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# Maturity and Stability Evaluation of Composted Yard Trimmings

**Linda J. Brewer and Dan M. Sullivan**
Department of Crop and Soil Science, Oregon State University, Corvallis, Oregon

The objective of this research was to evaluate a variety of stability and maturity indices for yard trimmings compost produced in the Puget Sound region of western Washington State. Compost samples were collected periodically during a 133-d composting cycle at a commercial composting facility, showing that indices of compost respiration rate were sensitive indicators of compost quality. All respiration rate indices identified a period of high respiration rates during active composting (first 27 d), and a period of relatively stable respiration rates during the latter part of curing (70 to 133 d). Chemical tests of compost solids showed less promise as maturity indicators, but provided valuable information on final compost quality. Mature yard trimmings compost had a C:N of 12, an $NH_4$-N to $NO_3$-N ratio of less than 4, a cation exchange capacity (CEC) of 400 cmol per kg of compost-C, and a pH between 6.5 and 7.0. Seed germination tests and sensory tests (color and odor) were of limited value in assessing compost maturity. Fully-cured compost produced with forced aeration had a Solvita $CO_2$ test value of 6 to 7 and a respiration rate via the alkaline trap method of 2 mg $CO_2$-C g compost-$C^{-1}$ $d^{-1}$. It reheated less than 2°C in an insulated Dewar flask in a 7 d incubation. Further evaluation and calibration of respiration test protocols for compost quality assurance testing programs are recommended.

## *Introduction*

Maturity is a general term describing fitness of the compost for a particular end use, while stability refers exclusively to the resistance of compost organic matter to further degradation (Sullivan and Miller 2001). Mature composts are ready to use; they contain negligible or acceptable concentrations of phytotoxic compounds like $NH_3$ or short-chain organic acids. However, some phytotoxic characteristics of compost (e.g. soluble salts, presence of persistent herbicides) are related mainly to feedstock quality.

Generally, less data is available on maturity and stability measures for yard trimmings than for biosolids or mixed solid waste composting systems. State or regional compost testing programs are also seeking calibration data for compost quality indices.

Laboratory tests of compost respiration rate are used to assess compost stability. Such tests generally provide near-optimum conditions for microbial respiration (e.g. moisture, nutrients, and oxygen supply). Respiration is measured by $CO_2$ evolution rate or $O_2$ uptake rate (Grebus *et al.* 1994; Iannotti *et al.* 1994; Lasaridi and Stentiford 1998). Self-heating of compost in an insulated vessel is also used as an index of respiration rate (Brinton *et al.* 1995). A decreasing respiration rate in a laboratory test implies a reduction in biodegradable C and increasing C stability.

Compost maturity assessment is more of an art than compost stability assessment, since acceptable maturity varies depending on compost end-use. A wide range of maturity tests have been proposed, but the utility of the tests varies among feedstocks (Sullivan and Miller 2001; Henry and Harrison 1996; Jiménez and Garcia 1989). Immature compost can inhibit seed germination or reduce plant growth via the toxicity of water-soluble organic acids or ammonia (Forster *et al.* 1993; Jiménez and Garcia 1989), or via rapid $O_2$ consumption and anaerobic conditions in potting media (Brin-

ton and Evans 2001). Phytotoxicity is often evaluated by root- and shoot-mass measures conducted with water extracts of the sample material (Inbar *et al.* 1993b; Shiralipour *et al.* 1997) or with the sample incorporated into a potting mixture (Warman 1999; Garcia *et al.* 1992). Many other tests have been considered as maturity indices for compost. These include color, odor, volatile solids reduction, cation exchange capacity, C:N ratio and inorganic N concentrations (Sullivan and Miller 2001).

Most yard trimmings composting facilities in the Pacific Northwest began operation in the early 1990s. Initially, most facilities used the turned windrow composting method and composted outdoors. Recently, facility designs have shifted toward indoor composting and/or forced aeration systems to control odors (Touart 1999; Croteau *et al.* 1996; Hilts 1995). The added cost of this technology has increased interest in minimizing processing time. Aerobic processing of yard trimmings is also thought to provide compost quality benefits by providing a more optimal and uniform environment for organic matter decomposition. The objectives of this research were to (i) evaluate a variety of stability and maturity indices for yard trimmings compost, and (ii) evaluate the effect of forced aeration on compost quality.

## *Materials and Methods*

### *Compost Facility*

Land Recovery, Inc. conducted composting and curing at their Compost Factory facility located in Puyallup, Washington, USA. This facility, which began operation in 1999, incorporates state-of-the-art technology to control odors, to speed the composting process, and to produce consistent compost products (Touart 1999). The Compost Factory incorporates many elements of a successful forced-air composting facility operated since 1992 in nearby Purdy, Washington (Hilts 1995).

### *Feedstock Preparation for Composting*

Source separated yard trimmings from curbside collection were ground and blended within 24 h of receipt at the compost facility. A grinder and trommel/blender (Universal Refiner Super Contender, Universal Refiner Corp., Montesano, Washington) was used to grind, screen, and mix the yard trimmings. The initial substrate was a roughly 50/50 v/v mixture of grass clippings and woody prunings. Front-end loaders stacked the prepared yard debris into two windrows. Each windrow was approximately 15 m long by 5 m wide by 2.5 m high. Ground yard trimmings were delivered to the two windrows simultaneously to minimize differences in yard trimmings characteristics. Each windrow, having an approximate volume of 185 $m^3$, was then turned twice with a Scat 4932 self-propelled windrow turner (Scat Engineering, Division of ATI Incorporated, Delhi, Iowa) to promote homogeneity of the materials and to establish consistent porosity. Samples taken immediately after windrow formation showed an initial moisture content of 620 g $kg^{-1}$.

### *Aeration Treatments*

We used the same batch of well-mixed yard trimmings for two compost processing treatments, PA (passive aeration) and FA (forced aeration). Composting proceeded in a two-stage process: active composting (Day 0 to Day 35) and curing (Day 36 to Day 133). Composting began indoors on 4 August 1999 for both treatments.

Composting was conducted in windrows on a concrete pad for both treatments. During active composting, forced aeration was supplied to the FA pile via ports in the concrete floor; the PA pile did not receive forced aeration. The yard trimmings were then placed into outdoor covered bins for curing (Day 36 to Day 133; three bins per aeration treatment). The PA bins were not aerated during curing; the FA bins received forced aeration during curing. Composting process control procedures for each treatment are described in Table 1 and in the following sections on active composting and curing.

