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Assessing How the Ratio of Barley Mash to Wood Chips in Compost Affects Rates of Microbial Processing and Subsequent Vegetable Yield

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ABSTRACT
The composting of food waste coupled with urban agriculture presents an opportunity to increase nutrient recycling in urban ecosystems. One potential constraint limiting the expansion of aerobic food waste composting is the availability of carbon-rich recalcitrant materials, such as wood chips. We measured the differences in nutrient retention throughout the compost life cycle for different mixtures of barley mash to wood chips, to assess whether composting using proportionally less wood chips would lead to higher nutrient recycling rates. Nine compost piles (1 m^3) were constructed at varying ratios barley mash to wood chips, ranging from 10:90 to 90:10. During the composting process, the 50:50 mixture maintained internal temperatures above 55°C for 30 days, with drop-offs as mixtures diverged in either direction. Food waste content was positively related to internal moisture and CO_2, and negatively related to internal O_2, throughout the ensuing 3 months. The finished compost was used in raised-bed garden plots during the following summer. Yields of arugula and tomatoes increased with compost barley mash content, saturating at high levels. Across all treatments, <5% of N and <2% of P were recycled from barley mash into new vegetable production. Although the maximum amount of nutrients was recycled using high barley mash compost, these treatments also had lower nutrient recycling efficiency compared to intermediate mixtures. These results indicate that the use of wood chips in composting increases the efficiency nutrient retention from food waste and in turn enhances nutrient recycling in urban environments.

Introduction

Densely populated urban environments account for an increasingly large component of global biogeochemical fluxes, contributing to eutrophication and climate change (Grimm et al. 2008). Because the import of food and export of food-associated wastes comprise a substantial proportion of these fluxes (Baker 2011; Baker et al. 2001; Metson et al. 2014), strategies that increase food waste recycling and local agriculture could significantly decrease biogeochemical impacts of urban areas. In industrialized countries, an estimated 25%–40% of all food is wasted (Gustavsson et al. 2011; Kantor et al. 1997). Food waste that ends up in landfills acts as a source of methane emissions (Lou and Nair 2009) and represents a significant sink for nutrients (Baker 2011), even as some scientists have recognized the possibility of phosphorus (P)-induced food shortages in the future and are recognizing the importance of recycling these nutrients (Cease et al. 2015; Childers et al. 2011).

Composted municipal waste has been applied to agricultural land to improve soil properties (Mylavarapu and Zinati 2009), and small-scale composting of urban food waste coupled with urban agriculture has the potential to increase nutrient recycling in cities, transforming nutrients from food waste into new. For example, although urban agriculture contributes to <1% of Montreal's food supply, 73% of the P inputs for urban agriculture were from recycled sources, suggesting that system-wide P recycling could be increased considerably by scaling up urban agriculture (Metson and Bennett 2015). However, if a substantial fraction of nitrogen (N) or P is lost as leachate or runoff, then scaling up urban composting and urban agriculture could create hotspots of nutrient pollution. Quantifying nutrient recycling and loss through the entire composting/growing process

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is thus important in making any policy recommendations aimed at increasing urban nutrient use efficiency.

One likely driver of nutrient use efficiency in urban agriculture is the nature and quantity of carbon sources used in composting. High carbon, recalcitrant material such as wood chips is a key component of composting because it provides substrate for microbes to accelerate the conversion of organic food waste to inorganic material (Carpenter and Rosenthal 2012; Fox 2011). Wood chips in compost piles can also increase microbial activity by facilitating aeration, which is especially important in small-scale bin composting where piles are not turned (Carpenter and Rosenthal 2012). Increased aerobic activity produces heat that eliminates harmful pathogens within the compost pile (Noble and Roberts 2004), increases the rate of decomposition, and reduces unpleasant odors associated with anaerobic activity (Fox 2011; Sundberg and Jonsson 2008).

Competing economic demands may limit the availability of recalcitrant carbon materials for urban composting, and ultimately constrain the ability to recycle nutrients from urban food waste. In some cities, wood from urban tree removal is used primarily for energy production (Wiltsee 1998). Quantitative information on the value of wood chips and other recalcitrant carbon materials to small-scale urban composting will help municipalities devise policies to maximize the community and environmental benefits from these operations. Such information can also serve to identify the best practices for maximizing nutrient recycling in coupled composting/crop production operations.

