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Winter Cover Crop Growth and Weed Suppression on the Central Coast of California[1]

ERIC B. BRENNAN and RICHARD F. SMITH[2]

Abstract: Winter cover crops are increasingly common on organic and conventional vegetable farms on the central coast of California between periods of intensive vegetable production. A 2-yr study was conducted in Salinas, California, to quantify (1) cover crop and weed biomass production during cover cropping, (2) early-season canopy development of cover crops, (3) weed seed production by burning nettle during cover cropping, and (4) weed emergence following cover crop incorporation. The cover crops included oats, a mustard mix, and a legume/oats mix that were planted in October and soil-incorporated in February. Weed and cover crop densities, early-season cover crop canopy development, above-ground weed and cover crop biomass production, seed production by the burning nettle, and postincorporation weed emergence was evaluated. Mustard produced more early-season biomass than oats and the legume/oats mix. There were no differences in above ground biomass production by the cover crops at the end of their growth period. Suppression of weed biomass and seed production of burning nettle was greatest in mustard, and least in oats and the legume/oats mix. The weed suppressive ability of each cover crop was affected by early-season canopy development and was highly correlated with cover crop plant density. Weed emergence following cover crop incorporation was in order of legume/oats mix > oats > mustard in yr 1, but was not different in yr 2. This study provides initial information on cover crop effects on weed management in irrigated and tilled vegetable production systems in the central coast of California. The results suggest that the legume/oats mix could exacerbate weed problems in subsequent vegetable crops.

Nomenclature: Burning nettle, *Urtica urens* L. #[3] URTUR; bell beans, *Vicia faba* L.; common vetch, *Vicia sativa* L.; lana vetch, *Vicia villosa* ssp. *dasycarpa* Roth; mustards, *Brassica juncea* (L.) Czern., *Brassica hirta* Moench; oats, *Avena sativa* L.; peas, *Pisum sativum* L.

Additional index words: biomass production, canopy development, weed seed production, weed-suppressive ability.

Abbreviations: DAI, days after incorporation; DAP, days after planting.

INTRODUCTION

Winter cover crops are important in conventional and organic vegetable production systems in the central coast of California. In these high-value and high-input systems, vegetables are grown with irrigation during the dry spring and summer (March to September), and fields are cover cropped during the winter (November to February) or are left fallow. Cover crops may enhance the sustainability of agricultural systems by increasing soil organic carbon and nitrogen (Sainju et al. 2002), reducing nitrate leaching (Di and Cameron 2002; Jackson 2000), improving soil tilth (Stirzaker and White 1995), and suppressing pests and diseases (Abawi and Widmer 2000; Peachey et al. 2002; Teasdale 1996). Cover crop research in the central coast of California has focused on nitrate leaching and nitrogen cycling by nonleguminous cover crops in conventional systems (Jackson 2000; Jackson et al. 1993; Lundquist et al. 1999; Wyland et al. 1996). The effects of cover crops on weed management in the intensively tilled vegetable production systems like those in California's central coast are poorly understood.

Three main types of winter cover crops are used on vegetable farms in the region including cereals (i.e., *Avena sativa* L., *Hordeum vulgare* L., and *Secale cereale* L.), mixes of cereals and legumes (i.e., *Pisum sativum* L. and *Vicia*), and mustards [i.e., *Brassica juncea* (L.) Czern., *B. hirta* Moench]. Cereals are most common on

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[2] Research Horticulturist, Organic Research Program, USDA-ARS, 1636 East Alisal Street, Salinas, CA 93905; Vegetable Crop and Weed Science Farm Advisor, University of California Cooperative Extension, 1432 Abbott Street, Salinas, CA 93901. Corresponding author's E-mail: ebbrennan@ucdavis.edu.

[3] Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*, Revised 1989. Available only on computer disk from WSSA, 810 East 10th Street, Lawrence, KS 66044-8897.

conventional farms and large-scale organic farms (>100 ha), whereas legume/cereal mixes are generally preferred on smaller organic farms because of the potential nitrogen input from biological nitrogen fixation by the legumes. Mustard cover crops are relatively new in the region and their popularity is mainly due to their potential disease-suppressive ability (Brown and Morra 1997). Lettuce (*Lactuca sativa* L.) head drop is the major soil-borne disease in the area, and farmers are optimistic that mustard cover crops will suppress the causative agent (*Sclerotinia minor* Jagger) as has broccoli (*B. oleraceae* L. var. *italica* Plenck) (Hao et al. 2003). Many farmers in the area avoid using legumes (i.e., *P. sativum* L., *Vicia dasycarpa* Ten.) and other cover crops (i.e., *Phacelia tanacetifolia* Benth.) that are known hosts of *S. minor* (Koike et al. 1996).