TABLE 1.
Composting process control during active composting and curing.

| Active Composting | |
|---|---|
| Chipping procedure | Rotary disk mill |
| Mixing method | Self-propelled windrow turner |
| Residence time | Day 0 to Day 35 (35 d) |
| Turning frequency | Weekly |
| Target compost moisture after water addition | 500 g $kg^{-1}$ |
| Windrow dimensions (l x base x h) | 15 m x 5 m x 2.5 m |
| Aeration | Forced aeration (FA) |
| | Passive aeration (PA) |
| **Curing** | |
| Residence time | Day 35 to 133 (98 d) |
| Mixing or turning method | None |
| Initial and final moisture content | 590 and 660 g $kg^{-1}$ |
| Water addition | None |
| Aeration | Forced aeration (FA) |
| | Passive aeration (PA) |
| Curing bin volume | FA: 30 $m^3$; PA: 38 $m^3$ |

### *Active Composting*

The compost was turned and watered by the self-propelled windrow turner (Scat 4932) on the same schedule regardless of aeration treatment. This turner lifts, waters and moves compost, but does not effect appreciable grinding. Compost was tested for moisture levels the day before turning; the target moisture level after turning and watering was 500 g $kg^{-1}$.

Windrow temperatures were monitored using two Tele-Probes (Green Mountain Technologies, Seattle, Washington) in the PA and FA windrows. Each wireless temperature probe radioed thermal information to a computer every five minutes. Sensor placement was designed to measure temperatures near the center of the 2.5 m high compost windrow; sensors were separated by a vertical distance of 0.9 m in the 2.5 m high windrow. Temperature data from both FA and PA piles was lost due to equipment failure from Day 22 to the end of active composting (Day 35).

The process control software used in conjunction with the FA windrow was programmed to remove heat and to hold temperature and oxygen gradients to a minimum. Temperature data from the FA windrow was used to automatically adjust the blower on/off time and the direction of forced air supplied to the FA windrow. Air was supplied from the floor to the top of the pile (positive blower direction), and from the pile to the floor (negative blower direction).

### *Curing*

Yard trimmings from the FA treatment were cured in three 30-$m^3$ tarp-covered bins (NaturTech Curing Bins, St. Cloud, Minnesota), with a forced air line connected to a plenum in the container floor. Automated temperature data collection continued for these materials during curing. Yard trimmings from the PA treatment went into three 38 $m^3$ hard-topped bins. The curing bin for the PA materials was not equipped to collect temperature data. The yard trimmings were not mechanically mixed during curing. Temperature data from Day 35 to Day 43, and from Day 113 to 133 was lost due to equipment failure.

### *Sample Collection and Preservation*

Sample collection, sample reduction, and sample preservation protocols used in this study were generally those recommended in Test Methods for the Examination of Composting and Compost (Method 2.01, Field Sampling of Compost Materials; USDA, 2002) which were recently summarized briefly by Sullivan and Miller (2001). We used a working draft version of TMECC released in 1997 as the basis of our sampling and testing protocols. Actively composting yard trimmings were sampled on 0, 7, 14, 21, and 27 d, and during curing on 43, 56, 70, 85, 98, and 133 d. Sample collection protocols were slightly different during active composting and curing. During active composting, grab samples were collected from three 60 $m^3$ sections of windrow immediately after the windrows were turned. During curing, grab samples were collected at a depth of approximately 0.5 m from the top of each curing bin.

The protocol used for mixing grab samples and reducing sample volume was the same during active composting and curing. Thirty grab samples were collected to form a composite sample of approximately 20 L. The composite sample volume was reduced to 9 L via sub-sampling. Aliquots of the composite samples were then shipped on ice to participating analytical laboratories. Iced samples arrived at the laboratories within 24 to 48 h of collection.

### *Analysis of Compost Solids*

Total solids in compost were determined by drying at 85°C. Moist "as-is" samples were used for determination of total Kjeldahl-N, $NH_4$-N and $NO_3$-N. Values for the $NH_4$-N and $NO_3$-N analyses were expressed on a dry weight basis using the corresponding total solids data for each sample. Samples were prepared for all other solids analyses by drying at 60°C, then grinding with a flail-type grinder to pass a No. 4 screen (sieve opening of 4 mm).

Test methods used for compost were modified slightly from routine methods for soil and plant tissue analysis (Gavlak *et al.* 1994). Total C and N were determined on 0.2-g dried samples using high-temperature furnace oxidation and subsequent direct measurement of C and N by an infrared detector (LECO Instruments Model CNS 2000, LECO Instruments, St. Joseph, Michigan; Sweeney 1989) at the Oregon State University Central Analytical Laboratory. The other tests were performed at a commercial laboratory (AgriCheck Inc., Umatilla, Oregon). Volatile solids, or loss-on-ignition, was determined by heating at 550°C for 3 h. Cation exchange capacity (CEC) was determined by saturating a 1-g dried sample with $NaC_2O_3$ at a pH of 7, then displacing the adsorbed Na with $NH_4C_2O_3$. The displaced Na was determined via atomic absorption spectrophotometry. Ammonium-N, $NO_3$-N and total Kjeldahl N (including nitrate-N) from a 10-g

fresh compost sample were determined using macro-Kjeldahl distillation methods; $NH_4$-N in the distillation extracts was determined by boric acid titration. The pH of 5-g dried samples was determined after adding 10 mL deionized water, and allowing the compost:water mixture to equilibrate for 15 minutes. The electrical conductivity of the extract from the pH measurement procedure was determined with a conductivity meter. The quantity of water added for our conductivity determination (2:1 water:compost mixture) was roughly equivalent to that required to form a saturated paste.

### *Compost Respiration Rate*

Prior to conducting the respiration tests, the fresh compost samples were preincubated at 37°C for 36 h in open-topped zippered bags in an effort to restore mesophillic microbial activity. During this preincubation period, sample moisture loss was minimal (less than 50 g $kg^{-1}$). Each sample was mixed again thoroughly after preincubation. Large sticks, stones and foreign matter were removed from compost samples by hand.