The aim of the present study is to quantify how barley mash:wood chips ratios (hereafter "% barley") in small-scale (1 m^3) compost piles affect the composting process and the efficiency of converting compost-derived nutrients into new food. Barley mash is relatively homogenous, readily available, and is used in compost that is applied to urban farms in the Twin Cities. We assess the effects of compost source material ratios on the dynamics of the composting process and subsequent vegetable production, and use these data to calculate nutrient recycling efficiencies for N and P at different % food waste. We predicted that compost piles with high % barley would exhibit anaerobic conditions including higher CH_4 flux, and would lose more nutrients through leachate. In addition, we predicted that compost with lower % food waste would be lower in available N and P and subsequently result in lower vegetable yield. We hypothesized that nutrient recycling efficiency would be highest at intermediate % barley.

Materials and Methods

Composting Process

Nine compost piles were constructed using cylindrical enclosures (1-m diameter) made of rebar and chicken wire. Compost was created from mixtures of wood chips and barley mash, with a total initial volume of 1 m^3. Barley mash was collected from local microbreweries and wood chips were supplied by a local tree service (representing a mixture of common tree species, such as maple, oak, elm, and ash). Barley mash had an initial N content of 29.8 g/kg dry weight, initial P content of 8.0 g/kg dry weight, and a C:N (mass) ratio of 13.5. Wood chips were approximately 3 cm $\times$ 1.5 cm $\times$ 0.5 cm, and had an intial N content of 3.4 g/kg dry weight, an initial P content of 2.2 g/kg dry weight, and a C:N ratio of 115.1. Different ratios (by volume) of woodchips to barley mash were used: 10:90, 20:80, 30:70, 40:60, 50:50, 60:40, 70:30, 80:20, and 90:10. Due to space limitations, each of the nine treatment combinations was represented by a single compost pile. Compost piles were constructed using alternating 5-cm layers of wood chips and barley mash, which were then mixed, typical of small-scale compost piles at urban farms or community gardens. Compost piles were set up on May 30, 2014. For the next 5 months, compost piles were not turned, and moisture content was not actively managed (i.e., piles were open and received ambient precipitation). On November 1, 2014, compost piles were moved to a new location where they were covered and remained over the winter.

Compost Pile Biogeochemical Rate Measurements

From June–August 2014, internal temperature in each compost pile was measured at 4-hour intervals using waterproof temperature data loggers (HOBO Water Temp Pro v2 logger, Onset Computer Corporation, Bourne, MA, USA) deployed in the center of each pile (ca. 0.5 m from edge). During this time, weekly measurements of compost pile internal moisture, O_2, and CO_2 were conducted using a Compost-Manager CMS2010 probe (CompostManager, East

Sussex, UK). During this same period, CO_2 efflux from compost piles was measured at weekly intervals using a LI-COR LI-8100A (LI-COR Biosciences, Lincoln, NE, USA) automated soil gas flux system. From June–July 2014, CH_4 efflux was also measured on seven dates, based on CH_4 buildup over 5 min in a chamber of known area (356 cm^2) and volume (1424 cm^3). CH_4 concentrations were measured using a portable flame ionization detector (Inficon, Santa Clara, CA, USA).

Compost samples were analyzed for elemental composition in May 2014 (initial source material), July 2014, and April 2015 (finished compost). Samples were dried (50°C for 5 days) and homogenized using a coffee grinder. Total carbon and nitrogen were analyzed using a Thermo Electron Flash EA 1112 Series CN analyzer (Thermo Fisher Scientific, Waltham, MA, USA). Total phosphorus was measured by ashing samples (500°C for 2 h) followed by persulfate digestion, and analyzed spectrophotometrically using the ascorbic acid method (Murphy and Riley 1962), using NIST apple leaf standards (NIST SRM 1515, Sigma-Aldrich, St. Louis, MO, USA) as a reference.

Leachate from compost piles was collected on four dates following rain events (June 9, 18, 22, and August 4) from an impervious plastic barrier installed at the base of the pile, draining into a buried collection bottle. Not all collection bottles received leachate inputs following a rain event, and collection bottles overflowed in some treatments, so we were not able to quantify volume of leachate. Leachate samples were digested in persulfate (100°C for 10 min) and total dissolved phosphorus was measured by spectrophotometric analysis using the ascorbic acid method (APHA 2005).

Crop Production Experimental Design

In April 2015, finished composts were added to a series of 36 raised bed gardens (1 m length × 0.3 m width × 0.3 m depth) and mixed with topsoil purchased from a local landscaping center at a ratio of 50:50 by volume. This topsoil had 14.1% organic content, pH of 7.1, 226 ppm available potassium, 12.1 ppm NO_3^-N, and 176 PPM Bray P (table 1). Each bed received 0.045 m^3 of finished compost. Four beds received only soil, and each compost treatment was applied to either four replicate beds (for the 30, 40%, 50, 60, and 70% barley composts) or three replicate beds (for the 10, 20, 80, and 90% barley composts).

