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Composting Reduces Seed Viability of Garlic Mustard (*Alliaria petiolata*) and Common Buckthorn (*Rhamnus cathartica*)

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Composting is a common practice for management of herbaceous yard materials and other decomposable materials. Although composting is promoted by state agencies for many materials, a notable exception is invasive plants due to concerns about spreading propagules with the finished product. To address this issue, we measured the viability of garlic mustard and common buckthorn seeds exposed to turned or static composting methods. Piles were built in 2012 and 2013, and seeds from both species were inserted and monitored for viability. Seed viability was reduced rapidly regardless of year, composting method, or species. Viability of seeds was zero within 7 and 15 d of composting for garlic mustard and common buckthorn, respectively, in both years. Results indicate that composting facilities are able to render the seeds of these invasive plants nonviable using either composting method because inactivation is within the composting timeframes typically practiced by the industry. This includes the process to further reduce pathogens (PFRP) with thresholds of 55 C for 15 d for the compost management process used for this trial.

Nomenclature: European buckthorn, *Rhamnus cathartica* L.; garlic mustard, *Alliaria petiolata* (Bieb.) Cavara & Grande.

Key words: Composting, invasive, seed viability.

Invasive plants pose a challenge to land mangers because they can reproduce rapidly, compete with desirable vegetation, and alter ecological services in areas where they become established (Mack et al. 2000). Management efforts have focused on minimizing these impacts through a wide range of control options. Although several options to manage invasive populations exist, many involve physical removal of aboveground portions of plants (e.g., hand pulling, mowing, or cutting the stem). Aboveground material that is removed can contain viable propagules (seed or perennial organs). These propagules can sustain populations if left in controlled areas or lead to further spread if the material is transported off site. Land managers typically pile this material at the location or transport it to another location. Landfills are often recommended for disposal to prevent establishment and spread of these propagules (City of Madison 2014; Wisconsin Department of Natural Resources 2010). Although this is considered an effective best management practice (BMP) (Wisconsin Council on Forestry 2014), large amounts of invasive plant material can be deposited in landfills. For example, a local Garlic Mustard Challenge in Michigan annually pulls over 90,000 kg (99 tons) of vegetation (The Stewardship Network 2014). One study of buckthorn-dominated forests in southern Wisconsin estimated aboveground biomass at 146 metric tons ha^{-1} (65 tons ac^{-1}) (Mascaro and Schnitzer 2011). These values illustrate that removal efforts can generate substantial volumes of material being disposed of at landfills.

Composting invasive plant material to inactivate viable invasive plant seeds may be a workable alternative to landfilling. Composting has been shown to be effective at inactivating a range of plant species by exposing seeds to elevated temperatures for extended periods of time (Eghball and Lesoing 2000; Egley 1990; Larney and Blackshaw 2003; Meier et al. 2014; Tompkins et al. 1998). However, the effectiveness of composting varies among plant species. For example, seed viability of redroot pigweed (*Amaranthus retroflexus* L.) was reduced to zero in 4 wk (Eghball and Lesoing 2000), but 14% of velvetleaf (*Abutilon theophrasti* Medik.) seeds remained viable after a 4 to 5 mo composting process (Tompkins et al. 1998). Although several aquatic invasive plants have been found susceptible to composting (Meier et al. 2014), we are not aware of studies on invasive terrestrial plant seeds that are common in

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Management Implications

Land managers will continue their efforts to control the spread of invasive plants in natural areas. These efforts will generate a volume of plant material that needs to be managed as a waste. This research demonstrates that the use of landfilling for disposal is not the only option available for garlic mustard- and European buckthorn-infested material. Well-managed compost facilities are more than capable of achieving the temperatures necessary to render seeds from these species unviable. Placement of the materials within static managed piles with proper moisture and carbon-to-nitrogen ratios create conditions that are favorable for the destruction of seeds from these species in a short time period. An additional practice that could easily be adopted would be to require placement of infested material in the center of the compost piles and leave them unturned for a period of up to 7 d. This would expose any seeds present to maximum pile temperatures, thus reducing seed viability while still allowing facility operators adequate time to meet the process to further reduce pathogens (PFRP) turning requirements. Other options for waste management include composting materials on site to produce a soil amendment, thus eliminating the cost of transporting and disposal of plants materials as currently practiced.

