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Compost for Management of Weed Seeds, Pathogen, and Early Blight on Brassicas in Organic Farmer Fields

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*Low-input methods for addressing economic and management challenges of plant pathogens and weed seeds will advance sustainable farming practices. Objective 1 was to demonstrate that U.S. National Organic Standards (NOS) for compost are sufficient to kill plant pathogens and weed seed. Known quantities of early blight inoculum (*Alternaria brassicinae*) and giant crab grass (*Digitaria sanguinalis*) seed were enclosed in bags and inserted into manure-based compost containing different sources of C: 1) manure–silage, 2) hay, 3) softwood, and 4) hardwood. Except for the manure–silage control, treatments represented C:N ratios prescribed by NOS. Bags were removed at five times during the compost process. Both pathogenicity and seed germination were reduced to zero by following NOS guidelines. Patterns of microbial enzyme activity illustrated that labile substrates were abundant in manure–silage and hay, but limited in softwood and hardwood treatments. For Objective 2, field trials were conducted at two farms. Compost treatments were applied after the first cultivation as mulch as follows: 1) manure–silage, 2) hay, and 3) hardwood. Non-mulched plots were used as bare controls. When compost was applied at a rate of 54.8 ton/ha (20 ton/acre), compost made with hardwood bark suppressed severity of early blight disease more than compost made with softwood, hay or manure–silage.*

KEYWORDS Compost, Alternaria brassicinae*,* Digitaria sanguinalis*, crab grass, National Organic Standards, extracellular enzyme assays, NOFA (National Organic Farming Association)*

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INTRODUCTION

Early blight disease (*Alternaria* spp.) is widespread and devastating on crops within the Solanaceae (tomato, eggplant, potato), Cruciferaceae (*Brassica*) and Apiaceae (carrot) families. The primary inoculum of the pathogen is typically splashed onto the foliage from infested soil. Inoculum load is influenced by the soil texture and abundance of the pathogen of surface soils or mulches. Sanitation is important to reduce initial inoculum and, thus, diseased material must be disposed of in a manner that destroys the pathogen. Because early blight pathogen has saprophytic capabilities that facilitate survival and dispersal, on site disposal techniques are avoided in favor of diverting material to the landfill. However, composting these materials on local farms has the potential to kill these pathogens and weeds, which would allow farmers to reduce export of nutrients and organic matter from their operation and generate a local source of disease- and weed-free planting medium (Liebman and Davis 2000; Larney and Blackshaw 2003).

Composting is an aerobic process, during which organic waste is biologically degraded by micro-organisms to humus-like material. The end product should not contain virulent pathogens or viable seeds and it should be stable and suitable for use as a soil amendment. The National Organic Standards (NOS) Board Program (www.ams.usda.gov/nop) proposes that compost piles are managed to maintain a temperature between 55°C and 77°C for a minimum of 15 days, and turned a minimum of five times, to insure lethal conditions for resident pathogens and weeds. Compost piles reach temperatures lethal to plant pathogens and weed seeds if they contain feedstock blends that average 25:1 to 30:1 C:N ratio, have 55–60% moisture, and are turned frequently for aeration.

There are three distinct successional phases driving chemical and microbial changes through time, phases that are determined primarily by changes in temperature: mesophilic (moderate temperatures rising to 45°C), thermophilic (high temperatures peaking at 80°C), and curing (cooling to ambient temperature). Organic certification follows NOS which define minimum requirements for the thermophilic phase but stops short of defining the curing phase. The curing phase offers a substrate and climate conducive for microbial recolonization which can be accomplished either by inoculating post-thermophilic compost or preparing a palatable substrate that provides a competitive advantage for colonization by bacteria and fungi that offer biological control, slow-release fertility, and plant growth promotion (Hoitink and Boehm 1999).

Composted organic wastes can serve as a biological inoculant for field soils to reduce the severity of root diseases in natural and field systems (Hoitink and Boehm 1999; Stone et al. 2001). Disease suppression from composts is from experiments conducted on fungal and oomycota pathogens in containers or controlled environments rather than field conditions (Hoitink

and Boehm 1999; Stone et al. 2001; Noble and Coventry 2005; Noble 2011). Results are notoriously inconsistent from the paucity of field experiments, which can be at least partially explained by the lack of calibration by compost recipe, maturity or application rate (Hoitink amd Fahy 1986; Bailey and Lazarovits 2003; Stone et al. 2004; Bonanomi et al. 2007). For example, if properly and consistently prepared, peat-based compost naturally suppresses *Pythium* and *Phytophthora* (Chen et al. 1988; Chung et al. 1988; Harris et al. 1997). Populations of biocontrol agents are linked with carbohydrate content (Chen et al. 1988). Once carbohydrates are depleted, the microbial communities degrading them decline. NOS do not specify the type of carbon in compost. C sources can include straw, paper, woodchips, sawdust, or bark, all of which have contrasting biochemical structure and resistance to decay. Hardwoods typically have a higher C:N ratio and higher lignin:cellulose ratio than softwoods and straw, making them more resistant to decay and extending the longevity of the suppressive effect. At high C:N ratios, thermophilic bacteria decompose less of the easily available C because of N limitation, leaving more organic matter for fungal decomposition during the curing phase with lower temperatures, resulting in high levels of fungi (Eiland et al. 2001).