### *$CO_2$ Evolution Via Alkaline Trap Method*

We used vials containing NaOH to collect $CO_2$ produced during incubation of a compost sample at 37°C. Our procedure was similar to that described in TMECC method 5.08-B, Carbon Dioxide Evolution Rate (USDA 2002), except that we used a smaller incubation vessel (0.5 L) than recommended in the procedure (4 L). We placed a 25 g fresh compost sample, and a vial containing 20 mL of 0.11 M NaOH in glass canning jars with airtight lids. The sealed jars were placed in a water bath at 37°C. Carbon dioxide was trapped for periods of 0-24, 24-48 and 48-72 h. Each incubation included a blank, consisting of a sealed jar containing a NaOH trap, but no compost. The respiration rate from the compost sample was expressed as a fraction of the total C content of the compost, as determined by the LECO combustion analyzer.

The respiration rate was calculated as:

$R = A\ B\ [V_{blank} - V_{sample}]\ M^{-1}\ D^{-1}$

Where:

R= respiration rate, mg $CO_2$-C g $C^{-1}$ $d^{-1}$

A = millequivalent weight of $CO_2$-C, 6 mg $meq^{-1}$

B = molarity of HCl used to titrate NaOH, mmol $mL^{-1}$

$V_{blank}$ = volume of HCl used to titrate the NaOH trap from the no-compost blank, mL

$V_{sample}$ = volume of HCl to titrate the NaOH trap exposed to compost respiration, mL

M = mass of carbon in the sample, g

D = time, d

### *$CO_2$ Evolution Via Solvita Test Method*

We administered the Solvita test (Woods End Research Laboratory, Mt. Vernon, Maine; TMECC Method 5.08-E) according to the kit directions. This test utilizes a colorimetric reaction between $CO_2$ and a gel-impregnated plastic paddle to estimate $CO_2$ loss per volume of compost over a 4 h incubation period at room temperature (18°C in our study). The manufacturer provided an interpretive color scale with numerical values and interpretive statements (Woods End Research Laboratory 1999). Numerical values for the Solvita $CO_2$ test range from 1, "fresh, raw compost, typical of new mixes" to 8, "inactive, highly matured compost." The Solvita test kit also included a second plas-

tic paddle impregnated with a gel to colorimetrically estimate $NH_3$ loss. We performed one Solvita $CO_2$ and $NH_3$ test per composite compost sample at each sampling event.

### *$CO_2$ Evolution Via Dräger Tube Method*

This test measured the $CO_2$ concentration in the headspace of an incubation vessel. Our procedure was an adaptation of a method used to measure soil respiration rate (Liebig *et al.* 1996; Parkin *et al.* 1996). Compost samples (500 g) were incubated in 3.8 L glass jars with airtight lids at room temperature (18°C). After four hours, we measured $CO_2$ concentration by drawing a 100 mL air sample from the incubation vessel through a $CO_2$ detection tube (Dräger $CO_2$ Detection Tubes 0.1-6 vol %, Drägerwerk, Lübeck, Germany) over a fifteen-second period. A 120 mL syringe was used to remove the air sample. The $CO_2$ detection tubes detect $CO_2$ via a colorimetric reaction; white granular material packed inside the tubes turns purple upon reaction with $CO_2$. The tubes used in our study were capable of detecting $CO_2$ concentrations from 0.1 to 6.0% $CO_2$.

### *Self-Heating Via Dewar Flask Method*

We performed a standardized procedure for measurement of compost heat production (Brinton *et al.* 1995; Method 5.08-D in TMECC). This test is an indirect indicator of respiration rate. We placed 1-L moist compost samples into open-topped insulated vacuum flasks (Compost Self-Heating Flask #2119, Woods End Research Laboratory). Digital minimum/maximum indoor-outdoor thermometers (#63-1021, Tandy Corporation, Fort Worth, Texas) measured maximum temperatures inside the flask and the room temperature (18°C). Temperatures were recorded daily, for two days beyond the maximum temperature measured in the Dewar flask. The test period in this study was not longer than six days. At each sampling event, we performed one Dewar self-heating test on a mixture of the three composite compost samples collected from the PA pile, and one test on a mixture of composite samples from the FA pile.

### *Phytotoxicity Evaluation (Seed Germination Test)*

The germination test utilized fresh compost (not preincubated at 37°C) incorporated into commercial potting media at 50 % by volume. The control was 100 % potting soil; a product that includes composted bark fines, peat moss, and pumice. Three replicates of each experimental unit were included in the test. The pots had a volume of 800 $cm^3$ with a surface area of 100 $cm^2$. Twenty barley (*Hordeum vulgare* L.) or zucchini (*Cucubita pepo*) seeds were placed in moist media in each pot. The germination test was conducted at room temperature (18°C), and was illuminated by fluorescent light for 16 h each day. The number of sprouts visible in each pot was counted and recorded 5 and 14 d after seeding.

### *Sensory Analysis (Odor and Color)*

Odor and color were evaluated according to TMECC, Method 5.03-A, Quick-Test for Field Assessment of Compost Color and Odor, prior to incubation (USDA 2002). Color was evaluated outdoors in bright shade. The samples were compared to Munsell Chart color chips. Samples were viewed through the hole in the chips to determine the closest color match. Odor was rated by comparing the odor to written odor descriptions given in TMECC Method 5.03-A.

## *Results and Discussion*

This study evaluated compost quality using composting systems and compost sample collection and analytical procedures available to commercial composting operators. The results presented here are applicable to yard trimmings compost facilities west of the Cascade Mountains in Washington and Oregon. During the summer months, the grass component of yard trimmings (largely perennial ryegrass; *Lolium perenne*) makes up about one-third to two-thirds of the incoming volume at most Puget Sound composting facilities. Because the plant materials and other debris (e.g. soil) we used are somewhat unique to our region, caution should be exercised in extrapolating our findings to yard trimmings compost from different regions.

The mixing, grinding and piling of the yard trimmings at the start of this experiment was designed to create two starting piles with the same approximate composition of yard trimmings. Large piles were needed for an operational evaluation of forced aeration effects on compost quality. Samples of raw, uncomposted yard debris on Day 0 (immediately after grinding and piling) indicated similar characteristics for the yard trimmings in the FA and PA piles, although some analyses had high variability (Figures 1 to 5).

