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Grass–Legume Mixtures and Soil Fertility Affect Cover Crop Performance and Weed Seed Production

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

Summer leguminous cover crops can improve soil health and reduce the economic and environmental costs associated with N fertilizers. However, adoption is often constrained by poor weed suppression compared to nonlegume cover crops. In field experiments conducted in organic vegetable cropping systems in north-central New York, two primary hypotheses were tested: (1) mixtures of legume cover crops (cowpea and soybean) with grasses (sorghum–sudangrass and Japanese millet) reduce weed seed production and increase cover crop productivity relative to legume monocultures and (2) higher soil fertility shifts the competitive outcome in favor of weeds and nonlegume cover crops. Cover crops were grown either alone or in grass–legume combinations with or without composted chicken manure. Under hot, dry conditions in 2005, cowpea and soybean cover crops were severely suppressed by weeds in monoculture and by sorghum–sudangrass in mixtures, resulting in low legume biomass, poor nodulation, and high levels of Powell amaranth seed production ($> 25{,}000$ seeds m^{-2}). Under more typical temperature and rainfall conditions in 2006, cowpea mixtures with Japanese millet stimulated cowpea biomass production and nodulation compared to monoculture, but soybeans were suppressed in mixtures with both grasses. Composted chicken manure shifted competition in favor of weeds at the expense of cowpea (2005), stimulated weed and grass biomass production (2006), and suppressed nodulation of soybean (2006). In a complementary on-farm trial, cowpea mixtures with sorghum–sudangrass suppressed weed biomass by 99%; however, both common purslane and hairy galinsoga produced sufficient seeds (600 seeds m^{-2}) to replenish the existing weed seedbank. Results suggest that (1) mixtures of cowpeas with grasses can improve nodulation, lower seed costs, and reduce the risk of weed seed production; (2) soybean is not compatible with grasses in mixture; and (3) future costs of weed seed production must be considered when determining optimal cover crop choices.

Nomenclature: Common purslane, *Portulaca oleracea* L.; hairy galinsoga, *Galinsoga ciliata* (Ref.) Blake ; Powell amaranth, *Amaranthus powellii* S. Wats; cowpea, *Vigna unguiculata* (L.) Walpers. 'Red Ripper'; Japanese millet, *Echinochloa frumentacea* (Roxb.) Link; sorghum–sudangrass, *Sorghum bicolor* (L.) Moench × *Sorghum sudanese* (P.) Stapf, 'Sweetleaf II'; soybean, *Glycine max* (L.) Merr.; buckwheat, *Fagopyrum esculentum* (L.) Moench.

Key words: Cover crop mixtures, weed seed production, fecundity, manure, legumes, nodulation.

Las leguminosas de verano usadas como cultivos de cobertura pueden mejorar la salud del suelo y reducir los costos económicos y ambientales asociados con fertilizantes de N. Sin embargo, su adopción es limitada debido a la poca supresión de malezas en comparación con los cultivos de cobertura que no sean leguminosas. En experimentos de campo llevados a cabo en sistemas de cultivo de vegetales orgánicos en la parte central norte de Nueva York, dos hipótesis principales fueron evaluadas: 1) las mezclas de leguminosas en cultivos de cobertura (garbanzo y soya) con gramíneas (híbrido de *Sorghum bicolor* × *S. sudanese* y *Echinochloa frumentacea*) reducen la producción de semillas de malezas e incrementan la productividad del cultivo de cobertura en comparación al monocultivo de leguminosas; y 2) mayor fertilidad del suelo altera el resultado de la competencia en favor de las malezas y cultivos de cobertura que no sean leguminosas. Los cultivos de cobertura se sembraron solos o en combinaciones de zacate-leguminosas con o sin compost de gallinaza. Bajo condiciones cálidas y secas en 2005, los cultivos de cobertura garbanzo y soya fueron severamente suprimidos por las malezas en el monocultivo y en mezclas con *S. bicolor* × *S. sudanese*, resultando en baja biomasa de la leguminosa, nodulación pobre y altos niveles en la producción de semilla de *Amaranthus powellii* ($> 25\ 000$ semillas m^{-2}). Bajo condiciones de temperaturas y lluvias más típicas en 2006, la mezcla de garbanzo y *E. frumentacea* estimuló la producción de biomasa y nodulación de la leguminosa en comparación con el monocultivo, pero la soya fue suprimida en la mezcla de ambos zacates. La gallinaza modificó la competencia en favor de la maleza a expensas del garbanzo (2005), estimuló la producción de maleza y la producción de biomasa de los zacates (2006) y suprimió la nodulación de la soya (2006). En un estudio complementario ''en finca'', las mezclas de garbanzo con *S. bicolor* × *S. sudanese* redujeron la biomasa de la maleza en 99%, sin embargo, *Portulaca oleracea y Galinsoga ciliata* produjeron suficientes semillas (600 semillas m^{-2}) para reponer el banco de semillas de maleza existente. Los resultados sugieren que 1) mezclas de garbanzo con zacates pueden mejorar la nodulación, reducir los costos de la semilla y disminuir el riesgo en la producción de semillas de malezas; 2) la soya no es compatible con zacates en mezclas de cobertura; y 3) los costos futuros debido a la producción de semilla de maleza, deben ser considerados para determinar las opciones óptimas de cultivos de cobertura.