There is little information on the impact of mixes vs. monoculture cover crops on weed management despite the increasing importance of organic farms in the area (Klonsky et al. 2001) and their reliance of cover crop mixes of legumes and cereals. However, a preliminary study at a certified organic site found that cereal and mustard cover crops were more suppressive of weed growth and weed seed production than legume/oat mixes (Brennan and Smith 2003).

Cover crops may reduce weed management costs if the cover crop reduces or prevents weed seed production during cover cropping and if it suppresses weed emergence and growth during subsequent cash crops. Studies evaluating cover crop effects on weed management in vegetable systems often focus on weed suppression by cover crop mulch (Creamer et al. 1997; Fisk et al. 2001; Hutchinson and McGiffen 2000; Teasdale 1993; Teasdale and Abdul-Baki 1998). However, the mechanisms of weed suppression by cover crop mulch are not applicable in vegetable production systems on the central coast of California where frequent and intensive tillage is used to prepare seed beds suitable for precision planting of small seeded vegetables (i.e., lettuce, broccoli). There are few studies (Boydston and Hang 1995; Schonbeck et al. 1991) evaluating cover crop effects on weeds in tilled, direct-seeded vegetable systems, and even less information on weed biomass or seed production during the cover cropping period (Akemo et al. 2000; Brennan and Smith 2003). There is evidence that organic amendments from compost and rye cover crops can reduce populations of some weed species in vegetable production systems in the region (Fennimore and Jackson 2003). This article describes a 2-yr study on the effects of cover crops on weed growth and weed seed production during the winter cover cropping period and on weed emergence following cover crop incorporation. Cover crops included oats, a mustard mix, and a legume/oats mix. The objectives were to quantify (1) cover crop and weed biomass production during cover cropping, (2) early-season canopy development of the cover crops, (3) weed seed production during cover cropping, and (4) weed emergence following incorporation of cover crop biomass.

Table 1. Cover crop densities and effective seeding rates.

Cover crop	Cover crop density Yr 1	Cover crop density Yr 2	Effective seeding rate Yr 1	Effective seeding rate Yr 2
	plants/m²		kg/ha	
Legume/oats[a]	86	137	77	123
Mustard[b]	474	591	21	26
Oats[c]	261	289	80	90

[a] Mix by weight includes 35% Bell Beans (*Vicia faba*), 25% 'Magnus' peas (*Pisum sativum*), 15% common vetch (*Vicia sativa*). 15% 'Lana' vetch (*Vicia villosa* ssp. *dasycarpa*). 10% 'Cayuse' oats (*Avena sativa*). L.A. Hearne Company, King City, CA.

[b] Mix known as 'Caliente 105' (High Performance Seed Company, Moses Lake, WA), and by weight includes 50% *Brassica hirta* and 50% *B. juncea.*

[c] Cayuse oats (*A. sativa*).

MATERIALS AND METHODS

The experiment occurred at the USDA Agriculture Research Station in Salinas, CA, during two winter periods from 2001 through 2003. The soil at the site is a Chualar loam (fine-loamy mixed thermic Typic Argixerolls) with 52% sand, 43% silt, 5% clay, and 2% organic matter. Lettuce variety trials have been conducted in the experimental plot during the summer for more than 10 yr and occurred there each summer of the experiment. The field was disked before planting the cover crop in yr 1 (2001 planting). The field was disked, ripped, and land planed in several directions just prior to planting the cover crop in yr 2 (2002 planting). Potential carryover effects from yr 1 to yr 2 of the experiment were minimized by the intensive fertilization, tillage, and irrigation between the cover crops and by planting the treatments in strips in the north-south direction in yr 1 and the east-west direction in yr 2. The experimental design was a randomized complete block with three cover crop treatments and three and four replicates in yr 1 and yr 2, respectively (Table 1).