### *Composting Process Control*

Pile temperature and moisture measurements were collected to monitor the composting process (Figure 1 and 2a). The composting process was not limited by moisture. Gravimetric moisture content of the yard trimmings (50 to 60%; 400 to 500 g $kg^{-1}$ total solids) was generally in the range recommended for rapid composting. The higher moisture content (lower total solids) measured near the end of curing was due to condensation. Moisture carried by convective currents within the outdoor curing vessels condensed against the colder curing bin covers, adding moisture to the upper layer of compost. Day 119 was December 1 in our study.

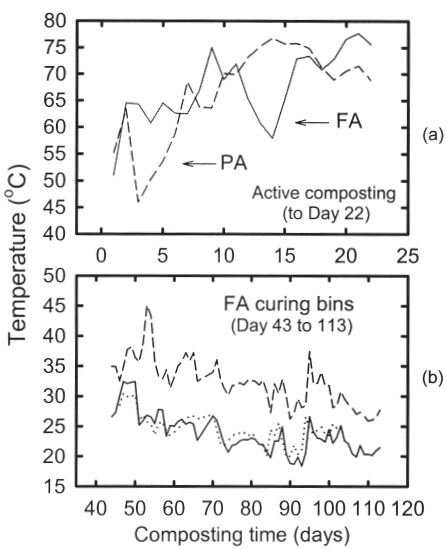


Figure 1. Compost pile temperatures during active composting (a) and curing (b). FA = forced aeration; PA = passive aeration. Temperature data missing from Day 22 to Day 42 and from Day 113 to 133 due to equipment failure. Curing temperatures (b) recorded only for the three bins supplied with forced aeration.

Pile temperatures were in the thermophillic range during active composting (Figure 1a). Active composting temperatures, typically 65 to 75°C, were higher than optimum for rapid organic matter decomposition. The forced aeration used in the FA piles removed heat. In spite of this heat removal, FA pile temperatures were similar to those observed with passive aeration (PA). We were able to measure temperatures only in the FA compost bins during curing (43 to 113 d). Curing temperatures were generally in the mesophillic range (Figure 1b). Compost temperatures were approximately 25 to 40°C for Day 40 to 60, and fell to 20 to 35°C after Day 70.

Changes in electrical conductivity (Figure 2c) and pH (Figure 2b) over composting time provided additional information about the composting process. Soluble salts, as estimated by electrical

conductivity determination, were generally in the range of 4 to 8 dS $m^{-1}$ for both FA and PA piles. The relative uniformity of conductivity measurements across sampling dates was expected, since leaching from the piles did not occur during active composting or curing. Sample pH values were lowest during the first days of active composting. At the initiation of composting (Day 0), both FA and PA piles had initial pH values near 5, reflecting an accumulation of organic acids under anaerobic conditions prior to the start of composting. During the first 14 d of composting, sample pH was about one pH unit higher for the FA pile compared to the PA pile. We attribute this pH difference to the destruction of organic acids under the more aerobic environment found in the FA pile. After 21 d, pH values were above 6 and similar for both piles. A gradual increase in pH was observed during curing, reaching a pH near 7 by the end of curing. Although compost pH is not generally useful as a compost maturity indicator, it was correlated with other compost stability and maturity indices evaluated in this study (see following sections).

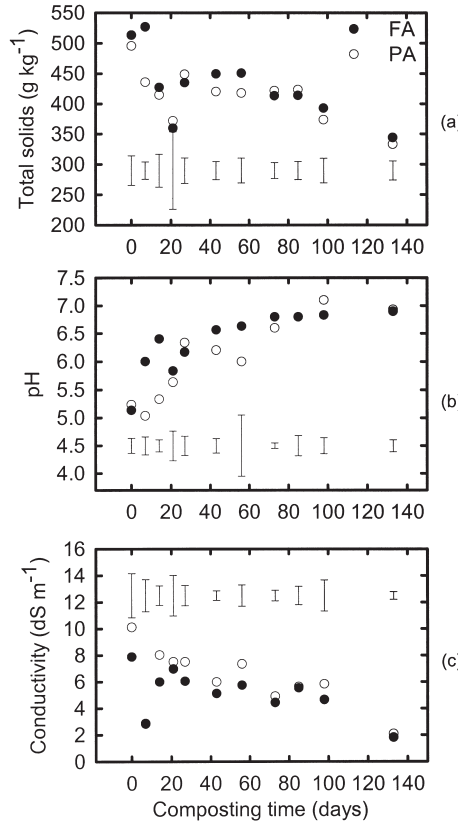


Figure 2. Total solids (a), pH (b) and electrical conductivity (c) of yard trimmings compost samples. Error bar is ± SE of the mean (n = 3).

### *Evaluation of Maturity and Stability Indices for Compost*

This study included a broad range of tests suggested or recommended for compost maturity and stability evaluation. From a test interpretation standpoint, we define promising or useful tests as those that (i) show a large change in analytical values over composting time compared to variability within a sampling event, (ii) follow a pattern that corresponds with existing knowledge about the composting process, and (iii) provide the most clear delineation between partially composted trimmings and fully cured yard trimmings. We did not focus on other important characteristics of useful compost testing procedures, such as applicability to a wide range of feedstocks, cost, or ease of administering the test. We also did not evaluate the usefulness of these tests exclusively for compost marketing purposes. Some of the compost quality tests we evaluated will be of more interest to composters than to compost marketers. We used a limited number of composite samples per pile per sampling event (n = 3) to simulate the limited compost sampling and testing budget constraints faced by commercial composters.

The error associated with mean analytical values for a sampling event (Day) in our study is a combination of two separate errors: sampling error and analytical error. The sampling error is the failure to collect a completely representative sample from a compost pile. The analytical error is the failure to obtain the same analytical result for repeated analyses of the same sample. We expected greater variability than reported for

composts collected from small piles or composting chambers. The use of small in-vessel research scale composters reduces sampling error, but does not reflect the situation encountered by commercial compost facility operators.

### *Carbon and Nitrogen Tests*

#### *Total C Concentration*

We evaluated changes in total C during composting via two methods: a combustion analyzer equipped with an infrared detector (Sweeney 1989), and loss-on-ignition (volatile solids). Total C was equivalent to organic C in our yard trimmings because they did not contain significant concentrations of inorganic C (e.g. carbonates). Volatile solids determined by the loss-on-ignition method (data not shown) had greater variability within sampling events and a more variable trend over time. The ratio of total C to volatile solids in our samples was 0.58 during active composting, and 0.55 during curing.