Summer cover crops can play an important role in improving soil characteristics and suppressing weeds in many cropping systems. They have particular importance in cropping systems where short-duration crops are grown (e.g., vegetables), where degraded land is being rehabilitated for cash-crop production, and where other approaches to

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managing weeds and soil fertility are unavailable (e.g., organic production). Potential benefits of summer cover crops include (1) protection of soil from extreme rain and wind events that can result in erosion and agrochemical runoff (Flach 1990); (2) production of an abundance of organic residues to enhance biological and physical characteristics of soils for crop production (Karlen et al. 1990; MacRae and McDole 1987); (3) improvements in soil fertility through N fixation and improved nutrient retention; and (4) reduction in insect, disease, and weed pressures through various mechanisms including life-cycle disruption, reduction in propagule dispersion, provision of habitat for predators, and release of pest-suppressive allelochemicals (Andow et al. 1986; Carmona and Landis 1999; Hill et al. 2006; Liebman and Dyck 1993; Reader 1991). Rising N fertilizer costs and awareness of the adverse environmental impacts associated with N fertilizer use provide increased incentives for growers to adopt legume cover cropping as an alternative source of N.

Despite the potential benefits of summer legume cover crops, their adoption has been limited due in part to costs associated with establishment and maintenance during the busy months of summer, and poor weed suppression relative to nonlegume summer cover crops including sorghum–sudangrass and buckwheat (Creamer and Baldwin 2000; Fitzgerald and Bryan 2002). Although many summer legumes are poor weed suppressors, cowpeas and forage soybeans have strong potential as weed suppressors. Among six summer annual legumes tested in North Carolina, cowpea and forage soybean were the most effective at suppressing weeds and produced large amounts of biomass and N (Creamer and Baldwin 2000). Fitzgerald and Butler (2002) showed that in comparison to other summer annual leguminous cover crops, cowpea and soybean had the fastest early growth rate. Prior to the widespread use of herbicides, both cowpea and soybeans were recommended for suppression of weeds (Muenscher 1935; Pieters 1927; Robbins et al. 1942).

Growing summer legumes in mixtures with grasses is a potentially valuable approach to improving weed suppression, lowering seed costs, and increasing successful adoption. Grass species such as sorghum–sudangrass often have lower seed costs and are better weed suppressors than legumes, so substitutive grass–legume mixtures can reduce seed costs and improve weed suppression relative to legume monocultures. Mixtures often improve resource capture and result in greater biomass production than could be obtained by growing each crop separately (Clark et al. 1994; Fukai and Trenbath 1993). Greater resource capture in turn may result in improvements in weed suppression of mixtures relative to monocultures (Liebman and Dyck 1993).

Several reports have recommended mixtures of cowpea and soybean with nonlegumes (Madge and Jaeger 2003; Sustainable Agriculture Network 1998). These mixtures have been found to be valuable in warm climates, including North Carolina (Creamer and Baldwin 2000), but information related to these mixtures for northern climates is limited. In addition, little information is available on how soil characteristics may influence the success of grass–legume mixtures. Most studies involving grass–legume mixtures have focused on the effects of inorganic fertilizer addition on intercrops involving cash crops (e.g., Itulya et al. 1997; Waterer et al. 1994).

Soil N fertility is one of the most important factors influencing the competitive balance between legumes, grasses, and weeds in mixtures. Under high soil N, the competitive advantage often shifts to grasses in grass–legume mixtures and toward weeds in competition with legumes (Staniforth 1962). Because cover crops generally have larger seed reserves than competing weeds, they can establish better under conditions of low soil fertility than most weed species, which rely more heavily on soil fertility for early growth (Mohler and Liebman 2001). The emergence and growth of many weed species is also frequently stimulated by inorganic soil N (e.g., Blackshaw et al. 2003; Brainard et al. 2006; Schimpf and Palmblad 1980). Staniforth (1962) found that weeds had greater response to soil N than soybeans, and that high N fertility resulted in greater reductions in soybean yield due to weeds.

Very few studies evaluating weed suppression of cover crops evaluate the number of weed seeds produced during cover crop growth. Most studies report only on the level of weed biomass suppression. Results from these studies may be misleading for two reasons: (1) weed biomass may not be well correlated with weed seed production—particularly in short-duration cover crops which are terminated before some weed species have time to produce viable seeds and (2) weeds whose biomass is strongly suppressed by cover crops relative to unweeded controls may still produce sufficiently large numbers of seeds to reduce yields, or increase weed management costs in subsequent crops. Therefore, a complete assessment of the costs and benefits of cover cropping depends on more careful observations of the extent of weed seed production. Evaluation of the potential costs associated with weed seed production depends on empirical estimates of the number of seeds produced relative to the existing weed seedbank, as well as an understanding of the fate of those seeds in the soil (Cousens and Mortimer 1995).