This study was designed with two practical objectives for organic farmers. First, demonstrate that compost, properly made, will heat and kill disease early blight inoculum and giant crab grass (*Digitaria sanguinalis*) weed seeds. Second, conduct a replicated field trial to determine whether compost would suppress early blight disease on cruciferous crops. We predicted that compost containing hardwood bark as a C source would suppress early blight disease more than compost with hay or softwood as a C source.

METHODS

Compost Pile Creation and Environmental Monitoring

In spring 2010, 7.65 m^3 piles of manure-based compost were established at Highfields Center for Composting in Hardwick, VT (http://www.highfieldscomposting.org/). Composts prepared were four-fold: 1) manure–silage, 2) hay, 3) softwood, and 4) hardwood (Table 1). Each treatment was replicated three times with a total of 12 piles. All the treatments, except the manure–silage control, represented proper recipes that optimized C:N ratios and moisture content. The manure–silage control treatment was a mixture of heifer manure and corn silage that would typically be found in an unmanaged compost pile on a Vermont dairy farm. All treatments contained some manure, all of which originated from the same source. Temperatures were monitored at 0.3 and 1 m depths in each compost pile one to two times per week to determine when to turn each pile. The indicator for turning was a decline in temperatures resulting from reduced aeration. Pile turning

TABLE 1 Compost recipes in 2011 and 2012 made by windrow and aerated static pile, respectively (recipe development was based on % C, % N, moisture, and bulk density analysis)

	2011	2012
Bare	No compost added	No compost added
Control	7.65 m^3 manure/silage	22.94 m^3 manure/silage
Hay	3.06 m^3 manure/silage	11.47 m^3 manure/silage
	9.17 m^3 hay	34.41 m^3 hay
Softwood	2.29 m^3 manure/silage	N/A[a]
	1.53 m^3 softwood mulch	
	3.06 m^3 softwood shavings	
Hardwood	3.82 m^3 manure/silage	9.17 m^3 manure /silage
	3.82 m^3 hardwood bark	9.17 m^3 hardwood bark
	2.29 m^3 softwood shavings	5.35 m^3 softwood shavings

[a]Not applicable.

was performed with a front-loader bucket mounted on a tractor. The bucket was sanitized using Breyers soap in warm water between piles to avoid contamination between piles.

Assays of Pathogenicity, Seed Viability, and Microbial Activity

Pathogen and weed seed were placed into two types of bags, one with No-see-um polyester netting (The Rain Shed, Inc., Corvallis, OR, USA) and the second in a sealed Whirl-Pak. The mesh bag tested the effect of heat and biota and the sealed bag tested the effect of heat alone. Fluorescently colored plastic flagging tape was sewn around the bag perimeter with polyester thread, to color code the pathogen and weed treatments and make them visible for collection after being mixed within a compost pile. Pathogen bags (10.2 × 10.2 cm inside dimensions) contained an air-dried 100 mm agar disk of *Alternaria brassicinae* that was isolated from Brussels sprout (*Brassica oleracea*) leaves in fall 2009 and cultured axenically on potato dextrose agar. Weed bags (5.1 × 5.1 cm inside dimensions) contained 2.5 ml (hundreds of seeds) of crab grass seed. Crab grass seed was chosen because of its large size and long germination period. We inserted 1–4 pebbles per bag to provide weight to minimize their "floating" to the top of the pile. Fifteen bags of each of the four treatments were prepared per pile of which 3 were analyzed as a baseline prior to mixing at the formation of the pile, and 12 were mixed with the original feedstocks while creating the compost recipe. Feedstocks were measured by volume and mixed using a front-loader tractor. Extra bags were included to account for some loss.

