	0.0	1.5	1.38	20.50	0.05	0.00	6.48	11.5
Mustard	2	Incorporated	4.0	2.5	0.0	0.8	4.75	25.00	0.78	0.88	8.20	11.4
Mustard	2	Surface	1.3	1.0	0.8	1.3	2.38	14.40	0.35	0.08	3.35	28.8
Mustard	6	Incorporated	1.0	0.0	0.0	0.0	0.00	0.10	0.00	0.00	0.00	6.6
Mustard	6	Surface	0.0	0.0	0.5	0.0	0.28	12.50	0.23	0.00	0.35	2.8
LSD _(0.05)			4.8	3.9	2.2	4.4	2.30	NS ^w	NS	NS	NS	19.9

^zLarge crabgrass (*Digitaria sanguinalis*); barnyardgrass (*Echinochloa crus-galli*); common purslane (*Portulaca oleracea*); redroot pigweed (*Amaranthus retroflexus*); annual bluegrass (*Poa annua*); annual ryegrass (*Lolium multiflorum*); common chickweed (*Stellaria media*); horseweed (*Conyza canadensis*); little mallow (*Malva parviflora*); resident weeds consisted primarily of *Poa annua*, *Lolium multiflorum*, *Calandrinia ciliata*, and *Capsella bursa-pastoris*.

^yEmergence counts of summer annual weeds were taken 1 month after planting and winter annual weed biomass was collected 2 months after planting; a frost event killed all summer weeds shortly after the emergence count.

^xIncorporated = incorporated 10 cm into bed tops; surface = meal spread on soil surface.

^wNS = nonsignificant at the *P* < 0.05 level.

LSD = least significant difference.

Table 5. Weed emergence and biomass in strawberry microplots amended with Brassica seed meal, second year experiment (2007–2008).^z

Seed meal	Rate (t/acre)	Placement	Annual bluegrass ^z		Common chickweed ^z		Horseweed ^z		Little mallow ^z		Annual ryegrass ^z	
			Emerg	Dry wt	Emerg	Dry wt	Emerg	Dry wt	Emerg	Dry wt	Emerg	Dry wt
			(no.)	(g)	(no.)	(g)	(no.)	(g)	(no.)	(g)	(no.)	(g)
None (control)	—	—	49.8 ^y	125	15.3	900	90	125	18	118	40.8	525
Canola	2	Incorporated ^x	50.3	1525	8.8	350	28.8	200	11.5	283	21	5075
Canola	6	Incorporated	51.5	450	3	10	13.8	0	3.3	38	21.3	900
Mustard	1	Incorporated	45	775	8	300	76.5	750	12.5	225	23.3	2325
Mustard	2	Incorporated	44.3	925	5	340	46	655	10.5	270	18.8	3675
Mustard	6	Incorporated	25.8	200	1.3	25	7.5	25	1.5	28	18.8	1050
LSD _(0.05)			13	680	6.8	NS	49.7	417	4.3	193	9.8	2450

^zAnnual bluegrass (*Poa annua*); common chickweed (*Stellaria media*); horseweed (*Conyza canadensis*); little mallow (*Malva parviflora*); annual ryegrass (*Lolium multiflorum*).

^yEmergence counts (number per 30-cm row) and weed biomass (g per 30-cm row) were determined 2 months after planting.

^xIncorporated 10 cm into bed tops; surface = meal spread on soil surface.

LSD = least significant difference; NS = nonsignificant.

Table 6. Yield and nutrient concentrations in strawberry fruit grown in soils amended with Brassica seed meals in the first growing season under field conditions.^z