Wisconsin. Complete inactivation is critical in Wisconsin and many other states that regulate the movement of invasive plant propagules (Boyce 2003).

The objective of this study was to determine the effectiveness of two methods of composting commonly used by municipalities in eliminating viability of garlic mustard [*Alliaria petiolata* (Bieb.) Cavara & Grande] and European buckthorn (*Rhamnus cathartica* L.) seeds. These species were chosen because they are common invasive plants in Wisconsin and across the midwestern United States, grow in urban environments (and thus are likely to be introduced into the waste management system), and have a range of fruit development and structure that might affect survival during the composting process. We hypothesized that large-scale composting eliminates seed viability if compost temperatures reach and maintain recommended temperatures for 15 d. Accordingly, we placed garlic mustard and buckthorn seeds into static and turned compost piles, and measured the viability of seeds over time in 2 successive yr. To ensure results were applicable to the composting industry, compost pile temperature data were obtained from nine licensed compost facilities across Wisconsin and compared to research pile temperatures to confirm that trial conditions corresponded with industry practice.

Materials and Methods

Compost Pile Construction. Compost piles were constructed and managed at the University of Wisconsin's West Madison Agricultural Research Station in Madison, Wisconsin (43.061°N, 89.533°W). Piles were constructed and managed for 120 d (July 17 through November 14) in 2012 and for 30 d (June 19 through July 19) in 2013. Precipitation was atypical in both years. Precipitation during the trial periods was below 30-yr average (76%) during 2012 and above 30-yr average (170%) during 2013. Air temperatures varied, but were within 5% of 30-yr daily air temperature average over both years. Compost piles were composed of leaves from deciduous trees collected the previous fall, freshly chopped grass, freshly chopped corn (2012 only), corn stalks (2013 only), and woodchips. Different proportions of material were used in 2012 and 2013 due to availability of feedstocks. Materials were mixed together in ratios intended to meet carbon to nitrogen ratios of 30 : 1 and moisture levels of 50 to 60%, simulating typical licensed compost facility requirements. The resulting piles were 1.5 m (5 ft) tall, 3 m wide at the base and 10 m in length.

Compost and Feedstock Sampling. The materials used for building the compost piles and the initial compost mix were sampled and analyzed according to test methods for the evaluation of compost and composting (TMECC; Composting Council Research and Education Foundation 2002). A 2-L sample of the initial compost mix was collected and combined from fifteen sites randomly selected from each pile. Samples were sent to the Pennsylvania State Agricultural Analytical Services Lab for analysis of solids/moisture, organic matter, pH, soluble salts, total nitrogen, total carbon, and carbon : nitrogen ratio. TMECC methods used characterized all analytes except solids and moisture. For solids and moisture, method 2504B from the Standard Methods for the Examination of Water and Waste Water (American Public Health Association 1992) was utilized.

Experimental Design. A randomized design with three replicates was used, requiring that a total of six piles be constructed each year. Raw materials were placed into piles and mixed thoroughly with a compost windrow turner (Aeromaster PT-130, Tampico, IL), then randomly assigned to a static or turned management method. Turned piles were managed according to United States Environmental Protection Agency (EPA) process to further reduce pathogens (PFRP), which requires that temperatures in excess of 55 C (131 F) are maintained for 15 d, and piles are to be turned five times within the 15-d time period (EPA 2013). Static managed piles remained unturned after creation. Static piles were included in this study because they represent the most common method of compost management found at licensed compost facilities in Wisconsin (Van Rossum 2012).

Seed Packet Construction and Placement. Garlic mustard and European buckthorn seeds were collected from local populations in 2011, and stored under refrigeration until use. Seed packets constructed from nylon mesh screen material were 7.5 cm^2 (1.2 in^2) with seams sealed with an impulse heat sealer. Seed packets for garlic mustard contained 50 seeds, whereas the buckthorn packets contained 40 seeds extracted from berries. Seed packets were placed in the center of each pile, 30 cm (1 ft) from the surface of the pile base, and 30 cm from the surface of the top of the pile. In 2012, six seed packets from each species were placed at each of these three positions. In static piles, the packets remained at these positions until removed. In turned piles, the packets were removed prior to pile turning and then the seed packet was reinserted at a random position immediately after turning to simulate the process in a windrowed pile. In 2013, five seed packets were placed in only two positions: at the center of the pile, and 30 cm above the pile base.

