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Composting of Aged Reed Bed Biosolids for Beneficial Reuse: A Case Study in New Jersey, USA

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ABSTRACT

Reed beds with *Phragmites australis* (common reed) have been utilized to decrease the water, nutrient, and volatile solids content of sewage sludge. An efficient disposal/reuse option was sought for reed bed biosolids accumulated over a 15-year period at a wastewater treatment facility in New Jersey, USA. The study facility had 14 reed beds, each with 1000 wet tons capacity, which were full, and so the solids needed to be removed. Because *P. australis* is considered an invasive species in New Jersey and several other states in the United States, disposal or reuse of solids containing this plant is regulated. Composting was examined as a potential treatment for destroying the plant's reproductive rhizomes. The high temperatures achieved during composting were also tested to determine if regulatory criteria for pathogen reduction could be met, making the composted product suitable for unrestricted land application. Preliminary studies indicated the sludge had stabilized to the point where self-heating did not occur. Among the carbon amendments tested in the laboratory to stimulate compositing activity, *Phragmites* above-ground biomass was determined to be most suitable. In a field test, *Phragmites* above-ground biomass was mixed with reed bed biosolids at a 1:2 (w/w) ratio. The temperatures achieved resulted in complete mortality of *Phragmites* rhizomes. In laboratory tests, rhizomes placed in a drying oven at 50°C for 24 h, or 55°C for 12 h, showed 100% plant mortality. However, under field conditions pile temperatures could not be maintained long enough for the sludge to meet the USEPA 503 biosolids time-temperature pathogen rule requirements for unrestricted land application, even though sample fecal coliform counts did meet regulatory limits.

Introduction

Reed beds are a type of constructed wetland used to dewater and remove nutrients from wastewater sludge (Kuusemets and Lohmus 2005; Toet et al. 2005). Because of efficient dewatering and mineralization achieved at an inexpensive cost compared to conventional dewatering technologies, reed beds are in use worldwide. Nielsen (2008) reported that there are over 140 full-scale reed bed systems operating in Denmark alone. Others have reported operational reed bed systems in the United Kingdom (Edwards et al. 2001), France (Troesch et al. 2008), China (Yubo et al. 2008), Italy (Giraldi et al. 2009), and the USA (Begg, Lavigne, and Veneman 2001; Burgoon et al. 1997; Kim and Smith 1997). Typically, reed beds increase the total solids content to 20–30% from an initial concentration of 1–4%, and can achieve a volatile solids reduction of 25–30% (Uggetti et al. 2010). Begg, Lavigne, and Veneman (2001) reported that reed beds have over 90% removal efficiency for sludge dewatering, total suspended solids, and biochemical oxygen demand, and that nitrates and total phosphorus removal rates were 90 and 80% of the initial concentrations, respectively.

Vegetation commonly used in these treatment systems are emergent aquatic species, such as cattail (*Typha latifolia*), rush (*Scirpus ancistrochaetus*), and common reed (*Phragmites australis*) (Gersberg et al. 1985). Characteristics of common reed, such as fast growth; tolerance to different water levels, drought, and variability of pH and salinity; and deep growing rhizome and root systems, enable this plant to adapt

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to many environments (De Maeseneer 1997). However, these qualities also contribute to the plant's potential to become an invasive species if accidentally released in a habitat where they are non-native.

A 9-million-gallons/day (MGD) (0.4 m^3/s) capacity wastewater treatment plant located in New Jersey has utilized 14 *Phragmites australis* reed beds (1000 t wet sludge/bed) for over 15 years to de-water anaerobically digested sewage sludge. These beds were filled to capacity and the accumulated biosolids needed to be removed so the beds could be reused. Since *P. australis* is identified as an invasive weed species by the United States Department of Agriculture (USDA 2015), the presence of live *Phragmites* rhizomes (reproductive organ) restricted economical disposal and recycling options. Since an objective of reed bed sludge treatment is to obtain a final product suitable for land application, methods of *Phragmites* removal that would be cost effective and environmentally sustainable were explored.

