Effect of Composted Sewage Sludge on Several Soilborne Pathogens and Diseases

R. D. Lumsden, J. A. Lewis, and P. D. Millner

Research plant pathologist and soil scientist, Soilborne Diseases Laboratory, Plant Protection Institute; and research microbiologist, Biological Waste Management and Organic Resources Laboratory, Agricultural Environmental Quality Institute; USDA, ARS, Beltsville, MD 20705, respectively.

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ABSTRACT

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The effect of composted sewage sludge (hereafter referred to as compost) on several soilborne pathogens and diseases was tested in the greenhouse. Aphanomyces root rot of peas; Rhizoctonia root rot of bean, cotton, and radish; Sclerotinia drop of lettuce, Fusarium wilt of cucumber; and Phytophthora crown rot of pepper were significantly decreased by addition of 10% compost to soil. Other diseases, Pythium damping-off of pea and bean, Fusarium root rot of pea, and Thielaviopsis root rot of bean and cotton were not affected or were increased by compost. Suppression of diseases caused by *Pythium* and *Rhizoctonia* spp. was enhanced by increasing the time between soil amendment and planting. Survival of *S. minor, R. solani,* and *Pythium* spp. was not decreased by the compost, but the activity of these pathogens in soil may be affected by an increase in microbial activity stimulated by addition of compost to soil.

Additional key words: biological control, municipal waste, organic matter, soil ecology.

Solid organic wastes accumulate in the U.S. at the rate of 800 million dry tons annually (26), and are considered valuable agricultural resources. Composting of organic wastes prior to agricultural use reduces odors, decreases undesirable physical properties, increases nutrient availability, and eliminates human pathogens (27). These advantages especially apply to municipal sewage sludge which can be transformed from an undesirable waste to a valuable soil conditioner and fertilizer by the process of composting (21). About 23% of municipal sewage sludge is applied to land (21), a percentage expected to increase as ocean dumping and land-fill disposal of sludge decreases because of environmental concerns.

Soilborne pathogens and the diseases they cause are increased, decreased, or unaffected by the addition of organic matter to soil (10,19). Very little is known about the effect of organic wastes on soilborne pathogens and essentially nothing is known about the effects of sludges and sludge composts on plant disease development. Composts made from waste hardwood and pine bark, valuable as ornamental crop potting media (6), are suppressive to several diseases caused by soilborne pathogens, including *Phytophthora cinnamomi* (5,22,23), *P. cactorum* (24), *Pythium ultimum*, and *Rhizoctonia solani* (3,13,25).

The effects of sewage sludge composts on soilborne pathogens and the diseases they cause need to be examined, especially in view of the known beneficial effects of these composts on crop plant growth and nutrition (21), and the potential for increased use of these composts in small farm crop production operations (20). For these reasons we investigated the effect of sludge compost on several soilborne plant pathogens and the diseases they cause.

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Preliminary reports of this research have been published (9,11,12,20).

MATERIALS AND METHODS

Preparation of compost and amendment of soil. Composted sewage sludge (hereafter referred to as compost) was produced by the Beltsville forced-aeration method (28), aged for at least 30 days, and screened (<1 cm) to remove large wood chips used as a bulking agent. A previous report (20) established the following typical chemical properties of the compost produced by the Beltsville method from undigested sewage sludge obtained from the Blue Plains waste water treatment plant, Washington, DC: pH 7.3, 35% water, 23% organic carbon, 1.3% total N, 1.5% P, 0.2% K, 1.4% Ca, 4.5% Fe, 340 ppm Zn, 147 ppm Cu, 5.9 ppm Cd, 16 ppm Ni, 800 ppm Mn, and 76 ppm Pb. The compost has a relatively low macronutrient content (which is released slowly) and also a low heavy metal content, considered low enough for safe use in vegetable production (20). The compost was always added to the pathogen-infested soils on a dry weight basis (w/w, compost:soil). Soils were usually amended 1 wk prior to planting. In most cases, a single batch of compost was used to test the effects on disease. However, the effect of five different batches of compost on the incidence of Sclerotinia drop of lettuce and Rhizoctonia damping-off of cotton was tested. Each batch was collected from a separate pile composted by forced-aeration for 21 days with peak heat at 75 C. Composts 1 through 4 were cured for 30 days, and compost 5 for 60 days, then screened (<1 cm). Compost was also added to soil in the field (1:10, w/w), incubated in the field for 1 yr, then planted in the greenhouse with cotton and pea seed to assess the effect of long-term incubation of compost in soil on disease.