Turning Schedule. During both years, turned piles were turned five times within the initial 15 d of the composting process. Piles created in 2012 were turned on July 20, July 24, July 27, July 30, and August 1. Two additional turnings were done (August 21 and September 11) to add water to return moisture content to recommended levels. Piles created in 2013 were turned on June 21, June 24, June 28, July 1, and July 3 with no additional turning because adequate moisture was maintained due to above normal rainfall.

Temperature Monitoring. Compost pile temperature was measured during the trial for each pile and averaged across three locations (1, 5, and 9 m from the north end of the windrow) at a 100-cm depth using a dial thermometer with a 121-cm probe (ReoTemp, San Diego, CA). Temperature was measured daily for the first 15 d or until PFRP requirements were met, then on Mondays, Wednesdays, and Fridays through d 45 of the trial, and then weekly beyond d 45.

Seed Packet Removal. Seed packets were removed on a set schedule to test seed viability. In 2012 seeds were removed 7, 15, 30, 60, 90, and 180 d after initial placement. Based on results from 2012, the 2013 trial focused on the early stages of the composting process and was sampled 1, 4, 7, 15, and 30 d after initial placement. Upon removal, the packets were stored under refrigerated conditions until they were evaluated for viability. Packets were evaluated within 7 d of removal from the pile.

Seed Viability. Seed viability was determined by the tetrazolium seed viability test using a 1% (w/v) solution of 2,3,5-triphenyl tetrazolium chloride (TZ) (Miller and Peters 2010). Separate procedures for using the TZ assay were followed for each species. For garlic mustard, seeds were soaked in deionized water for 24 h, then a small portion of the distal end of each seed was cut with a scalpel to enhance uptake of TZ. Afterward, seeds were immersed in the TZ solution in the dark at 23 C (73 F) for 24 h (Sosnoskie and Cardina 2009). After incubation, seeds were cut longitudinally through the embryo to detect the insoluble formazan product. A seed was deemed viable if the embryonic axis was completely stained and more than one-half of the cotyledons were stained. European buckthorn seeds were imbibed in deionized water for 24 h, then the seed coat was broken by placing each seed in a vise and gently turning until the seed coat cracked. Seeds were then returned to water for 24 h, followed by the TZ solution for 24 h under dark conditions at 30 C. To be considered viable, the buckthorn embryos needed to be completely stained, with the exception of the distal ends of the radicle and cotyledons (Youngblood 2008).

Data Collection from Licensed Compost Facilities. During summer 2013, facility managers at 218 licensed compost facilities were contacted to solicit interest in placing a temperature data logger within one of the facilities' active compost piles. A total of 14 facilities responded to the solicitation from which 10 were randomly selected. Facility managers were mailed HOBO® pendant-type data loggers (Onset Computer Corporation, Pocasset, MA) to monitor compost pile temperatures. The data loggers recorded pile temperature every 4 h beginning at 3 pm on June 17, 2013. This date corresponded with the start date of the 2013 trial, which also utilized data loggers to collect temperature data from the six compost piles utilized for the 2013 trial under either static or turned management.

Managers were instructed to place the data logger approximately 1 m off the ground and 30 cm in from the surface of the compost pile at their facility that had most recently received feedstock materials. Managers were also instructed to remove data loggers if piles were turned, then return to the pile after turning. Data loggers were removed on August 19, 2013 (60-d residence time) and returned in the envelope provided. Information was collected on feedstock composition, and amount of time material was composted prior to data logger insertion, as well as other pile management activities. Procedures were followed as stated above for the research piles, except data loggers were removed after 30 d of composting.

Data analysis focused on the 30 d in which the 2013 compost trial was taking place because 2012 data indicated this time interval was sufficient to render garlic mustard and buckthorn seeds nonviable. Temperature data from the compost facilities and the 2013 compost trial were converted to composting degree day (CDD) developed by Larney et al. (2003) (Equation 1).

$$CDD = (T_{min} + T_{max})/2 - 40 \qquad [1]$$

This model accounts for the intensity of temperature and duration of the exposure of materials to this

Table 1. Analysis results of initial compost pile composition for analytes of interest for the management of the composting process. Samples were composite samples collected according to test methods for the examination of composting and compost (TMECC; Composting Council Research and Educational Foundation 2002; 02.01 Field Sampling of Compost). All parameters were within acceptable ranges for composting in both years.