Land application of sewage sludge in the U.S. is regulated by the U.S. Environmental Protection Agency (USEPA) under Title 40, Code of Federal Regulations, Part 503 (USEPA 1994a). For land application, Part 503 classifies sewage sludge as either exceptional quality (EQ) or non-exceptional quality (non-EQ) based on USEPA standards for metals (As, Cd, Cr, Cu, Pb, Hg, Mo, Ni, Se, Zn), pathogen requirements (bacteria, viruses, parasites), and attractiveness to disease vectors (rodents, flies, mosquitoes) (USEPA 1994a). Sewage sludge that meets the most stringent requirements for the three criteria is classified as EQ and can be surface disposed of or land applied without restrictions. Sewage sludge that does not meet one or more of the parameters is non-EQ, and restrictions are placed on surface disposal or land application, increasing disposal costs.

In addition, based on pathogen reduction, Part 503 classifies biosolids into Class A or Class B. Biosolids meeting requirements for processes to further reduce pathogens (PFRP) are considered Class A, and have no use restrictions. Under the 503 rule, windrow composting is considered a PFRP if the composting pile temperature can be maintained at 55°C (131°F) or higher for 15 consecutive days, during which period the pile must be turned five times. Demonstrated pathogen kill can also be used to show achievement of Class A status (e.g., Tata et al. 2000), but was not attempted in this study.

Composting is a microbial self-heating process in which heat generated through microbial metabolism of organic material accumulates, increasing its temperature (Finstein et al. 1987). Composting is known to destroy pathogens found in sewage sludge (Burge, Colacicco, and Cramer 1981; Pourcher et al. 2005), as well as to inactivate weed seeds (Dahlquist, Prather, and Stapleton 2007).

The primary objective of this study was to determine if composting the reed bed biosolids would result in 100% mortality of *Phragmites* rhizomes. Additionally, we wanted to see if composting could also result in meeting the USEPA Class A designation for pathogen reduction, further enhancing the final reuse options of the material.

Materials and Methods

Preliminary field study

A composting test pile 7 × 6 × 6 ft (2.1 × 1.8 × 1.8 m) (l × w × h) of reed bed biosolids was constructed to see if it would self-heat. Temperature readings were taken at several heights (above ground) and at various insertion depths on days 4, 8, 13, 21, and 53. Because no temperature increases were observed, bench top laboratory experiments were conducted to determine if carbon amendment would induce self-heating.

Laboratory carbon amendment screening experiments

Reed bed biosolids were mixed with various organic amendments and placed in well-insulated 1-gallon (3.8 L) containers (plastic thermoses with 5–8 cm additional foam insulation added externally on sides, bottom, and top) to encourage self-heating. (Note: although this method is not recommended for most quantitative composting lab testing, it can be suitable for demonstrating self-heating as a screening method, e.g., Finstein 1972.) In selecting an amendment, the main criteria considered were availability, ease of use, and minimizing an increase in the amount of final material requiring disposal or reuse, which all relate to cost effectiveness. A variety of materials were tested since the conditions at specific sites might favor different materials. Moisture content was adjusted to 60% and pH to 7 by addition of granulated limestone slurry. Aeration was provided by small air pumps

(Aquatic Gardens 8000, Petco) designed for 20- to 40-L aquariums. Temperature was monitored using a mercury glass stem thermometer.

Field trials

For Field Trial 1, a composting pile approximately 6 × 6 × 3 ft (1.8 × 1.2 × 0.9 m) (l × w × h) was constructed, composed of a 1:1 (w/w) shredded green *Phragmites* above-ground biomass (GPAGB):reed bed biosolids mixture. Initial pile temperature and ambient air temperature were measured. Moisture contents of the mixture (55.4%) as well as of the biosolids (53.8%) and the GPAGB (58%) were separately determined. Temperature measurements at 16 different points within the pile were taken on days 3, 6, and 12.

Based on the results of Field Trial 1, a larger pile (Field Trial 2) approximately 12 × 12 × 6 ft (3.6 × 3.6 × 1.8 m) (l × w × h), was constructed, composed of a 1:2 (w/w) GPAGB:reed bed biosolids mixture. This pile was turned on days 9 and 16 using a front-end loader. Temperature and oxygen content at the mid-length point of the pile were measured nine times from day 0 to day 18 at heights of 1, 3, and 5 ft (0.3, 0.9, and 1.5 m) above ground, and at up to seven different insertion depths at each height. Some additional temperature measurements were made 1 ft (0.3 m) farther along the pile to check uniformity. Moisture content of the initial pile mixture was 57%.