Cover crops evaluated were oats (*Avena sativa*), a mustard mix (50% *Brassica hirta* : 50% *B. juncea* by weight), and a legume/oats mix (35% *Vicia faba*, 25% *Pisum sativum*), 15% *Vicia sativa*, 15% *Vicia villosa* ssp. *dasycarpa*, 10% oats) (Table 1). In yr 1 the cover crops were planted on October 16, 2001, with a grain drill[4] in 30 m long by 2.2 m wide strips with 20-cm spacing between seed lines. The mustard cover crop was initially drilled too deep and was reseeded at the same population with a hand seeder[5] on October 25, 2001. All references to time after planting refer to the initial planting dates each year. In yr 2 the cover crops were drilled on October 25, 2002, with a grain drill[6] in 30 m long by 3 m wide strips with 15 cm between seed lines. Approximately 5 to 7 cm of sprinkle irrigation was applied to stimulate germination. The winter rainfall was 21 and 11 cm from October to February of yr 1 and 2, respectively. Table 1 shows the densities of the cover crops that were determined by counting emerged cover crop plants in at least three 1-m-long seed line sections of each plot on November 20, 2001 and December 3, 2002. The effective seeding rates (Table 1) were calculated based on plant density and provide an approximate seeding rate, assuming 100% of the seeds emerged. The target seeding rates of these cover crops that are typical for this area were 112 (legume/oats), 90 (oats), and 22 kg/ha (mustard). In yr 1, above-ground cover crop and weed biomass were measured by harvesting two 30 by 30 cm quadrats from each plot during three harvest periods (December 18, 2001; January 7 to 9, 2002; February 21, 2002). In yr 2, above ground cover crop and weed biomass were harvested from 1 m^2 and 30 by 30 cm quadrats, respectively, on three harvest periods (December 3, 2002; January 9 to 13, 2003; February 10, 2003). Emerged weed seedlings were counted in a 30 by 30 cm quadrat in each plot at each harvest date up to January. Biomass samples were oven dried at 60 to 65 C until their weight stabilized. When the amount of fresh biomass exceeded the space available in drying ovens, the fresh weight was measured in the field, and the dry weight was estimated from an oven-dried subsample that was representative of the total, above-ground harvested fresh sample.

Seed production by burning nettle was determined between January 7 to 9, 2001, and January 14, 2002, by vacuuming nettle seeds from the soil surface of a 30 by 30 cm quadrat from each plot. There was no apparent delay in nettle seed rain among the cover crops, and although this determination was a good relative measure of cover crop effect on nettle seed production, it underestimated the final seed production because seed rain continued beyond these dates. Seeds were separated from soil particles using water and a #30 (600 μm) sieve and were air dried. Burning nettle seed viability was determined by imbibing seeds on moist filter paper for 12 h and then applying a previously described technique (Fennimore and Jackson 2003), whereby seeds were split open with a forceps and scalpel to expose the embryo. Firm, white embryos were considered viable. This method was used for all seeds from plots with fewer than 51 seeds per 30 by 30 cm quadrat, and was estimated from a subsample of 50 seeds from plots with greater than 51 seeds per quadrat.

Digital photographs were taken of the cover crops from a stand positioned 1 m above the ground on November 20, 2001 (35 days after planting [DAP]) and November 22, 2003 (28 DAP) in yrs 1 and 2, respectively. The resulting images included at least five seed lines of a 100 by 74 cm area. Using Microsoft PowerPoint,[7] a grid with 100 crosses was digitally superimposed over the same area over three seed lines in each photograph. Percentage ground cover was estimated by counting the number of grid crosses intersected by cover crop vegetation. This method is similar to that used by Adams and Arkin (1977).

The cover crops were flail mowed to approximately 8 cm above the ground with two passes and immediately incorporated with two passes with a rototiller to a depth of 15 cm on March 6, 2002 (141 DAP) and February 10, 2003 (111 DAP). Incorporation occurred as early in the spring as possible so that the field could be ready for vegetable planting by early to mid April. Mowing and residue incorporation occurred in separate passes over each treatment strip to prevent mixing of residue between treatments. Following incorporation, the plots were sprinkle irrigated with approximately 5 to 10 cm of water as needed to stimulate weed emergence and residue decomposition. Emerged weeds were counted in eight 50 by 50 cm quadrats, and five 30 by 30 cm quadrats in each strip on April 11, 2002 (36 days after incorporation [DAI]), and March 27, 2003 (48 DAI), respectively.