Three replicate bags of each of the four treatment types (2 organisms × 2 bag types × 3 blocks) were collected at four times during the compost process: formation of the pile (T0), compost duration at thermophilic phase

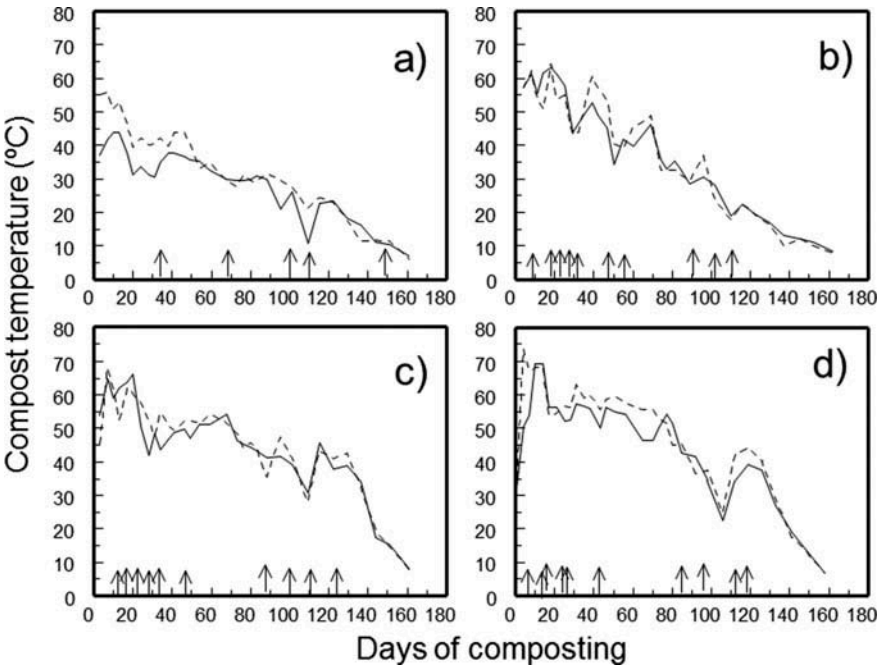

FIGURE 1 Temperature at 0.3 m (dashed line) and 1 m (solid line) depths in the compost pile of four recipes: a) manure–silage, b) hay, c) softwood, and d) hardwood. Arrows indicate times each pile was turned. One of three replicates is shown as representative examples.

required for organic certification (T1, when NOS for organic compost were first met), end of the thermophilic phase when the temperatures drop below 55°C (T2), mid-cure when temperatures drop below 38°C (T3), and end of cure, when aeration as a result of turning the pile, no longer induces an increase in temperature (T4). Sampling dates were unique for each pile depending on the temperature regime and were earlier for hay and followed progressively by softwood, hardwood, and manure–silage (Figure 1). All 12 treatment bags per pile were collected into a single resealable plastic bag. An additional 500 ml subsample of bulk compost was collected at each time to perform microbial assays. Samples were transported to the laboratory in an insulated container to avoid exposure to extreme temperatures that could bias pathogenicity or seed viability. In the laboratory, pathogen and weed seed samples were stored at 4°C until analyzed for pathogenicity and seed germination. Microbial samples were frozen immediately and kept at –70°C until analyzed.

Pathogenicity was tested as a bioassay on individual leaves of a Brussels sprout plant. Inoculum was swabbed onto a leaf with a cotton swab. Leaves were misted daily to maintain high humidity. Development of lesions was monitored on a daily basis for up to 14 days and compared to a positive

control (conidia from a dried cultures stored in the lab, to determine whether the pathogen was viable, that is, visible as a lesion.

The percentage of seed germination was tested by spreading 96 randomly selected seeds per bag onto moist blue germination paper (Anchor Paper, St. Paul, MN, USA) in a glass petri dish. Eight milliliters of filtered distilled water was added to each germination pad. Plates were incubated at 20°C for 7 days after which the percentage of seeds that had sprouted ("viable") was enumerated using a stereo microscope.

Microbial activity was quantified using activity of six extracellular enzymes: α-1,4-glucosidase (αG), β-1,4- glucosidase (βG), β-1,2-N-acetylglucosominidase (NAG), peroxidase (Perox), L-leucine aminopeptidase (LAP), and urease. Four enzymes are involved in soil C and nutrient cycling: αG and βG catalyze starch and cellulose, respectively. NAG breaks down chitin and fungal cell walls. Perox degrades lignin. LAP catalyzes leucine hydrolysis from the N-terminus from proteins and peptides as a representative amino acid utilization, and urease targets urea (Saiya-Cork et al. 2002; Sinsabaugh et al. 2008; Sinsabaugh 2010). The protocol of Saiya-Cork et al. (2002) was tailored with the following modifications. One hundred milliliters of 50 mM bicarbonate buffer (pH 8.2) was added to 0.5 g of soil. Sixteen replicate wells of 200 µL aliquots per sample were dispensed into 96-well microplates. A 50 µL portion of substrate solution containing fluorogenically labeled substrates (methylumbelloferone, MUB) were added to each well for αG, βG, NAG, and LAP. Microplates were incubated in the dark at 20°C for 3 h. Fluorescence was quantified using a microplate fluorometer (FLx800, BioTek Instruments, Inc., Winooski, VT, USA) with 360 nm excitation and 460 nm emission filters. The oxidative enzyme Perox, as well as urease, were quantified spectrophotometrically in clear polystyrene 96-well, 300 µL microplates, using the substrate 10 mM 1-3,4-dihydroxyphenylalanine (L-DOPA) and 0.3% hydrogen peroxide (for Perox) and incubating clear plates for 2 h at 20°C and reading absorbance on a microplate spectrophotometer (BioTek) with a 460 nm filter. Corrections were made for standards, plate, and buffer. All enzyme activities are expressed in units of nmol h^{-1} g^{-1}. Urease plates were incubated for 20 h before the addition of Hach reagents (Sinsabaugh et al. 2000).