Samples for fecal coliform determination were obtained on six different occasions. Composite samples collected from the surface of the reed bed whose contents were used in setting up the pile were analyzed for fecal coliforms before the beginning of the field trial. Subsequently, samples from the field test pile were collected and analyzed for fecal coliforms on day 0 when the pile was being set up, from the pile interior on the day of the first turning (day 9), from the pile interior on the day of the second turning (day 16), and from the pile interior one week later (day 23). The samples were composited by collecting 15 samples from 1, 3, and 5 ft heights (5 from each) of the pile. The sample collection and preparation were carried out according to the USEPA 503 rule for solids sample preparation for fecal coliform analysis (USEPA 2013).

Three *Phragmites* rhizomes, each containing new buds and three intact nodes (Ravit et al. 2007), were collected on site and placed in a mesh bag; five replicate bags were placed at 1, 3, and 5 ft (0.3, 0.9, and 1.5 m) heights during pile construction. Three of the bags from each height were removed and replaced with new bags on the day 9 pile turn. The six remaining bags plus nine replacement bags were retrieved on day 23, a week after the second pile turn. Recovered rhizomes were transferred to a Rutgers experimental greenhouse where they were planted in Scott's Miracle-Gro Potting Mix (Model #75664300, Marysville, OH, USA). Ambient temperatures were maintained at 16–18°C, and light levels at 90 μEinsteins for 16 h/day.

Rhizome heat kill experiments

To confirm the temperature and time period required to achieve complete mortality of *Phragmites* rhizomes, tests were conducted in a temperature controlled drying oven. Viable rhizomes were provided by Mr. Scott Davis of Constructed Wetlands Group, Inc. (New York, NY, USA). Rhizomes with at least three growing buds were buried 1 in. (2–3 cm) deep in biosolids collected from the field site and heated in the oven at four temperatures (40, 45, 50, and 55°C) over two time periods (12 and 24 h) ($n = 40$; five rhizomes for each time at each temperature). Controls were also buried in field biosolids (five for each temperature tested), but controls were left at room temperature. After the heat treatment, rhizomes were planted in Scott's Miracle-Gro Potting Mix and placed in the greenhouse as described above. Water (200 mL) was added daily and shoot formation monitored over a 3-week period.

Analytical methods

Field temperatures were determined using a thermocouple probe (Type T, Omega Engineering, Inc., Stamford, CT, USA). Oxygen concentrations were obtained using a model 630 oxygen analyzer and compost oxygen probe (Woods End Research Laboratory, Inc., Mt. Vernon, ME, USA). Biosolids samples were analyzed at the Rutgers Soil Testing Laboratory for standard soil parameters. Moisture contents for other samples were determined using USEPA Method 1684 (USEPA 2001). To determine fecal coliform counts, the *Standard Methods* (Clesceri, Greenberg, and Eaton 1998) multiple tube fermentation technique employing presumptive and confirmed tests was used, with five tubes per dilution. The most probable number (MPN) obtained was compared to USEPA regulatory

limits for land application of sewage sludge (USEPA 1994), which require an MPN <1000/g total solids (dry weight).

Results and Discussion

Preliminary field results

The preliminary composting test pile (un-amended biosolids set up in winter) reached a maximum temperature of 14°C. This lack of self-heating after moderate aeration that was provided by building of the pile was expected. The reed bed material had already been stabilized to a considerable extent during anaerobic digestion, followed by storage in the beds for more than 10 years. Anaerobic digestion typically reduces organic matter by 40 to 60% (Tchobanoglous, Burton, and Stensel 2003). Analysis of the biosolids (table 1) showed an organic matter content of 44%, which is lower than many finished composts, indicating very little readily available carbon remaining. Raw sludge usually has an organic matter content of ~85% (Tchobanoglous, Burton, and Stensel 2003). Additionally, the material was acidic (pH 4.6). Optimum pH for composting is more neutral (Krogmann, Körner, and Diaz 2011), but pH in the observed range does not prevent self-heating (Strom 1985). Moisture content and C:N ratio were suitable for composting (Diaz, Savage, and Golueke 2002). The C:N for sewage sludge is usually much lower, but uptake of nitrogen by *Phragmites* likely offset the removal of carbon as carbon dioxide (CO_2). In light of these observations it was decided that addition of a carbon amendment was needed for sufficient self-heating to occur.