Total C declined exponentially from approximately 400 g $kg^{-1}$ at the start of composting to 250 g $kg^{-1}$ after 133 d (Figure 3a). Total C loss during composting (Day 0 to Day 133) was approximately 40% of that present at Day 0. Over half of the C lost during the entire composting period (133 d) was lost during the first 21 d. Total C monitoring did not detect consistent differences between the FA and PA processing methods.

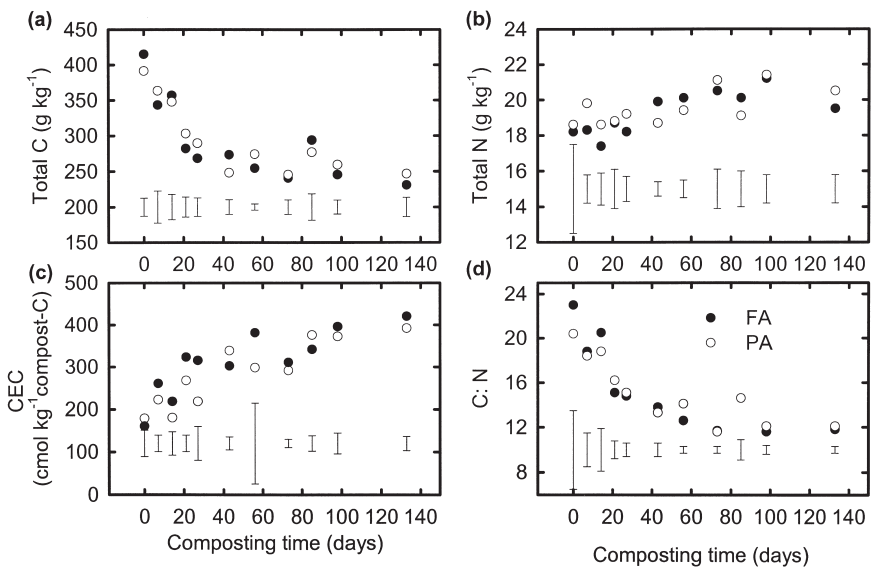


Figure 3. Total C (a), total N (b), cation exchange capacity of compost-C (c) and C:N ratio (d) of yard trimmings compost samples. Error bar is ± SE of the mean (n = 3).

#### *Total Nitrogen*

Total N increased only slightly with composting time, and so was not a viable indicator of compost maturity or stability (Figure 3b). We evaluated changes in total N content of yard trimmings using two procedures, a macro-Kjeldahl method and a combustion analyzer equipped with an infrared detector. The ratio of total combustion N to total Kjeldahl N in our samples was 1.04 during active composting, and 1.02 during

curing. We present only the data for the combustion method here, because it had the lowest variability within sampling events and a more consistent trend over composting time. During composting, the compost total N concentration increased by about 10% relative to values on Day 0.

### *C to N Ratio*

The change in C:N during curing was not a good indicator of compost maturity, but it did illustrate the success of the composting process in producing a final product similar to soil organic matter. The ratio of total C to total N in yard trimmings (as determined by the LECO combustion method) decreased from 22:1 at Day 0 to 12:1 at Day 98 and Day 133 (Figure 3d). Most of the change in C:N ratio occurred during active composting. C:N ranged from 15 to 12 during curing. The final C:N of the yard trimmings, approximately 12:1, was similar to the C:N of soil humus, which is typically 10 to 12 (Stevenson 1994). Most of the change in C:N ratio over time resulted from reduced total C concentrations (Figure 3a). Total N concentrations did not change much during composting (Figure 3b). During curing, the C:N ratio was very reproducible across sampling dates. The standard error of the mean (n = 3) was generally 10 to 15% of the mean value.

### *Cation Exchange Capacity of Compost C*

Cation exchange capacity (CEC) of organic matter is an indicator of humification. As composting proceeds, the remaining C compounds in the compost have more functional groups (e.g. carboxyl groups) that can adsorb cations. Thus, humification increases CEC. We expressed CEC on an ash free basis (CEC per unit of compost organic C) to permit comparison with other organic matter sources (Figure 3c). Ash-free CEC increased two fold from Day 0 to Day 133. Cation exchange capacity was higher for FA than for PA samples during active composting; it was similar for FA and PA samples during curing. The higher CEC in FA samples during active composting is another indicator of more rapid stabilization of organic matter in the FA pile than in the PA pile. At the end of curing, both treatments reached a CEC (400 cmol $kg^{-1}$ compost C) similar to that of soil organic matter at pH 6 to 7 (200 to 600 cmol $kg^{-1}$ soil C; Stevenson 1994).

### *Ammonium N*

Ammonium-N concentrations provided some indication of compost maturity. We measured $NH_4$-N in fresh compost samples to prevent loss of gaseous N forms during sample drying. Ammonium-N concentrations were highest (2000 to 3000 mg $kg^{-1}$) during the first 21 d of active composting, reflecting active organic matter degradation (Figure 4a). The FA samples had lower $NH_4$-N concentrations than the PA samples at 7d and 14 d, perhaps due to greater loss of volatile N compounds via forced aeration. Most of the $NH_4$-N present during active composting was likely derived from rapidly decomposing grass. Ammonium-N concentrations were lower during curing, reaching approximately 1000 mg $kg^{-1}$ after 85 d. At the end of curing, our $NH_4$-N concentrations were similar to those reported for $NH_4$-N in composted yard trimmings determined by a distillation-titration method (approximately 1100 mg $kg^{-1}$; Grebus *et al.* 1994), but substantially higher than reported by others in mature compost (below 200 mg $kg^{-1}$; Bernal et al 1998, Forster *et al.* 1993). Some of this