Table 1. Carbon, nitrogen, and phosphorus content of source materials and finished compost.

Source material	C (g/kg dry wt)	N (g/kg dry wt)	P (g/kg dry wt)	C:N (mass)
Woodchips	391.3	3.4	2.2	115.1
Barley	401.1	29.8	8.0	13.5
Finished Compost				
% Barley	C (g/kg dry wt)	N (g/kg dry wt)	P (g/kg dry wt)	C:N (mass)
10	56.0	3.9	0.8	14.4
20	70.0	4.3	1.6	16.4
30	57.1	5.2	2.0	11.0
40	79.3	7.1	1.4	11.2
50	57.8	6.5	2.2	8.9
60	92.3	8.9	2.4	10.4
70	169.8	13.8	2.0	12.3
80	101.1	9.8	2.6	10.3
90	85.1	5.4	1.3	15.7

Arugula (*Eruca vesicaria sativa*) was planted on one half of each raised bed. Multiple seeds, from Johnny's Selected Seeds (Winslow, ME, USA), were planted directly in the raised bed in 30 plugs on April 28. After 24 days, the arugula was thinned to one plant per plug or 30 arugula plants per raised bed. A single tomato plant (yellow pear heirloom from Johnny's Selected Seeds that had been started in the greenhouse, and transplanted at a height of 15 cm) was planted on the other half of the raised bed plot on May 20. Plots were watered twice weekly as necessary to offset evapotranspiration rates calculated daily using an evapotranspiration calculator (Raes and Munoz 2009).

Soil samples were collected from 0–10 cm depth on June 2, 2015, combining five subsamples collected at the center and near the corners of each plot. Samples were air-dried and were analyzed for organic content (loss on ignition), pH, available potassium (atomic absorption spectrometer), Bray-1 extractable P, and nitrate + nitrite ($CaSO_4$ extraction followed by cadmium reduction and colorometric measurement) at the Research Analytical Laboratory at the University of Minnesota.

Sampling and Plant Analysis

Arugula was harvested on day 42 of the field experiment, before plants had bolted. The entire aboveground plant was removed and weighed immediately. Three to four mature leaves from each plot (12 leaves per treatment) were dried for 5 days at 50°C, and weighed to obtain a wet to dry mass ratio that was used to estimate total dry mass. Dried arugula samples were ground using a mortar and pestle and analyzed for N and P content as described above. Tomatoes were harvested weekly from July 31–September 16. Tomatoes were weighed each week, and a subsample were dried, ground, and measured for N and P content as described above.

Statistical Analyses and Nutrient Budget

We assessed the effects of compost mixture on the composting process, garden soil nutrient levels, and crop production. We considered % food waste in compost as a continuous numerical variable. Internal compost pile CO_2, O_2, and moisture (from June–August 2014) were modeled using multiple linear regression as a function of date and % food waste. Residuals were examined to ensure that assumptions about normality were satisfied. The effects of compost composition on garden soil NO_3-N and Bray P (June 2015) were analyzed using linear regression. The effects of compost composition on yields of arugula and tomatoes were assessed by fitting quadratic models. All statistical analyses were performed using JMP 11.0 (SAS Institute, Cary, NC, USA).

We estimated N and P budgets for all treatments at four time points in the experiment. Initial (May 2014) compost pile N and P for each treatment was estimated based on measurements of %N and %P, and bulk density of the source material (table 1). Subsamples (0.25 L) of barley and woodchips were collected, dried, and weighed, and bulk density was estimated for each compost mixture based on the proportion of these two sources. Nutrient measurements for individual compost piles were used to calculate total N and P in each compost pile in July 2014 and May 2015. We assumed that bulk density was constant throughout the compost process. Finally, we estimated N and P recovered in harvested vegetables. Because arugula and tomato %N and %P did not vary significantly across treatments, overall means were used. To estimate the N and P contributions in vegetables that were derived from compost (because compost was mixed with soil at a 50:50 ratio), we subtracted half of the mean N and P values for harvested vegetable biomass in the control plots (which contained 100% soil) from the total N and P in harvested vegetable biomass for all other treatments, and considered the remaining N and P in harvested vegetable biomass to be compost-derived. Plant roots did not extend into the hard-packed soil below the raised beds, so we assume that plants derived all nutrients from the soil-compost mixtures. Because we only used a fraction of the total finished compost in the garden experiment, in order to estimate the fraction of original compost N and P that was recovered in harvested plant biomass, we scaled the estimate of recovered compost-derived N and P by the original 1 m^3 volume to estimate what could have been recovered had all finished compost been used.