Data across both years were subjected to ANOVA in SAS[8] using the MIXED procedure. For analyses of cover crop biomass, weed biomass, and weed emergence during cover cropping, fixed effects were cover crop, year, cover crop by year, month (nested within year), and cover crop by month (nested within year), whereas random

[4] Tye, Model 304-399; AGCO Corp., 4205 River Green Parkway, Duluth, GA 30096.

[5] Cole Planet Jr. No longer manufactured.

[6] Great Plains 1500 drill (1560 East North St. Salina, KS 67401) with seed cones added by Kincaid Equipment Manufacturing (210 West 1st St., Havan, KS 67543).

[7] Version 9.0.2716, Microsoft Corp. Redmond, WA.

[8] Version 8.0, SAS Institute, Cary, NC.

effects were replicate (nested within year) and cover crop by replicate (nested within year). For analysis of cover crop canopy development, fixed effects were year and cover crop. For analyses of weed seed production and weed emergence following cover crop incorporation, fixed effects were cover crop, year, and cover crop by year, whereas replicate (nested within year) was a random effect. To stabilize variances, natural log transformations were applied to cover crop biomass, weed seed production, and weed emergence data following cover crop incorporation, and square root transformations were applied to early-season weed emergence and weed biomass. Mean separation is based on transformed data but nontransformed means are presented for clarity. Bonferroni *t* tests were used for multiple comparisons of cover crop and weed biomass production, weed emergence, and weed seed production. The Tukey–Kramer test was used for multiple comparisons of cover crop canopy development.

RESULTS AND DISCUSSION

Cover Crop Density. Cover crop emergence varied between years but was within the typical range of plantings in the region (Table 1). Cover crop densities were higher in yr 2 than in yr 1 by 37% (legume/oats mix), 20% (mustard), and 10% (oats). The higher density in yr 2 was probably due to the more optimal seed placement and soil-seed contact that was achieved by the grain drill used in yr 2 that had a press wheel that compacted the soil over each seed line. The higher annual variation of the density of the legume/oats mix is typical and was likely caused by the inconsistent germination of the peas. Peas are often the least consistent component in this mix possibly due to soil-borne diseases. Cover crop studies typically report seeding rate but not resulting stand density or population (i.e., Akemo et al. 2000; Al Khatib et al. 1997; Boydston and Hang 1995; Creamer et al. 1997; Schonbeck et al. 1991; Teasdale and Abdul-Baki 1998). However, reporting stand density is important because it may be more indicative than seeding rate of a cover crop's competitive ability.

Cover Crop Biomass Production. The relative performance of the cover crops within each year was consistent (Figure 1), however significantly more biomass was produced in yr 1 than yr 2 ($P < 0.001$). Mustard produced significantly more biomass than the legume/oats mix up to January in both years. Mustard biomass production also exceeded that of oats in December of yr 2. There was no difference in final biomass production for oats, mustard, or the legume/oats mix in both years. Early-season biomass production by cover crops increases evapotranspiration and thus reduces the risk of nitrate leaching below the root zone (Meisinger et al. 1991). The relatively low early- and mid-season biomass production by the legume/oat mix in our study suggests that it has the least potential for trapping nitrate of the cover crops evaluated. However, this does not account for potential nitrate trapping by the weeds that grew especially well in the legume/oats mix.