Field Experiment for Disease Suppression

Field trials were conducted in 2011 and 2012 at two farms with a history of growing certified organic brassica crops: Intervale Community Farm (Burlington, VT; 44°29′58.73″N latitude, 73°12′27.13″W longitude, 253 masl) and Riverside Farm (East Hardwick, VT; 44°31′48.94″N latitude, 72°25′22.37″W longitude, 253 masl). A second field was added to the study

at Riverside Farm in 2012 (44°30′40.67″N latitude, 72°19′00.26″W longitude, 298 masl). We worked with the existing fertility and cultivation practices of the farm and took precautions not to introduce any pathogens or seed. All fields routinely received applications of compost as the primary source of fertility. Therefore, treatments imposed were in addition to standard agricultural practices.

Each year, we arranged four compost treatments in a randomized completed block design at each farm. Blocks were added throughout the growing season to accommodate the staggered planting regime by each farmer to provide a continuous supply to market. Compost treatments were 1) bare without compost, 2) manure–silage, 3) hay, and 4) hardwood as described above. Compost was applied after the first cultivation at 54.8 ton/ha (20 ton/acre) and spread manually to avoid transplant damage. Each block contained one experimental unit of each of the four treatment types. Experimental plots were three beds (5.5 m) wide by 7.6 m lengths of a cropping row. Disease severity of early blight was assessed from the eight plants in the middle of the center bed within a block to avoid interplot interference. The sampling region always contained *Brassica oleracea*, whether broccoli or cabbage. Disease severity was rated a minimum of six times in a season for all fields except for the Intervale farm in 2011 when the field became submerged under water following a tropical storm after the third disease rating. Disease was quantified using a categorical scale related to the number of lesions per leaf: 1 (≤3 lesions), 2 (4–6 lesions), 3 (>6 or many lesions), and 4: severe. Severity per plant was the sum of values for all symptomatic leaves per plant.

Statistical Analysis

Proportion of seed viability and pathogenicity were transformed as the arcsine of the square root prior to performing a two-way analysis of variance. The independent variables were compost treatment and sampling time. Extracellular enzyme data were analyzed as a two-way Kruskal–Wallis test with enzyme activity as the dependent variables and compost type and time as independent variables with both main effects and a two-way interaction terms in the statistical model. Means were compared by Tukey post-hoc tests to control for excessive Type I errors. Disease progress curve data were analyzed by repeated measures analysis of variance for each farm and year combination separately. The statistical model was a randomized complete block with disease severity as the response variable and compost treatment as the independent variable with time as a random effect. Orthogonal contrasts were performed to determine which compost treatments differed from each other significantly.

RESULTS

Temperature in Compost Through Time

Temperatures increased within 24 hours after constructing a compost pile (Figure 1). With the exception of manure–silage, piles were turned 10 times between pile formation and the end of cure. Temperatures reached a minimum of 75, 68, 65, and 55°C in hardwood, softwood, hay, and manure–silage recipes, respectively (Figure 1). NOS were achieved except for the manure–silage recipe.

Viability of Pathogen and Weed Seeds

Seed germination was reduced to 0% by T1 and T2 for all treatments in mesh and solid bags, respectively, (Figures 2a and 2c). Pathogenicity was 0% for all treatments by T1 and T3 in mesh and solid bags, respectively, (Figures 2b and 2d).

