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Integrated management of strawberry pests by rotation and intercropping

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Abstract

'Saia' oats (*Avena strigosa*) and 'Triple S' sorgho-sudangrass (*Sorghum bicolor* x *S. sudanense*) were investigated as rotation crops and as interplanted companion crops the following year for their individual and combined effects on strawberry root pathogens, weed species composition and density, weevil and white grub densities in soil, rhizosphere microbial populations, nutrient content of crowns, and strawberry yield. Treatments were compared with 'Garry' oats (*Avena sativa*) or continuous 'Honeoye' strawberries at two sites in Connecticut. Lesion nematode (*Pratylenchus penetrans*) recovery was greater from Garry oats than for strawberry, Saia oats or sorgho-sudangrass. Bait root infection by *Rhizoctonia fragariae* was highest for strawberry. Weed density was inversely related to rotation crop density. White grub larvae were most common in strawberry. Rotation crop did not affect isolation of *Rhizoctonia* or *Pythium* in 1996 or 1997. Weed growth in plots in 1996 was suppressed after sorgho-sudangrass in 1995, but not in 1997. Intercropping was similar to herbicide application, but only when the intercrop was present. Rotation crop did not affect pathogen recovery from roots of 2-year old strawberry crowns. Numbers of European chafer larvae were greatest in Saia oats, which may have been attractive to gravid females. Japanese and Asiatic garden beetle populations were positively correlated with soil organic matter. Rhizosphere populations of fluorescent pseudomonads were unaffected by treatment. Fruit yield (1997) was greatest in plots previously planted to Garry or Saia oats and least after sorgho-sudangrass, possibly due to phytotoxic properties of residues. Production of rotation crops such as sorgho-sudangrass or Saia oats may suppress pathogen densities, weeds, and white grub densities prior to planting strawberries but may also adversely affect strawberry growth and yield.

Keywords: Insects; Nematodes; *Pratylenchus penetrans*; *Rhizoctonia fragariae*; Weeds; White grubs

1. Introduction

Perennial strawberry plantings in the United States can be affected by a variety of pests, and the severity of problems associated with these pests increases with age. Soilborne pathogens, weeds, root weevils, and nematodes can limit yields and result in the loss of production fields (Cooley and Schloemann, 1994; LaMondia, 1999a). Black root rot, one of the most serious diseases of perennial strawberries, causes death of feeder roots, rotting of the root cortex, and reduces plant vigor, productivity and survival (LaMondia and Martin, 1989; Maas, 1998). Black root rot is a disease complex (LaMondia and Martin, 1989; Plakidas, 1964; Townshend, 1962) involving more than one pathogen. *Rhizoctonia fragariae* is a cortical root rotting pathogen of strawberry (Hussain and McKeen, 1963; Wilhelm et al., 1972), and is the primary component of the black root rot complex in Connecticut (Martin, 1988). Disease severity is increased by concomitant root infection with the lesion nematode, *Pratylenchus penetrans* (LaMondia and Martin, 1989).

Soil fumigation and chemical pest management have been important components of black root rot control in strawberries (Wolfe et al., 1990; Yuen et al., 1991), broad-spectrum biocides, fumigants also impact insect and weed management. Weeds cause losses in strawberry due to competition (Caylor et al., 1991). In the matted row system, mechanical weed control is impractical, so growers rely heavily on fumigation and herbicides (Caylor et al, 1991; Patterson, 1988). The recent or

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impending loss of fumigants such as methyl bromide for use on strawberries has accelerated the need for alternative methods of managing soilborne pathogens, insects, nematodes, and weeds. Rotation crops are a non-chemical option: an appropriately chosen species may be a non-host and, thereby, minimize the opportunity for pests to develop in the field, and may also influence the soil and crop ecology through competition and production of biologically active secondary plant compounds.

Two promising grain crops for rotation with strawberries are diploid 'Saia' oats (*Avena strigosa*) and 'Triple S' sorgho-sudangrass (*Sorghum bicolor* x *S. sudanense*). These crops are poor hosts of the lesion nematode (Colbran, 1979; Fay and Duke, 1977). In field microplot experiments, Saia oats and Triple S sorgho-sudangrass reduced both *P. penetrans* and *R. fragariae* more than 'Garry' oats, rye, buckwheat, canola or continuous strawberries (LaMondia, 1999b). Oats and sorghum are also known to be allelopathic (Einhellig and Souza, 1992; Lehle and Putnam, 1983; Neustruyeva and Dobretsova, 1972; Putnam and DeFrank, 1983; Weston et al., 1989) and could suppress annual weed establishment as a living grass mulch (Newenhouse and Dana, 1989). Some oat accessions exuded up to three times as much scopoletin, a root growth-inhibiting compound, as the commonly grown Garry oats (Fay and Duke, 1977). Oats and sorghum have also been shown to produce root exudates toxic to soilborne fungi such as *Fusarium*, *Gaumannomyces* and *Rhizoctonia* (Crombie and Crombie, 1986; Odunfa, 1978; Papavizas, 1963).