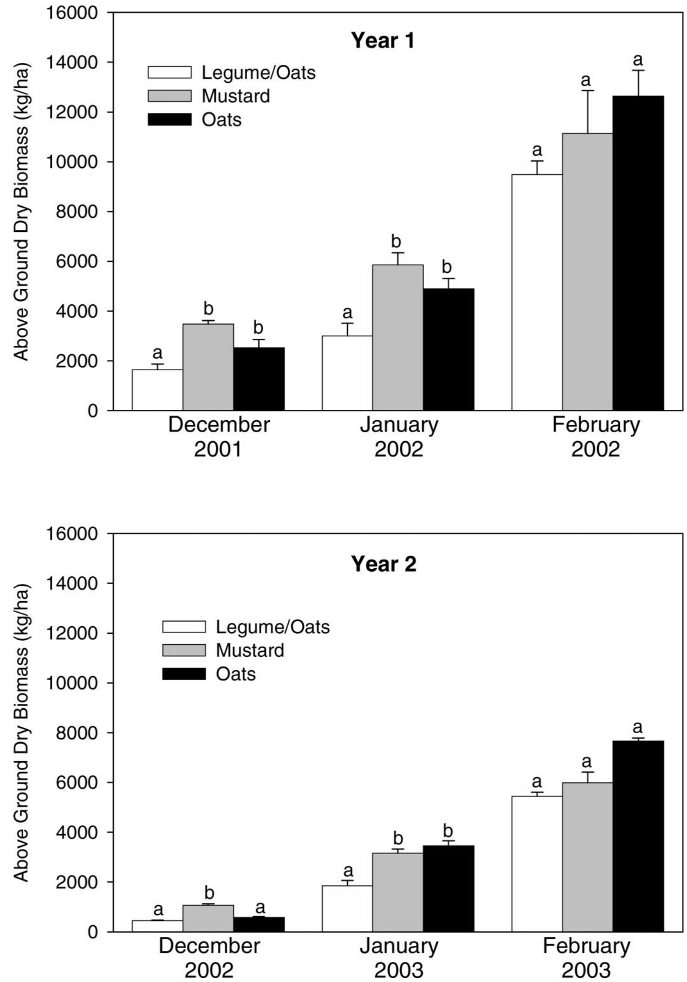

Figure 1. Cover crop biomass production on three harvest dates during the cover cropping period for years 1 and 2. Bars are mean ± SE. Within each harvest date and year, significant differences are indicated by bars topped with different letters ($P \leq 0.05$ experiment-wise error rate).

The three cover crops differed markedly in their relative growth rates over the season. Averaged across both years, mustard produced 53% of its final biomass by January, whereas oats and the legume/oats mix had only produced 42 and 32% of their final biomass by January, respectively. Mustard was flowering by the final harvest date each year, suggesting that biomass production had peaked and that the February kill date was optimal. In contrast, oats and legume/oats mix were relatively vegetative by the final harvest and presumably could have accumulated additional biomass. Although kill date may have affected potential biomass production, we would not expect it to affect weed suppression because most weeds had senesced by cover crop incorporation.

Weed Emergence during Cover Cropping. Several weed species grew during the cover cropping period, including burning nettle, shepherd's-purse (*Capsella bursa-pastoris* L. Medikus), henbit (*Lamium amplexicaule* L.), common sowthistle (*Sonchus oleraceus* L.), common groundsel (*Senecio vulgaris* L.), and annual bluegrass (*Poa annua* L.). Burning nettle comprised at least 85% of the emerged weeds in both years. Weed emergence was unaffected by cover crop treatment from planting date to January in both years (data not shown). Average weed densities across all treatments were 1,430 and 1,474 plants/m² in December of yr 1 and 2, respectively. Most of the weeds emerged in the first 50 DAP, which may explain why cover crop treatment did not affect weed emergence. Crop effects on weed emergence are more common in late-emerging weed species (Huarte and Arnold 2003). There were 72 and 70% fewer live weeds under the cover crops in February than January of yr 1 and 2, respectively (data not shown), indicating that most emerged weeds had senesced before the end of the cover crop season.

Weed Biomass Production. There was significantly less weed biomass in yr 2 ($P < 0.001$), but the relative affects of the cover crops on weed biomass production were consistent each year (Figure 2). Weed biomass was highest in the legume/oats mix followed by oats. Mustard was the most effective cover crop at suppressing weeds throughout the season. Cover crop effects on weed biomass were apparent early in the season and up to January after which the weeds began to senesce. Weed biomass increased under the legume/oats mix peaking January. A similar but less dramatic trend occurred in weed biomass under oats. In contrast, weed biomass was relatively low and stable under mustard throughout the season. The dynamics of weed biomass under the cover crops illustrate the importance of multiple sample dates throughout the season to accurately measure weed suppression by cover crops.