Table 1. Reed bed biosolids laboratory analysis results.*

Parameter	Units	Value
pH		4.6
Electrical conductivity	mmho/cm	1.21
Organic matter	%	43.7
Organic carbon	%	25.4
TKN	%	0.8
Ammonium-N	mg/kg	80
Nitrate-N	mg/kg	170
Moisture content	%	60
C:N		25
P	mg/kg	360
K	mg/kg	46
Mg	mg/kg	130
Ca	mg/kg	3550
Cu	mg/kg	32
Mn	mg/kg	58
Zn	mg/kg	230
B	mg/kg	5.4
Fe	mg/kg	330

Note. TKN: total Kjeldahl nitrogen (ammonia-N + organic-N); C:N: carbon to nitrogen ratio.
*Bulk density = 0.65 g/mL.

Carbon amendment laboratory experiments

Results of the laboratory carbon amendment tests are shown in table 2. The effectiveness of a carbon amendment (which may also act as a "bulking" agent to add porosity) that can aid in composting is dependent on factors, such as availability of labile carbon, particle size, moisture content, and C:N ratio. Cat food and horse manure were used as positive controls as they have large amounts of easily metabolized organic material and nutrients. Unground oak (*Quercus alba*) leaves were too slow to degrade to make them useful as an amendment, while the un-dewatered primary and secondary sludges were too dilute (moisture content >95%) to be effective. Cured compost has little readily available carbon as most of it is degraded during the composting process.

It is unclear why the sawdust trial was unsuccessful. Sawdust has a C:N ratio in the range of 100–500:1, perhaps raising the ratio of the mixture too high and potentially limiting composting (Dickson, Richard, and Kozlowski 1991). Alternatively, the particle size of the substrate may have been too small, causing clumping or compaction that could impede oxygenation. It is also possible that the particular wood used was slow to degrade.

The wastewater treatment facility had a fats, oils, and grease (FOG) control program for food service establishments, and vegetable oil was tested as a surrogate for this available carbon amendment. Vegetable oil amended flasks showed an increase in temperature from 16.5 to 36°C within 5 days. Lemus et al. (2004) showed that yard trimmings amended with grease trap sludge added at 5% dry solids resulted in enhanced performance in terms of temperature profile and rate and extent of biodegradation of solids and lipids. However, this amendment was not field tested due to a lack of on-site mixing equipment and out of concern for attracting vermin.

GPAGB added at 33% (dry weight basis) to reed bed biosolids helped increase the temperature from 19 to 27°C in less than 24 h. GPAGB was preferred to other amendments because, in addition to its high organic matter content (almost 40% C; Longhi, Bartoli, and Viaroli 2008), it is available on site and its use would not increase the overall mass of material

Table 2. Amendments tested in laboratory to induce self-heating of reed bed biosolids.

Amendment	Amend (%)	Time (days)	Temperature change (C)		Increase	Comments
			From	To		
Dry cat food*	50 (v/v)	4	19	50	Yes	Positive control
Dry cat food	50 (v/v)	4	18	56.5	Yes	Positive control
Horse manure†	100	6	21	35	Yes	Positive control
Oak leaves	67 (v/v)	5	18.5	18.5	No	Resistant to degradation
Primary sludge	10 (v/v)	5	16	17	No	Low (<5%) total solids
Digested sludge	10 (v/v)	5	16	17	No	Low (<5%) total solids
Saw dust	67 (v/v)	4	19	17.5	No	Resistant to degradation
Vegetable oil	71 (dwb)	5	16.5	36	Yes	Surrogate for food grease
CC	50 (dwb)	3	18	18.5	No	Already stabilized
GPAGB	63(v/v)‡	4	19	20.5	No	Retest with higher ratio
GPAGB	50 (dwb)	<1	19	35	Yes	Chosen for field test
GPAGB	33(dwb)	<1	19	27	Yes	Chosen for field test

Note. Unless noted, moisture content adjusted to 60% and pH to 7. GPAGB = green *Phragmites* above-ground biomass; Amend (%) = % amendment used in relation to total of biosolids plus amendment; dwb = dry weight basis; CC = cured compost.
*Moisture content unadjusted, 9%
†moisture content unadjusted, 50%
‡~16% dwb.

requiring disposal. GPAGB was field tested in two ratios (1:1 and 1:2 w/w) with respect to biosolids.