Research has shown that black root rot disease severity was reduced with ammonium sulfate fertilization (Elmer and LaMondia, 1999). In that study, leaf analyses revealed a correlation between black root rot suppression and increased N and Mn concentrations. Cover crops or companion crops can also affect the nutritional status of soil and, in turn, affect disease. For example, growing soybeans or alfalfa prior to wheat increases wheat diseases and decreases N and Mn uptake (Huber and McCay-Buis, 1993). Oats and lupines have been reported to suppress wheat diseases and increase nutrient availability (Huber and McCay-Buis, 1993). Both disease severity and the availability of Mn can be related to the microbial activity in the rhizosphere of strawberry plants. The role of rotation crops on nitrogen and trace element availability, microbial activity, and disease suppression in strawberry needs to be examined, as high levels of these nutrients may be associated with plant health.

In these experiments, we investigated the use of diploid Saia oats (*A. strigosa*) and Triple S sorgho-sudangrass (*Sorghum bicolor* x *S. sudanense*) as rotation or interplanted companion crops on pathogen populations, root disease, weed species composition and density, white grub populations in soil, microbial populations in the rhizosphere, nutrient content of crowns, and fruit yield. Treatments were compared with 'Garry' oats (*Avena sativa*) or continuous 'Honeoye' strawberries in naturally infested perennial strawberry plantings at two sites in Hamden and Windsor, CT.

2. Materials and methods

2.1. Influence of rotation crops, 1995

Strawberry plantings in Windsor, CT and Hamden, CT that both exhibited symptoms of black root rot were tilled into the soil by means of a tractor-mounted rototiller three times over 2 days. Plots (1.8 m × 1.2 m with 1.8 m borders between plots) were planted with strawberry crowns (cultivar Honeoye) or seeded to rotation crops on July 6, 1995 in Windsor, CT and on July 11, 1995 in Hamden, CT. Plots were established in a Merrimac sandy loam soil (73.4% sand, 22.3% silt, 4.3% clay, pH 5.9) in Windsor, and a Yalesville fine sandy loam (56.4% sand, 30.8% silt, 12.8% clay, pH 6.1) in Hamden. Strawberry crowns were planted in three rows of nine crowns per row per plot. Garry oats, Saia oats, or Triple S sorgho-sudangrass rotation crops were planted at rates of 28 kg seed/ha. There were 48 plots (12 replicate plots per crop) at each location.

Seeds of Virginia pepperweed (*Lepidium virginicum*) were spread in all plots to supplement natural weed populations on July 11 in Windsor and on July 14 in Hamden. Rotation crop and weed densities were evaluated on September 29 in Hamden and on October 3 in Windsor by visual estimates of percent plot coverage for each species. On October 10 and 16, 1995, 20 weeks after planting rotation crops, three samples per plot consisting of rotation crop roots and surrounding soil were removed from each plot in both locations. At this time, the height of the rotation crops was approximately 1, 1, and 2 m for Saia, Garry, and Triple S sorgho-sudangrass, respectively. The survival and inoculum potential of *R. fragariae* and *Pythium* spp. were determined by isolation from eight 1-cm-long surface-disinfested (0.5% NaOCl for 1 min) sections of strawberry root placed on 50 cm^3 soil in a 100 mm-diameter petri dish for 24 h, again surface-disinfested and transferred to acidified water agar. Hyphal tips of recovered fungi were transferred to potato dextrose agar for identification. *Pratylenchus* populations were recovered from 2 g of plant roots per plot by shaker extraction (Niblack and Hussey, 1985).

The number and species of insect larvae in the soil samples were determined from 1.0 to 5.8 l soil samples (the combined soil collected on October 10 and 16) by sieving and counting. Larvae were identified to species based on their characteristic pattern of bristles (Vittum et al., 1999), and data were normalized as number per liter of soil prior to analysis of variance.

2.2. Influence of companion crops and previous rotation crop, 1996

Stubble debris from rotation crops was mowed and left in place on April 3, 1996, and plots were rototilled with a hand tiller. On May 5 (Windsor) and May 13, 1996 (Hamden), Honeoye strawberry crowns were planted in all plots in three rows of nine crowns per row per plot. After planting, plots designated to receive a standard herbicide treatment were sprayed with DCPA (Dacthal 75W). DCPA was applied to Windsor plots on May 15 (6.7 kg/ha a.i.), and to Hamden plots (10.1 kg/ha a.i.) on May 17. Two weeks after transplanting strawberry crowns, Saia oats and Triple S sorgho-sudangrass intercrops (companion crops) were planted in 0.3 m strips between rows at rates of 28 kg seed/planted ha. Between June 8 and June 24 (when intercrops were 15–20 cm tall), these plots were sprayed with the herbicide sethoxydim (Poast) at 0.45 kg/ha a.i. plus Dash (proprietary blend of surfactant and fatty acids (BASF)) at 2.3 l/ha. This treatment killed the companion crops as well as any grassy weeds present in the plots.

Two crowns per plot were destructively sampled from the outer rows of each plot on July 8, and again on September 24, 1996 in Windsor and July 18 and September 30 in Hamden. Roots were separated from the above-ground portions and used in assays described below. Leaf area (A) was determined by the equation: $A = 3.02 + 1.77LW$; in which the L and W are the length and width of the middle leaflet of each strawberry leaf. This equation was generated by regressing the products of the lengths and widths from 84 Honeoye strawberry leaves against their leaf areas ($r^2 = 0.98$) which were determined on a leaf area meter (Delta-T Devices, Pullman, WA). The above-ground parts were washed in deionized water, oven dried, and weighed.