Weed biomass can account for a large proportion of the total biomass production during cover cropping. For example, weeds contributed 43 and 38% of total aboveground biomass production in the legume/oats mix in December and January in yr 1, respectively. In contrast,

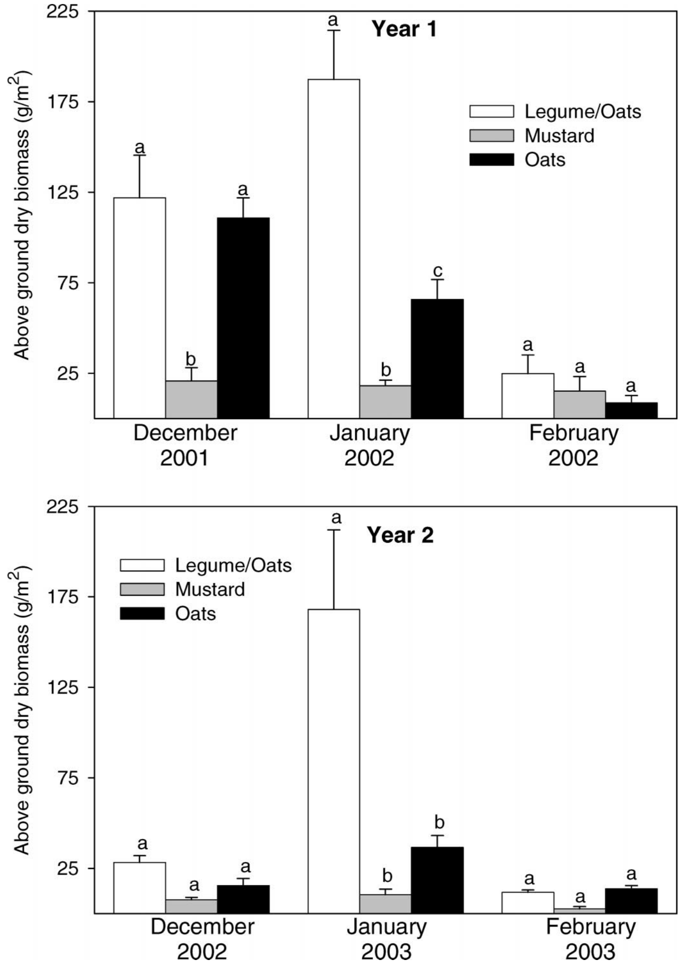

Figure 2. Weed biomass production on three harvest dates during the cover cropping period for years 1 and 2. Bars are mean ± SE. Within each harvest date and year, significant differences are indicated by bars topped with different letters ($P \leq 0.05$ experiment-wise error rate).

weeds accounted for 30 and 12% of the total aboveground biomass in the oats, and only 6 and 3% biomass in mustard on these dates. The results of this study support previous research that found the legume/oats mix poorly competitive with another weed (chickweed, *Stellaria media* L.) (Brennan and Smith 2003). The inability of the legume/oats mix to suppress weeds is most likely due to the relatively low plant density that results in slow canopy development. Crop density influences competition (Mohler 2000) and although optimal planting densities are well studied in cash crops, there are few studies (Akemo et al. 2000) on optimal seeding rates for cover crops.

Cover Crop Canopy Development. There were significant differences in the rates of early-season canopy development by the cover crops that help to explain their differences in weed suppression (Table 2). Canopy development of the cover crops was consistent across both

Table 2. Ground cover by cover crops, and seed production of burning nettle in cover crops.[a]

Cover crop	Ground cover[b]	Burning nettle seed production: Yr 1 (83–85 DAP)	Burning nettle seed production: Yr 2 (81 DAP)
	%	Viable seeds/m²	
Legume/oats	19 a	13,622[c] a	4,282 a
Mustard	78 b	1,283 b	14 b
Oats	27 c	6,010 a	1,861 a

[a] Abbreviation: DAP, days after planting.

[b] Ground cover is pooled for yr 1 (35 DAP) and yr 2 (28 DAP). Means followed by different letters are different at an error rate of $P < 0.05$, based on the Tukey–Kramer procedure.

[c] Means followed by the same letter within each year are not different according to an experiment-wise error rate of $P \leq 0.05$, based on the Bonferroni *t*-tests.

years and was in order of mustard > oats > legume/oats mix. These rankings are consistent with cover crop suppression of early-season weed biomass (Figure 2) and weed seed production (Table 2). The slow rate of canopy development in the legume/oats mix is consistent with its relatively low early- and mid-season light interception compared with mustard, oats, and rye (Brennan and Smith 2003). McLenaghen et al. (1996) also reported relatively poor early-season canopy development in legume cover crops and suggested that their slow early-season growth explained why they were less effective than nonlegumes at reducing nitrate leaching.

