Allelopathic Effects of Sunnhemp (*Crotalaria juncea* L.) on Germination of Vegetables and Weeds

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Abstract. Sunnhemp (*Crotalaria juncea* L.) is a tropical legume that could be an important summer cover crop in the southeastern United States, but it has the potential for suppressing both crops and weeds. Allelopathic effects of sunnhemp on weeds, vegetable crops, and cover crops were evaluated in greenhouse and growth chamber experiments. In the greenhouse, ground dried sunnhemp residues (applied mixed with the soil at 1.6% w/w) reduced percent germination of lettuce (*Lactuca sativa* L.) and smooth pigweed (*Amaranthus hybridus* L.) to a similar degree as that caused by cereal rye (*Secale cereale* L. subsp. *cereale*) residues (applied at 1.5% w/w). The allelopathic activity of sunnhemp was greater in the leaves than in the roots or stems. In growth chamber studies, the mean reduction in germination (relative to the control) caused by sunnhemp leaf aqueous extracts was: bell pepper (100%), tomato (100%), onion (95%), turnip (69%), okra (49%), cowpea (39%), collard (34%), cereal rye (22%), sweet corn (14%), Austrian winter pea (10%), crimson clover (8%), cucumber (2%), and winter wheat (2%). In lettuce, carrot, smooth pigweed, and annual ryegrass, sunnhemp aqueous leaf extract reduced seedling emergence to a degree similar as that produced by rye aqueous leaf extract. Sicklepod [*Senna obtusifolia* (L.) H.S. Irwin & Barneby CA] germination was not inhibited by any of the sunnhemp or rye aqueous extracts. In conclusion, sunnhemp reduced the germination percentage and seedling growth of various crop species. The allelochemical activity in sunnhemp was primarily in the leaves and remained active at least 16 d after harvest under dry conditions. Sunnhemp's allelochemical effect may be a useful attribute for weed management in sustainable production systems. However, plant growth in the field in crops such as bell pepper, tomato, onion, and turnip may be impacted as a result of allelopathic activity of sunnhemp residues. Thus, weed management may be more effective when sunnhemp is grown in rotation with crops that tolerate the allelochemicals from sunnhemp, resulting in optimization of the rotation effects.

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Cover crops are important in sustainable agricultural systems because they help improve soil organic matter and reduce soil erosion, among other benefits. Sunnhemp is a tropical legume that could be used as a summer cover crop in the southeastern United States (Mansoor et al., 1997; Reeves, 2007; Scholberg et al., 2005) because it produces significant biomass and nitrogen in 60 to 90 d (Marshall, 2002; Schomberg et al., 2007). Additionally, sunnhemp has also been reported to suppress populations of plant parasitic nematodes including root-knot (*Meloidogyne* spp.), soybean cyst (*Heterodera glycines* Ichinohe), and reniform (*Rotylenchulus reniformis* Linford and Oliveira) (Wang et al., 2002).

Nitrogen fixation by sunnhemp is similar to that of hairy vetch (*Vicia villosa*) and

crimson clover (*Trifolium incarnatum*) (Akanvou et al. 2001; Mansoor, et al., 1997; Scholberg et al., 2005). Sunnhemp could supply a significant amount of nitrogen (N) needed by either a fall/winter vegetable crop or by a spring crop (Mansoor et al., 1997; Scholberg et al., 2005). In Georgia, sunnhemp was found to have maximum biomass and N ranging from 8.9 to 13.0 Mg·ha⁻¹ and 135 to 285 kg·ha⁻¹, respectively. The probability for sunnhemp to become invasive in the continental United States is small. Sunnhemp will not set seed north of 28° N latitude (Reeves, 2007).

Cover crops can help suppress weeds by establishing unfavorable conditions for weed growth and competing for resources (Phatak and Díaz-Pérez, 2007; Teasdale, 1998). In some cases, weed suppression has been attributed to production of allelopathic chemicals by cover crops (Putnam and Duke, 1978; Putnam and Tang, 1986). Allelopathy is a trait that could be beneficial in sustainable agriculture systems to reduce weed pressures and herbicide use (Adler and Chase 2007; Putnam and Tang, 1986; Singh et al., 2003).