Analyte (Unit)[a]	Trial year 2012	Trial year 2013
pH	7.0	6.3
Soluble salts (mmhos/cm)	2.87	3.28
Solids (%)	53.9	41.7
Moisture (%)	46.1	58.3
Organic matter (%)	72.3	84.5
Total nitrogen (%)	1.83	1.18
Ammonium nitrogen (%)	0.05	0.02
Carbon (%)	35.9	32.5
Carbon : Nitrogen	19.9	27.5

[a] Test results are on a dry-weight basis, except for solids and moisture. Test methods followed TMECC 2002 methods except for solids and moisture, which utilized Method 2504B (American Public Health Association 1992).

temperature. CDDs were calculated by adding the piles' daily maximum (T_{max}) to the daily minimum temperature (T_{min}), dividing the sum by two (daily mean temperature) and subtracting 40 C. If the mean temperature was < 40 C, then CDD for that day was zero. The CDDs were then summed over the course of the 30-d period to produce an accumulated CDD. The 40 C was chosen as it represents the lower threshold for thermophilic bacteria common to the composting process (Ryckeboer et al. 2003).

Statistical Analysis. The Fishers Exact Test was used to test for differences in proportion of seed viability and if treatments differed from zero, for each of the sampling periods and species. This test was chosen because results were not normally distributed and this test does not have an assumption of normality (McDonald 2009). Tests were performed using JMP software version 11.0.0 (SAS Institute Inc., Cary, NC), and differences were considered significant if $P < 0.05$.

To assess the effects of composting methods on time on invasive plant seed viability, we used regression analysis. We determined the relationship between days of composting on the invasive plant seed viability regardless of year. The effect of composting on seed viability has been previously described utilizing an exponential decay model of the form shown in Equation 2:

$$y = a\exp(-bx) \qquad [2]$$

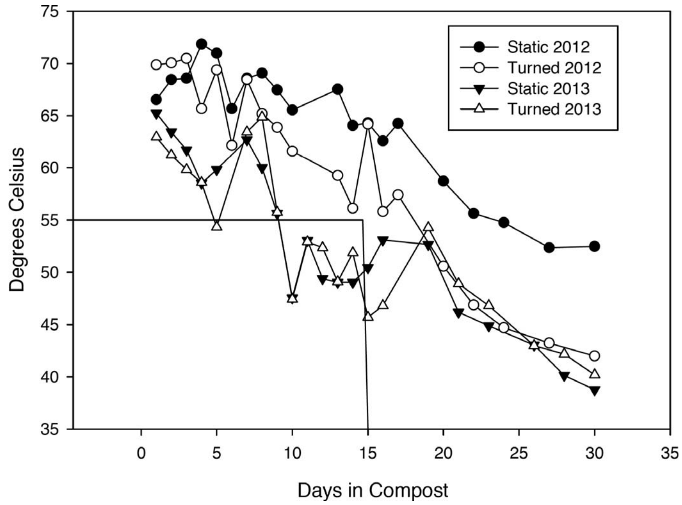

Figure 1. Effect of year and compost treatment on pile temperature. Values were the average of three measurements per pile of compost. Pile temperature measured at a depth of 1 m from the top of piles. The horizontal line at 55 C and the vertical line at 15 d represent the limits of the process to further reduce pathogens (PFRP) (EPA 2013).

where y = seed viability, x = days of composting, a = initial seed viability, and b = decay rate of seed viability (Larney and Blackshaw 2003). Relationships were explored for each species using initial seed viability as d 0 viability. Regression analysis was performed using Sigma Plot for Windows version 12.3 (Systat Software Inc, San Jose, CA).

The CDD data were analyzed via linear regression (time vs. accumulated CDD) with the y-intercept set to 0.

The slope was calculated from the linear regression and tested using the Student's t test to determine if differences existed between the facilities and the 2013 research trial. The null hypothesis (calculated slopes are equal) were to be rejected if $P < 0.05$. All statistical analyses were performed using JMP software version 11.0.0 (SAS Institute Inc.).