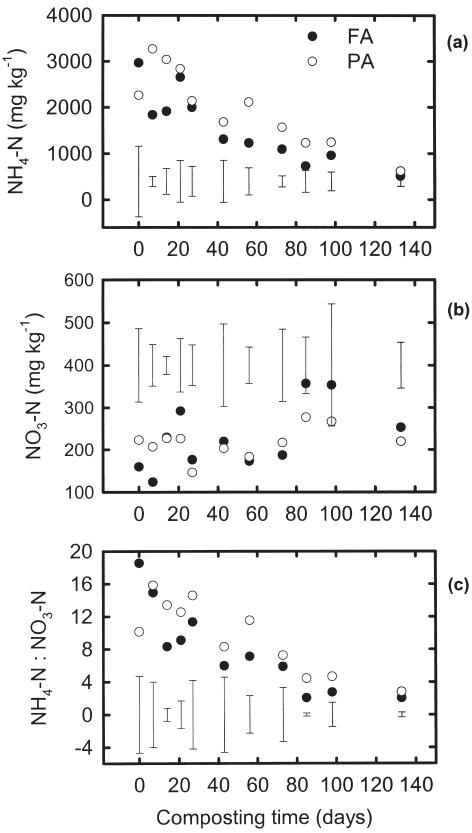


Figure 4. Inorganic N in yard trimmings compost samples. Ammonium-N (a), nitrate-N (b) and ammonium-N to nitrate-N ratio (c). Error bar is ± SE of the mean (n = 3).

difference may be related to our analytical procedure. In our study, a strong base (NaOH) was added to the yard trimmings sample in the distillation method we used for ammonium-N determination. Strong bases typically solubilize some of the organic-N present in microbial biomass, thereby increasing sample $NH_4$-N concentrations.

### *Nitrate N*

Nitrate-N concentration did not change greatly during composting and was of limited value in assessing compost maturity (Figure 4b). Nitrate-N concentrations were 100 to 300 mg $kg^{-1}$ during active composting, reaching 200 to 400 mg $kg^{-1}$ after 43 d. The standard error of the mean (n = 3) for each sampling event was approximately 25 to 50% of the mean values. We expected nitrate-N concentrations to rise during curing when temperatures were generally below 35°C. Bacteria responsible for nitrification are strongly inhibited by temperatures greater than 40°C (Jiménez and Garcia 1989). Nitrate-N reached its highest concentration for the FA samples (350 mg $kg^{-1}$) at 70 and 85 d when pile temperatures were 20 to 35°C. Lower $NO_3$-N in the final samples at 133d may have been the result of leaching from saturated compost or denitrification; compost moisture (w/w) was greater than 65% at this date (Figure 2a).

The compost $NO_3$-N concentrations observed during curing are indicative of a mature yard trimmings compost that does not immobilize N after soil incorporation. Previous research with yard trimmings composts produced near Seattle, Washington (D.M. Sullivan, unpublished data 1994) showed that composts containing at least 100 mg $kg^{-1}$ $NO_3$-N did not immobilize inorganic N in short term (28-d) soil incubation experiments.

### *Ammonium-N to Nitrate-N ratio*

The ratio between $NH_4$-N and $NO_3$-N decreased with composting time (Figure 4c). Most of the change in the ratio was due to declining $NH_4$-N concentration. The ratio was above 8 during active composting. It fell to 2 to 5 after 85 d of composting time. At most sampling dates, the FA samples had a lower $NH_4$-N to $NO_3$-N ratio than PA samples, suggesting greater compost maturity. Ammonium-N to $NO_3$-N ratios of less than 1 are generally considered indicative of mature compost (Bernal *et al.* 1998; Larney 2000; Paré *et al.* 1998). Our final ratios are higher than 1 for both PA and FA samples, probably as the result of elevated $NH_4$-N concentrations obtained via the distillation method.

### *Indices of Compost Respiration Rate*

We evaluated four indices of compost respiration rate: sample $CO_2$ loss to an alkaline trap, sample temperature rise in an insulated vessel (Dewar flask), and semi-quantitative evaluations of $CO_2$ loss via the Solvita™ method and the Dräger tube method. All of the respiration indices evaluated in this study (**Table** 2 and **Figure** 5) had greater sensitivity in measuring compost stability than measures of total C concentration, or the CEC of compost-C (Figure 3a and 3c).

TABLE 2.
Effect of aeration treatment on yard trimmings compost stability during curing (70 to 133 d).

| Compost Aeration Treatment[a] | Respiration Test Method | Composting Time 70 d | 85 d | 98 d | 133 d | Average | Pooled Error[b] |
|---|---|---|---|---|---|---|---|
| | | Solvita $CO_2$ measurement, 1 to 8 scale | | | | | |
| FA | Solvita[c] | 6.7 | 6.7 | 6.0 | 6.3 | 6.4 | 0.6 |
| PA | | 4.7 | 6.3 | 5.3 | 4.0 | 5.1 | 1.5 |
| | | $CO_2$ in chamber headspace, % by volume | | | | | |
| FA | Dräger tube | 0.8 | 1.0 | 1.0 | 0.9 | 0.9 | 0.3 |
| PA | | 2.2 | 1.7 | 1.8 | 1.6 | 1.8 | 0.7 |
| | | mg $CO_2$-C g compost C-1 $d^{-1}$ | | | | | |
| FA | Alkaline trap | 0.7 | 1.9 | 1.9 | 3.2 | 1.9 | 1.1 |
| PA | | 4.6 | 2.2 | 4.5 | 3.2 | 3.6 | 1.3 |

[a] Compost processed with forced aeration (FA) or passive aeration (PA).
[b] Pooled error is the standard error of the mean for each treatment (PA or FA) across the four sampling events (3 subsamples per sampling event).
[c]Qualitative color scale corresponding to relative amount of $CO_2$ evolution. Numerical values range from 1, "fresh, raw compost, typical of new mixes" to 8, "inactive, highly matured compost". A reading of 6 is interpreted as "curing; aeration requirement reduced" and a reading of 7 as "well-matured, aged compost, curing grade; few limitations for usage" (Woods End Research Laboratory, 1999)

The respiration rates measured in our study were not influenced by high ammonia concentrations in the compost. The Solvita ammonia test consistently gave the lowest reading, a "5" on a 1 to 5 scale indicating "very low ammonia" according to the product insert (Woods End Research Laboratory 1999). The absence of detectable ammonia volatilization was consistent with the acidic pH (below 7; Figure 2b) consistently measured in the yard trimmings compost.