Previous work on sunnhemp demonstrated allelopathic properties of ground dried residues and aqueous leaf extracts on certain weeds (Adler and Chase, 2007; Cole, 1991). Aqueous leaf extracts and residues of sunnhemp were found to suppress growth of wheat (*Triticum aestivum*), goosegrass (*Eleusine indica*), livid amaranth (*Amaranthus lividus*), and bell pepper (*Capsicum annuum*) but had little effect on tomato (Adler and Chase, 2007; Ohdan et al., 1995). Effects varied as a result of the concentration of the extract or amount of residue added to the growth medium. There is a growing interest in using sunnhemp as a cover crop in vegetable and row crop systems in the southeast United States. Before recommendations can be made to farmers interested in using sunnhemp, more information is needed about its potential allelopathic effects. The objectives of this study were to determine the potential allelopathic effects of sunnhemp on some selected weeds, vegetable crops, and cover crops grown in the southeastern United States. Weeds evaluated are of economic importance in the southeastern United States (Webster and MacDonald, 2001).

Materials and Methods

Expt. 1: Effect of sunnhemp and rye residues on germination of lettuce, carrot, and the weeds smooth pigweed, annual ryegrass, and sicklepod

Sunn hemp residues. 'Sunn hemp-1' residue came from plants grown in the field in Watkinsville, GA, at the J. Phil Campbell Sr. Natural Resource Conservation Research Center. The soil (Cecil soil—sandy clay loam, fine, kaolinitic, thermic, Typic kanhapludult) was tilled to provide an adequate seed bed (Schomberg et al., 2006). Sunnhemp ('Tropic Sun') was planted at the recommended seeding rate for broadcast seeding, 45–67 kg·ha⁻¹ (Rotar and Joy, 1983). Whole plants [tops

(leaves, stems, and flowers) and roots] at the flowering stage were collected 65 d after planting (DAP), dried in an oven at 50 °C for 3 d, ground, and subsequently frozen at -70 °C. 'Sunn hemp-1' residue was only used on smooth pigweed and lettuce seeds as a result of insufficient residue available for testing with other species.

'Sunn hemp-2' residue was obtained from plants grown in trays (56 cm long × 27 cm wide × 6.4 cm deep; Model F1721; Hummert, Earth City, MO) in the greenhouse for 65 d (5 Aug. to 9 Oct. 2005). The rate of seeding was 5 g·m⁻² (0.73 g/tray) (Rotar and Joy, 1983). Plants were fertilized once a week with liquid fertilizer, 20N-8.8P-16.6K, and watered as needed. Sunn hemp was grown under optimal water and nutrient conditions in the greenhouse and was not stressed. Sunn hemp leaves and stems were harvested at the vegetative stage and allowed to dry in the sun (inside the greenhouse) for 16 d. Leaves and stems were dried in an oven at 50 °C for 1 week and then frozen at -70 °C.

Rye residues. Rye 'Wrens Abruzzi' was planted on the same field as sunn hemp in Watkinsville, GA. It was planted at a seeding rate of ≈90 kg·ha⁻¹. 'Rye-1' residue consisted of plant tops harvested when they were ≈10 cm long. Leaves were oven-dried immediately after excision from the plant. 'Rye-2' residue consisted of plant tops that were cut at the late boot stage and allowed to dry in the field before bailing. Bales were covered and stored in a barn for ≈8 weeks before the study. Rye residues were chopped in a standard food processor to reduce size of the residue fragments to ≈2-4 cm in length. Rye residues were dried and frozen in the same way as sunn hemp residues.

The cover crop ground dried residue treatments were: control (no cover crop residues), 'Sunn hemp-1' leaf, 'Sunn hemp-2' leaf, 'Rye-1' leaf, and 'Rye-2' leaf. The species evaluated included lettuce (*Lactuca sativa* L. 'Black Simpson'), carrot [*Daucus carota* (L.) 'Nantes'], and the weeds, smooth pigweed (*Amaranthus hybridus* L.), annual ryegrass (*Lolium multiflorum* L.), and sicklepod [*Senna obtusifolia* (L.) H.S. Irwin & Barneby CA]. A germination test conducted before the experiment indicated that germination was ≈80% for all the species, although germination in smooth pigweed was lower than 80% during the experiments.