The adhering rhizosphere soil was shaken loose from the roots, placed in plastic bags and held on ice until stored at $-4°C$. The rhizosphere soil was serially diluted into sterile normal saline blanks within 24 h after sampling. Aliquots (0.1 ml) of each dilution were spread onto King's B agar to enumerate fluorescent pseudomonads, and Mn-dioxide agar (5 g Mn-dioxide, 30 g sucrose, 1 g Difco yeast extract, 15 g agar) for Mn-oxidizing and Mn-reducing bacteria. Three plates of each medium per dilution were prepared and incubated in the dark for 2–3 days at 25°C. Moisture of the rhizosphere soil was determined independently. Fluorescent pseudomonads were enumerated by viewing the King's B agar plates under short-wave UV light 2 days later. Mn-oxidizing microbes were detected on Mn-dioxide agar by the blackened halo around colonies. Mn-reducing microbes were detected by the clear zones that appeared around the colony. Fluorescent pseudomonads and Mn-reducers were expressed as log densities/g soil (oven dry weight equivalent).

R. fragariae and *Pythium* spp. were assayed from roots. Eight 1-cm-long surface-disinfested (0.5% NaOCl for 1 min) sections of strawberry root were placed on acidified water agar. Hyphal tips of recovered fungi were transferred to potato dextrose agar for identification. *Pratylenchus* populations were recovered from 2 g of plant roots per plot by shaker extraction.

White grub populations were counted as described for 1995 (soil samples varied from 0.6 to 4.0 l). Because soil organic matter content might influence beetle oviposition or survival (Cowles and Villani, 1994), soil organic matter from each plot was determined by weight loss on ignition of oven-dried soil samples. The organic matter determination was included as a covariate in the analysis of variance for white grub population data.

Weed densities were evaluated on July 5 in Windsor and July 19 in Hamden. Percent weed coverage by species was estimated in each plot. Weeds were then removed from all plots.

The standard herbicide plots were treated with napropamide (Devrinol 50DF) at 3.4 kg/ha a.i. on September 6, and with terbacil (Sinbar 80WP) at 0.22 kg/ha a.i. on November 6 prior to covering plots with straw.

2.3. Influence of companion crops and previous rotation crop, 1997

In 1997, standard herbicide plots were treated with DCPA (10.1 kg/ha a.i.) on May 3, and with napropamide (2.2 kg/ha a.i.) plus terbacil (0.22 kg/ha a.i.) on August 1 and again on November 13 (Windsor) and November 20 (Hamden) prior to covering with straw. Weed densities were evaluated on July 1 in Windsor and July 3 in Hamden.

Ripe fruits were harvested from the center row of each plot. Berries were harvested at each location on ten occasions throughout June 1997. The number and sum weight of berries were recorded.

Two crowns per plot were destructively sampled from the outer rows of each plot on September 2 in Windsor and September 15, 1997 in Hamden. Fungal and nematode populations in roots were estimated as described above.

3. Results

3.1. Influence of rotation crops, 1995

P. penetrans recovery was greater from Garry oats than from strawberry, Saia oat or sorgho-sudangrass

Table 1
Recovery of strawberry root pathogens and insects from rotation crops in field plots at two locations in Connecticut in 1995

	Pratylenchus[a]	Rhizoctonia[b]	Pythium[b]	Grubs[c]
Crop				
Saia	35a[d]	2.2a	0.4	0.6a
Triple S	19a	1.8a	1.0	0.5a
Garry	143b	1.5a	1.0	0.5a
Strawberry	67a	4.2b	1.1	1.2b
Significance (*P*)	0.001	0.001	ns	0.001
Site				
Windsor, CT	49.0	2.9	0.4	0.6
Hamden, CT	84.3	1.9	1.4	0.8
Significance (*P*)	ns	0.001	0.001	ns

[a] Nematodes per gram root recovered by shaker extraction for 10 days.
[b] Fungi recovered from strawberry bait roots (number of eight 1-cm root segments) exposed to soil for 24 h.
[c] Grubs recovered per liter soil; identified as scarab beetles.
[d] Means in columns within major effects followed by the same letter are not different ($P = 0.05$) according to Fischer's LSD test.

Table 2
Rotation crop and weed densities in field rotation crop plots at two locations in Connecticut in the fall of 1995

	Percent plot area occupied by plants			
	Rotation crop	Grasses	Broadleaves	Total weeds
Rotation crop				
Saia	59.2c[a]	19.5b	16.3a	35.8b
Triple S	84.4a	8.6d	2.0c	10.6d
Garry	71.5b	13.8c	9.7b	23.4c
Strawberry	21.7d	56.3a	17.0a	73.3a
Significance (*P*)	0.001	0.001	0.001	0.001
Site				
Windsor, CT	55.6b	28.3a	10.5	38.8
Hamden, CT	62.7a	21.0b	12.1	33.2
Significance (*P*)	0.001	0.001	ns	ns

[a] Means in columns within major effects followed by the same letter are not different ($P = 0.05$) according to Fischer's LSD test.

(Table 1). Bait roots placed in continuous strawberry soils were infected by *R. fragariae* 53% of the time, whereas the other crop soils yielded between 19% and 28%. *Pythium* recovery was similar for all crops. *R. fragariae* recovery from bait roots was greater in the better-drained site (Windsor) and *Pythium* recovery was greater in the heavier soil type (Hamden).