Results and Discussion

Composting. The compost pile feedstock carbon-to-nitrogen ratio (C : N) differed between years with 20 : 1 in 2012 and 28 : 1 in 2013 (Table 1). This likely varied due to changes in feedstock between years. The 2012 trial was conducted in the midst of a prolonged dry period, reducing the availability of feedstock high in nitrogen (e.g., grass clippings). The dry period of 2012 also contributed to fewer fall leaves being available for the 2013 trial. Although compost feedstock material varied between years, this can be viewed as similar to the challenges faced by compost facility operators, because they are not always able to control the flow of feedstock into their facilities. Although feedstock composition varied, the analysis results of pile

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Table 2. Effect of composting on garlic mustard seed viability in 2012. Results are the average viability from 50 garlic mustard seeds replicated three times over a 120-d period. Packets were placed in the center of each pile, 30 cm from the surface of the pile base, and 30 cm from the surface of the top of the pile within the pile. Garlic mustard seed viability at the initiation of this experiment was 76%.

Treatment	Position	Days in compost pile 7	15	30	60	90	120
		% Seed viability*					
Turned[a]	All	0.2	0	0	0	0	0
Static	Center	0	0	0	0	0	0
Static	Bottom	0	0	0	0	0	0
Static	Top	0	0	0	0	0	0

[a] Because the turned treatment pile was mixed, values are averaged across all three positions for this treatment.

*Indicates where seed viability did not differ from zero; Fisher Exact Test, alpha = 0.05, two-sided.

composition found the parameters were within reasonable ranges for rapid composting (Rynk et al. 1992).

Moisture content of feedstock can directly affect composting rates. Dry conditions in 2012 resulted in compost pile moisture levels below the recommended level of 40% (Rynk et al. 1992). To correct for this, water was added using the compost windrow turner to the turned piles to return moisture levels to recommended levels. Water was not added to the static piles; thus, composting rates likely were reduced in 2012 for this treatment. In contrast, higher-than-average precipitation in 2013 led to compost piles with moisture content above optimal levels for both treatments. High moisture content likely resulted in reduced airflow into the piles, reducing composting temperature (Figure 1) and rate.

Temperature and Pile Management. Pile temperatures were higher during the 2012 season compared with 2013 (Figure 1). Temperatures remained above the target temperature of 55 C for 17 d in 2012 for the turned piles and 22 d in the static piles. During 2013, a rain event resulted in the pile temperatures dropping below 55 C on the fifth day in the turned treatment, but as piles dried, temperature rose above 55 C within 48 h. In contrast, the static pile temperatures remained above 55 C for 9 d. As a result, PFRP temperature requirements (55 C for 15 d) were not achieved for the turned treatment in 2103.

Seed Viability. Seed viability was reduced to zero in 85 and 63% of the seed packets for garlic mustard and buckthorn, respectively, regardless of year, treatment, exposure, or packet position (Tables 2–5). Viability was initially influenced by placement in the compost pile as static piles retained some viability of garlic mustard seeds at the bottom of piles 4 d after composting in 2013 ($P < 0.05$) (Table 3) and buckthorn seeds in the center of piles 7 d after compositing in 2012 (Table 4). Others have found similar results (Daugovish et al. 2007; Egley 1990) and postulated that they were due to temperature differences within the pile. However, differences did not persist, and by 15 d, viability was similar to zero for both species across years, treatments, and positions within the pile.

The exponential decay model fit the relationship between viability and composting duration for both garlic mustard and European buckthorn ($r^2 > 0.98$). Because the

Table 3. Effect of composting on garlic mustard seed viability in 2013. Results are the average viability from 50 garlic mustard seeds replicated three times over a 30-d period. Packets were placed in the center of each pile and 30 cm from the surface of the top of the pile within the pile. Garlic mustard seed viability at the initiation of this experiment was 62%.

Treatment	Position	Days in compost pile 1	4	7	15	30
		% Seed viability				
Turned	Center	0*	0*[a]	0*[a]	0*[a]	0*[a]
Turned	Bottom	37				
Static	Center	0*	0*	0*	0*	0*
Static	Bottom	20	16	4*	1*	0*

[a] Because the turned treatment was mixed, values are averaged across both locations.

*Indicates where seed viability did not differ from zero; Fisher Exact Test, alpha = 0.05, two-sided.

Table 4. Effect of composting on European buckthorn seed viability in 2012. Results are the average viability from buckthorn seeds replicated three times over a 120-d period. Packets were placed in the center of each pile, 30 cm from the surface of the pile base, and 30 cm from the surface of the top of the pile within the pile. Buckthorn seed viability at the initiation of this experiment was 85%.