Cover crop ground dried residues were mixed with a soil mixture and added to pots (Styrofoam cup containing 650 g of soil mixture). The soil mixture, which had been sterilized by heating for 4 h at 93 °C, was composed of 75% Cecil sandy loam and 25% sand (by volume). The amount of crop residue added per pot (9.4 g for rye or 10.1 g for sunn hemp) was based on observed field biomass production of 7.6 Mg·ha⁻¹ (Schomberg et al., 2006) and 8.1 Mg·ha⁻¹ (Martini, 2004) for rye and sunn hemp, respectively. The goal was to provide a concentration of the residue similar to what would be provided by the cover crop under field conditions. The concentrations (by weight) of the ground dried

residues in the soil mixture were ≈1.5% and 1.6% for rye and sunn hemp, respectively.

Ten seeds of a single species were planted in pots containing the soil mixture and watered to ≈70% of field capacity. The pots were kept in the greenhouse and were covered with Saran film to reduce water evaporation. Germination was recorded twice per week and the final germination was determined 28 DAP. Germination was defined as the emergence of the hypocotyl. Germination percent was calculated as:

$$\text{Germination percent} = \left(\frac{\text{\# seed germinated}}{\text{Total \# seed}} \right) \times 100\%$$

Expt. 2: Effect of aqueous leaf, stem, and root residue extracts of sunn hemp and rye on germination and seedling growth of lettuce, carrot, smooth pigweed, annual ryegrass, and sicklepod

Aqueous extracts of sunn hemp root, leaf, and stem and rye leaf residues were prepared by mixing 5 g of residue with 150 mL of distilled water (3.3% w/v solution on a dry weight basis). The mixture was agitated for 16 h at room temperature on an orbital shaker at 100 rpm (2.24 g_n) (White et al., 1989). The slurry was filtered through four layers of cheesecloth and vacuum filtered on a Buchner funnel. The aqueous extracts were used at full strength (3.3%) or at half strength [1.65% (diluted 1:1 with distilled water)]. After preparation, extracts were stored overnight at 4 °C. The same sources of sunn hemp ('Sunn hemp-1') and rye ('Rye-1') ground dried residues as in Expt. 1 were used. Twenty-five seeds of each test species were placed on a filter paper disk in a 10-cm petri dish and 10 mL of the residue extract was added. The petri dish was wrapped with parafilm to reduce water evaporation. Petri dishes were kept in a growth chamber (16-h photoperiod, 30/20 °C day/night cycle) (Buhler and Hoffman, 1999). Germination percentage and seedling length [length of radicle plus hypocotyl (dicots) or length of radicle alone (monocots)] were measured for all species 4 DAP, except for carrot, which were measured at 6 DAP. Germination was defined as the emergence of the radicle. Four d was sufficient for most of the seed in the unamended controls for all species to germinate, whereas most non-germinated seeds in the sunn hemp aqueous extracts appeared necrotic at that time.

Expt. 3: Effect of aqueous leaf extracts of sunn hemp and rye on germination of common southern vegetables and cover crops

Vegetable crops were selected based on their economic importance in the southeast United States according to the Georgia Farm Gate Report (Boatright and McKissick, 2010), whereas the cover crops evaluated were among those commonly grown in vegetable rotations. Seeds of the following species were evaluated: Austrian winter pea (*Pisum sativum* L.), bell pepper 'California Wonder' (*Capicum annum* L.), rye 'Wrens Abruzzi' (*Secale*

cereale L.), collard 'Georgia Southern' (*Brassica oleracea* L.), cowpea 'Colossus' (*Vigna unguiculata* L.), crimson clover 'Dixie Reseeding' (*Trifolium incarnatum* L.), cucumber 'Long Green Improved' (*Cucumis sativus* L.), okra 'Perkins' (*Hibiscus esculentus* L.), onion 'Savannah Sweet' (*Allium cepa* L.), sweet corn (*Zea mays* var. *rugosa*), tomato 'Big Boy' (*Solanum lycopersicum* L.), turnip 'Seven Top' (*Brassica campestris* L.), and winter wheat 'AR 494' (*Triticum aestivum* L.).

Sunn hemp and rye leaf ground dried residues were obtained from the same sources as in Expt. 1 and the aqueous extracts were prepared as in Expt. 2. Fifteen seeds of each test species were placed on a piece of filter paper in a petri dish and 5 mL of aqueous extract added. Cowpea seeds imbibed all of the added solution to a greater degree than the other seeds; thus, on Day 2, an additional 5 mL of aqueous extract was added to each dish containing cowpea seeds. Petri dishes were placed in a growth chamber and maintained at 20 °C (12 h) and 25 °C (12 h) with no light. Germination was evaluated by recording hypocotyl emergence on Day 4.