Averaged over both sites, the percent area covered by weeds in plots containing rotation crops was estimated as follows: strawberries (73%), Saia oats (36%), Garry oats (23%), and Triple S sorgho-sudangrass (11%) (Table 2). Weed density was inversely related to rotation crop density. Weeds in strawberry plots included large crabgrass, stinkgrass, carpetweed, prostrate spurge, redroot pigweed, common lambsquarters, galinsoga,

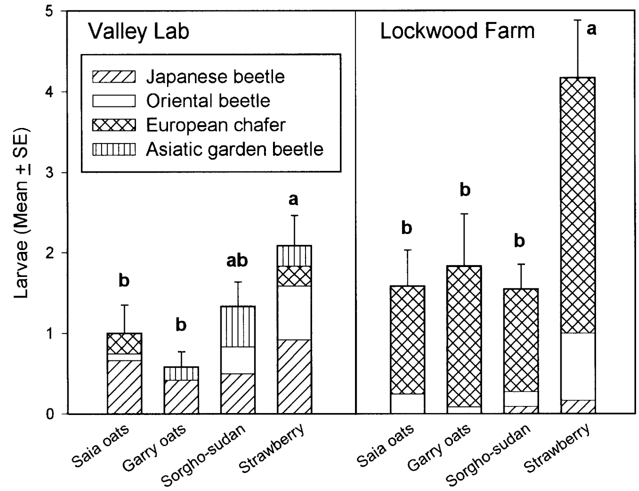

Fig. 1. Numbers of four species of white grubs sampled from rotation crop plots in Windsor (Valley Lab) and Hamden (Lockwood Farm), CT in 1995. Mean separations (SNK test, $P < 0.05$) and standard errors ($n = 12$) are for total larval counts normalized by the soil volume.

dandelion, and winter annual mustard spp. Broadleaf weed populations were reduced in plots containing the oat crops, but crabgrass and stinkgrass filled open areas.

The species composition of scarabs differed between the two sites in 1995. The 111 larvae recovered from Hamden samples consisted of European chafer (83%), oriental beetle (14%), and Japanese beetle (3%). At Windsor, the species composition of the 62 larvae was European chafer (11%), oriental beetle (23%), Japanese beetle (48%), Asiatic garden beetle (16%), and one northern masked chafer (Fig. 1). Although the sites differed in population densities, the general pattern of white grub infestation relative to rotation crops was similar. White grub larvae (averaged over both sites) were more common in strawberry (1.2/l) than for other crops (0.5–0.6/l soil). One strawberry root weevil larva was recovered from a Hamden sample.

3.2. Influence of companion crops and previous rotation crop, 1996

Fewer lesion nematodes were extracted from strawberry roots of plants grown in plots previously planted to Saia oats than all other crops (Table 3). There were no differences in nematode extraction from plots due to weed control or grain intercrops. Rotation treatments did not affect isolation of *Rhizoctonia* or *Pythium* fungi. Fungal pathogen isolation was greater from plants grown in Windsor than in Hamden, CT.

Plots in which sorgho-sudangrass was grown in 1995 had lower weed densities in 1996 than plots in which strawberries or either oat species were grown the previous year (Table 4). This sorgho-sudangrass effect was considerably greater at the Hamden site than at the Windsor site. At both sites in 1996, the DCPA

Table 3
Effect of previous rotation crop and weed control or intercrop on recovery of root pathogens from strawberry in field plots at two locations, 1996

	Pratylenchus[a]	Rhizoctonia[b]	Pythium[b]
Previous crop			
Saia	45a[c]	1.4	0.6
Triple S	122b	1.1	0.8
Garry	174b	1.6	0.5
Strawberry	147b	1.6	0.6
Weed control			
Weedy control	104	1.5	0.6
Herbicide	91	1.6	0.5
Saia intercrop	128	1.3	0.7
Triple S intercrop	162	1.3	0.8
Site			
Windsor, CT	121	1.9	0.8
Hamden, CT	122	0.9	0.5
Timing			
July	175	1.2	0.8
September	69	1.6	0.5
ANOVA factor	Significance (*P*)		
Previous crop	0.001	ns	ns
Weed control	ns	ns	ns
Site	ns	0.001	0.03
Timing	0.001	ns	0.03
Site × timing	0.003	0.001	ns
Other interactions	ns	ns	ns

[a] Nematodes per gram root recovered by shaker extraction for 10 days.
[b] Fungi recovered from strawberry bait roots (number of eight 1-cm root segments) exposed to soil for 24 h.
[c] Means in columns within major effects followed by the same letter are not different ($P = 0.05$) according to Fischer's LSD test.

Table 4
Effect of previous rotation crop and weed control or intercrop tactics on percentage of weed cover in strawberry field plots, 1996 and 1997

	1996[a]	1997
Previous crop		
Saia	43.6b[b]	40.0
Triple S	35.4a	44.8
Garry	46.3b	43.5
Strawberry	45.5b	37.5
Weed control		
Weedy control	86.6c	49.2b
Herbicide	23.4a	20.8a
Saia intercrop	31.6b	49.2b
Triple S intercrop	29.3ab	46.7b
Site		
Windsor, CT	47.9	53.1
Hamden, CT	37.6	29.8
ANOVA factor	Significance (*P*)	
Previous crop	0.004	ns
Weed control	0.0001	0.0001
Site	0.0001	0.0001
Cover × site	0.001	ns
Weed control × site	0.001	ns
Other interactions	ns	ns

[a] Data analyzed after arcsine transformation to stabilize variance.
[b] Means in columns within major effects followed by the same letter are not different ($P = 0.05$) according to Fischer's LSD test.

treatment, and the Saia oat or sorgho-sudangrass companion crop killed by sethoxydim, resulted in suppression of weeds relative to the untreated check (Table 4). At the Hamden site, DCPA-treated plots contained the lowest weed densities. DCPA prevents the emergence of annual grasses and many broadleaf weeds such as pigweed and oxalis.