Brassica treatment ^y (t/acre)	Total fresh yield (g)	Calcium	Magnesium	Potassium	Phosphorus	Manganese	Copper	Zinc	Selenium ($\mu\text{g}\cdot\text{kg}^{-1}$)
(mg·kg ⁻¹)									
Control (0)	1,513 ^{ac} (25)	1,350 ^c (25)	1,002 ^c (95)	12,231 ^b (208)	2,021 ^d (198)	20 ^d (0)	4 ^a (0)	8 ^a (0)	28 ^d (2)
Canola-S-(2)	1,828 ^d (28)	1,765 ^b (31)	1,321 ^a (22)	12,361 ^b (249)	2,462 ^b (49)	22 ^d (1)	4 ^d (0)	10 ^a (0)	38 ^c (2)
Canola-I-(2)	2,285 ^{bc} (29)	1,931 ^a (34)	1,282 ^{ab} (25)	12,021 ^b (261)	2,131 ^c (50)	22 ^d (1)	4 ^d (0)	8 ^a (0)	40 ^{bc} (2)
Canola-S-(6)	2,506 ^b (27)	1,542 ^d (30)	1,102 ^b (27)	13,264 ^a (293)	2,216 ^c (42)	35 ^c (1)	3 ^a (0)	9 ^a (0)	47 ^b (2)
Canola-I-(6)	2,000 ^{cd} (28)	1,625 ^{bc} (29)	1,221 ^b (30)	13,344 ^a (281)	2,546 ^a (53)	37 ^c (1)	4 ^a (0)	10 ^a (0)	38 ^c (2)
Mustard-S-(2)	3,014 ^a (52)	1,518 ^{cd} (33)	1,050 ^c (22)	12,062 ^b (241)	2,032 ^d (43)	26 ^d (1)	4 ^a (0)	8 ^a (0)	46 ^b (3)
Mustard-I-(2)	3,209 ^a (51)	1,613 ^{bc} (35)	1,226 ^b (27)	13,342 ^a (268)	2,431 ^b (49)	40 ^c (2)	4 ^a (0)	10 ^a (0)	47 ^b (3)
Mustard-S-(6)	1,740 ^{dc} (26)	1,421 ^e (30)	1,255 ^{ab} (29)	13,920 ^a (281)	2,520 ^{ab} (53)	88 ^b (2)	5 ^a (0)	11 ^a (0)	66 ^a (4)
Mustard-I-(6)	883 ^f (18)	1,401 ^e (29)	1,041 ^c (26)	13,629 ^a (272)	2,623 ^a (60)	110 ^a (3)	4 ^a (0)	10 ^a (0)	45 ^b (4)

^zOnly fruit from 24 Mar. 2007 through 11 May 2007 were analyzed.^yS (meal applied to surface) and I (meal incorporated).^xValues represent the means with SE in parentheses from all fruit picked from a minimum of five replicates. Means followed by the same letter within each column are not significantly different ($P < 0.05$) according to Duncan's multiple range test for each respective parameter.Table 7. Yield and nutrient concentrations in strawberry fruit grown in soils amended with Brassica seed meals in the second growing season under field conditions.^z

Brassica treatment ^y (t/acre)	Total fresh yield (g/plot)	Calcium	Magnesium	Potassium	Phosphorus	Manganese	Copper	Zinc	Iron	Selenium ($\mu\text{g}\cdot\text{kg}^{-1}$)
(mg·kg ⁻¹)										
Control (0)	1,753 ^{bx} (149)	1,655 ^c (160)	1,261 ^a (258)	12,489 ^a (1,232)	1,857 ^b (183)	22 ^d (4)	3 ^a (1)	8 ^a (1)	64 ^{bc} (8)	22 ^c (4)
Canola-I-(2)	1,854 ^{ab} (185)	1,932 ^b (314)	1,259 ^a (273)	12,430 ^a (1,089)	2,164 ^d (381)	32 ^{bc} (5)	4 ^a (1)	11 ^a (2)	69 ^b (6)	33 ^b (6)
Canola-I-(6)	488 ^c (76)	1,783 ^c (200)	1,245 ^a (165)	12,929 ^a (1,360)	2,212 ^a (229)	68 ^a (7)	5 ^a (1)	11 ^a (1)	66 ^{bc} (5)	44 ^a (9)
Mustard-I-(1)	1,768 ^b (152)	2,306 ^a (370)	1,236 ^a (208)	12,121 ^a (1,044)	2,233 ^a (306)	28 ^c (5)	4 ^a (1)	11 ^a (2)	76 ^a (6)	41 ^a (8)
Mustard-I-(2)	2,017 ^a (193)	2,159 ^{ab} (366)	1,261 ^a (160)	12,570 ^a (1,067)	2,138 ^a (244)	39 ^b (4)	4 ^a (1)	12 ^a (2)	77 ^a (9)	33 ^b (7)
Mustard-I-(6)	575 ^c (78)	1,745 ^c (231)	1,116 ^a (206)	11,750 ^a (1,003)	1,819 ^b (274)	69 ^a (7)	4 ^a (1)	10 ^a (2)	62 ^c (6)	39 ^a (7)