Expt. 4: Osmotic potential and pH of sunn hemp and rye extracts and the effect of osmotic solutions on germination of carrot, lettuce, and the weeds smooth pigweed, annual ryegrass, and sicklepod

Osmotic potential of the sunn hemp and rye tissue aqueous extracts was measured to determine whether the inhibitory effects on germination may be the result of decreased water potential. Osmotic potential of the tissue aqueous extracts was determined by placing 1 g of plant tissue in 5 g of water and the slurry was allowed to sit at room temperature (≈25 °C) for 24 h. This slurry was then filtered through a syringe with glass wool in the tip. The filtrate was centrifuged at 6500 rpm for 10 min and the solute concentration of the supernatant was measured on an osmometer (Osmette A; Automatic Osmometer, Precision Systems, Inc., Natick, MA). Osmotic potential was determined on a more concentrated supernatant compared with the germination experiments because the latter were below the detection limits of the osmometer.

Seeds of carrot, lettuce, sicklepod, annual ryegrass, and pigweed were evaluated for their sensitivity to the osmotic potential (ψ_s) present in the aqueous tissue extracts. Solutions with ψ_s of 0 MPa [control (distilled water only)], -0.03 MPa, and -0.1 MPa were made using polyethylene glycol (PEG). The ψ_s at -0.03 MPa and -0.1 MPa corresponded to the actual ψ_s of the tissue extracts used in Expts. 1 and 2. Twenty-five seeds of each species were placed on a piece of filter paper in a petri dish and 10 mL of the PEG solution added. The dishes were wrapped with parafilm and placed in a growth chamber at 30 °C day and 20 °C night with a 16-h photoperiod. After 4 d, germination percent was determined.

Statistical analysis

A completely randomized design with four replications was used for all four experiments.

The data were analyzed using a mixed model analysis of variance (PROC MIXED) and Dunnett's multiple comparison procedure. The values for germination percent were arcsine-transformed for the analysis to normalize data distribution and then untransformed for presentation of the data. The analyses were performed using the SAS for Windows 2006, Version 9.1 (SAS Institute, Cary, NC).

Results

Expt. 1: Effect of sunnhemp and rye ground dried residues on germination of lettuce, carrot, smooth pigweed, annual ryegrass, and sicklepod

There was no germination in any species for the first 14 d. Percentage germination of lettuce, carrot, smooth pigweed, annual ryegrass, and sicklepod 28 DAP in a soil mixture containing sunnhemp and rye ground dried residues is shown in Table 1. Lettuce and smooth pigweed germination was significantly reduced by sunnhemp (both 'Sunnhemp-1' and 'Sunnhemp-2') and rye (only 'Rye-1') residues relative to the control. 'Rye-1' residue had a stronger inhibitory effect on lettuce and annual ryegrass germination compared with 'Rye-2' residue. Germination of carrot and sicklepod was unaffected by the four cover crop treatments.

Expt. 2: Effect of aqueous leaf, stem, and root residue extracts of sunnhemp and rye on germination and seedling growth of lettuce, carrot, smooth pigweed, annual ryegrass, and sicklepod

Germination. The magnitude of the inhibitory effect on germination was dependent on the strength and type of plant aqueous extract (Table 2). Full-strength aqueous leaf extracts of both sunnhemp and rye reduced germination compared with the control in all species except in sicklepod. Sicklepod germination was not inhibited by any of the aqueous extracts. Full-strength sunnhemp leaf extract reduced germination in lettuce, smooth pigweed, and annual ryegrass more effectively than the full-strength rye leaf extract. Full-strength sunnhemp leaf extract reduced germination more than the half-strength extract, and the inhibitory effect was similar or greater than full-strength rye extract for all species except sicklepod. Full-strength sunnhemp leaf extract had a greater inhibitory effect on lettuce and smooth pigweed germination than did full-strength rye leaf extract. Rye leaf extracts had no effect on smooth pigweed germination. Half-strength rye leaf extract inhibited germination only for carrot. In contrast to sunnhemp leaf extracts, sunnhemp root and stem extracts had no effect on germination of any of the species compared with the control.