TABLE 1. Effects of soil amendment with composted sewage sludge (hereafter referred to as compost) on the incidence or severity of soilborne diseases in greenhouse trials

Disease and pathogen	Host	Disease incidence or severity	
		Control soil	Compost-amended soil[a]
Root rots[b]			
Aphanomyces solani	Pea		
	Perfected Freezer	1.9	0.4*[d]
	Alaska	1.7	0.1*
Fusarium solani f. sp. *pisi*	Pea		
	Perfected Freezer	0.1*	1.0
	Alaska	0.6*	1.9
Rhizoctonia solani	Bean		
	Blue Lake	2.5	1.0*
	Tendercrop	2.1	1.0*
	Cotton		
	Stoneville	3.5	2.4*
Thielaviopsis basicola	Bean		
	Blue Lake	3.3*	3.9
	Cotton		
	Stoneville	3.8	3.8
Damping-off[c]			
Pythium ultimum	Pea		
	Perfected Freezer	97.0	94.0
	Alaska	39.0*	68.0
	Bean		
	Topcrop	48.0	36.0
Rhizoctonia solani	Radish		
	Scarlet Globe	88	32*
Pythium myriotylum	Bean		
	Topcrop	59	22*
Pythium aphanidermatum	Bean		
	Topcrop	27	23
Crown rot[c]			
Phytophthora capsici	Pepper		
	California Wonder	97	55*
Lettuce drop[c]			
Sclerotinia minor	Lettuce		
	Boston	91	50*
	Paris White	84	33*
Wilt[c]			
Fusarium oxysporum f. sp. *melonis*	Melon		
	Fordhook Gem	85	34*

[a] Soils were amended with 10% compost (w/w, on a dry weight basis).
[b] Disease rated as an index from 0 to 4: 0 = no disease, 4 = severe disease.
[c] Disease expressed as a percentage of total plants or seeds infected or killed.
[d] Asterisk indicates value that is significantly less than the alternative treatment, according to Duncan's multiple range test ($P = 0.05$).

Disease assays in the greenhouse. Two naturally and six artificially infested field soils were used to assess the effect of compost on several diseases in the greenhouse. Pea root rot was examined in a sandy loam field soil from Beltsville naturally infested with *Pythium ultimum* Trow and *Fusarium solani* (Mart.) Sacc. f. sp. *pisi* (Jones) Snyd. & Hans., and artificially infested with zoospores of *Aphanomyces euteiches* Drechs. (17). The soil was maintained in the greenhouse and repeatedly cropped to peas (*Pisum sativum* L.) before use. Infection of seed of cultivars Perfected Freezer and Early Alaska pea by the three pathogens was assessed under the following three regimes: First, in order to favor *A. euteiches*, pea seeds were planted in the infested soil and incubated at 15 C for 1 wk in well-drained pots, 2 wk with soil near saturation, and a 3rd wk at 28 C in well-drained pots. At the end of the 4th wk the plants were removed from the soil, washed, and rated for Aphanomyces root rot by a disease severity index (DSI) of 0 = healthy to 4 = dead plants. Because of the severity of preemergence damping-off in this soil and some others, seeds were routinely treated with thiram unless *Pythium ultimum* was being evaluated. Second, in order to favor *F. solani* f. sp. *pisi*, pea seeds were planted in soil incubated at 28 C in relatively dry soil. After 2 wk, red lesions caused by the pathogen were evaluated on a scale of 0 = healthy to 4 = severe disease. Third, preemergence damping-off caused in peas and cultivar Top Crop snapbeans (*Phaseolus vulgaris* L.) by *P. ultimum* was assessed in the soil maintained at 15 C for 2 wk and at 21 C for 1 wk after which percentage plant stand was determined. In each case, 10 seeds were planted in each 10-cm-diameter pot and at least four replicates were evaluated. Aphanomyces and Fusarium root rots were assessed in two experiments that were successively planted at three dates with similar results at each planting. Pythium damping-off was evaluated five times.