Seed production of hairy galinsoga, common purslane, and Powell amaranth is particularly important because these species reduce crop yields and interfere with harvest in many cropping systems. Hairy galinsoga and common purslane are particularly problematic for many intensive vegetable growers due in part to their ability to rapidly produce seeds. All three species may produce seeds below cover crop canopies without accumulating large amounts of biomass. To better understand the tradeoffs associated with cover crop use, estimates of seed production during cover crop growth of these important species is essential.

The primary objectives of this study were to understand how mixtures of legume and grass cover crops influence cover crop biomass, weed dry-weight accumulation, and weed seed production under two levels of soil fertility. We hypothesized that mixtures of cowpea and soybean with sorghum–sudangrass and Japanese millet would improve weed suppression and increase legume nodulation relative to legume monocultures, and that these benefits would be greatest where composted chicken manure was not added. Secondary objectives included (1) evaluating the effects of different rates of sorghum–sudangrass in combination with cowpea on biomass production and (2) obtaining estimates of seed production for Powell amaranth, hairy galinsoga, and common purslane in various cover crop treatments.

Materials and Methods

The effects of grass–legume mixtures and composted chicken manure were evaluated at the H. C. Thompson Vegetable Research Farm near Freeville, NY, on a Howard gravel loam soil (Loamy-skeletal mixed mesic Glosoboric Hapludalf) during the 2005 and 2006 growing seasons. Effects of cowpea and sorghum–sudangrass mixtures on seed production of hairy galinsoga and common purslane were evaluated in 2006 at Starflower Farm, a diverse vegetable farm located in Candor, NY.

Freeville Research-Farm Trial. In 2005 and 2006, cowpeas ('Red Ripper', 168 kg ha^{-1}), soybeans (Tyrone; 168 kg ha^{-1}) and sorghum–sudangrass ('Sweetleaf II', 56 kg ha^{-1}) were sown. In 2006, Japanese millet (17 kg ha^{-1}) was included as an additional grass species. Cover crops were grown either alone or in all legume–grass combinations at half the monoculture seeding rate. A no–cover-crop, unweeded treatment was included for comparison. Legume seeds were triple-inoculated with appropriate rhizobia immediately before planting. In 2005, cover crops were broadcast and incorporated to 2.5 to 5 cm using a harrow on July 8. In order to improve the uniformity of cover crops in 2006, cover crops were established using a grain drill (18 cm between-row spacing) on July 18. Plots were arranged in a split-plot design with four replicates, with cover crop as the main plot factor, and fertilization as the subplot factor. Cover crop main plots measured 2.5 by 12.2 m in 2005 and 3.0 by 9.1 m in 2006. Each main plot was divided into two equal subplots and either unfertilized, or fertilized with "composted" (aged and pelleted) chicken manure (5–5–3)[1] at a rate of 56 kg N ha^{-1} prior to planting. Prior to application, four 500-ml samples of manure were mixed with potting soil (50 : 50), spread in flats in greenhouse, watered as needed, and observed for potential weed seed contamination. No seedling emergence was detected from these samples. Manure was broadcast by hand and incorporated with a field cultivator to approximately 10 cm.

In both years, initial weed and cover crop emergence by species was evaluated in two 0.25-m^2 quadrats per subplot 14 d after seeding (DAS). Cover crop and weed density and biomass samples were taken from two 0.25-m^2 quadrats at 63 DAS in 2005 and 57 DAS in 2006. At harvest, aboveground cover crop and weed biomass were separated, dried, and weighed. Powell amaranth seed production was estimated following Brainard et al. (2005) by (1) separating and weighing all seeds from a subset of 15 plants selected to span a wide range of sizes, (2) estimating seed number of those individual plants based on total seed weight and the weight of a subsample of 300 seeds, (3) determining linear regression coefficients for seed number vs. plant weight, and (4) estimating seed number from plant weight for each plot using these regression coefficients.

Legume nodulation was assessed by exhuming and washing roots of 10 randomly selected legumes from each subplot and visually assessing nodulation on a scale from 0 to 10, with 0 corresponding to no nodulation and 10 corresponding to numerous healthy (pink and large) nodules on all plants.