Results

Compost Production

In all compost treatments, internal temperature increased to a maximum value of 40–70°C within 7 days, and then gradually decreased over ensuing months. The compost pile temperature had a unimodal association with % barley. Compost piles containing 30, 40, 50, 60, and 80% barley all had 10 or more days above 55°C, with the 50% barley treatment remaining above 55°C for 30 days (figure 1). Other treatments (10, 20, and 70% food waste) had fewer than 10 days above 55°C, and the 90% barley treatment never reached 55°C.

Compost pile internal moisture, O_2, and CO_2 concentrations were significantly correlated with % barley and all changed over time ($p < 0.001$) as microbial activity slowed and internal conditions equilibrated with the external environment. Increasing % barley

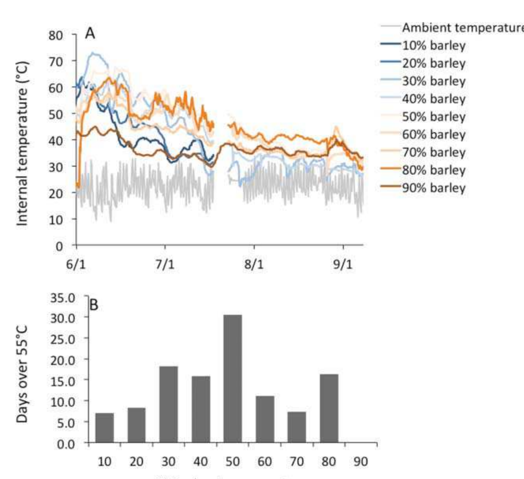

Figure 1. Internal temperature (*A*) and number of days above 55°C (*B*) for different compost treatments.

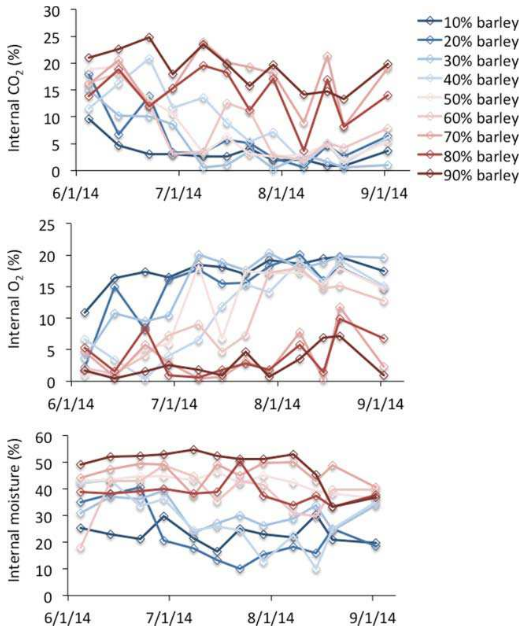

Figure 2. Weekly measurements of internal CO_2, O_2, and moisture in compost piles.

was positively associated with internal CO_2 ($p < 0.0001$, $r^2 = 0.61$), negatively associated with internal O_2 ($p < 0.0001$, $r^2 = 0.70$), and positively associated with internal moisture ($p < 0.0001$, $r^2 = 0.58$; figure 2). Carbon efflux as CO_2 efflux was approximately 1000-fold greater compared to C efflux as CH_4 (figure 3). CH_4 efflux was generally below 10 μg C m^{-2} s^{-1}.

Compost leachate P concentrations were highly variable for high barley content compost mixtures, but average leachate P concentration was ca. 45-fold higher

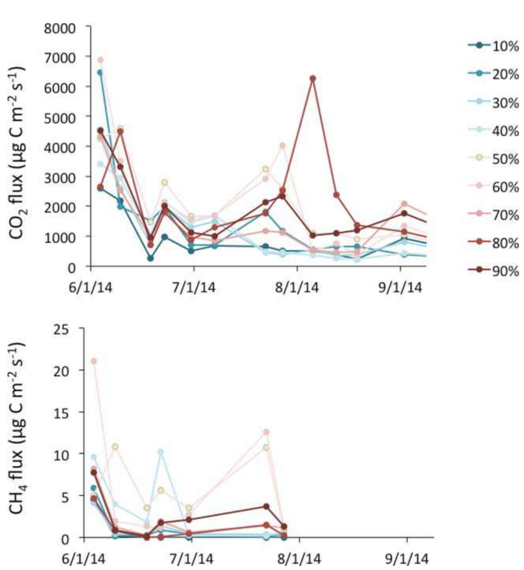

Figure 3. Measured rates of CO_2 and CH_4 flux from compost piles.