Postemergence damping-off or blight of Top Crop bean was evaluated in a sandy loam from Salisbury, MD, naturally infested with *Pythium aphanidermatum* (Ed.) Fitz. or *Pythium myriotylum* Drechs. Seeds (10 per pot) were planted in soil and when all seeds had emerged (1 wk at 20 C), the pots were incubated for an additional week at 32 C. At this time, the percentage of blighted seedlings was determined. Soils were also artificially infested with oospores of *P. aphanidermatum*, produced as previously described (2).

Rhizoctonia solani Kühn was added as a 2-wk-old, sand-cornmeal culture (3 g cornmeal, 100 g sand, and 15 ml water) to sandy-loam and clay-loam soil from Beltsville, MD, at the rate of 1%. The soils were incubated in the greenhouse for 2 wk before being planted with thiram-treated Blue Lake bean seeds, Stoneville cotton (*Gossypium hirsutum* L.) seeds, or Scarlet Globe radish (*Raphanus sativus* L.) seeds (10 seeds per pot). The pots were maintained at 28 C for 3 wk, seedling stand was recorded, and the remaining plants evaluated for root rot severity (DSI, 0 = healthy to 4 = hypocotyl girdled with a lesion).

A field soil artificially infested with macroconidia of *Fusarium oxysporum* Schlecht. f. sp. *melonis* obtained from a 2-wk-old, potato-dextrose agar culture (10^3 macroconidia per gram of soil) was used to assess disease on melon (*Cucumis sativus* L. 'Burpee's Fordhook Gem'). Seedling transplants were placed in the soil, incubated at 23 C for 3 wk, and the percentage wilt of seedlings was determined. Sandy loam soil from Beltsville, naturally infested with *Thielaviopsis basicola* (Berk. & Br.) Ferr., was planted with thiram-treated cultivar Blue Lake bean and cultivar Stoneville cotton seed. Pots were kept at 18 C for 3 wk and were rated for

stand count and severity of root rot on a scale of 0 (healthy) to 4 (dark discoloration of radicle and secondary roots).

A sandy-loam soil from Salisbury, MD, was artificially infested with sclerotia of *Sclerotinia minor* Jagger (three per gram of soil), harvested from 1-mo-old oat kernel cultures (oats:water 1:1, w/v). Seedlings (1 wk old) of lettuce (*Lactuca sativa* L.) cultivars Boston and Paris White were planted (10 seedlings per pot, six replicates) in 10-cm-diameter pots in the infested soil and incubated for 4 wk in plastic film-covered moist chambers at 15 C. Numbers of infected lettuce plants were recorded and removed daily. At least two tests were run for each cultivar with similar results.

Pepper crown rot caused by *Phytophthora capsici* Leonian was evaluated with soil artificially infested with oat cultures of the pathogen as previously described (16). Five-week-old pepper (*Capsicum annuum* L., 'California Wonder') plants (five per pot, four replicate pots) were transplanted into the soil and incubated at 25–28 C for 3 wk and diseased plants were counted. All tests were set up in randomized complete block designs and were analyzed by Duncan's multiple range test.

Survival and activity of pathogens. *Rhizoctonia solani, S. minor, P. aphanidermatum*, and *P. ultimum* were studied further to determine the effect of amendment with compost on survival of their propagules. Sand-cornmeal medium, described above, on which *R. solani* was grown for 1 wk was added to compost-amended soil (0.1% w/w) and the ability of the pathogen to colonize beet seed (15) was assessed over a 13-wk period.

Sclerotia of *S. minor* were recovered from 50-g samples of infested soils by a flotation-sieving method (1). The percentage survival was determined from the number of sclerotia retrieved in relation to the original number of sclerotia added (three per gram of soil). Survival was assessed over 6 mo.

The population density and survival of *P. aphanidermatum* and *P. ultimum* were determined by two methods. The effect of amendment with compost on populations of the two pathogens in soil was assayed by a differentially selective isolation technique (8). Survival of oospores for both *Pythium* spp. was studied with a trapping method recently described (7).