Candor On-Farm Trial. In 2006, a complementary field trial was established at the Starflower Farm in Candor, NY, on a field previously cropped with a diversity of vegetables and a known history of severe common purslane infestation. Treatments examined included (1) Sweetleaf II sorghum–sudangrass grown alone at 84 kg ha^{-1}; (2) sorghum–sudangrass at 28 kg ha^{-1} and Red Ripper cowpea at 140 kg ha^{-1}; (3) sorghum–sudangrass 14 kg ha^{-1} and cowpea at 140 kg ha^{-1}. Two 0.25-m^2 unweeded microplots were left within bare soil (hand-weeded) control treatments to estimate weed biomass and seed production. The experimental design was a randomized complete block with four replications. Relatively high cover crop seeding rates and small unweeded microplots were used in this trial to accommodate the grower's desire to minimize weed seed production in the experimental area. Cowpeas were sown using a set of four Earthway seeders[2] set at 3 cm depth with 13 cm between-row spacing. Sorghum–sudangrass was broadcast and lightly raked. All cover crops were sown on June 16 and sampled on August 28 (73 DAS). Weed and cover crop densities and biomass by species were measured from two 0.25-m^2 quadrats in each plot. To assess weed seed production, total mature seed heads were counted from each quadrat and multiplied by the number of seeds per seed head, based on seed counts from a subsample of 15 seed heads from each treatment.

Results and Discussion

Freeville Research Farm. Environmental conditions varied considerably across the 2 yr of the trial (Table 1). In particular, conditions during the 2005 cover crop growing period were hot and dry compared to 2006. During the first 3 wk of August 2005, high temperatures combined with low rainfall resulted in low soil moisture and potential drought stress for all cover crops. Although total rainfall during the 2005 cover crop growth period was substantial, over 60% of it occurred in a single rainfall event beginning on August 30. In contrast, the 2006 season had consistent rainfall and lower temperatures throughout the cover crop growing period. Due to significant year effects on all measured responses, data were analyzed separately by year.

Freeville 2005. Sorghum–sudangrass in monoculture produced approximately 8 t ha^{-1} dry weight compared to 3 t ha^{-1} for cowpea and soybean (Figures 1A and 1B). Mixtures of both legumes with sorghum–sudangrass resulted in severe reductions in legume dry weight accumulation; both cowpea and soybean produced less than 1 t ha^{-1} biomass in mixture, compared to 8 t ha^{-1} for sorghum–sudangrass. Addition of composted chicken manure had no detectable effect on soybean or sorghum–sudangrass biomass, but reduced cowpea biomass in monoculture.

Weed density and biomass production were very high in 2005 with Powell amaranth and redroot pigweed (*Amaranthus retroflexus* L.) dominating. In the absence of cover crops, weeds produced almost 9 t ha^{-1} dry weight and approximately 400,000 seeds m^{-2} (Table 2). In monoculture, both legumes were poor competitors with weeds, resulting in weed biomass of between 2 and 4 t ha^{-1} (Figure 1A) and weed seed production of over 100,000 seeds m^{-2} (Table 2). In contrast, sorghum–sudangrass either alone or in mixture with

Table 1. Weekly temperature and precipitation during cover crop growth, Freeville, NY, 2005 and 2006.

Date (week beginning)	Average temperature (C)		Precipitation (cm)	
	2005	2006	2005	2006
July				
July 8	22.5	NA	1.4	NA
July 15	24.9	24.2	0.0	2.0
July 22	22.5	22.3	1.8	3.6
July 29	22.3	25.1	0.2	3.7
August				
August 5	23.7	19.4	0.1	0.0
August12	22.0	17.7	0.3	0.1
August 19	19.9	19.9	0.6	5.1
August 26	21.3	17.9	7.4	6.0
September				
September 2	18.2	16.4	0.0	3.1
September 9	NA	15.8	NA	1.4
Average/total	21.9	19.9	11.8	25.0