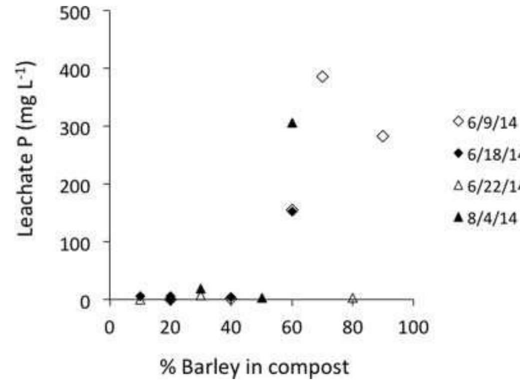

Figure 4. Dissolved P concentrations in leachate samples collected from compost piles on four different dates.

from compost piles containing >50% barley than from compost containing ≤50% barley (figure 4).

Crop Yield from Composts

Compost composition significantly affected initial nutrient concentrations in amended soil in the crop growth experiment (figure 5). Both NO_3^--N and Bray P concentrations in soils increased with % barley in compost (NO_3^--N: $R^2 = 0.139$, $P = 0.035$; Bray P: $R^2 = 0.56$, $P < 0.001$). Only soil amended with compost containing >40% barley had higher NO_3^--N and Bray P concentrations than control soils, which generally corresponded with elevated total N and total P in the finished compost (table 1). Within-treatment variability in NO_3-N concentrations was high for treatments containing >40% barley compost.

Both arugula and tomato yield increased with % barley up to the 70% barley treatment (quadratic

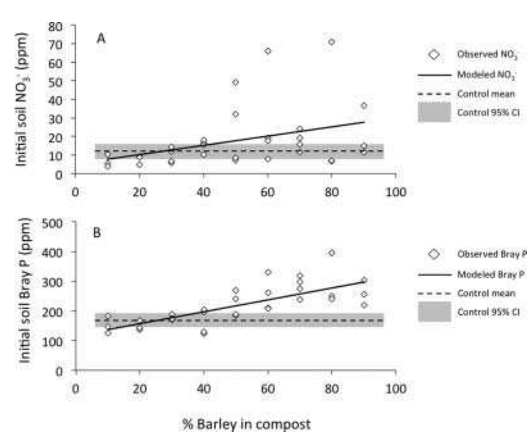

Figure 5. Initial soil NO_3-N and Bray P for soil amended with each compost treatment, relative to control plots which received no compost.

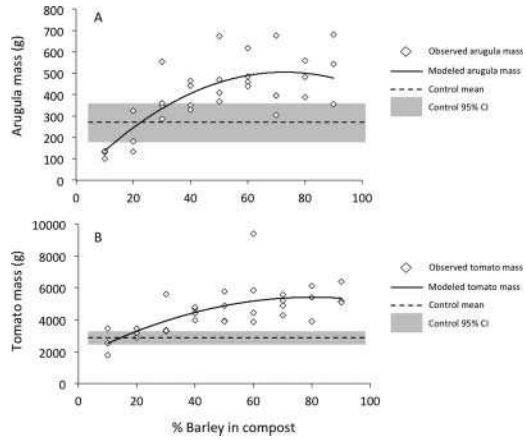

Figure 6. Yield (wet mass) of arugula and tomatoes harvested from 0.3 m^2 raised bed gardens amended with each compost treatment, relative to control plots which received no compost.

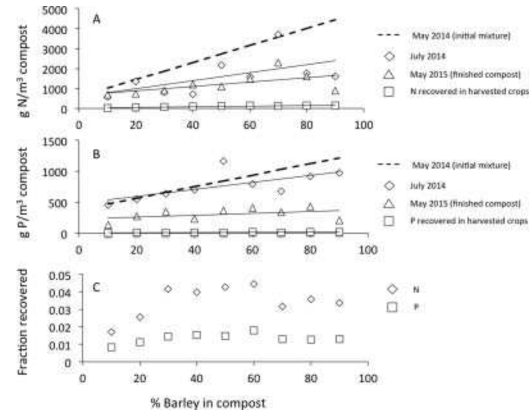

Figure 7. Budgets for N (*A*) and P (*B*) for each compost treatment, for four time points across the 2-year study.

model $r^2 = 0.56$ [arugula] and 0.45 [tomato]; figure 6; table 2). Highest % barley treatments produced ~2 times more arugula and tomato mass than did control soil. Arugula yield in the 10% barley treatment fell below the values measured in the control plots (figure 6).