Using sethoxydim to kill the companion grass crop also provided post-emergence control of crabgrass and other grasses. However, strawberry plants in plots treated with sethoxydim plus the surfactant Dash were injured at both sites. Plant damage, in the form of stunted growth and leaf chlorosis, was likely exacerbated by the warm, humid weather at the time of treatment, and the use of Dash as a spray adjuvant.

Weed populations around strawberry crowns were suppressed in 1996 (Hamden only) after growth of Triple S sorgho-sudangrass in 1995 (Table 4). However, this effect was no longer evident by 1997. Additionally, intercropping with Saia oats or sorgho-sudangrass reduced weed populations in a manner similar to herbicide application, but weeds were suppressed only when the intercrop was present. The effects were lost by the next season. Weed populations, especially of grassy weeds such as large crabgrass and stinkgrass, were consistently higher in Windsor than in Hamden in 1996 and 1997.

White grub species composition differed at the two locations in 1996 (Fig. 2), and nearly doubled compared with 1995 populations. The 277 larvae recovered from Hamden samples consisted of European chafer (21%), oriental beetles (62%) Japanese beetles (8%), and Asiatic garden beetles (9%). At Windsor, the species composition of the 98 larvae was European chafer (17%), oriental beetles (42%), Japanese beetles (9%), and Asiatic garden beetle (32%). The dominance of oriental beetle and the large increase in Asiatic garden beetle numbers over the previous year were the most consistent changes observed at both sites.

European chafer populations were most influenced by the presence of a companion crop. The numbers of larvae in plots with Saia oats were consistently greater than for other treatments, especially compared with the "herbicide" and "no-herbicide" treatments ($P = 0.01$ and 0.06 for Windsor and Hamden, respectively) (Fig. 2B). We suspect that the presence of dying oats, which had been treated with herbicide, may have been

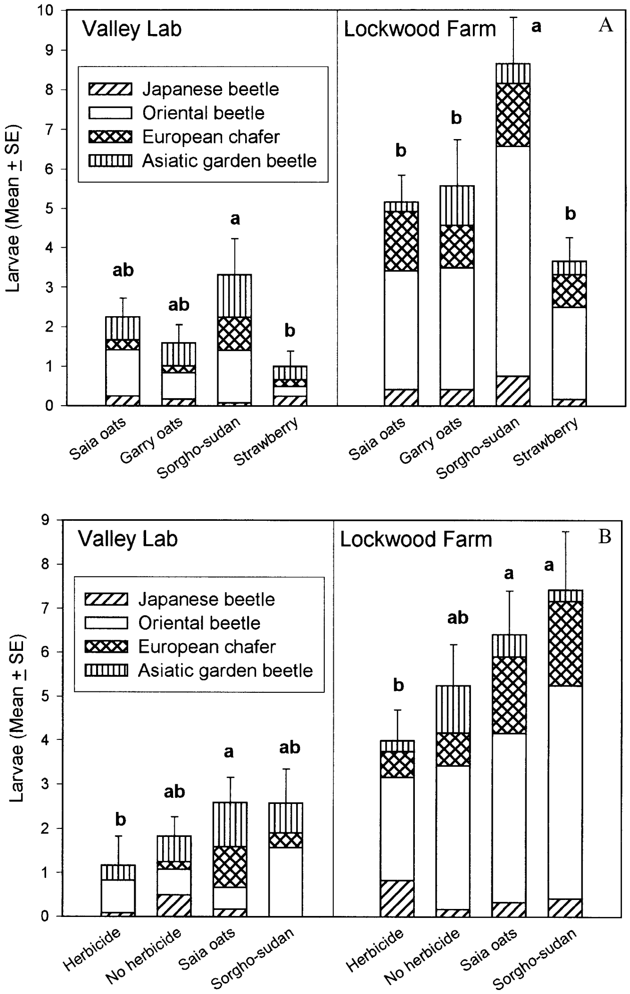

Fig. 2. Numbers of four species of white grubs sampled strawberry plots in Windsor (Valley Lab) and Hamden (Lockwood Farm), CT in 1996. (A) Main effects of previous rotation crops grown in 1995. (B) Main effects of weed management and companion crops in 1996. Mean separations (SNK test, $P<0.05$) and standard errors ($n=12$) are for total larval counts normalized by the soil volume. Additional statistical comparisons based on individual species are given in the text.