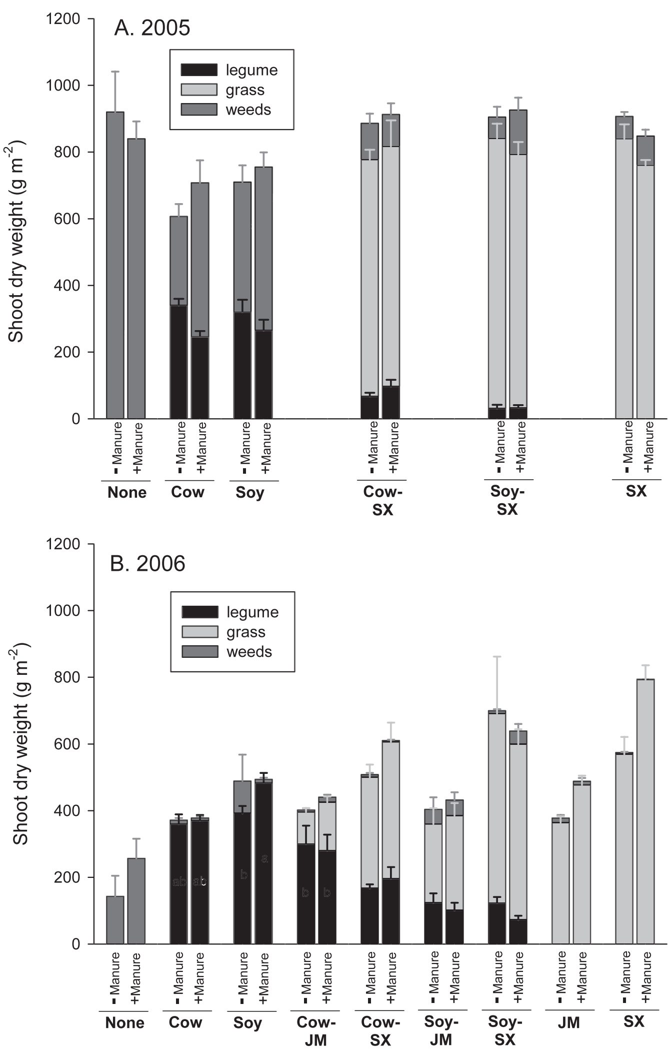

Figure 1. Mean (± SE) dry weight of legume cover crops, grass cover crops, and weeds with or without composted chicken manure Freeville, NY, 2005 (A) and 2006 (B).

Table 2. Mean total weed dry shoot weight, and estimated Powell amaranth seed production, Freeville, NY, 2005 and 2006.

Treatment[a]	2005		2006	
	Dry wt	Seeds[b]	Dry wt	Seeds[b]
	(kg ha^{-1})	(1,000 m^{-2})	(kg ha^{-1})	(1,000 m^{-2})
Cover crop main effects				
Cowpea	3,515 b[c]	130 b	64 b	0.6 b
Soybean	4,342 b	166 b	142 b	1.3 b
JM	NA	NA	92 b	0.7 b
SX	743 c	20 c	37 b	0.2 b
Cowpea/JM	NA	NA	82 b	0.6 b
Cowpea/SX	933 c	27 c	66 b	0.3 b
Soybean/JM	NA	NA	252 b	3.4 b
Soybean/SX	852 c	24 c	193 b	2.0 b
None	8,727 a	386 a	2,211 a	48.7 a
Fertilization main effects				
Fertilized	2,885 A	107 A	141 A	1.3 A
Unfertilized	2,319 B	84 B	144 A	1.1 A
Significance Level				
Cover crop	***	***	***	***
Fertilizer	*	*	NS	NS
Cover crop × fertilizer	NS	NS	NS	NS

[a] Abbreviations: JM, Japanese millet; SX, sorghum–sudangrass; NA, not applicable; NS, not significant.

[b] The only species to produce seeds was Powell amaranth.

[c] Within each main effect, means in each column followed by the same letter are not significantly different ($P < 0.05$ Tukeys).

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

legumes reduced weed biomass to less than 1 t ha^{-1}. Although this represents over 91% reduction in weed biomass relative to the unweeded control, weed seed production in sorghum–sudangrass treatments exceeded 20,000 seeds m^{-2} and represents a significant contribution to the weed seedbank. Empirical estimates of the seedbank density of Powell amaranth in an adjacent field with similar levels of Powell amaranth emergence ranged from 1,000 to 4,300 seeds m^{-2} to a depth of 20 cm (Brainard and Bellinder 2006). Therefore, the observed seed rain of 20,000 seeds m^{-2} likely led to at least a fivefold increase in the weed seedbank. As hypothesized, the addition of composted chicken manure shifted the competitive advantage toward weeds (mostly Powell amaranth) at the expense of cowpeas; weed biomass in cowpea monoculture was approximately doubled with the addition of manure, whereas cowpea biomass declined by over 25% (Figure 1A). This result is consistent with previous studies demonstrating that *Amaranthus* species exhibit both higher emergence and greater biomass accumulation at high levels of N compared to many other species (Blackshaw et al. 2003; Brainard et al. 2006) whereas legume nodulation and growth are often inhibited at high levels of N (e.g., Giller and Cadisch 1995).

Legumes grown in mixture with sorghum–sudangrass were severely suppressed compared to monocultures (Figure 1A) and did not produce healthy nodules (Figures 2A and 2B). Nodulation in monoculture was suppressed by over 50% for both legumes when composted chicken manure was used (Figures 2A and 2B). Poor nodulation in 2005 may have been the result of hot and dry conditions, which predominated