Rapid respiration rates were observed during the first 27 d of active composting. Measurements for the Solvita test and the self-heating test are shown in Figure 5 for all sampling events, while data for the alkaline trap method and the Dräger tube method are shown only for Day 70 to 133 (Table 2). Measured respiration exceeded detection limits during

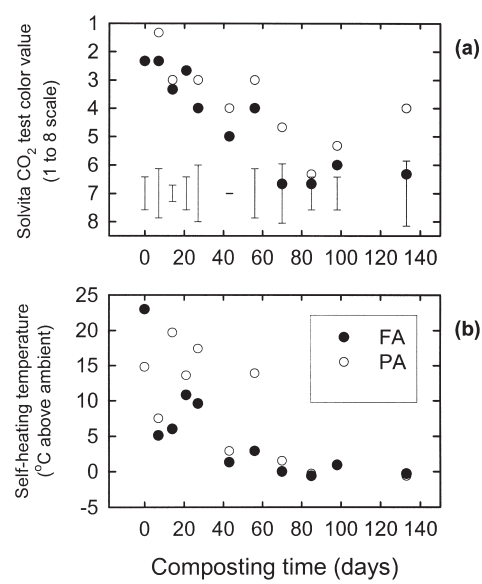


Figure 5. Respiration indices for yard trimmings compost samples. Solvita $CO_2$ test score (a) and self-heating temperature in Dewar flask (b). Error bar is ± SE of the mean (n = 3).

active composting for the alkaline trap and the Dräger tube method (data not shown). We were not able to measure respiration rates above approximately 10 mg $CO_2$-C g compost-$C^{-1}$ $d^{-1}$ with the alkaline trap method because of depletion of $O_2$ in the 0.5 L chambers. This problem could be rectified by using larger chambers. Similarly, values for the Dräger tube method were greater than the maximum detection limit (> 6 % $CO_2$) for the first 21 d of composting. This measurement problem could be rectified by using a smaller compost sample.

Low, relatively stable respiration rates were measured from Day 70 onward by all tests (Figure 5 and Table 2). All of the tests were capable of detecting changes between active composting (Day 27) and fully cured compost (Day 70 onward). Test results were more variable during the transition period from active to stable compost (Day 43 and 56; Figure 5). During the latter part of curing (Day 70 to 133) the FA compost had a temperature rise less than 2°C via the Dewar self-heating test; a Solvita value of 6 to 7, a Dräger test value of 1 % $CO_2$, and a respiration rate via the alkaline trap method of 2 mg $CO_2$-C g compost-$C^{-1}$ $d^{-1}$. A Solvita value of 7 is described as "well-matured, aged compost, curing grade, few limitations for usage" (Woods End Research Laboratory 1999). The respiration value measured with the alkaline trap is in the range suggested for "very stable compost: no potential for VFA toxicity and odor" (less than 2 mg $CO_2$-C g volatile $solids^{-1}$ $d^{-1}$ in TMECC Method 5.08-B; USDA 2002). In our study, the ratio of compost-C to volatile solids was approximately 1:2, so our final respiration rate was equivalent to approximately 1 mg $CO_2$-C g volatile $solids^{-1}$ $d^{-1}$. Thus, respiration standards developed for other composts appear to be reasonably accurate for yard trimmings compost.

Dewar flask self-heating values in our study (Figure 5b) did not correlate well with interpretive statements designed for this test (TMECC Method 5.08-D; USDA 2002). The Dewar test over-estimated compost stability. For example, the temperature rise observed with samples from active composting (0 to 27 d) was generally in the 10 to 20°C range, for which the standard interpretation is "maturing, moderately stable, curing compost." Dewar test values for the FA compost from Day 42 onward (temperature rise less than 10°C) are routinely interpreted as "very mature, stable, well-aged compost." Other respiration rate indices indicated that the Day 42 compost was not fully cured (Solvita test, Figure 5a; data not shown for Dräger tube and alkaline trap).

### *Seed Germination*

Seed germination was not a sensitive indicator of compost maturity (Table 3). At most sampling dates, the difference in germination among treatments was of similar magnitude as the standard error of the mean. The seed germination test failed to consistently detect phytotoxicity during the period of active composting, when organic acid accumulation was most likely. It also did not differentiate between the PA and FA aeration treatments. Seed germination for barley and zucchini (% of control) averaged 80+% during active composting, and 90+% during curing. Also, seed germination measured 5 d after seeding (data not shown) did not demonstrate phytotoxicity during active composting. Our results with seed germination tests are similar to those of Warman (1999), who concluded that "the commonly used compost extract test and the compost-soil germination and growth tests were not sensitive enough to detect differences between mature and immature composts."

Soluble salts were in the range considered non-phytoxic or marginally phytoxic in our germination tests. The average EC value for the control medium was approxi-

TABLE 3.
Effect of compost addition to potting media on seed germination[a].

| Seed | Compost Added[b] | Composting Time (days) 14 d | 21 d | 27 d | 42 d | 56 d | 72 d | 85 d | 98 d | 133 d | Active 14-27 d | Curing 42-133 d |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Seed Germination, % | | | | | | | | | | |
| Barley | Control | 97 | 98 | 90 | 95 | 93 | 98 | 98 | 88 | 98 | 95 | 95 |
| | FA | 82 | 93 | 53 | 88 | 87 | 92 | 97 | 72 | 82 | 76 | 86 |
| | PA | 88 | 98 | 75 | 80 | 92 | 93 | 93 | 78 | 87 | 87 | 87 |
| | SE[c] | 7 | 6 | 7 | 7 | 10 | 5 | 4 | 7 | 10 | | |
| Zucchini | Control | 98 | 97 | 90 | 97 | 92 | 100 | 100 | 90 | 90 | 95 | 95 |
| | FA | 82 | 97 | 83 | 90 | 92 | 95 | 93 | 95 | 92 | 87 | 93 |
| | PA | 83 | 98 | 87 | 87 | 87 | 95 | 93 | 88 | 93 | 89 | 91 |
| | SE | 8 | 3 | 5 | 5 | 6 | 3 | 5 | 6 | 10 | | |

[a]Germination measured 14 d after seeding.
[b]Compost produced via forced aeration (FA) or passive aeration (PA). FA and PA compost added at 50 % by volume to potting media; no compost added to control media.
[c]Standard error of the mean (n = 3).

mately 1 dS $m^{-1}$. The EC of the compost samples averaged 6 dS $m^{-1}$ (Figure 2c). Thus, the EC of a 50% mixture of compost plus control potting media was approximately 3 to 4 dS $m^{-1}$. Salt tolerance of plant species is evaluated in terms of percent yield reduction at a given conductivity in the growing media (Bresler *et al.* 1982; Shannon 1997). Barley is very salt tolerant; no yield reduction is reported at a conductivity of 4 dS $m^{-1}$. Barley yield is reduced by only 20% at an EC of 10 dS $m^{-1}$. Zucchini is less tolerant; yields are reduced by 0 to 30% at an EC of 4 dS $m^{-1}$.