Nutrient Budget

Initial compost mixtures ranged from 6.0 g N/kg dry mass and 2.8 g P/kg dry mass in the 10% barley treatment, to 27.2 g N/kg dry mass and 7.4 g P/kg dry mass in the 90% barley treatment. Nitrogen values for July 2014 were variable, but on average treatments had lost 40% of the original N, with the highest losses measured for the 80 and 90% barley treatments (figure 7). After the first 6 weeks of incubation, measurable P loss had occurred only in compost treatments containing >50% barley. July 2014 nutrient concentrations ranged from 3.4 g N/kg dry mass and 2.6 g P/kg dry mass in the 10% barley treatment to 9.8 g N/kg dry mass and 5.9 g P/kg dry mass in the 90% barley treatment. Finished compost ranged in N content from 3.9 g/kg dry weight (10% barley treatment) to 13.8 g/kg dry weight (70% barley treatment), and in P content from 7.9 g/kg dry weight (10% barley treatment) to 26.1 g/kg dry weight (80% barley treatment; table 1). Finished compost contained between 20% (in 90% barley treatment) and 64% (in 70% barley treatment) of initial N, and between 17% (in 90% barley treatment) and 53% (in 30% barley treatment) of initial P were shown in figure 7. Finished compost C:N (mass) ratios ranged from 8.9 (50% barley treatment) to 16.4 (20% barley treatment).

Table 2. Parameter estimates for quadratic models of crop yield vs. % barley in compost; Arugula yield $r^2 = 0.56$; Tomato yield $r^2 = 0.45$.

Arugula yield Term	Estimate	Std. error	t Ratio	*P*-value
Intercept	244.2	47.7	5.11	<0.0001
% Barley	4.248	0.78	5.44	<0.0001
$(\% \text{ Barley} - 50)^2$	−0.0931	0.0335	−2.78	0.0095
Tomato yield Term	**Estimate**	**Std. error**	**t Ratio**	***P*-value**
Intercept	3094.8	484.3	6.39	<0.0001
% Barley	35.61	7.92	4.50	<0.0001
$(\% \text{ Barley} - 50)^2$	−0.591	0.340	−1.74	0.0928

On a per-volume basis, the initial 1 m^3 compost piles contained between 1000 g N m^{-3} (10% barley treatment) to 4400 g N m^{-3} (90% barley treatment), and from 470 g P m^{-3} (10% barley treatment) to 1200 g P m^{-3} (90% barley treatment). Finished compost ranged from 680–1620 g N m^{-3} and 140–430 g P m^{-3} (based on the original volume and bulk density of the compost piles).

Harvested crops contained between 0.55–3.07 g N/ 0.3 m^2 plot as arugula and 2.59–7.63 g N/0.3 m^2 plot as tomatoes, and between 0.02–0.11 g P/ 0.3 m^2 plot as arugula and 0.52–1.17 g P/0.3 m^2 plot as tomatoes. Assuming that half of the plant nutrients were derived from compost, these values represent 3%–17% of the total N applied as compost, and 2%–8% of total P applied as compost. Applying these rates to the original 1 m^3 of compost, we estimate that recovery of N from barley during one growing season ranged from 1.7% (in 10% barley treatment) to 4.4% (in the 60% barley treatment). Estimated recovery of P from barley was less variable across treatments relative to N, ranging from

0.8% (in the 10% barley treatment) to 1.8% (in the 60% barley treatment; figure 7).

Discussion

Effects of Barley: Wood Chip Ratios on Compost Process and Nutrient Retention

Because wood chips may be a limiting resource for small-scale urban compost operations, it is important to quantify their effect of compost quality and the environmental impact of composting. Here, we show that composts made with higher barley:wood chip ratios (>70% barley) resulted in high yields of common vegetables, but had low internal compost temperature, high leachate P concentrations, and low N and P recycling efficiency. In contrast, composts made with intermediate ratios of barley:wood chips (40%–60% barley) had higher internal compost temperatures, lower leachate P concentrations, higher N and P recycling efficiencies, and produce yields that were ~90% as high as those of composts made with higher % barley. These results quantify how wood chips in composting can help ensure food safety and increase nutrient retention, underscoring their general value to urban agriculture.

Our results show that higher % barley in compost increases the mass of nutrients that are recycled, but also decreases the fraction of nutrients recovered through harvested crops. These results illustrate the important, and complex, role of recalcitrant carbon materials in nutrient dynamics during the compost life cycle. During the composting process, 20%–67% of original N and 17%–53% of original P was retained. In the composting phase of the experiment, wood chip content was *positively* related to N ($r^2 = 0.39$) and P ($r^2 = 0.79$) retention. In the crop production phase of the experiment, nutrients in harvested crops represented 3%–17% of N, and 2%–8% of P that was applied as compost, and retention of both N and P was *negatively* related to wood chip content ($r^2 = 0.48$ for N; $r^2 = 0.73$ for P).