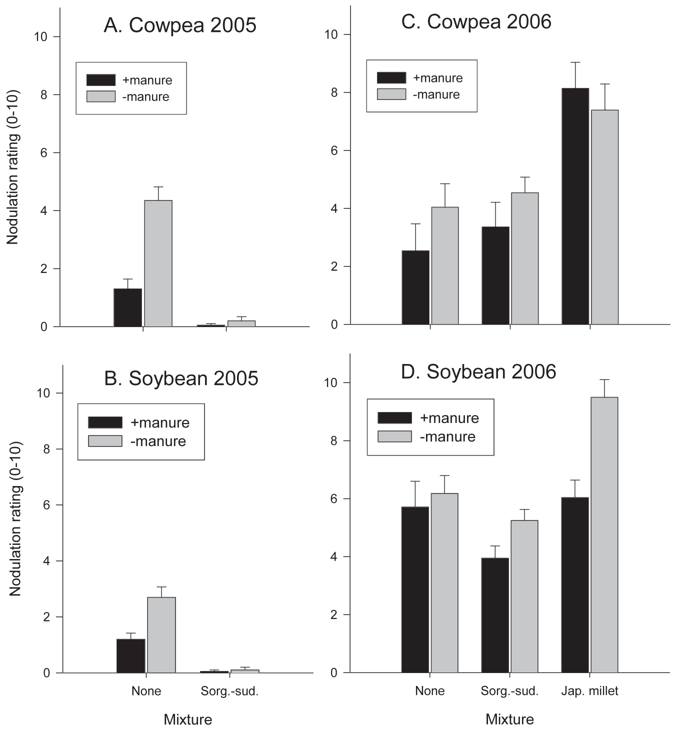

Figure 2. Mean (± SE) legume nodulation ratings for cowpea (A and C) and soybean (B and D) grown alone or in combination with grasses, with or without composted chicken manure, Freeville, NY, 2005 (A) and 2006 (B).

shortly after planting (Table 1). In addition, the experimental area had not been previously planted to either legume, so natural levels of rhizobia in the soil may have been low.

Freeville 2006. In 2006, sorghum–sudangrass in monoculture produced approximately 6 to 8 t ha^{-1} dry weight compared to approximately 4 to 5 t ha^{-1} for cowpea, soybean, and Japanese millet (Figure 1B). Mixtures of soybean with sorghum–sudangrass or Japanese millet resulted in soybean dry weights of less than 50% of the monoculture weight (Figure 1B). Since legumes in mixtures were sown at 50% of their monoculture rate, soybean biomass production of less than 50% represents a reduction in biomass per seed sown. In contrast, cowpea performed well in combination with both grasses, producing equivalent dry weight per seed sown when grown in combination with sorghum–sudangrass and greater dry weight per seed sown when grown in combination with Japanese millet compared to cowpea monoculture (Figure 1B). Composted chicken manure stimulated grass biomass production in monoculture, but had no detectable effects on legume dry weight or the performance of either component in mixtures (Figure 1B).

Nodulation of cowpea was stimulated when grown in mixture with Japanese millet but not with sorghum–sudangrass (Figure 2C). Nodulation of cowpea in mixture was approximately doubled when grown with Japanese millet compared to monoculture. Nodulation of soybean was stimulated when grown in mixture with Japanese millet, but only when no manure was applied (Figure 2D). In contrast, nodulation of soybean was suppressed when grown in combination with sorghum–sudangrass and manure. Composted chicken manure suppressed soybean nodulation in mixture (Figure 2D), but did not have any detectable effect on cowpea nodulation (Figure 2C).

Differences in the relative height of cover crops, and hence the relative importance of competition for light and N may help explain the different responses of legumes to mixtures. Sorghum–sudangrass height exceeded 1.5 m, whereas all other cover crops were 1 m or less (data not shown). As a result, legumes in mixture with sorghum–sudangrass were more heavily shaded than those grown alone or in mixtures with Japanese millet. Shade-induced reductions in nodulation have been observed for many legumes including soybean and cowpea (Ericson and Whitney 1984; Lawn and Brun 1974). In contrast, the relative importance of competition for N was likely to have been more important in mixtures with the lower-growing Japanese millet cover crop, contributing to the stimulation of nodulation in these mixtures through reductions in soil N, particularly where manure was not added (Figures 2C and 2D).

In 2006, weedy control plots were dominated by Powell amaranth, which produced over 2 t ha^{-1} dry weight and approximately 50,000 seeds m^{-2} representing about 25% of the weed biomass and 12% of the weed seed production observed in 2005 (Table 2). Cooler temperatures in 2006 compared to 2005 (Table 1) likely accounted for this difference in overall growth and fecundity of Powell amaranth, a heat-loving C_4 weed. In cover crop treatments weed dry weight and seed production were reduced by over 95% compared to the weedy control (Table 2). However, no differences in weed biomass or seed production were detected between cover crop treatments. Mean Powell amaranth seed production in cover crop treatments was 1,100 seeds m^{-2}. This level of seed production falls at or below the seedbank density estimated in an adjacent field with similar cropping history and similar level of Powell amaranth emergence (Brainard and Bellinder 2006). Given typical annual rates of seed loss of 50% due to predation and decay, the level of weed suppression observed in cover crop treatments in 2006 is likely to result in net reductions in the Powell amaranth seedbank over time.

Candor Trial. Sorghum–sudangrass produced almost 11 t ha^{-1} biomass in monoculture compared to about 7 t ha^{-1} for mixtures of sorghum–sudangrass and cowpea (Table 3). In mixtures, use of a lower sorghum–sudangrass seeding rate (12 kg ha^{-1} vs. 24 kg ha^{-1}) resulted in 26% increase in cowpea biomass at harvest without any detectable difference in total biomass production or weed suppression.