Changes in Microbial Community and Temperature in Compost

There were main effects of compost type for αG, βG, NAG, LAP, and urease but not perox (Table 2). Activity of all enzymes fluctuated in time (Table 2). There was a significant two-way interaction of compost type and time for αG, βG, NAG, LAP, and perox but not urease (Table 2). In the manure–silage and hay treatments, activity of hydrolytic enzymes rapidly peaked between T0 and T1, quickly decreased from T1 to T2 and remained low through T4 (Figures 3a–3d). Activity of hydrolytic enzymes was less in the softwood treatment than other compost types for all times. Activity was high initially in the hardwood treatment but diminished by T1. Peroxidase activity was similar among compost types ($p = 0.586$) but varied temporally depending on compost type. After initial highs, levels of peroxidase activity plummeted until after the end of the thermophilic phase in all treatments, after which it increased through T4 (Figure 3e). Urease activity was less in manure than hay, softwood or hardwood composts (Figure 3f). Fluctuations through time were similar for hardwood and hay treatments with activity high at T0, low at T1, increased from T1 to T2 through T4 (Figure 3f). In the softwood treatment, initial urease activity was lower than activity at T2. Urease activity was negligible in the manure–silage treatment except at T3.

Field Trials and Disease Suppression

Disease severity was reduced when compost was added, regardless or recipe, compared to the bare soil at the Intervale farm in both years

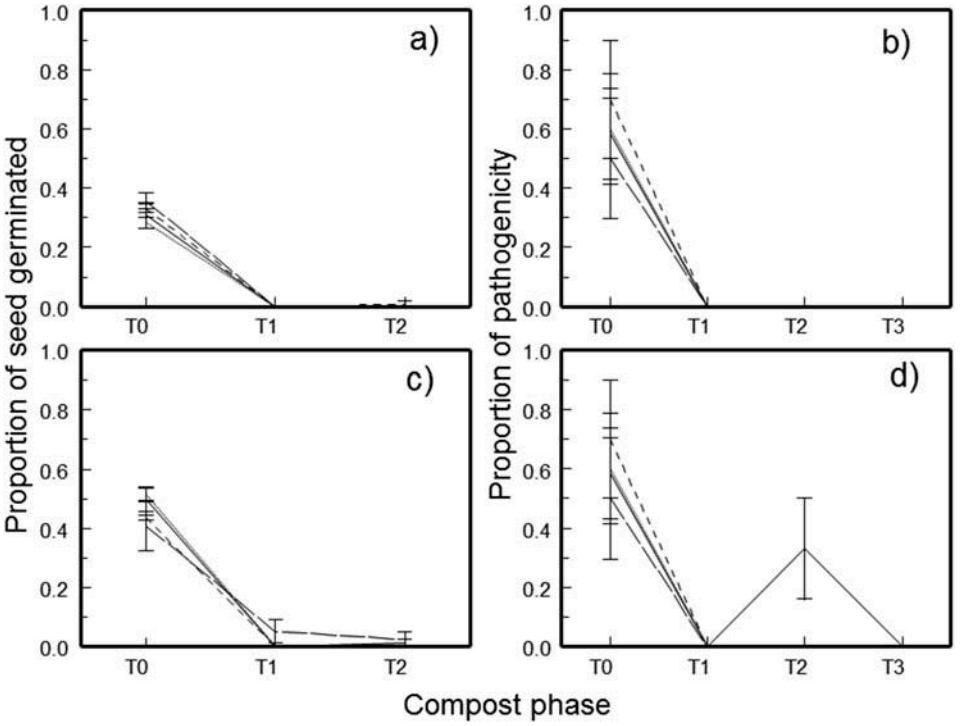

FIGURE 2 Pest viability at compost stages. T0: formation of the pile; T1 when NOS were first met; T2 the end of the thermophilic phase when the temperatures drop below 55°C; and T3 the mid-cure when temperatures drop below 38°C. Proportion of giant crab grass (*Digitaria sanguinalis*) seed germinated (left column) and pathogenicity of *Alternaria brassicinae* (right column) for mesh bags that allow both heat and microbes (top row) and solid plastic bags to allow only heat and no microbes (bottom row). Treatments are represented by line patterns (solid = manure–silage; long dash = hay; short dash = softwood; dotted = hardwood). Means ±1 S.D. are illustrated for $n = 3$ per replicate × 3 reps = 9 per time. Crab grass seed germination prior to insertion into compost piles was 34%.

TABLE 2 Two-way Kruskal-Wallis results of extracellular enzyme activity (Fisher statistic values are illustrated)

Dependent variables[a]	Treat ($df = 3$)	Time ($df = 4$)	Treat × time ($df = 12$)
αG	7.96***[b]	15.66***	2.50*
βG	6.87***	10.92***	1.97*
NAG	3.44*	2.66*	2.11*
LAP	7.23***	14.08***	4.69***
Perox	0.65[n.s.]	86.42***	2.14*
Urease	5.47**	3.00*	1.69[n.s.]