Frequency of occurrence of fungi in soils was assayed with a medium containing (per liter of H_2O): oxgall, 15 g; peptone, 10 g; dextrose, 10 g; agar, 20 g; and gentamicin (0.1%). Bacteria were assessed on trypticase-soy agar (BBL, Cockeysville, MD) containing 50 μg of cycloheximide per milliliter; and actinomycetes on Czapek's agar containing 24.2 g of KCl per liter, 50 μg of cycloheximide and 0.025 g ferric ammonium citrate per milliliter.

RESULTS

Effect of soil amendment with compost on diseases. Compost (10%) added to infested soil had a variable effect on the disease response of ten different pathogens on eleven different hosts. Disease decreased, increased, or was unaffected (Table 1).

Significant decrease in disease was observed with six different pathogens. Among these, Aphanomyces root rot of peas was reduced from an average DSI of 1.9 in control soil to an average of 0.1 in compost-amended soil. A similar reduction occurred with root rot of beans and damping-off caused in radish by *R. solani*. Other diseases that were significantly reduced by the amendment were: Pythium damping-off of bean (from 59 to 22% disease in the control and compost-amended soils, respectively); Phytophthora crown rot of pepper (from 97 to 55% disease); Sclerotinia drop of two lettuce cultivars (from 91 to 50%, in cultivar Boston lettuce; and from 84 to 33% in cultivar Paris White lettuce); and Fusarium wilt of melon (from 85 to 34%).

The incidence of some diseases increased in compost-amended soil. Root rot of pea, which is caused by *F. solani* f. sp. *pisi*, gave a DSI of 1.0 in compost-amended soil compared to a DSI of 0.1 in control soil. Other diseases, including Thielaviopsis root rot of bean, and Pythium damping-off of pea were significantly increased in compost-amended soil, but these diseases were not significantly affected by compost on other hosts. For example, disease on cotton was not significantly different in soil infested with *T. basicola* with or without compost. Also, *P. ultimum* on Perfected Freezer pea and *P. aphanidermatum* on bean were unaffected by amendment with compost.

The amount of compost added to soil was varied from 0 to 30% (w/w) and tested against four diseases (Table 2). Aphanomyces root rot of pea and Rhizoctonia root rot of bean were clearly decreased by the compost amendment. Two other diseases, Thielaviopsis root rot of bean and Pythium damping-off of bean were increased or not affected by the addition of compost. In all cases, no differences were noted among 5, 10, 20, or 30% (w/w, dry wt.) compost-amended soils.

The length of time between soil amendment and planting affected the incidence of damping-off and root rot induced in

TABLE 2. Effects of soil amendment with various amounts of composted sewage sludge (hereafter referred to as compost) on root rot caused in bean by *Rhizoctonia solani* and *Thielaviopsis basicola*; root rot caused in pea by *Aphanomyces euteiches*; and damping-off caused in bean by *Pythium aphanidermatum*

Pathogen	Host (cultivar)	Compost-soil amendment[w] (%, w/w)	Disease rating[x]
Aphanomyces euteiches	Pea (Freezer Perfection)	0	2.36 a[y]
		5	0.76 b
		10	0.44 b
		20	0.68 b
		30	0.36 b
Pythium aphanidermatum	Bean (Tendercrop)	0	86.0 a[z]
		5	61.0 a
		10	88.0 a
		20	94.0 a
		30	80.0 a
Rhizoctonia solani	Bean (Blue Lake)	0	2.5 a[y]
		5	1.5 b
		10	1.0 b
		20	1.0 b
		30	0.7 b
Thielaviopsis basicola	Bean (Tendercrop)	0	0.5 b[y]
		5	1.5 a
		10	1.5 a
		20	0.9 ab
		30	1.2 ab

[w] Soil amended with compost (w/w, on a dry weight basis).
[x] Numbers for each pathogen followed by the same letter do not differ, $P = 0.05$, according to Duncan's multiple range test.
[y] Disease severity index based on a disease rating scale from 0 = healthy to 4 = severely diseased.
[z] Percentage damping-off.