		Days in compost pile					
Treatment	Position	7	15	30	60	90	120
		% Seed viability					
Turned[a]	All	1*	0*	0*	0*	0*	0*
Static	Center	12	4*	3*	0*	0*	0*
Static	Bottom	0*	0*	0*	0*	0*	0*
Static	Top	0*	3*	2*	1*	0*	0*

[a] Because the turned treatment pile was mixed, values are averaged across all three positions for this treatment.

* Indicates where seed viability did not differ from zero; Fisher Exact Test, alpha = 0.05, two-sided.

data were not normally distributed, we did not test for differences in the response between pile management methods, but compared across methods. We found a rapid reduction in viability, with the decay rate of 1.56 ($P < 0.001$) and 2.13 ($P < 0.001$) for garlic mustard (Figure 2) and buckthorn, respectively, (data not shown). The decay rates observed for garlic mustard and buckthorn were greater than those previously calculated for wild buckwheat (*Polygonum convolvulus* L.) (0.04 to 0.06), redroot pigweed (0.18 to 0.21), green foxtail [*Setaria viridis* (L.) Beauv.] (0.18 to 0.49), and wild oat (*Avena fatua* L.) (0.18 to 0.65) (Larney and Blackshaw 2003). Regression analysis found 1 d of composting reduced viability by 79% for garlic mustard and 88% for buckthorn, with predicted 99% inactivation after 3 d for both species. Viability persisted longer for buckthorn than for garlic mustard, but decay rates were higher for buckthorn seeds, although not statistically different. The higher survival of buckthorn seeds might be due to the harder seed coat compared with that of garlic mustard. Variation in seed survival at temperatures obtained through the composting process has been attributed to seed coat water permeability, seed dormancy, and seed moisture content (Egley 1990; Nobel et al. 2011). Additional factors beyond temperature, such as phytotoxic leachates from the composting process, create additional complexity within the compost time/temperature/seed viability relationship (Larney and Blackshaw 2003).

Garlic mustard results are consistent with Larney and Blackshaw (2003) for wild mustard (*Sinapis arvensis* L.), a related species. They found wild mustard seeds exposed for 7 d in a manure-based compost yielded zero viable seeds. Although an example of the effects of composting on seed viability from a woody plant could not be found, our results are comparable to a soil solarization study conducted on seeds of orange wattle [*Acacia saligna* (Labill.) H. L. Wendl.], a woody plant found to be invasive in Mediterranean ecosystems. With this species, Cohen et al. (2008) found that nondormant seeds treated at 50 C for 72 h had 0% viability.

Data Collection from Licensed Compost Facilities. Nine of ten data loggers were returned, although only seven facilities provided management information. Six of the nine facilities were included in the CDD analysis. Three were excluded because the data loggers were placed into compost piles that were established > 30 d prior to

Table 5. Effect of composting on European buckthorn seed viability in 2013. Results are the average viability from 40 buckthorn seeds replicated three times over a 30-d period. Packets were placed in the center of each pile and 30 cm from the surface of the top of the pile within the pile. Buckthorn seed viability at the initiation of this experiment was 69%.

		Days in compost pile				
Treatment	Position	1	4	7	15	30
		% Seed viability				
Turned	Center	6	5*[a]	0*[a]	0*[a]	0*[a]
Turned	Bottom	23				
Static	Center	0*	0*	0*	0*	0*
Static	Bottom	8	20	3*	5*	0*

[a] Because the turned treatment was mixed, values are averaged across both locations.

* Indicates where seed viability did not differ from zero; Fisher Exact Test, alpha = 0.05, two-sided.