[a]α-1,4-glucosidase (αG), β-1,4- glucosidase (βG), β-1,2-N-acetylglucosominidase (NAG), peroxidase (Perox), L-leucine aminopeptidase (LAP).

[b]n.s.: $p > 0.06$, $^{*}p \leq 0.06$, $^{**}p \leq 0.01$, $^{***}p \leq 0.001$.

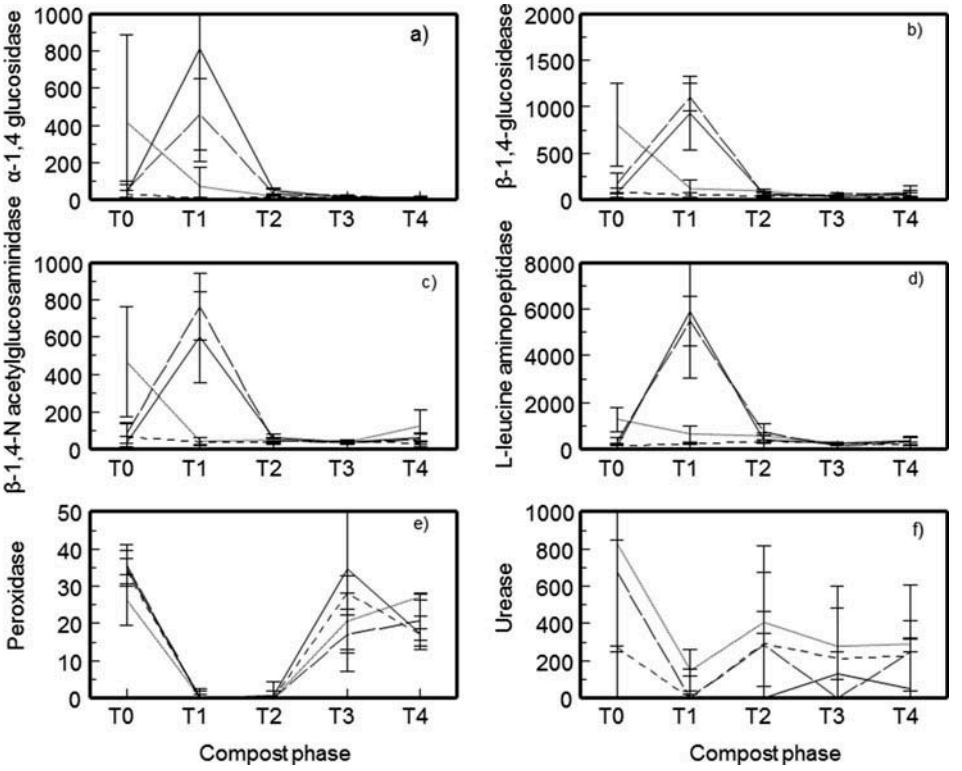

FIGURE 3 Activity (nmol g^{-1} h^{-1}) of a) α-1,4 glucosidase, b) β-1,4-glucosidase, c) β-1,4-N-acetylglucosaminidase, d) L-leucine aminopeptidase, e) peroxidase, f) urease at four phases during composting. T0: formation of the pile; T1 when NOS were first met; T2 the end of the thermophilic phase when the temperatures drop below 55°C; T3 is mid-cure when temperatures drop below 38°C; and T4 the end of cure, when aeration as a result of turning the pile, no longer induces an increase in temperature. Line patterns represent contrasting enzyme recipes (solid = manure–silage; long-dash = hay; short-dash = softwood; dotted = hardwood).

(Figures 4b and 4d). The same pattern occurred at the Riverside farm except the hardwood treatment suppressed disease more than hay or manure–silage treatments in both years (Figures 4a and 4c).

DISCUSSION

Organic certification requires compliance with NOS that recommend a minimum of 15 days of temperatures exceeding 55°C to destroy pathogens and weed seeds. This recommendation exceeds temperatures in cattle manure composting known to kill *Escherichia coli* and *Salmonella enteritidis* (Lung et al. 2001). The concern is that most farmers do not follow