TABLE 3. Effects of preplant incubation on the efficacy of soil amendment with composted sewage sludge (hereafter referred to as compost) for the reduction of damping-off and root rot caused in cotton by *Rhizoctonia solani*

Preplant incubation (wk)	Compost-soil amendment (%)	Stand at 3 wk (%)	DSI[z]
0	0[x]	17 a[y]	2.6 a
	10	1 b	...
1	0	38 a	3.0 a
	10	41 a	2.8 a
2	0	18 b	3.1 a
	10	50 a	2.5 b
4	0	59 b	2.6 a
	10	88 a	1.9 b

[x] Sandy-loam soil amended with 10% compost (w/w, on a dry weight basis).
[y] Pairs of values at the same planting date followed by the same letter are not significantly different, $P = 0.05$, according to Duncan's multiple range test.
[z] DSI = disease severity index: 0 = healthy and 4 = severe lesions on seedlings.

cotton by *R. solani* (Table 3). Soils that were infested with sand-cornmeal cultures of *R. solani* (1%, w/w) and planted immediately after the addition of 10% compost had a plant stand of 1% compared to 17% for the unamended control soil. With increased incubation prior to planting, plant stand increased significantly and the DSI decreased in compost-amended soil. After 4 wk, the percent disease control increased to 71% and the DSI decreased 27%.

The effect of time between amendment and planting was tested also with *P. ultimum* and *P. aphanidermatum* (Table 4). Disease caused by *P. aphanidermatum* was not affected by the addition of compost to soil when the soil was infested with oospores of the pathogen (200 per gram of soil) and planted to cucumber immediately after amendment or 30 days after amendment. However, the same soil amended with compost in the field 1 yr previously and allowed to incubate under natural conditions in the field was somewhat suppressive to disease caused by *P. aphanidermatum* when planted under greenhouse conditions. The soil maintained its disease suppressiveness for three additional plantings. The soil amended with compost in the greenhouse did not become suppressive even after several repeated plantings. In contrast to disease caused by *P. aphanidermatum*, that induced in pea by *P. ultimum* in soils infested with natural inoculum (3,000–4,000 propagules per gram) was significantly increased by the addition of freshly prepared compost. After 1 mo, however, slight disease suppressiveness was induced in the compost-amended soil. The soil amended with compost in the field and allowed to remain there for 1 yr was partially suppressive to infection of peas by *P. ultimum* and the suppressiveness was maintained for several plantings, as for *P. aphanidermatum*. The soil amended with compost in the greenhouse also maintained its suppressive properties after three successive plantings.

TABLE 4. Effects of soil amendment with composted sewage sludge (hereafter referred to as compost) on the incidence of Pythium damping-off caused in cucumber by *Pythium aphanidermatum* and caused in pea by *P. ultimum* in soils freshly amended with 10% compost or amended for 1 yr prior to planting in the field

Host, pathogen, and soil treatment	Damping-off (%) time elapsed before planting (days)	
	0	30
Cucumber—*P. aphanidermatum*[x]		
Control soil	89 a[y]	92 a
Soil freshly amended with 10% compost	76 ab	88 a
Soil amended for 1 yr with 10% compost	66 b	58 b
Pea—*P. ultimum*[z]		
Control soil	62 b	97 a
Soil freshly amended with 10% compost	78 a	72 b
Soil amended for 1 yr with 10% compost	45 c	52 c

[x] Soils uniformly infested with 200 oospores of *P. aphanidermatum* per gram.

[y] Values followed by the same letters in the same column for each host are not significantly different, $P = 0.05$, according to Duncan's multiple range test.

[z] Natural infestation of 3,000–4,000 propagules per gram of soil.

TABLE 5. Effects of different batches of composted sewage sludge (hereafter referred to as compost) on damping-off caused in cotton by *Rhizoctonia solani* and drop caused in lettuce by *Sclerotinia minor* in amended soils in the greenhouse 1 and 4 wk after amendment

Compost[y] batch	*R. solani* causing cotton damping-off (%)		*S. minor* causing lettuce drop (%)	
	1 wk	4 wk	1 wk	4 wk
1	38 b[z]	14 b	22 b	22 b
2	76 a	13 b	48 ab	29 b
3	88 a	11 b	35 b	70 a
4	47 b	11 b	32 b	40 b
5	76 a	12 b	45 ab	40 b
No compost	72 a	25 a	73 a	60 a

[y] Composts produced by forced aeration for 21 days at different dates; batches 1–4 were aged for 30 additional days, batch 5 was aged for 60 additional days.

[z] Values were obtained 3 wk after planting; those followed by the same letter in each column do not differ significantly, $P = 0.05$, according to Duncan's multiple range test.