^zOnly fruit from 24 Mar. 2007 through 11 May 2007 were analyzed.^yMeals were only incorporated.^xValues represent the means with SE in parentheses from all fruit picked from a minimum of five replicates. Means followed by the same letter within each column are not significantly different ($P < 0.05$) according to Duncan's multiple range test for each respective parameter.

production was reduced by seed meal treatments; however, in other cases, an apparent fertilizer effect or reduced intraspecific competition appeared to increase productivity of weeds that were able to establish. Improvements to the weed control efficiency of this technique may be possible through additional research on Brassica seed meal amendment rates, application timing, and application techniques. In particular, additional research is needed on determining optimal treatment time relative to strawberry transplanting and facilitating the rapid release and enhanced retention of volatile phytotoxic compounds, e.g., by covering beds with plastic tarps (Gao and Wang, personal communication, 2010). Both Brassica seed meals, especially mustard, were able as organic sources of fertilizer to increase essential nutrients, e.g., Ca, P, and Mn, in the berry fruit composition in both our growth chamber and field evaluation studies. The increased concentration of these nutrients, including the trace element Se, was especially noticeable in fruit produced from the growth chamber studies, where the plants were grown in root-confined 4-L growing pots. Compared with field-grown plants, roots from the pot-grown plants had more direct access to the green source of nutrients added to the soil through seed meal.

Reeves (1997) also reported that incorporating organic materials such as mustard and canola meals into the soil enhances the organic pool of nutrients available for plant uptake. However, the content and form of GLS (contained within Brassica seed meals) and their influence on microbial biomass N and soil N mineralization (as discussed by

Snyder et al., 2009) may also impact the role of microbial activity and root growth on influencing nutrient uptake. The higher accumulation of Ca, a major nutrient, may be of special interest for future research, especially in light of Ca's influence on post-harvest physiology of fruit (Ferguson et al., 1995). This increase could have significant importance for strawberry fruit storage, because higher fruit Ca content can provide additional cellular stability for transporting fruit to distant markets (Marschner, 1995).

In regard to Se accumulation, Bañuelos et al. (1992) have also reported that other plants, i.e., alfalfa, absorbed Se from organic sources of Se-enriched plant material added to soils in potted greenhouse studies. Similarly, the strawberry plants were clearly able to absorb Se from the added Se-enriched Brassica seed meals and translocate it to the strawberry fruit in the growth chamber studies. Mineralization processes associated with Se uptake from organic sources of Se, as discussed by Ajwa et al. (1998), may provide some insight for future research as to how and when plants absorb Se from organic sources added to soil. Clearly the production of Se-enriched strawberries in the growth chamber studies shows the potential for biofortifying fruit products with Se under ideal growing conditions. This potential biofortification strategy for Se could be of more importance for people living in Se-deficient regions, e.g., Keshan, China. However, the production of Se-enriched strawberries was less pronounced under field conditions. Certainly, the small amount of absolute Se added to the soils through seed meal and the lateral,

vertical, and surface movement of Se contained within the seed meals occurring in the field studies reduced the amount of potential Se available for eventual plant uptake. In addition, root exploration (although not evaluated) was likely beyond the seed meal-amended zone under field conditions. Management strategies for seed meal application would need to be improved and developed for field-growing conditions to enhance the likelihood that more Se could be absorbed from Se-enriched Brassica seed meal. Using seed meals with higher concentrations of Se could potentially lead to higher concentrations of Se in the plant such as in the fruit. In addition, we also assume that volatilization of Se (as dimethyl selenide) occurred under both growth chamber and field conditions (not measured), which would also lower levels of Se eventually available for plant absorption (see Zayed et al., 2000). The typical aroma of volatile Se was apparent during the growth chamber studies.

Although weed management solely with Se-enriched Brassica seed meal is unlikely to reach acceptable standards in conventional strawberry production, as part of an integrated pest management and fertility plan, amending soils with seed meals may have commercial viability in organic agriculture. When considered in an agricultural system context, the coupling of phytomanagement of Se-contaminated soils, biofuel production, organic fertilizer and pest management, and Se-biofortification of a food crop may provide central California growers a unique production and marketing opportunity and is worthy of further research.

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