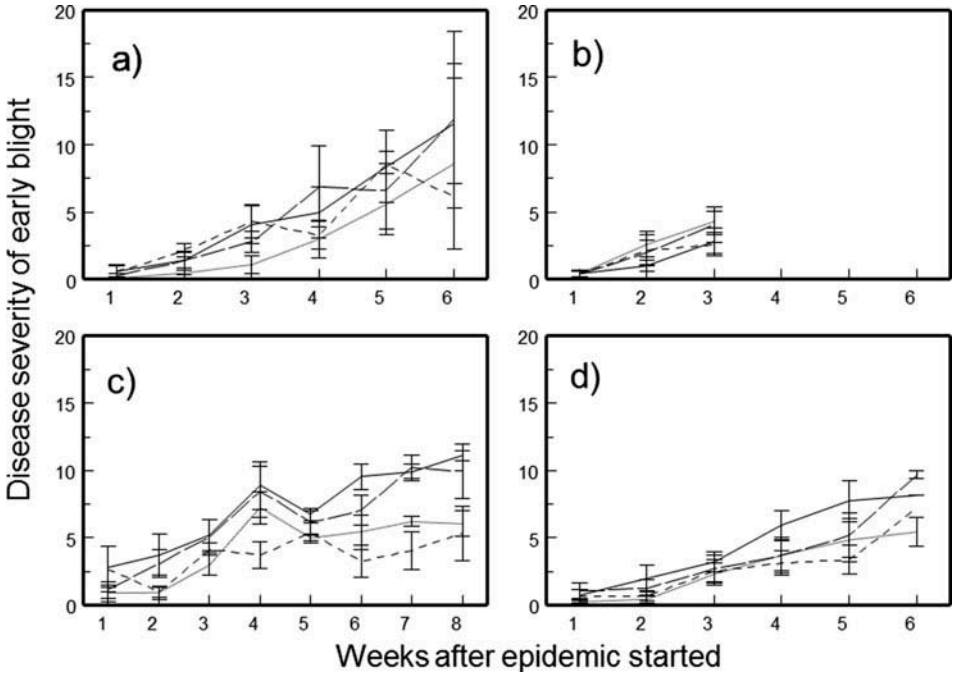

FIGURE 4 Disease progress curves. Disease severity of early blight in 2011 (top row) and 2012 (bottom row) at two farms (left column: Riverside; right column: Intervale). Treatments are represented by line patterns (solid = bare; long dash = manure–silage; short dash = hay; dotted = hardwood). Disease was quantified using a categorical scale related to the number of lesions per leaf: 1 (≤3 lesions), 2 (4–6 lesions), 3 (>6 or many lesions), 4: severe. Severity per plant was the sum of values for all symptomatic leaves per plant. Means ±1 S.D. are illustrated. Blocks were replicated through time and space, so time reflects relative phenology. Time values correspond with the following calendar dates at Intervale Community Farm (August 9, 19, 23 in 2011; July 23, 31, August 6, 13, 21, 27, and September 3 in 2012) and Riverside Farm (August 8, 17, 22, September 6, 12, and 19 in 2011; July 19, 27, August 3, 9, 15, 25, 29, and September 6 and 13 in 2012).

these recommendations. In Vermont, dairy farmers may attempt to compost manure (17:1 C:N ratio) but have insufficient C to develop an appropriate ratio, or do not turn the pile frequently enough to reach proper aeration and temperatures. Attainment of these temperatures require a higher C:N ratio as attained in the hay (23.2:1), softwood (30:1), and hardwood (34.2:1) treatments. Compost recipes, including the farmer control of manure–silage, will eventually negate viability of the early blight pathogen and crabgrass seed once NOS temperature and pile turning standards are met, which is represented by our T1 sampling. However, achievement of T1 required 5 months for the manure treatment compared to 1 or 2 months for hay, softwood, and hardwood recipes. The manure–silage piles were formed with denser and more homogenous materials and were more difficult to aerate than other treatments.

Thermophilic Kill on Pathogens and Weeds

Heat alone negated weed seed viability by the end of the thermophilic phase (T2) in most cases. However, the activity of heat plus microbes killed weed seeds faster (by T1). Pathogenicity of *A. brassicinae* was eliminated when exposed to heat alone or heat and microbes combined at T1 with one exception. Some pathogenicity still remained at T2 in the manure–silage treatment. Heat and microbes are necessary to insure degradation of pathogen inoculum and weed seeds within the NOS (T1).

One explanation for decreased pathogen virulence and seed viability in samples exposed to both heat and microbes is the activity of the hydrolytic enzymes degrading components of the weed seed coat and the fungal cell wall (Hadar and Papadopoulou 2012). These enzymes degrade labile forms of C, from simple sugars and starch to cellulose (Hoitink and Boehm 1999). This study supports this explanation but indicates that the source of C affects the timing and magnitude of hydrolytic enzyme activity (de la Cruz et al. 1993). While hydrolytic enzymes in the hardwood treatment at T0 suggest labile substrates were present on the surface of the hardwood component before pile formation, their concentration in the softwood and hardwood treatments, from T1 to T3, indicates the limited availability of labile substrates throughout the composting process. In contrast, hydrolytic enzymes in the manure–silage and hay treatment suggest that labile substrates were more abundant throughout the pile because their activity continued to increase through T1. One of these hydrolytic enzymes, NAG, is known to degrade chitin, a constituent of *Alternaria* cell walls. This concept has been applied to developing varieties of broccoli resistant to *A. brassicicola* through biotechnology by inserting a *Trichoderma harzianum* endochitinase gene (Mora and Earle 2001). The subsequent down-regulation of hydrolytic enzyme activity from T1 to T2 signals the end of the thermophilic phase when the concentrations of highly usable substrates are depleted and, thus, limit the growth and heat output of microbial respiration in the pile.