The lack of significant seed germination inhibition during active composting may be related to our experimental procedure. Our test procedure simulated compost use under greenhouse conditions. Organic acids that may have been present in the compost pile could have been degraded during the 3 d that elapsed between sampling and initiation of our germination test.

### *Compost Color and Odor*

Compost color was not a significant indicator of compost maturity (data not shown). Values ranged from "1" to "2" on the TMECC color rating system (Method 5.03-A; USDA 2002) at Day 0. A value of "1" is the darkest color (black, very dark brown) on a scale of 1 to 5. All samples scored a "1" on this scale from 7 d onward.

Compost odor values estimated by the TMECC protocol (Method 5.03-A) ranged from "3" to "5" during active composting (data not shown). This odor rating scale has numerical values (1 to 5 scale) that correspond to written descriptions of odor. A value of "5" indicates "fresh yard debris, wet leaves, hay, strong pine odor," a value of "3" indicates "fruity, sweet, black licorice, slight pine, slight ammonia, tobacco, burnt odor," and a value of "1" indicates "earthy, soil-like, no odor." Values were not different for the FA and PA samples during active composting, averaging an odor score of 3.3. During curing, the PA samples had slightly greater odor. Over the sampling dates from 43 d onward, the PA samples averaged an odor rating of 2.2 while the FA samples averaged a value of 1.3.

When considered together, compost color and compost odor provided a rough indicator of compost maturity, differentiating among three levels of maturity using TMECC Method 5.03-A, Field Approximation of Compost Color and Odor (USDA 2002). The compost was rated "immature" on the TMECC combined odor and color

scale for 0 and 7 d. The compost was rated "moderately mature" for 14-56 d and "very mature" from 70 d onward. There was no difference between the combined color and odor rating for the FA and PA samples at any sampling date.

### *Effect of Forced Aeration on Compost Quality*

Aerobic processing of yard trimmings is thought to provide compost quality benefits by providing a more optimal environment for more complete and uniform organic matter decomposition. This study showed small, subtle differences between compost produced with continuous aeration (FA samples) and compost produced without forced aeration (PA samples). The aeration effect was small relative to the effect of composting time.

The effects of aeration on the composting process were apparent during the first 27 d of active composting. FA samples had higher pH and lower $NH_4$-N concentrations than PA samples during active composting, indicative of more aerobic conditions in the pile. Respiration indices and CEC measurements also provided evidence of more rapid stabilization of compost in FA piles during active composting. During active composting, FA samples had greater humification of organic matter (as estimated by CEC; Figure 3c) and lower $CO_2$ evolution rates (Table 2) than PA samples.

During the final stages of curing (70 to 133 d), FA compost had a lower respiration rate and less variability among replicate samples than did PA compost (Table 2). All three measures of compost respiration rate (Solvita, Dräger tube, and alkaline trap) showed a higher respiration rate for PA samples compared to FA samples. For example, FA samples had a Solvita reading of 6 to 7 at all dates (70 to 133 d), whereas Solvita values for the PA samples averaged ranged from 4 to 6. For the Solvita and Dräger tube tests, the pooled standard error of the mean for test values was about three-fold lower for FA samples compared to PA samples (Table 2). Temperature rise in the Dewar self-heating test did not show a difference in stability between FA and PA samples (Figure 5b) during the final stages of curing (70 to 133 d).

## *Summary and Conclusions*

This study evaluated a broad range of tests suggested or recommended for compost maturity and stability evaluation. We evaluated these tests only for one composting cycle of 133 d at one yard trimmings compost facility. Therefore, our results should be used primarily to identify promising test procedures for further research. The yard trimmings composted in this study are typical of those processed at composting facilities west of the Cascade Mountains in the Pacific Northwest during spring and summer.

We found that indices of compost respiration rate were the most promising tests for further study and refinement. Since we did not include the same number of replications of each test within a sampling event, we could not compare the precision of the different respiration indices. All respiration rate indices identified a period of high respiration rates during active composting (first 27 d) and a period of relatively stable respiration rates during the latter part of curing (70 to 133 d).

Chemical tests of compost solids showed less promise as maturity indicators, but provided valuable information on final compost quality. Mature yard trimmings compost had several characteristics that are very similar to typical values for soil organic matter. Analytical ratios incorporating data from more than one chemical test were slightly better compost quality indicators than a single chemical test. Mature compost had a C:N of 12, an $NH_4$-N to $NO_3$-N ratio of less than 4, a cation exchange capacity

(CEC) of 400 cmol per kg of compost-C, and a pH between 6.5 and 7.0. The largest change in chemical indices took place during active composting. During curing, changes in chemical test values were relatively small. Evaluation of chemical test parameters at the start and termination of active composting, and once again at the end of curing will likely yield sufficient information for most composting operations.

We were unable to measure consistent effects of composting time or compost processing method (FA and PA treatments) on seed germination of barley and zucchini in a potting media containing 50% compost (v/v). We do not recommend direct-seeding germination tests to evaluate the maturity or stability of yard trimmings compost.

Aerobic processing of yard trimmings is thought to provide compost quality benefits by providing a more optimal environment for more complete and uniform organic matter decomposition. This study showed small, subtle differences between compost produced with continuous aeration (FA samples) and compost produced without forced aeration (PA samples). The aeration effect was small relative to the effect of composting time. During the final stages of curing (70 to 133 d), FA compost samples exhibited greater stability and less variability among replicate samples than PA samples. The reduced variability in respiration rate measurements provided by the FA composting method may be important to compost producers who target high value markets. Composts with consistent levels of stability are required for high value applications such as potting media or compost-mediated plant disease suppression.

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