Table 5
Effect of previous rotation crop and weed control or intercrop on vigor of strawberry plants from field plots, 1996

	Leaf area[a]	Dry wt.[b]	Runners[c]
Previous crop			
Saia	320	3.9a[d]	228b
Triple S	352	4.2b	198a
Garry	320	3.8a	204a
Strawberry	377	4.6b	222b
Weed control			
Weedy control	322	3.9a	189b
Herbicide	400	4.6b	287a
Saia intercrop	314	4.0a	180b
Triple S intercrop	334	4.0a	195b
Site			
Windsor, CT	279	3.6	183
Hamden, CT	405	4.7	243
ANOVA factor	Significance (P)		
Previous crop	ns	0.002	0.001
Weed control	ns	0.002	0.001
Site	0.001	0.001	0.001
Interaction	ns	ns	ns

[a] Leaf area was estimated on each leaf by measuring the length and width of the middle leaflet and using the equation $A = 3.02 + 1.77LW$ to predict total leaf area.
[b] Dry weight represents the means of 24 above-ground plant excluding the runners.
[c] Runners were counted and removed weekly from June to September. Values represent the means of 12 plots per treatment.
[d] Means in columns within major effects followed by the same letter are not different ($P = 0.05$) according to Fischer's LSD test.

especially attractive to gravid females. Japanese beetle numbers did not statistically differ with respect to treatments, but were positively correlated with soil organic matter ($P = 0.01$) in Windsor. Organic matter content of soil was positively correlated with Asiatic garden beetle populations ($P = 0.04$ and 0.02 at Windsor and Hamden, respectively). Oriental beetle populations may have been influenced by decomposing remains of the rotation crop at the Hamden site ($P = 0.05$), and the ranking of treatments is positively correlated with our visual assessment of the quantity of crop residue produced the previous year (ranked: sorgho-sudangrass > Garry oats > Saia oats > strawberries).

Vigor of strawberry plants was greater in Hamden than in Windsor (Table 5). Data from the first destructive harvest in July showed that leaf area, dry weight, and the number of runners were greater on plants from Hamden than that from Windsor. Pre-cropping with either cultivar of oats resulted in strawberry plants with significantly less dry weight than those pre-cropped with sorgho-sudangrass or strawberry. All of the weed control treatments increased the dry weight compared with control (bare ground). There were fewer runners present in September 1996 on strawberry plants pre-cropped with sorgho-sudangrass or Garry oats when compared with the other treatments. Plants treated with herbicides had more runners than other treatments.

Compared with continuous strawberry or Garry oats, rhizosphere populations of Mn-oxidizing bacteria were increased when plants were pre-cropped by Saia oats or Triple S sorgho-sudangrass (Table 6). There was an interaction when plants were pre-cropped and intercropped with Triple S sorgho-sudangrass that led to elevated levels of Mn-oxidizing bacteria. Mn-reducing bacteria and florescent pseudomonads were not affected by treatment.

Elemental analyses of the strawberry leaves sampled in September revealed that levels of most elements were greater at the Hamden location than at the Windsor site

Table 6
Effect of previous rotation crop and weed control or intercrop tactics on densities of manganese-transforming microbes in the rhizosphere of strawberry plants sampled in September 1996

	Herbicide	Mn oxidizers (log cfu/g soil)	Mn reducers (log cfu/g soil)
Previous crop			
Saia	Weedy control	5.1ab[a]	4.6
Saia1	Herbicide	5.0bc	4.3
Saia	Saia intercrop	5.3ab	4.4
Saia	Triple S intercrop	4.4c	4.4
Mean		5.0	4.4
Triple S	Weedy control	5.0bc	4.6
Triple S	Herbicide	4.8bc	4.4
Triple S	Saia intercrop	4.5c	4.4
Triple S	Triple S intercrop	5.6a	4.5
Mean		5.0	4.5
Garry	Weedy control	5.0bc	4.1
Garry	Herbicide	4.6bc	4.4
Garry	Saia intercrop	4.7bc	4.6
Garry	Triple S intercrop	4.8bc	4.3
Mean		4.8	4.4
Strawberry	Weedy control	4.3c	4.5
Strawberry	Herbicide	3.8d	4.3
Strawberry	Saia intercrop	4.7bc	4.7
Strawberry	Triple S intercrop	4.8bc	4.0
Mean		4.4	4.4
Site			
Windsor		4.6	4.5
Hamden		4.9	4.3
ANOVA factor		Significance (P)	
Previous crop		0.003	ns
Weed control		ns	ns
$P \times W$		0.006	ns
Site		0.004	0.02

[a] Means in columns within major effects followed by the same letter are not different ($P = 0.05$) according to Fischer's LSD test.

(Table 7). There were some significant interactions between the previous crop and the weed management program (data not shown). In general, the interaction was observed as reduced levels of P, K, Mn, Cu and B in plants pre-cropped with sorgho-sudangrass and intercropped with Saia oats when compared to plants in continuous strawberry and left as the bare ground treatment. Of the previous crops, the sorgho-sudangrass treatment resulted in plants that had less P and K, but more Fe when compared with other crops. The bare ground weed management program had the highest levels of P, K, Ca, Mn, Cu, and B whereas the Saia intercrop had lowest levels of P, K, Mn and Cu. Nitrogen levels were not affected by treatment.

3.3. Influence of companion crops and previous rotation crop, 1997

Pathogen recovery from roots of 2-year old strawberry crowns was not affected by the rotation crop grown 2 years earlier (Table 8). *Pratylenchus* populations were lower in plots treated with herbicide. Fruit yield was greatest in plots previously planted to Garry or Saia oats. Yields were least after growth of Triple S sorgho-sudangrass.

Weed densities in 1997 were lowest in the standard herbicide-treated plots. Neither rotation crops (1995) nor companion crops (1996) affected weed densities in 1997 at either site.