Variability in disease control among batches of compost was examined. Five compost preparations, four of which were aged for 30 days and a fifth batch for 60 days, were compared for their ability to control Rhizoctonia damping-off of cotton and Sclerotinia drop of lettuce. When soil was amended and incubated 1 wk prior to planting, disease caused by *R. solani* was significantly reduced by only two batches (1 and 4) of the five batches of compost (Table 5). Batches 1 and 4 also reduced *S. minor* on lettuce as did batch 3. In general, incubation of the composts in soil for 4 wk improved their disease suppressiveness. All five batches reduced disease caused by *R. solani* in soil replanted with cotton after 4 wk of incubation as compared to the control, and all batches except batch 3 reduced Sclerotinia drop of lettuce after the extended period of incubation in the soil.

Microbial populations associated with compost-amended soil. Attempts were made to determine whether certain microbial populations were associated with the disease suppression. Select groups or species of fungi were assayed, and bacteria and actinomycetes were determined. Soils amended with composts number 1 and 4 used in the experiment comparing batches of compost (Table 5), which were suppressive to *S. minor* and *R. solani*, were examined. From these soils, 16 genera and 35 species of fungi were isolated. Of these, only *Penicillium dupontii* Gr. and Maub., *Trichurus spiralis* Hasselbr. and *Sepedonium* sp. were consistently higher in numbers in both suppressive batches of compost-amended soil than in the control soil. *Scopulariopsis brevicaulis* (Sacc.) Bain., *Humicola* spp., and *Trichoderma harzianum* Rifai occurred in numbers significantly greater from those in control soil amended with compost batch 1. All of the above mentioned species except *T. harzianum* were present in the compost before it was added to the soil. Also, all except *Humicola* spp. and *S. brevicaulis* occurred in the control soil as well as in the compost. *Aspergillus niger* van Tieghem and *Fusarium* spp. were consistently lower in compost-amended soil than in the control soil. The populations of actinomycetes and bacteria were not significantly different in the compost-amended and control soils; however, the difference in the ratio of actinomycetes (A) to bacteria (B) was significantly higher in soil batch number 1 (A/B = 11.5) and number 4 (A/B = 2.5) than in the control (A/B = 0.0001). The pH of all the soils was nearly the same (pH 6.3–6.6).

Effect of compost on survival of pathogens. Four pathogens, *S. minor, R. solani, P. aphanidermatum*, and *P. ultimum* were examined with regard to their ability to survive in compost-amended soil in the laboratory. Numbers of sclerotia of *S. minor* were not significantly affected by burial for as long as 6 mo in soil that was amended with 10% (w/w, dry weight basis) compost. Survival of *R. solani* in compost-amended soil (15%, w/w) also was not affected even after 13 wk. In compost-amended soil, 87% of beet seed retrieved from the soil contained *R. solani* compared with 89% from nonamended soil.

Survival of oospores of *P. aphanidermatum* trapped in nylon mesh was enhanced by the addition of compost to soil. After 2 wk in the soil, 83% of *P. aphanidermatum* oospores survived in compost-amended soil, but only 17% survived in control soil. Survival of oospores of *P. ultimum* was not affected by compost amendment. In both compost-amended and control soils the survival rate was approximately 95% after 1 mo. The populations of *Pythium* spp. in compost-amended and unamended control soils incubated in the laboratory were not differentially affected by compost amendment. Again, *P. aphanidermatum* appeared to be slightly protected by the presence of compost; after incubation in soils for 4 mo, however, no differences were noted between the treated and control soils. With *P. ultimum*, no differences were detectable in numbers of propagules during a 6-mo incubation period.

DISCUSSION

Composts affect soilborne diseases in several ways so that generalizations as to their influence on disease should not be made. Some diseases were suppressed immediately, others only with time, and still others were increased in severity. Suppression occurred soon after amendment with sludge compost of soils infested with *A. euteiches, S. minor,* or *R. solani* (Tables 1 and 2) and with *R. solani* on turfgrass (14). Likewise, bark compost used as a container medium suppressed four pathogens (*Phytophthora cinnamomi, Pythium* sp., *R. solani*, and *T. basicola* (3,5,13,22,24).