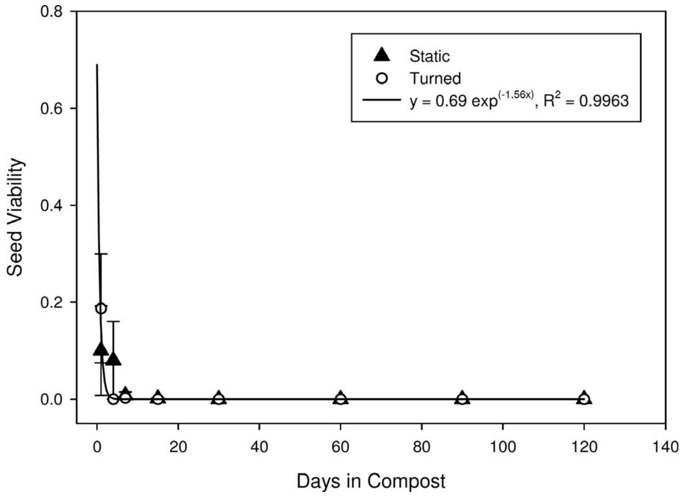

Figure 2. Effect of composting on garlic mustard seed viability over 2 yr and across treatments. Analysis using an exponential decay regression line fit to data points for each seed removal date. Because experimental design varied between years, the resulting number of data were 12 for d 1 and 4; 30 for d 7, 15, and 30; and 18 for d 60, 90, and 120. Seed packets each contained 50 seeds within each pile at various positions. Treatment differences were not tested, because data were not normally distributed. Bars represent standard error.

data logger insertion. These piles were not in the active phase of the composting process (Rynk et al. 1992); thus, they did not meet our recommendations for composting invasive plant propagules. Five of the seven compost facilities reported actively managing the composting process by turning their windrows, whereas two utilized a static pile system. In turned piles, piles were turned an average of three times, and temperatures were > 55 C for an average of 26 of the first 30 d that the data loggers were in the piles. Each of the six facilities whose temperature data was fully analyzed met the temperature requirements for PFRP.

Regression analysis was performed to determine the relationship between time and accumulated CDD for each facility ($n = 6$), compared with compost piles from 2013 research trials. Data for research trials were combined across turned and static treatments because no differences in slope was detected between treatments (data not shown). A larger slope was found at four of the six compost facilities (20.1 to 24.8) as well as the average of all facilities (20.2) compared with field trails (14.3) in 2013 ($P < 0.029$) (Table 6). The larger slope of individual and grouped licensed compost facilities indicates that compost degree-days accumulated faster than the research trial in 2013. One of the goals of this research was to replicate the conditions that occur at compost facilities in Wisconsin, utilizing the same or similar compost feedstock. Although we were not successful in this at most sites, the faster accumulation of CDD of licensed compost facilities suggest that inactivation of invasive plant seeds would have been similar or more effective at compost facilities than in our research trials.

The seed viability for both species in all treatments and trial years was reduced to zero within the typical composting times for the methods used in this trial (Rynk et al. 1992). In 2013, although PFRP requirements were not achieved, zero seed viability was reached within the time period of the trial. EPA's PFRP is an industry standard for both temperature requirements and management practices. Compost facilities meeting the PFRP requirements will be able to safely compost garlic mustard and European buckthorn plant debris. These results are consistent with the findings of previous research, which focused on weed seeds commonly found in animal manure that was composted prior to being used for agricultural purposes (Eghball and Lesoing 2000; Larney and Blackshaw 2003; Tompkins et al. 1998).

Achieving PFRP is the first step compost facility operators must take to prevent the spread of these invasive

Table 6. Summary of composting degree day (CDD) linear regression analysis results for participating licensed compost facilities and research trial in 2013. Slope was calculated with the y-intercept set to 0.

Facility	Slope	Differ than research trials (P value)	95% Confidence interval	r^2
F3	16.01	0.345	15.46–16.59	0.9569
F4	15.75	0.420	15.30–16.20	0.9689
F5	24.80	0.001*	24.15–25.45	0.9747
F6	20.11	0.016*	19.84–20.38	0.9938
F7	21.75	0.006*	21.04–22.46	0.9564
F8	22.66	0.003*	22.13–23.19	0.9802
All facilities	20.18	0.029*	19.64–20.72	0.9719
2013 Trial	14.32	—	11.13–17.51	0.9259

*Indicates slopes differed from 2013 trial ($P < 0.05$).

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species. They must also prevent contamination of compost products by implementing procedures that prevent cross-contamination from incoming feedstock and partially composted materials. Facility managers should also monitor and remove any weeds at the compost facility that have the potential to produce propagules that could potentially be deposited onto compost during the curing phase or product storage. Survival of seeds on the surface of static piles might still occur due to lack of exposure to a high enough temperature on the surface of unturned piles. Facilities that utilize static piles should determine if this is occurring by conducting a weed seed analysis of surface compost as described in the TMECC. This analysis is available for any facility wishing to label their compost as weed/invasive plant-free prior to distribution. Further research is needed to assess the viability of seed from other invasive species during composting, as well as for practices at compost facilities that prevent their spread.

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