Ground cover early in the season was highly correlated with cover crop density in yr 1 ($r = 0.92$) and yr 2 ($r = 0.99$). This response suggests that the rate of early-season ground cover development could be increased in relatively low-density cover crops like the legume/oats mix by increasing the seeding rate of either the whole mix or of a smaller seeded component of the mix. The correlation also indicates that cover crop density may have had as much influence as cover crop variety on performance. The slightly lower densities of the cover crops in yr 1 than yr 2 did not apparently affect canopy development. The impact of planting density on weed suppression in monocultures is well known (Teasdale 1998; Tollenaar et al. 1994) but has received little attention in polycultures like the legume/oats mix in our study. Seeding rate is more complex in polycultures because it affects competition with weeds and the performance of the components of the mix (Akemo et al. 2000; Willey 1979).

Weed Seed Production. Seed production by burning nettle was significantly greater in yr 1 than yr 2 ($P < 0.01$), and was affected by cover crop in both years (Table 2). Reduced seed production under all cover crops in yr 2 is consistent with the significant reduction in weed biomass during yr 2. During both years, seed production was highest under the legume/oats mix, intermediate in the oats, and lowest under mustard, although the apparent difference between the legume/oats mix and oats was not significant. These results suggest that the nettle seed bank will increase most with legume/oats cover crops and least with more weed-suppressive cover crops like mustard. This comparison does not account for other factors that may differ under the cover crops such as seed predation. Furthermore, burning nettle seed rain by the end of the season would likely be greater than indicated by our data that are based only on seed on the soil surface by January. At a nearby certified organic site, seed production by chickweed was also higher under the legume/oats mix used here than under cover crops of rye, oats, or mustard (Brennan and Smith 2003).

Weed Emergence after Cover Crop Incorporation. There were significant differences ($P < 0.05$) in weed seedling densities following incorporation of the cover crops in yr 1 when weed seedling densities in plants/m² ranked in order of legume/oats mix (377) = oats (246) > mustard (113). This pattern also occurred in yr 2 but was not significant (data not shown). Burning nettle accounted for more than 85% of the postincorporation weed seedling densities that also included shepherd's-purse, henbit, common sowthistle, common groundsel, purslane (*Portulaca oleraceae* L.), hairy nightshade (*Solanum sarrachoides* Sendtner), and burclover (*Medicago polymorpha* L). Soil-incorporated *Brassica* cover crop residue has reduced emergence of many weed species (Al Khatib et al. 1997; Boydston and Hang 1995; Krishnan et al. 1998) and this reduction may be caused by isothiocyanates known to affect weed seeds (Teasdale and Taylorson 1986). The relatively poor growth of the cover crops in yr 2 (Figure 1) may explain their inconsistent effect on postincorporation weed emergence.

Practical Implications. Farmers use cover crops for a number of benefits that are well documented (Dabney et al. 2001); however, the ability of a cover crop to provide benefits depends on its performance (i.e., growth rate, biomass production). It can be difficult for farmers to evaluate cover crop performance because cover crops are seldom harvested and are essentially unmanaged from planting to kill date. Furthermore many potential benefits (i.e., nutrient cycling and soil improvement) are difficult to assess and change slowly. However, the impact of cover crops on weeds during the cover crop is relatively simple to assess and is extremely important because of the long-term impacts of the weed seed bank on production costs and yields. This study provides some of the first information on cover crop effects on weed management in high-input, irrigated, and tilled vegetable production systems in the central coast of California. Our data suggest that the poor early-season growth of the legume/oats mix allows burning nettle to produce relatively large amounts of seed that may increase weed management costs in subsequent vegetable crops. This issue is particularly important in organic vegetable production where weed management tools are more limited and expensive. It is unclear if potential biological nitrogen-fixing benefits from the legumes in the legume/oats mix would offset possible increases in weed management costs and loss of nitrogen via leaching due to poor early-season growth. This issue warrants further study in irrigated, organic vegetable production systems in the region where legume/cereal mixes are widely used. The most consistent effects of these cover crops on weed management occur during the cover cropping period rather than following incorporation. Our data suggest that the mustard cover crop is the best of the three cover crops evaluated for weed control given its early-season growth and weed-suppressive abilities during the cover cropping period.

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