Field trial 1 (1:1 w/w GPAGB:biosolids)

In the first field trial, the pile interior reached a maximum temperature of 54°C by Day 6. While successful in stimulating self-heating, a 1:1 (w/w) *Phragmites*: biosolids ratio presented a materials handling problem. The bulk density of GPAGB (0.23 g/mL) was much lower than that of the biosolids (0.65 g/mL), so that a ratio of 4:1 (v/v) GPAGB:biosolids was required to achieve the 1:1 (w/w). Therefore, compostability at a reduced ratio of GPAGB:biosolids was tested.

Field trial 2 (1:2 w/w GPAGB:biosolids)

Figures 1 and 2 show the change in temperature and oxygen concentrations over the experimental period in field trial 2. Within a week, temperatures ≥55°C were observed in the pile interior (figure 1). The pile was generally hotter at a height of 3 ft above the ground compared to other regions. This could be due to the low heat loss at this height to the outside through conduction and convection. On day 8, the average temperature for all of the insertion depths combined at the 3 ft height was 52.4°C and a maximum temperature for the trial of 58.5°C was observed. Figure 3 shows the temperature profile of the pile at 3 ft height (average value of temperature measurements from all depths combined) during the experimental period.

The pile was turned on day 9. Temperature measurements taken on day 11 showed that pile temperatures remained below 50°C with a maximum temperature of 45°C observed at 5 ft height and 5 ft insertion depth. On day 15, the pile temperatures reached a maximum of 50.5°C at 3 ft height and 3 ft depth. The pile was turned a second time on day 16. After the second turn, measurements taken on day 18 showed that the pile temperatures remained below 35°C across the pile.

In the initial stages of pile set-up, the oxygen concentrations were comparable to ambient air concentrations. As biological activity increased over the first few days, as shown by an increase in temperature, the oxygen concentrations decreased. Very low oxygen concentrations (<1%) were observed on day 3 at 3 ft height (figure 2). These concentrations later increased, but still frequently remained below 10%. Although oxygen concentrations in this range are not ideal for composting, they are not uncommon as observed in the windrow composting of leaves (Strom et al. 1986). Even though the interior of the pile appeared to be anaerobic in some cases, no undesirable odors were observed. Introduction of oxygen from outside occurred during the first and second turns, but Michel et al. (1996) have shown that oxygen introduced by turning a pile becomes depleted within several hours. Figure 3 shows the oxygen profile at 3 ft height (average oxygen concentrations from all insertion depths combined) during the experimental period.

Based on these results, a 1:2 (w/w) ratio would not allow the tested reed bed material in a pile of this size to self-heat and maintain a 55°C temperature through the five turnings required to demonstrate further pathogen destruction. Additional GPAGB, a larger