Curing Phase

Transferring disease suppression from compost to the field requires re-colonization by desired biocontrol species during the curing phase. These disease antagonists are associated with the presence of lignin, sustained or increasing levels of oxidative enzymes (Hoitink and Boehm 1999). Peroxidase enzyme activity at T3 suggests that lignin utilization is limited until the curing phase. The presence of lignin during the curing phase plays an important role in determining what mesophilic microbes colonize the pile after the curing phase. For example, composts with lignocellulosic materials are typically colonized by *Trichoderma* (Hoitink and Boehm 1999). Although we did not find *Trichoderma* (Hypocreaceae) in our composts, other fungi in

the Hypocreales were common at the end of the curing process, for example, *Acremonium* (Neher et al. 2013).

Although the reason is unclear, the manure that was common to all treatments is a likely source of the initial activity of peroxidase at T0. The manure–silage treatment had a smaller C:N ratio than hay, softwood, and hardwood treatments suggesting ample nitrogen supply. This study supports this claim because urease activity indicates a limitation of N above and beyond what is made available by other enzymes. Urease activity was negligible in the manure–silage treatment until the curing phase. In contrast, urease produced was greatest in the hardwood treatment throughout the composting process. Urea can be converted rapidly to ammonia by urease. Ammonia has been credited for killing pathogens such as *Verticillium dahlia* in soil (Bailey and Lazarovits 2003). Furthermore, many manures have sufficient concentrations of volatile fatty acids to be considered potentially pathogen suppressive themselves (Bailey and Lazarovits 2003).

The variation present in the data reflects the reality of heterogeneity within treatments and among replications. The general trends of these data are more accurate and valuable than the individual measurements. The trends support the temporal patterns of microbial enzyme activity predicted by successional stage of decomposition observed previously (Vargas-García et al. 2010).

Field Trials on Disease Suppression

Compost preparation in this study involved a complete thermophilic phase and curing to allow natural colonization by biocontrol organisms. To our knowledge, this is the first report on use of compost to suppress early blight on whole plants (Ntougias et al. 2008; Noble 2011). At one of two farms, there was a trend toward suppressed early blight incidence and severity when hardwood compost was applied in comparison to manure–silage, softwood or hay. This trend was consistent for two years across farms, fields within a farm, and across crops with contrasting generation times (i.e., broccoli and cabbage are 60 and 90–100 day crops, respectively). There are at least two factors that contribute to the variability that diminished our ability to statistically distinguish levels of disease severity among hardwood, hay and manure–silage compost treatments. First, there is a dilution effect that occurs when top dressing of compost mixes with underlying soil (Buckley and Schmidt 2003). Furthermore, compost treatments were added to soil already mixed with compost chosen and incorporated by the farmer prior to planting. The farmer compost was spread across the entire experiment, including the bare treatment. Therefore, differences or changes observed represent the difference between the farmer compost and the compost treatments applied. Secondly, effect of compost on disease severity varied by the time of the growing season. Compost was more effective as a disease

suppressive substrate later in the season when temperatures were hotter. Either warmer temperatures or older age could add stress to the plants and, thus, accentuate disease severity.

As typical with integrating studies in a farmer's field, timing was occasionally imprecise. For example, one block of treatments was applied before cultivation and was incorporated into the soil. Under this circumstance, the hardwood compost continued to suppress disease and was as effective as the other blocks when compost was added after cultivation. This result indicates a microbial mechanism and not simply a physical barrier.

CONCLUSIONS

Application of compost shows promise for reducing disease severity of early blight on brassica crops in New England. Because compost effectiveness is disease-specific (Termorshuizen et al. 2006; Ntougias et al. 2008; Noble 2011; Hadar and Papadopoulou 2012), the next logical step will be to evaluate the most effective approaches to managing other widespread diseases faced by organic farmers on brassicas (e.g., Xanthomonas black rot) and other vegetables and small fruit, for example, potato scab, *Rhizoctonia* root rot, Verticillium wilt (Bailey and Lazarovits 2003). Using compost as part of the management package will incorporate nutrients and organic matter on the farm and saves purchase of external inputs. By analyzing the composting methodology, we can better calibrate the most effective approaches, while also potentially helping growers realize additional benefits.

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