Seedling growth. Sunnhemp aqueous leaf extracts and rye aqueous leaf extracts reduced seedling length relative to the control in all species except in sicklepod, and the degree of inhibition was affected by the extract strength and plant part used to make

the extract (Table 3). Full-strength sunnhemp leaf extract inhibited seedling growth by 100% (smooth pigweed), 99.4% (lettuce), and 96.4% (carrot and annual ryegrass), whereas half-strength rye leaf extract reduced seedling growth by 94.5% (annual ryegrass), 94.1%

(lettuce and carrot), and 82.3% (smooth pigweed) relative to the control. Half-strength sunnhemp root extract actually increased the length of the lettuce seedlings by 53% compared with the control. As expected, full-strength extracts had a higher

Table 1. Influence of sunnhemp (*Crotalaria juncea* L.) and rye (*Secale cereale* L. subsp. *cereale*) plant top dried residues mixed in soil on mean germination percentage (Day 28) of lettuce, carrot, and the weeds smooth pigweed (*Amaranthus hybridus* L.), annual ryegrass (*Lolium multiflorum* L.), and sicklepod (*Senna obtusifolia* L.) (Expt. 1).²

Cover crop residue ¹	Germination (%)				
	Lettuce	Carrot	Pigweed	Ryegrass	Sicklepod
Control	86	45	21	75	82
Sunnhemp-1	7*	ND ^x	1*	ND ^x	ND ^x
Sunnhemp-2	8*	17	5*	56	66
Rye-1	4*	16	3*	21*	58
Rye-2	36*†	23	10	84†	69

²Values within columns are significantly different from the control at * $P \leq 0.05$ or significantly different from full strength rye residue (Rye-1) at † $P \leq 0.05$ according to Dunnett's multiple comparison procedure ($n = 4$).

³Crop residue fragments were 2–4 cm long. Control = no residue fragments. 'Sunnhemp-1' was grown in the field and harvested at the flowering stage (65 d after planting); 'Sunnhemp-2' was grown in the greenhouse, harvested at the vegetative stage (65 d after planting), and dried for 16 d inside the greenhouse; 'Rye-1' was grown in the field and harvested at the vegetative stage (10 cm long); 'Rye-2' was grown in the field, harvested at the reproductive stage (boot stage), bailed, and stored in a barn for 56 d.

^xND = not determined.

Table 2. Influence of sunnhemp (*Crotalaria juncea* L.) aqueous leaf, stem, and root extracts and rye (*Secale cereale* L. subsp. *cereale*) aqueous leaf extracts on mean germination percentage of lettuce, carrot, and the weeds smooth pigweed (*Amaranthus hybridus* L.), annual ryegrass (*Lolium multiflorum* L.), and sicklepod (*Senna obtusifolia* L.) (Expt. 2).²

Cover crop extract	Extract strength ^y	Weed or crop species				
		Lettuce	Carrot	Pigweed	Ryegrass	Sicklepod
		Germination (%) ^z				
Control (water)		99	70	64	88	93
Sunnhemp leaf	Full	2*†	1*	0*†	0.2*†	92
	Half	57*†	10*	32*	57†	91
Sunnhemp stem	Full	85†	25	65†	80†	98
	Half	90†	72†	63	95†	97
Sunnhemp root	Full	87†	30†	71†	76†	94
	Half	84†	61†	77†	90†	91
Rye leaf	Full	34*	1*	39	10*	98
	Half	94†	3*	67†	68†	97

²Values within columns are significantly different from the control at * $P \leq 0.05$ or significantly different from full strength extract from rye leaf † $P \leq 0.05$ according to Dunnett's multiple comparison procedure ($n = 4$).

³Full strength = 3.3% w/v and half strength = 1.65% w/v, both on a leaf, stem, or root dry weight basis.