4. Discussion

Pre-plant fumigation has been a standard practice used to control strawberry black root rot, fungi, nematodes, soil-dwelling insects, and weeds. Rotation to small grains has been suggested as a component of an overall strategy to replace fumigation for control of these pests (Pritts and Wilcox, 1990; Zeller, 1932). Rotation to Saia oats and Triple S sorghum-sudangrass suppressed pathogens, weeds and soil insects. Garry oats suppressed most pests, but increased lesion nematodes.

Rotation to Saia oats or sorgho-sudangrass reduced infection by *P. penetrans* and *R. fragariae* (LaMondia, 1999b), important pathogens and components of the strawberry black root rot complex (Chen and Rich, 1962; Goheen and Smith, 1956;Klinkenberg, 1955; LaMondia and Martin, 1989). Oat and sorghum have been shown to produce fungicidal root exudates toxic to soilborne fungi such as *Fusarium* and *Gaumannomyces* (Crombie and Crombie, 1986; Odunfa, 1978). Recently, resistance to lesion nematodes was associated with increased avenocin production in Saia oats (B.B. Brodie, pers. comm.). The mode of action against lesion nematodes and *R. fragariae* was not investigated in these experiments. While the standard oat cultivar Garry reduced *R. fragariae* inoculum potential, it resulted in increased lesion nematode densities. These increased densities may offset the suppressive effect of oats on *R. fragariae* and explain the lack of efficacy observed after rotation with standard oats.

Grain or grass rotations and companion crops also conserve soil, reduce compaction, and increase water infiltration into soil (Newenhouse and Dana, 1989), reducing some of the environmental stresses associated with severe black root rot. While diploid Saia oats do not produce high quality grain, this crop may still be desirable for producing the straw used by many strawberry growers to protect plantings during the winter.

Table 7
Effect of previous rotation crop and weed control or intercrop tactics on elemental composition (μg/g tissue) of strawberry leaves sampled in September 1996

	N	P	K	Ca	Mg	Fe	Mn	Cu	B
Previous crop									
Saia	16,285	3125	10,544	9400	3932	459	99	6	24
Triple S	16,884	2764	8966	9207	4193	550	97	6	22
Garry	17,607	3193	9842	9887	3780	540	98	6	25
Straw	18,569	3477	10,214	7386	3962	515	98	6	24
Weed control									
Weedy control	16,825	3388	10,683	10,203	3973	431	1087	6	25
Herbicide	18,564	3099	10,546	8819	3488	490	97	6	24
Saia intercrop	17,587	2860	9301	9369	4057	467	85	6	22
Triple intercrop	15,987	3213	9432	10,077	4100	677	101	6	24
Site									
Windsor	16,985	3020	10,209	9195	3766	504	94	6	23
Hamden	18,567	3259	9772.	10,039	4042	529	102	6	24
ANOVA factor	Significance (*P*)								
Previous crop	ns	0.001	0.001	ns	ns	0.004	ns	ns	0.001
Weed control	ns	0.001	0.001	0.003	0.001	0.001	0.001	ns	0.001
P × W	ns	0.002	0.001	ns	ns	0.001	0.001	0.001	0.001
Site	0.001	ns	ns	0.001	0.001	ns	ns	ns	ns
Cover × site	ns	ns	ns	ns	ns	ns	ns	ns	
Weed control × site	ns	ns	ns	ns	ns	ns	ns	ns	
Other interactions	ns	ns	ns	ns	ns	ns	ns	ns	

Table 8
Recovery of root pathogens and fruit yield from strawberry in field plots, 1997

	Pratylenchus[a]	Rhizoctonia[b]	Pythium[b]	Yield[c]
Previous crop				
Saia	61	0.7	0.0	1532b[d]
Triple S	75	0.3	0.3	1074a
Garry	135	0.3	0.8	1641b
Strawberry	133	0.3	0.4	1334b
Weed control				
Weedy control	169b	0.6	0.5	1361
Herbicide	34a	0.4	0.6	1394
Saia intercrop	150b	0.2	0.0	1194
Triple S intercrop	51a	0.3	0.4	1632
Site				
Windsor, CT				1123
Hamden, CT				1667
ANOVA factor	Significance (*P*)			
Previous crop	ns	ns	ns	0.05
Weed control	0.05	ns	ns	ns
Site				0.001
Interaction	ns	ns	ns	ns

[a] Nematodes per gram root recovered by shaker extraction for 10 days.
[b] Fungi recovered from strawberry bait roots (number of eight 1-cm root segments) exposed to soil for 24 h.
[c] Ripe strawberry fruit harvested from the center row of a three row plot on 10 occasions over 3 weeks from June 9 to June 30, 1997 and presented as total weight (g/row).
[d] Means in columns within major effects followed by the same letter are not different ($P = 0.05$) according to Fischer's LSD test.