Mechanisms Controlling Nutrient Retention

The opposing effects of wood chips on nutrient retention during the composting process and crop production phases indicate different mechanisms controlling nutrient retention. The initial compost mixture containing 90% barley contained 4-fold more N and 2.5-fold more P than the 10% barley mixture, and yet the finished compost showed less variation in N (less than a 2-fold difference) and very little variation in P (figure 7). The measured N losses during the composting process across our treatments are similar to ranges reported by Eklind and Kirchmann (2000) in a study in which household organic wastes were composted with different litter additives. Gaseous losses of N (as NH_3, and to a lesser extent as NO_x) and leachate can both account for significant fractions of N loss during the composting process (Martins and Dewes 1992), with aeration rate playing an important role in N dynamics (de Guardia et al. 2008). The high C:N woodchips effectively diluted the nutrient-rich barley mash, and also facilitated aerobic conditions, which potentially could have led to increases in microbial biomass that could retain nutrients that had been hydrolyzed. The apparent high rates of P loss that we observed during the composting process are somewhat surprising, as P is not lost to volatilization, and generally P is thought to leach at lower rates compared to N. The high concentrations of P measured in leachate samples from compost bins with high % barley is consistent with high P losses through leachate, although we were not able to quantitatively sample leachate volumes. The fraction of total P lost during the composting process in this experiment was 2–3 times higher compared to reported P loss fractions in a study of cattle manure composted aerobically with straw (De Guardia et al. 2008). Nutrients lost from compost piles via leachate could potentially contaminate groundwater or surface waters, although we note that, for small-scale compost piles situated on urban farms or in community gardens, some fraction of the nutrients lost from compost piles may still be recovered through crop production; indeed, this is recommended practice in permaculture design (Falk 2013).

In the crop production phase of the study, nutrient recovery was controlled by plant biomass production. The soil that we used in this experiment to mix with compost was high in P and K, but low in NO_3-N, suggesting that N limited crop growth, although we cannot rule limitation by other micronutrients. Plant growth (figure 6) showed similar patterns to initial soil NO_3-N (figure 5), both positively related to the compost barley content. Measured total N of finished compost was highest at intermediate levels (50%–70% food waste), potentially indicating the highest rates of cumulative NO_3-N supply (Ahmad, Hue, and Radovich 2014). Compost with C:N ratios lower than 20 are generally sources of N (Cogger 2005), although it is interesting that finished composts for all treatments in our study fell below this threshold (table 1). Compost with higher levels of food waste led to continued increases in soil NO_3-N levels, but crop production plateaued beyond 60% food waste. In the compost treatments containing the lowest amount of barley (10%–20%), initial NO_3-N was lower than levels in control plots, consistent with N immobilization due to high C:N composts (Cogger 2005). Correspondingly, arugula production dropped below control treatment values in the 10% barley compost treatment. Because of the high P levels in the background soil in this experiment, the low nutrient recovery rates from the addition of P-rich compost may not be surprising. Previous studies have found mixed results on whether urban compost increases P availability in soils (Cabrera, Diaz, and Madrid 1989; Mkhabela and Warman 2005). In our study, Bray P exceeded control soil for compost containing $>50\%$ barley.

Sources of Error in Nutrient Budget

We acknowledge that there are several potential sources of error in our calculation of compost-derived N and P in harvested crop biomass. We assumed that in the 50:50 soil:compost mixture (by volume), plants derived half of their nutrients from compost. However, the bulk density of the soil was 10-fold greater than that of the finished compost, so the soil:compost mixtures were only 10% compost by mass, suggesting that the potential of the contribution of compost-derived nutrients may be lower than 50%. Moreover, our calculation assumes independent effects of the soil and compost, but potential synergistic effects (e.g., priming of soil N) or antagonistic effects (e.g., N immobilization) between soil nutrients and compost would also lead to errors in our estimation of compost-derived nutrients in vegetable biomass. The most conservative approach would be to simply subtract the nutrient content of crops in the control treatment from the other treatments; this assumption leads to recovery percentages of 0%–3.2% N, and 0%–1.2% for P across the various treatments. The least conservative approach would be to assume that all nutrients in crops are compost-derived; this assumption leads to recovery percentages of 4.2%–6.2% for N and 1.8%–2.4% for P. Despite the uncertainty in this calculation, the conclusion that a small fraction of the initial nutrients in compost was recovered through harvested crops during a single growing season is robust.