Table 3. Influence of sunnhemp (*Crotalaria juncea* L.) aqueous leaf, stem, and root extracts and rye (*Secale cereale* L. subsp. *cereale*) aqueous leaf extract on length of seedlings of lettuce, carrot, and the seedlings of the weeds smooth pigweed (*Amaranthus hybridus* L.), annual ryegrass (*Lolium multiflorum* L.), and sicklepod (*Sienna obtusifolia* L.) (Expt. 2).²

		Weed or crop species				
	Extract strength	Lettuce	Carrot	Pigweed	Ryegrass	Sicklepod
Cover crop ^y extract		Seedling length ^x (mm)				
Control		17	11	17	22†	12
Sunnhemp leaf	Full	0.1*†	0.4*	0*	0.8*†	10
	Half	4*	1*	6*	6*	10
Sunnhemp stem	Full	13*†	4*	15†	10*†	15
	Half	19†	6*†	18†	13*†	18
Sunnhemp root	Full	18†	4*	18†	9*	12
	Half	26*†	8*†	19†	16*†	14
Rye leaf	Full	1*	1*	3*	1.2*	7
	Half	6*†	2*	7*	6*	9

²Values within columns are significantly different from the control at * $P \leq 0.05$ or significantly different from full strength extract from rye leaf at † $P \leq 0.05$ according to Dunnett's multiple comparison procedure ($n = 4$).

³Control = water. Tissue aqueous extracts were prepared at full strength (3.3% w/v, on a dry basis) or half strength (1.65% w/v, on a dry basis). Sunnhemp ('Sunnhemp-1') was grown in the field and harvested at the flowering stage (65 d after planting); Rye ('Rye-1') was grown in the field and harvested at the vegetative stage (10 cm long).

^xLength of radicle (monocots) or length of radicle plus hypocotyl (dicots).

degree of inhibition than half-strength extracts. Full-strength sunnhemp leaf extract resulted in the radicles and hypocotyls of lettuce seedlings being shorter than those of lettuce seedlings exposed to full-strength rye leaf extract. Thus, sunnhemp leaf extracts inhibited seedling length the most and sunnhemp root extracts the least, and, as an average, sunnhemp leaf extracts reduced seedling length to a degree similar to that produced by full-strength rye leaf extract.

Expt. 3: Effects of aqueous leaf extracts of sunnhemp and rye on germination of common southern vegetables and cover crops

Germination in bell pepper, collard, cowpea, okra, and onion was reduced in the presence of residue aqueous leaf extracts compared with the control (distilled water). For these species, germination was similar for sunnhemp ('Sunnhemp-1' and 'Sunnhemp-2') and rye ('Rye-1') aqueous extracts (Table 4). Sweet corn germination was unaffected by sunnhemp aqueous leaf extracts but was significantly reduced by rye aqueous leaf extract, whereas tomato germination was affected by 'Sunnhemp-2' and rye aqueous leaf extracts. Turnip germination was inhibited more by 'Sunnhemp-2' aqueous leaf extract than by rye aqueous leaf extract. 'Sunnhemp-2' aqueous leaf extract reduced germination relative to the control in crimson clover, cucumber, and tomato, and the response was similar with rye aqueous leaf extract. 'Sunnhemp-1' aqueous leaf extract did not affect germination of crimson clover, cucumber, or tomato. Austrian winter pea, rye, and winter wheat were unaffected by either sunnhemp or rye aqueous leaf extracts. The mean reduction in germination (relative to the control) caused by sunnhemp aqueous leaf extracts was: bell pepper (100%), tomato (100%), onion (95%),

turnip (69%), okra (49%), cowpea (39%), collard (34%), rye (22%), sweet corn (14%), Austrian winter pea (10%), crimson clover (8%), cucumber (2%), and winter wheat (2%). Across species, aqueous leaf extracts reduced germination by 49% ('Rye-1'), 46% ('Sunnhemp-2'), and 31% ('Sunnhemp-1').

The mean germination percent values averaged over cover crop aqueous leaf extracts were: bell pepper (0.1%), onion (3%), tomato (29%), turnip (31%), okra (37%), cowpea (52%), collard (60%), sweet corn (77%), rye (78%), crimson clover (91%), Austrian winter pea (93%), winter wheat (96%), and cucumber (97%). These values showed that vegetable crops in this study were in general more susceptible to sunnhemp and rye aqueous leaf extracts than cover crops.

Expt. 4: Osmotic potential and pH of aqueous tissue extracts and the effect of osmotic solutions on germination of carrot, lettuce, and the weeds smooth pigweed, annual ryegrass, and sicklepod

The ψ_s of the aqueous plant tissue extracts ranged from -0.03 MPa to -11 MPa. Among sunnhemp extracts, leaf extracts (-0.11 MPa) had a lower ψ_s than either root (-0.04 MPa) or stem extracts (-0.03 MPa). The ψ_s of the sunnhemp leaf extract was the same as that of the rye leaf extract. PEG solutions of ψ_s similar to those of the aqueous tissue extracts had no effect on germination or seedling dry weight.