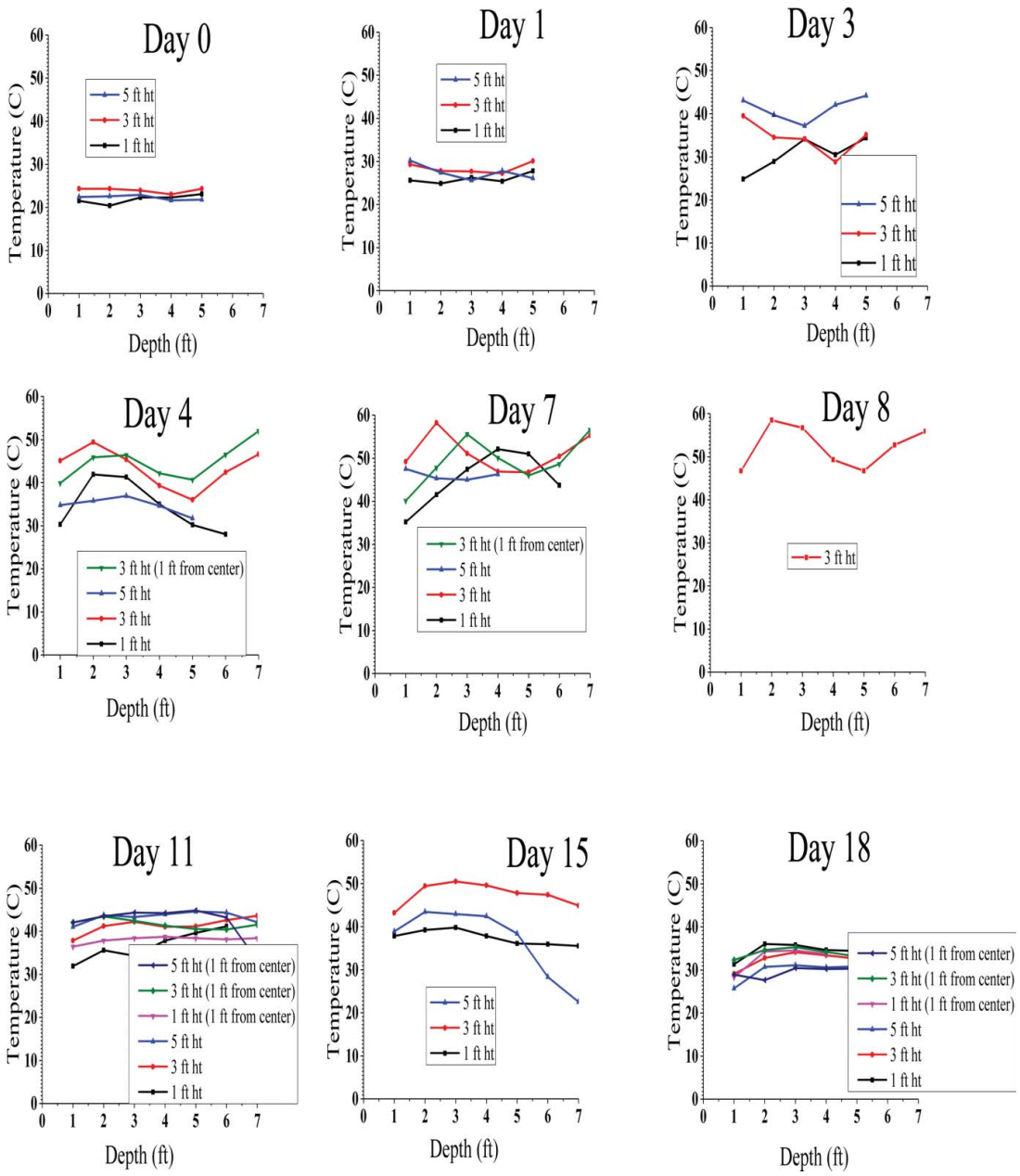

Figure 1. Temperature measurements in the composting pile (1 ft ≈ 0.3 m).

pile size, or an alternative composting strategy would be needed to achieve that goal.

Fecal coliforms

Results of the fecal coliform tests carried out on samples collected from the pile in field trial 2 are shown in table 3. Numerous studies have shown that thermophilic composting destroys plant, human, and animal pathogens (Bollen 1993; Burge, Colacicco, and Cramer 1981; Pourcher et al. 2005). Singh, Billingsley, and Ward (2006) reported that most bacterial pathogens are eliminated at 50°C within 3–15 days, while

Table 3. Fecal coliform test results.

Day	Sample location*	MPN†/dry wt.
	Undisturbed reed beds	175
0	Composting pile composite	4000
9	3 ft (0.9 m) height	550
16	3 ft (0.9 m) height	>225,000‡
16	1 ft (0.3 m) height	>225,000‡
23	3 ft (0.9 m) height	175

*Composites of several samples collected at each location.
†Most probable number; the 95% confidence interval of each test can be determined by dividing and multiplying the MPN by a factor for 3.30 based on a 5 tube per 10-fold dilution method (Meynell and Meynell 1970).
‡Required holding time of 6 h exceeded.