In all cover crop treatments, weed biomass was reduced by over 95% compared to the unweeded control, but both common purslane and hairy galinsoga were able to produce seeds (Table 3). Purslane seed production was reduced from 5,100 seeds m^{-2} in the absence of cover crops to approximately 600 seeds m^{-2} in cover crop treatments, and did not vary significantly with cover crop. Hairy galinsoga produced 263,000 seeds m^{-2} in the absence of cover crops. With cover crops, hairy galinsoga seed production ranged from 113 seeds m^{-2} in sorghum–sudangrass monoculture, to over 500 seeds m^{-2} in mixtures of sorghum–sudangrass and

Table 3. Mean cover crop and weed dry weights, and estimated weed seed production, Candor, NY, 2006.

Cover crop	Cover crop dry weight			Weed	Purslane	Galinsoga
	SX[a]	Cowpea	Total	Dry wt	Seeds	Seeds
	(t ha^{-1})			(kg ha^{-1})	(no. m^{-2})	
SX (84 kg/ha)	11.0 a	0.0 c	11.0 a	22 c	570 b	113 c
SX (28 kg/ha) + cowpea (140 kg/ha)	5.4 b	1.9 b	7.3 b	41 bc	590 b	575 bc
SX (14 kg/ha) + cowpea (140 kg/ha)	4.4 b	2.4 a	6.8 b	53 b	710 b	700 b
None	0.0 c	0.0 c	0.0 c	5,300 a	5,100 a	263,000 a

[a] Abbreviation: SX, sorghum–sudangrass.

[b] Within each column, means followed by the same letter are not significantly different ($P < 0.05$, Tukey's).

cowpea. For purslane, the observed level of seed production was likely small relative to the weed seedbank; we observed an average of over 200 purslane seedlings m^{-2} following cover crop establishment, but purslane exhibits high levels of seed dormancy. On the other hand, observed emergence of hairy galinsoga was only 16 seedlings m^{-2}, suggesting that the seed rain observed in cover crop treatments (100 to 500 seeds m^{-2}) represents a large fraction of the weed seedbank.

We hypothesized that mixtures of cowpea and soybean with sorghum–sudangrass and Japanese millet would improve weed suppression and increase legume nodulation relative to legume monocultures. In 2005, as hypothesized, legume mixtures improved weed suppression relative to legume monocultures. However, both legumes were severely suppressed in mixtures with sorghum–sudangrass, resulting in minimal legume biomass and poor nodulation. Therefore, mixtures in 2005 had no clear advantage relative to the sorghum–sudangrass alone. In 2006, mixtures provided no detectable weed-suppression benefits relative to monocultures; all cover crops were equally effective at suppressing weeds. However, mixtures of legumes with Japanese millet provided significant benefits relative to monocultures in terms of cover crop biomass and legume nodulation.

Our results demonstrate that the optimal choice of cover crops is likely to vary substantially with climatic conditions and soil fertility. Under hot and dry conditions (2005), heat-loving drought-tolerant weeds (Powell amaranth) and cover crops (sorghum–sudangrass) out-competed both cowpeas and soybeans. In contrast, cooler conditions (2006) resulted in more balanced growth of cover crop mixtures and better suppression of weeds. High soil fertility is also likely to favor nonlegumes (i.e., weeds and grass cover crops) at the expense of legumes and to suppress legume nodulation. This was most clearly demonstrated in cowpea mixtures in 2005 (Figures 1A and 2A). Because both temperature and soil fertility vary unpredictably, mixtures may reduce risks associated with cover crop responses to these factors. However, our results suggest that if weed suppression is the primary objective, monocultures of sorghum–sudangrass may be the least risky and least expensive choice among those treatments examined.

A critical measure of the acceptability of cover crops is their ability to minimize weed seed production. Our findings suggest that the risk of detrimental weed seed production is high when either soybean or cowpea are sown in monoculture (e.g., 2005). In the case of cowpea, this risk may be reduced, while maintaining benefits of the legume, through combinations with Japanese millet. However, for soybean, combinations with either grass do not appear to be justified due to suppression of soybean dry weight and nodulation in mixture.

Another important finding of this research was that even when weed biomass was reduced by 90% or more, certain weed species were capable of producing quantities of seeds that exceeded the initial weed seedbank. Powell amaranth and hairy galinsoga were identified as particularly problematic in this regard. Future research aimed at reducing the risk of seed production through complementary weed management practices would facilitate greater realization of potential benefits of these cover crops.

Sources of Materials

[1] Kreher's Poultry Farm, Clarence, NY 14031.
[2] Earthway Products Inc., Bristol, IN 46507.

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Literature Cited

Andow, D. A., A. G. Nicholson, H. C. Wien, and H. R. Willson. 1986. Insect populations on cabbage grown with living mulches. Environ. Entomol. 15:293–299.