Some diseases (Fusarium root rot of pea, and Thielaviopsis root rot of bean) were made more severe by sludge compost. However, compost amendment did not cause an increase in Thielaviopsis root rot of cotton. In addition, compost stimulated, had no effect, or decreased Pythium damping-off depending on the particular species of the pathogen, the host, the environment, and possibly nonuniformity of the compost. The latter possibility is exemplified by the variable results obtained with five batches of compost (Table 5). Only two of the five composts effectively suppressed *R. solani* and *S. minor* during the initial planting. Variability did not appear to be caused by aging of the compost before it was added to the soil, since compost aged for 2 mo (batch 5) was less effective than other composts aged for 1 mo (batches 1–4). Batch 3 (the same age as batches 1, 2, and 4) was the least effective for disease control. All composts, however, increased in effectiveness with increased time after incorporation into soil. This suggests a change in the compost or the soil environment once the soil was amended. A change was also suggested by the data for *R. solani* because disease was increased when cotton seed was planted immediately after compost incorporation (Table 3). Pythium diseases also responded to time-dependent modifications in the soil environment (Table 4). Even 30 days after compost incorporation, disease induced by *P. aphanidermatum* was not reduced and that induced by *P. ultimum* required an initial incubation period to prevent an actual increase in disease. Disease caused by both *Pythium* spp. was substantially reduced in field soil amended 1 yr before testing. These results suggest that time allows either for removal of materials from amended soil, or for antagonistic microbiota to develop, thus reducing pathogen aggressiveness. Perhaps this long-term effect might also apply to disease caused by *T. basicola* and *F. solani* f. sp. *pisi*, which were also increased by compost.

Variability in effectiveness was also shown with bark compost (13). Mild suppression of disease caused by *R. solani* was reported with pine bark compost as compared to hardwood compost. Excess wood chips (up to 60%) in hardwood bark compost destroyed the suppressive effect against *P. cinnamomi* and other pathogens as well (4), and the compost enhanced disease suppression more at pH 4.5 than at pH 6.0 (22). Wood chips in the finished and screened sludge compost could possibly affect variability in our studies because wood chips are used as a bulking agent at a ratio of chips:sludge (2:1, v/v) in the Beltsville aerated-pile method (21) of compost production. The pH of the amended soil, however, probably did not affect results in our study, because the pH of the soils was in the agricultural range of pH 6–7. Bark composts appear to be suppressive, at least in part, due to biological and/or chemical characteristics rather than physical factors related to drainage (4). In our studies, sludge compost appears to behave similarly. Fungistatic chemicals, especially the low levels of heavy metals (eg, 0.6 ppm Cd) do not seem, however, to play an important role in the suppression. During the early periods after compost addition to soil, disease was more severe in amended soils planted immediately after amendment with compost, especially with *R. solani* (Table 3) and *Pythium* spp. (Table 4). Instead, a biological mechanism is suggested by several points: Suppression of some diseases improved with time after addition of compost to soil, suggesting a requirement for changes in populations of microorganisms; addition of compost at a rate of 30% was not better than 5%, suggesting that the smaller amount of organic matter was sufficient to stimulate the microbiota; the overall microbial metabolic activity in compost-amended soil was greater than in the control (J. A. Lewis, *unpublished*), suggesting stimulation of the microbiota by the added organic matter; several widely different types of diseases were decreased, suggesting a broad action rather than a specific chemical action against the pathogens; populations of several fungi including *Trichurus spiralis, Penicillium dupontii, Sepedonium* sp., *Humicola* spp., and *Scopulariopsis brevicaulis*, all associated with compost before addition to the soil, and *Trichoderma harzianum*, which was found in soil but not in compost, were all higher in frequency of occurrence in compost-amended soil than in the control; and the survival of the pathogens did not appear to be affected, suggesting a fungistatic effect. The mechanism suggested is that the compost enhances the activity of microorganisms introduced with the compost and stimulates those resident in the soil. The fungi derived from compost were not previously associated with antagonism of soilborne plant pathogens, but *T. harzianum* is well-known as a microbial antagonist (18). These and other microorganisms in the compost-amended soil may increase competition and levels of antibiosis to affect the disease-causing ability of several of the pathogens studied, but not affect their ability to survive in the soil.

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