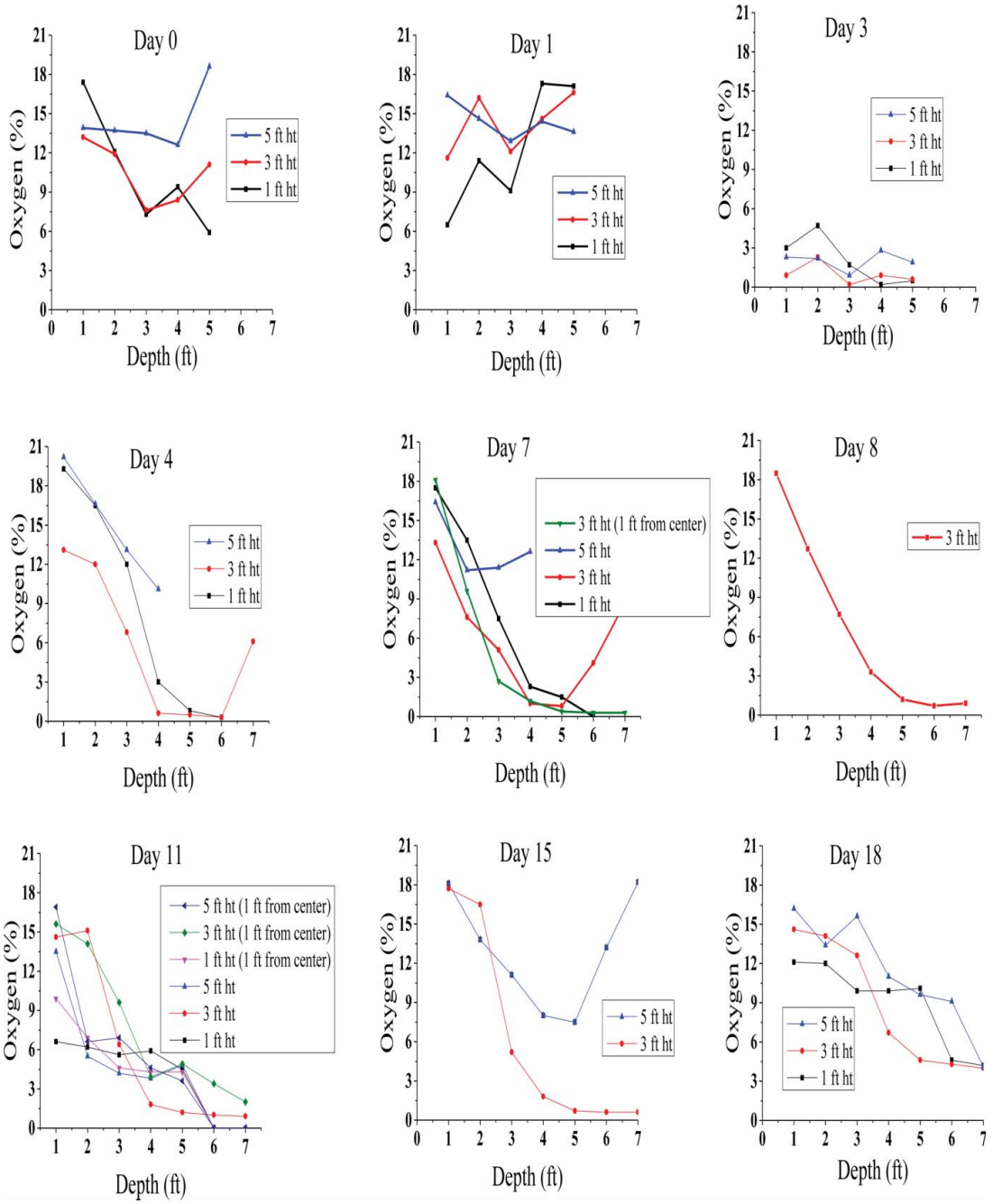

Figure 2. Oxygen measurements in the composting pile.

inactivation of plant fungal pathogens occurs at 55–63°C in 1–21 days; however, drier conditions could allow pathogens to survive longer and at higher temperatures (Bollen 1985).

The lowest MPN counts of 175 MPN/g dry weight solids were seen in the reed bed biosolids material collected prior to the composting experiment and also on Day 29 at the end of the composting period. On Day 0 the counts were 4000 MPN/g dry weight, exceeding the USEPA regulatory limit (<1000 MPN/g), but by Day 9 the count dropped to 550 MPN/g, which meets the limit. The high counts on Day 16 may represent regrowth, or incorporation of materials from pile edges with high counts, but also could be in part an artifact due to exceeding sample holding times. Overall, the MPN results suggest that under appropriate conditions a composting treatment for this material could result in MPN counts that would meet USEPA criteria.