A large fraction of the compost-derived nutrients that was not recovered during the 2015 growing season may have remained in the soil, either becoming part of the stable organic matter or being slowly released and thus potentially becoming available for crops in subsequent years. An analysis by Amlinger et al. (2003) found that approximately 15% of N from biowaste compost becomes available for plant uptake in the first year after application, with 2%–8% per year becoming available in subsequent years. Nutrient sequestration in other, non-harvested, crop biomass (especially tomatoes) may have been significant as well. Loss of N (Parkinson et al. 2004) and P (Eghball 2003) from soil through leachate represents another potential fate of unrecovered nutrients. Although P is generally bound to soils, repeated application of high P composts, e.g., to meet crop N demand (as often occurs in urban agriculture), could lead to P buildup in soils (Kleinman et al. 2007), potentially leading to elevated losses of dissolved P (Heckrath et al. 1995).

Implications of Wood Chips for Nutrient Recycling from Food Waste

It is well established by practitioners that a balance of food waste ("greens") and wood chips or other carbon substrate ("browns") is needed for successful aerobic composting. However, our study is the first that we are aware of to explore the consequences of diverging from a balanced ratio on nutrient recycling efficiency. While the availability of compostable food waste in many cities is very high, the supply of wood chips is limited. Assuming a fixed supply of wood chips, composting at higher food waste:wood chip ratios would allow for more food waste-derived nutrients to be recycled back into the human food system. In our study, the maximum N and P recycling efficiency was achieved with compost mixtures containing 30%–60% barley, but there is only a modest drop-off in recycling efficiency for compost mixtures from 70%–90% barley. For the 90% barley compost treatment (approximately 9 kg barley per kg of wood chips), an estimated 3% of initial N was recycled into crops, or 270 g of food waste-derived N per kg of wood chips, and 1% of P was recycled into crops, or 90 g of food waste-derived P per kg of wood chips. By contrast, for the 50% barley compost treatment (approximately 1 kg of food waste per kg of wood chips), an estimated 4% of initial N was recycled into crops, or 40 g of barley-derived N per kg of wood chips), and 1.5% of P was recycled, or 10 g of barley-derived P per kg of wood chips.

Because reducing nutrient pollution to surface waters and groundwater is generally a higher priority in many cities compared to increasing food waste nutrient recycling, this balance should be considered in increasing small-scale composting, which is generally not regulated. Considering the sharp increase in P content of leachate observed at 60% barley (figure 4), the fact that the greatest number of days above 55°C was observed in the 50:50 mixture (figure 1), and the asymptotic increases in crop production (figure 6), our data suggest that a 50:50 mixture of barley and wood chips optimizes benefits and minimizes environmental costs of composting.

Generality of Findings from this Study

Our study focused on small to intermediate-sized compost piles, typical of a backyard, community garden, or urban farm. Most composting research has been focused on large-scale commercial composting operations (Bongochgetsakul and Ishida 2008; Courvoisier and Grant Clark 2012), but the growth of urban agriculture has led to increased demands for smaller-scale composting. Scale is important in controlling the biogeochemical processes occurring during the composting process. The surface area:volume ratio affects the exchange of heat, O_2, and moisture in compost piles. Thus, the importance of wood chips for maintaining aerobic conditions may likely be even greater for compost piles larger than the 1-m^3 size used in this study. It would be informative to examine how compost-source material ratios affect nutrient recycling efficiency in larger-scale compost piles. Likewise, our study focused on barley mash as the source of labile organic matter, as it is readily available and commonly used in small-scale composting. Mixed food waste that may be added to backyard compost piles would likely be more heterogeneous than barley mash, potentially altering rates of microbial processing and nutrient transformation, but our findings on the effects of wood chips should generally apply to other feedstocks as well.

Conclusions

Cities are known to be hotspots of biogeochemical cycling, and the predominance of cities across the planet means that these fluxes are globally important (Grimm et al. 2008). The expansion of composting coupled with urban agriculture has potentially important implications for urban nutrient cycling, both in terms of nutrients recycled and nutrients lost through runoff and leachate. The availability of wood chips may serve as the immediate constraint on scaling up urban composting. While composting using higher fractions of food waste could recycle more nutrients back into the human food system, our results suggest that this approach could potentially lead to higher losses of nutrients to the environment, and potentially lead to sub-optimal O_2 concentrations and temperatures during the composting process. Increases in urban agriculture (combined with other uses such as landscaping) are creating increased demand for compost in cities, and food waste supply is more than adequate to meet this demand. Managing small-scale composting in such a way that maximizes the benefits of nutrient recycling while minimizing nutrient losses to the environment is an important challenge in urban sustainability.

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