The effects of rotation crops on nematode and pathogen populations generally lasted for a single season. Populations of both *P. penetrans* and *R. fragariae* rebounded fairly quickly during strawberry production. Only Saia oats resulted in a significant effect on *P. penetrans* populations after 1 year of strawberry growth. Lesion nematode densities 1 year prior to harvest were better correlated with fruit yield than densities at later dates (LaMondia, 1999a). Reduced pathogen populations at planting should result in increased initial growth and vigor, which may influence plant productivity beyond the time required for pathogen population increase. Weeds, which occurred to some extent in all plots, may have also played a role in supporting *P. penetrans* populations during rotation. The wide host range of *P. penetrans* (Bendixen, 1988) makes it very difficult to eliminate nematode populations despite the non-host status of some rotation crop roots. However, we noted that although Triple S sorgho-sudangrass as a previous crop did not reduce strawberry growth, it did reduce berry yield more than the other treatments. These results differ from microplot experiments that resulted in increased fruit yields after rotation to sorgho-sudangrass (LaMondia, 1999b). The major difference between the two experiments was that shoots were incorporated in soil in the present study while they were not in the microplot study. It is possible that the weed or pest-reducing properties of Triple S sorgho-sudangrass also had adverse effects on the strawberry plant as well as its pests. One indirect mechanism for the reduced berry yield by Triple S sorgho-sudangrass is its influence on microbial activity. We determined that sorgho-sudangrass plants increased Mn-oxidizing bacteria in soil. These microbes have been associated with root diseases of other plants (Huber and McCay-Buis, 1993). Sorgho-sudangrass residues may promote deleterious bacteria that affect nutrient availability. Elemental analyses also revealed that plants precropped with sorgho-sudangrass had lower levels of several elements than in other treatments. It is possible that Triple S sorgho-sudangrass residues may have restricted root growth.

We demonstrated weed suppression in 1996 following a rotation crop of Triple S sorgho-sudangrass at one of the two experimental sites. Sorghum residues have been shown to suppress weeds (Putnam and DeFrank, 1983; Weston et al., 1989), and chemicals such as sorgoleone from sorghum exudates have demonstrated herbicidal activity (Einhellig and Souza, 1992; Lehle and Putnam, 1983; Nimbal et al., 1996). The use of oats and sorghum as allelopathic rotation or companion crops has been shown to suppress a number of weed species (Neustruyeva and Dobretsova, 1972; Putnam and DeFrank, 1983). The production of Saia oats or sorgho-sudangrass intercrops further extended weed control.

Greater weed suppression with sorgho-sudangrass residues relative to oats may be due to greater herbicidal activity from the sorgho-sudangrass. Another possibility is relatively greater reduction in weed seed bank production. The sorgho-sudangrass rotation crop had a greater biomass, was tall, dense, and allowed fewer weeds to become established. Involvement of both allelopathy and competition is supported by the observed differences in Hamden vs. Windsor in weed suppression effects during the year following the sorgho-sudangrass rotation crop. The percent of plot area covered by sorgho-sudangrass in 1995 was greater at Hamden than at Windsor. Allelochemicals from sorgho-sudangrass residues could have dissipated via leaching or degraded more rapidly in the coarser-textured soil at the Windsor site, which also received more irrigation water than the Hamden site.

The number of herbicide options available to strawberry growers has diminished. As an example, DCPA (Dacthal), which was widely used by growers to prevent weeds in newly planted and established strawberries, has recently lost and regained its registration status and availability. Thus, fewer herbicides are registered, especially for newly planted fields. Effective use of allelopathic rotation crops, such as Saia oats or sorgho-sudangrass, could be especially helpful for weed management during the year of strawberry planting.

However, there are trade-offs for using intercrops or companion crops. If left unchecked, these crops may compete with strawberry crowns and reduce vigor and yield. Selective herbicides can mitigate this, and we were able to kill the intercrop prior to competition with strawberry, but the sethoxydim herbicide plus surfactant combination resulted in significant phytotoxicity and subsequent yield suppression of treated strawberry plants.

White grubs, the larvae of various scarab beetles, have become increasingly important in recent years and are most damaging when feeding on roots (Cooley and Schloemann, 1994). The numbers of white grubs were reduced by 57% in plots by having a cover crop present in 1995. During this growing season, the cover crops were allowed to grow to their full height, which we expect could have acted as a physical barrier to scarab flight close to the soil surface. We hypothesize that such interference with beetle flight would result in reduced oviposition and consequently reduce the larval population. This may prevent establishment of white grubs 1 year prior to planting, and may help protect strawberry crowns being planted in early spring, when overwintered white grubs may still be feeding. Excluding beetle flight by this method would be difficult in subsequent years because tall crops would compete excessively for light and other resources needed by the strawberry crop.

In 1996, the populations of white grubs increased dramatically over the previous year. This increase is consistent with the population levels in the continuous strawberry plots where tall grasses were not present in 1995. The increased populations in 1996 could have resulted from multiple and possibly interacting factors. These include (i) the lack of a physical barrier to scarab beetle flight in 1996 because companion crops were treated with herbicides when still only 15 cm tall; (ii) the presence of decaying vegetative matter from the previous year's rotation crop could add to the soil organic matter, which appeared to improve white grub survival; and (iii) herbicide-treated companion crops could stimulate oviposition. Therefore, the presence of rotation and cover crops could be expected to have only a short-term positive effect for white grub management, early during the first year a crop is planted.

While rotation or interplanted crops may have beneficial effects on perennial strawberry production associated with a reduction in lesion nematode populations, black root rot, weeds, and white grub densities, these effects were short-lived. In addition, the use of pest-suppressive rotation or interplanted crops may have adverse effects on strawberry growth and yield associated with competition and/or secondary plant metabolites. The deleterious effects of sorgho-sudangrass may be avoided by deep plowing in the fall as opposed to spring. Further research will be necessary to determine how best to maximize the beneficial effects of Saia oats, sorgho-sudangrass, or additional rotation or interplanted crops in perennial strawberry culture.

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