Rhizome survival

Important factors that determine plant and their seed mortality during composting are exposure

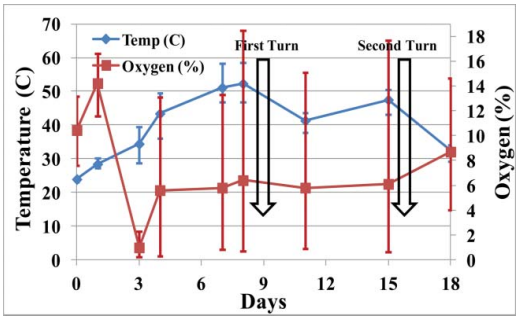

Figure 3. Temperature and oxygen profile at 3 ft height during the experimental period.

temperature, duration of exposure and moisture content of the compost (Dahliquist, Prather, and Stapleton 2007). Seeds in a drier environment are able to survive at a higher temperature than in a moist environment.

No re-growth was observed in any of the 72 rhizomes retrieved from the composting pile. All non-composted controls re-sprouted. These results indicate that temperatures achieved in the pile during composting with the 1:2 ratio of GPAGB:reed bed biosolids were sufficient to kill *Phragmites* rhizomes.

Laboratory heat kill rhizome experiments

Ambient temperatures in the reed beds reached at least 33°C during the summer and *Phragmites* survive in Death Valley, CA, where summer temperatures reach 43–46°C (USDA 2015), so it was assumed that *Phragmites* would exhibit heat tolerance. In a laboratory experiment, Dahlquist, Prather, and Stapleton (2007) showed that 90% of the seeds of six species of plants (annual sowthistle, barnyard grass, London rocket, common purslane, black nightshade, tumble pigweed) were killed after exposure to 60°C for less than 3 hours. In a laboratory study, Weise et al. (1998) showed that in composting manure at 35% moisture placed in an oven, sorghum, barnyard grass, pigweed, *Kochia* (burning bush), and johnsongrass seeds were all killed within 3 days at 49°C. However, 30% of the bindweed seeds tested did survive even 72°C for 30 days, and 20% survived 83°C for 1 day.

Rhizomes survived at temperatures of 40 and 45°C for 24 h; at 50°C they grew after 12 h, but 100% mortality was observed after 24 h. At 55°C, none of the replicates survived. These results indicate that temperatures achieved when composting reed bed solids with above ground biomass is potentially a treatment to kill live rhizomes, thus increasing land biosolids disposal and reuse options.

In addition to pathogen and vector attraction requirements, monitoring heavy metal concentrations in the reed bed biosolids determines their suitability for land application. Metal uptake by growing *Phragmites* reduces biosolids concentrations, but reincorporation of the plant materials for composting would return those metals to the final product. Organic matter mineralization can increase metals concentrations in the remaining solids while biosorption by the microbial biomass and metal complexation with the humic substances could change bioavailability (Cai et al. 2007). However, metal concentrations in biosolids are highly dependent on the source of wastewater being treated. While no metals analysis of the final compost was conducted, heavy metal analysis of the reed bed biosolids by the treatment plant's external contractor showed that metal concentrations (data not shown) were well below the USEPA ceiling concentration limits for biosolids applied to land and limits for pollutant concentrations in biosolids (USEPA 1994b), as well as New Jersey Department of Environmental Protection (NJDEP 1998) soil limits for cumulative metal loading.

In conclusion, in the current study, composting reed bed biosolids with green *Phragmites* aboveground biomass (readily available onsite) achieved temperatures that destroyed live *Phragmites* reproductive rhizomes. In addition, although the specific field trial did not succeed in meeting the time temperature requirements for Class A biosolids, the MPN fecal coliform counts suggest that composting could result in achieving the pathogen mortality requirements for beneficial reuse of reed bed biosolids. Composting fresher reed bed material instead of allowing it to accumulate and stabilize for such an extended period also could contribute to meeting USEPA EQ and Class A status for biosolids disposal/reuse.

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