Discussion

Like other research on sunnhemp (Adler and Chase, 2007; Cole, 1991), we found that sunnhemp ground dried residues inhibit germination and seedling growth of various vegetable and cover crops. In several cases, the effect was comparable to that caused by

rye, whereas in others, sunnhemp was more effective than rye in reducing germination (lettuce, turnip, smooth pigweed, and annual ryegrass). The effects of sunnhemp ground dried residues on germination and seedling growth varied for the different sunnhemp plant parts with the leaves having a higher allelopathic effect than either stems or roots.

Our results showed that sunnhemp aqueous leaf extracts strongly inhibited bell pepper germination. In contrast, Adler and Chase (2007) found that sunnhemp leaf extract (10%, w/v fresh weight basis) did not significantly reduce bell pepper or tomato germination compared with the control. One possible explanation for the contrasting results is that sunnhemp plants grown for their experiment were harvested after 14 d, when the plants were still in the juvenile stage (compared with our plants, harvested 65 DAP). Ohdan et al. (1995) collected sunnhemp plant biomass at the mature (flowering) stage and found that wheat root length was decreased compared with the control. It is possible that the level of allelochemical activity in sunnhemp may also be affected by environmental factors such as light (wavelength, intensity, or photoperiod), temperature stress, water stress, low nutrient availability, and disease pressures (Reigosa et al., 1999). These environmental factors could contribute to the plant producing higher levels of the allelochemical. A number of plants (rice, rye, and wheat) show an amplified allelochemical potential when grown in the field but when grown in the greenhouse, they still have allelopathic potential. The allelochemical compounds produced by sunnhemp have not been determined as to our knowledge.

The results suggest that allelochemicals leached from the sunnhemp leaf residue could reduce the germination of bell pepper, collard, cowpea, okra, onion, and turnip in the

Table 4. Influence of sunnhemp (*Crotalaria juncea* L.) and rye (*Secale cereale* L. subsp. *cereale*) aqueous leaf extracts on germination of important southern vegetables and cover crops (Expt. 3).^z

Crop species ^y	Control ^x	Sunnhemp-1		Sunnhemp-2		Rye-1	
	Germination (%)	Germination (%)	Reduction ^w (%)	Germination (%)	Reduction (%)	Germination (%)	Reduction (%)
Austrian Winter Pea	99	95	4	85	14	100	0
Bell pepper	95	0*	100	0*	100	0.4*	100
Collard	100	74*	26	58*	42	47*	53
Cowpea	100	62*	38	61*	39	32*	68
Crimson clover	100	99†	1	86*	14	87*	13
Cucumber	100	100†	0	96*	4	96*	4
Okra	83	36*	57	48*	42	26*	69
Onion	74	3.8*	95	3.2*	96	0.9*	99
Rye	99	90	9	65	34	79	20
Sweet corn	99	79	20	92	7	59*	40
Tomato	98	86†	12	0.4*	100	0*	100
Turnip	100	61*	39	1.3*†	99	31*	69
Winter wheat	100	99	1	97	3	93	7

^zValues within rows are significantly different from the control (distilled water) at * $P \leq 0.05$ or significantly different from those treated with full-strength extract from rye leaf at † $P \leq 0.05$ according to Dunnett's multiple comparison procedure ($n = 4$).

^yAustrian winter pea (*Pisum sativum* L.), bell pepper 'California Wonder' (*Capsicum annuum* L.), rye 'Wrens Abruzzi' (*Secale cereale* L.), collard 'Georgia Southern' (*Brassica oleracea* L.), cowpea 'Colossus' (*Vigna unguiculata* L.), crimson clover 'Dixie Reseeding' (*Trifolium incarnatum* L.), cucumber 'Long Green Improved' (*Cucumis sativus* L.), okra 'Perkins' (*Hibiscus esculentus* L.), onion 'Savannah Sweet' (*Allium cepa* L.), sweet corn (*Zea mays* var. *rugosa* L.), tomato 'Big Boy' (*Solanum lycopersicum* L.), turnip 'Seven Top' (*Brassica campestris* L.), winter wheat 'AR 494' (*Triticum aestivum* L.).