Blackshaw, R. E., R. N. Brandt, H. H. Janzen, T. Entz, C. A. Grant, and D. A. Derksen. 2003. Differential response of weed species to added nitrogen. Weed Sci. 51:532–539.

Brainard, D. C. and R. R. Bellinder. 2006. Estimating Weed Seed Banks for Improved Monitoring and Management of Weeds. http://www.nysipm.cornell.edu/grantspgm/projects/proj06/veg/brainard.pdf. Accessed: April 2, 2011.

Brainard, D. C., R. R. Bellinder, and A. DiTommaso. 2005. Effects of canopy shade on the morphology, phenology and seed characteristics of Powell amaranth (*Amaranthus powellii*). Weed Sci. 53:175–186.

Brainard, D. C., A. DiTommaso, and C. L. Mohler. 2006. Intraspecific variation in germination response to ammonium nitrate of *Amaranthus powellii* originating on organic versus conventional vegetable farms. Weed Sci. 55:218–226.

Carmona, D. and D. Landis. 1999. Influence of refuge habitats and cover crops on seasonal activity-density of ground beetles (Coleoptera: Carabidae) in field crops. Environ. Entomol. 28:1145–1153.
Clark, K. M. and R. L. Myers. 1994. Intercrop performance of pearl millet, amaranth, cowpea, soybean, and guar in response to planting pattern and nitrogen fertilization. Agron. J. 86:1097–1102.
Creamer, N. G. and K. R. Baldwin. 2000. An evaluation of summer cover crops for use in vegetable production systems in North Carolina. HortScience 35:600–603.
Cousens, R. and Mortimer, M. 1995. Dynamics of Weed Populations. Cambridge, UK: Cambridge University Press. 332 p.
Ericson, F. I. and A. S. Whitney. 1984. Effects of solar radiation regimes on growth and N_2 fixation of soybean, cowpea and bushbean. Agron. J 76:529–535.
Fitzgerald, C. B. and R. B. Bryan. 2002. New cover crops and cover crop management for organic vegetable producers in Maryland. Santa Cruz, CA: Organic Farming Research Foundation final project report. 11 p. http://ofrf.org/funded/reports/fitzgerald_01f11.pdf (accessed 4/2/11)
Flach, K. W. 1990. Low-input agriculture and soil conservation. J. Soil Water Conserv. 45:42–44.
Fukai, S. and B. R. Trenbath. 1993. Processes determining intercrop productivity and yields of component crops. Field Crops Res. 34:247–271.
Giller, K. E. and G. Cadisch. 1995. Future benefits from biological nitrogen fixation: an ecological approach to agriculture. Plant Soil 174:255–277.
Hill, E. C., M. Ngouagio, and M. G. Nair. 2006. Differential response of weeds and vegetable crops to aqueous extracts of hairy vetch and cowpea. HortScience 41:695–700.
Itulya, F. M., V. N. Mwaja, and J. B. Masiunas. 1997. Collard–cowpea intercrop response to nitrogen fertilization, redroot pigweed density, and collard harvest frequency. HortScience 32:850–853.
Karlen, D. L., D. C. Erbach, T. C. Kaspar, T. S. Colvin, and E. C. Berry. 1990. Soil tilth: a review of past perceptions and future needs. Soil Sci. Am. J. 54:153–161.
Lawn, R. J. and W. A. Brun. 1974. Symbiotic nitrogen fixation in soybeans. I. Effect of photosynthetic source–sink manipulations. Crop Sci. 14:11–16.
Liebman, M. and E. Dyck. 1993. Crop rotation and intercropping strategies for weed management. Ecol. App. 3:92–122.
MacRae, R. J. and R. E. McDole. 1987. The effect of green manuring on the physical properties of temperate area soils. Adv. Soil Sci. 3:71–94.
Madge, D. and C. Jaeger. 2003. Organic farming: green manures for vegetable cropping. Victoria, Australia: Department of Primary Industries Agricultural Note AG1084. 7 p.
Pieters, A. 1927. Green Manuring: Principles and Practice. New York: J. Wiley. 267 p.
Reader, R. J. 1991. Control of seedling emergence by ground cover: a potential mechanism involving seed predation. Can. J. Bot. 69:2084–2087.
Robbins, W. 1942. Weed Control: A Textbook and Manual. New York: McGraw Hill. 543 p.
Schimpf, D. J. and I. G. Palmblad. 1980. Germination responses of weed seeds to soil nitrate and ammonium with and without simulated overwintering. Weed Sci. 28:190–193.
Sustainable Agriculture Network. 1998. Managing Cover Crops Profitably. Handbook Series Book 3. Burlington, VT: Sustainable Agriculture Publications.
Staniforth, D. W. 1962. Responses of soybean varieties to weed competition. Agron. J. 54:11–13.
Waterer, J. G., J. K. Vessey, and E. H. Stobbe. 1994. Yield and symbiotic nitrogen fixation in a pea–mustard intercrop as influenced by N fertilizer addition. Soil Biol. Biochem. 26:447–453.

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