^xControl = water. Leaf aqueous extracts were prepared at full strength (3.3% w/v, on a leaf dry basis). 'Sunnhemp-1' was grown in the field and harvested at the flowering stage (65 d after planting); 'Sunnhemp-2' was grown in the greenhouse, harvested at the vegetative stage (65 d after planting), and dried for 16 d inside the greenhouse; 'Rye-1' was grown in the field and harvested at the vegetative stage (10 cm long).

^w'Reduction' was calculated based on the actual number of germinated seeds in the treatment relative to the control. For each treatment and species, the sum of 'Germination' and 'Reduction' was not always equal to 100% because germination in the control was not always equal to 100%.

field. The differential response of cucumber, tomato, and crimson clover to the two sunn-hemp sources may have been the result of differences in the stage of development (vegetative vs. reproductive) of the sunn-hemp plants from which the crop residues were obtained, suggesting that the concentration of allelochemicals in the leaves increases during the reproductive stage. Alternatively, it is also possible that the environmental conditions during plant growth (field vs. greenhouse) and after killing the cover crop may have had an impact on the allelopathic properties of the extracts. However, as a result of confounding effects of the characteristics of the sunn-hemp sources, it is not possible from this study to determine what caused the different crop responses to the two sunn-hemp sources (Reigosa et al., 1999).

Smooth pigweed and sicklepod are among the 10 most common and troublesome weeds in agronomic crop production in the southern United States (Webster and MacDonald, 2001). Smooth pigweed germination was affected by sunn-hemp ground dried residues but not by rye ground dried residues, whereas sicklepod was unaffected by either sunn-hemp or rye ground dried residues, which indicates that sicklepod may become a weed pest in production systems where sunn-hemp or rye is being used as a cover crop.

A cover crop such as sunn-hemp should not be a single solution for weed control but part of an integrated weed management system. One of the limitations of any allelopathic crop is that it has a fairly narrow range of weeds that are controlled or suppressed. Thus, good agronomic practices like rotating cash crops and cover crops and sanitation practices would be needed to control more resistant weeds such as sicklepod. Sunn-hemp is also not expected to control perennial weeds such as kudzu [*Pueraria montana* (Lour.) Merr. var. *lobata* (Willd.) Maesen & S. Almeida]. Unless the allelochemical is isolated and sprayed as a herbicide, sunn-hemp would provide control only on annual weeds.

Because sunn-hemp can be grown in the summer or early fall after a spring or summer cash crop, a late fall cash or cover crop is likely to be the next crop in rotation. The allelopathic effects of sunn-hemp are a beneficial attribute for weed control when using sunn-hemp as a summer cover crop. To be useful as a cover crop in a continuous cropping system, sunn-hemp would need to lose its allelopathic activity soon after sunn-hemp is destroyed so there is no inhibitory effect on the subsequent crop. It is likely that after winter fallow or an insensitive cover crop, any remaining allelochemicals from the sunn-hemp leaves would have dissipated so that subsequent crops would be unaffected by the sunn-hemp residues.

The pH of sunn-hemp aqueous extracts (mean pH = 6.5) was within the normal range for vegetable crop growth (pH = 5.0 to 7.0). The pH of the rye extract in Expt. 1 was the lowest among the extracts (pH = 4.3), and it was noticeably below what is considered normal for optimal growth for most vegetables. The pH of the rye aqueous extract was not adjusted, because it was not adjusted in other studies (Barnes and Putnam, 1986; White et al., 1989).

PEG solutions of ψ_s similar to those of the plant tissue extracts had no effect on germination or seedling dry weight. This suggests that the inhibitory effect of tissue aqueous extracts on germination is not an osmotic effect. Further work is needed to identify the possible allelochemicals that resulted in our observed reductions in germination and growth.

In conclusion, sunn-hemp ground dried residues and aqueous leaf extracts inhibited germination and seedling growth of several weeds and cover crops. Sunn-hemp leaves had a greater allelochemical effect than either roots or stems. This allelochemical property of sunn-hemp may be a useful attribute for weed management in sustainable production systems. However, plant growth in crops such as bell pepper, tomato, onion, and turnip may be impacted as a result of allelopathic activity of field sunn-hemp residues. Thus, weed management may be more effective when sunn-hemp is grown in rotation with crops that tolerate the allelochemicals from sunn-hemp, resulting in optimization of the rotation effects. Further work is needed to verify these results under field conditions.

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