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Original Research Article

Effects of compost age on the release of nutrients

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ABSTRACT

Composted organic materials are applied to help restore disturbed soils, speed revegetation, and control erosion; these changes are generally beneficial for stormwater quality. Ensuring that nutrient release from compost is adequate for plant needs without degrading stormwater quality is important since composts release nitrogen at variable rates (1–3% of total N/yr) and the leaching process can extend for many years. The aim of this work was to understand the effect of compost age on the extent and rates of nitrogen release by conducting detailed rainfall simulation studies of one compost type at three different ages. Models describing temporal changes in nitrogen release to runoff during a single storm and across multiple storms were developed and applied to the runoff data. Nitrogen content (%) and bulk density of compost increased with the increase in compost age and total nitrogen release decreased with increasing compost age. The three rain simulations (storms) performed on each of the three compost ages show that nitrogen release declined each day of the repeated daily storms. A first-order kinetic model was used to estimate the amount of nitrogen remaining on compost after several storms.

1. Introduction

Compost can help control erosion problems by mitigating formation of soil crusts because their rough surfaces promote percolation, increase water storage, lower surface flow velocities, dissipate the energy from rain drop impact and reduce the shear forces acting on the soil surface. The compost layer applied to the soil surface reduces evaporation and provides a more suitable environment for root growth and releases nutrients that improve the vegetative cover (Faucette, Risse, Nearing, Gaskin, & West, 2004). Compost addition has been shown to provide significant benefits in the restoration of disturbed soils in urban and highway settings, for example, because reestablishing vegetation and controlling erosion can significantly reduce total suspended solids loads transported to receiving waters by stormwater flows (Cogger, 2005). The Clean Water Act (CWA) amendments of 1987 initiated broad efforts to improve stormwater quality associated with disturbed soils such as those at construction sites (Glanville, Persyn, Richard, Laflen, & Dixon, 2004; Royse, 2010; Zougmoré, Mando, Stroosnijder, & Guillobez, 2004). A parallel stormwater quality concern in some receiving waters relates to nutrient inputs that can promote eutrophication. It is important that compost addition for soil restoration not lead to unacceptable increases in nutrient leaching from the restored site.

Composted organic materials release nitrogen at rates considered to be slow (1–3% of total N/year), and the leaching process can extend for many years as long as the composted organic materials are decomposing. In contrast, the nitrogen release rates from chemical fertilizers are considered to be high, the release persists for a much shorter time, and the nitrogen content is rapidly depleted (Claassen & Carey, 2007).

Crop and vegetable production is usually coupled with the use of nitrogen-rich fertilizers that result in high nitrogen release to soil (up to 150 kg N ha^{-1}) (Chaves, De Neve, Boeckx, Van Cleemput & Hofman, 2005). When organic matter decomposes, nitrogen usually experiences two different stages of mineralization and immobilization. Mineralization of nitrogen means that nitrogen is decomposed into plant accessible forms such as NH_4^+ (via ammonification) and NO_3^- (via nitrification). Immobilization of nitrogen occurs when the accessible nitrogen species are taken up by microorganisms preventing them from being accessible by plants. The rate and extent of nitrogen immobilization are related to the biochemical composition of the compost. A high C/N ratio in compost will promote nitrogen immobilization. The immobilized nitrogen will be available to plants after the microorganisms die and the nitrogen is released (Chaves, De Neve, Boeckx, Van Cleemput & Hofman, 2007). A model that predicts the nitrogen remaining in compost would assist in decisions related to the need for and timing of nitrogen fertilizer additions (De Neve & Hofman,

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1996), while a model of nitrogen leaching from compost to water will help to assess the potential stormwater quality implications of compost addition.

The forms and availability of nitrogen in compost change as composting proceeds. Agencies that apply compost as part of soil restoration and stormwater quality enhancement programs may be able to control the amount and timing of nutrient release by specifying that composts are subject to additional aging beyond typical minimum values. To support such decisions, the aim of this work is to understand the effect of compost age on the extent and rate of nitrogen release by conducting detailed studies of one compost type at three different ages. The results are used to construct mathematical models of nitrogen released to stormwater and that remaining in the compost following repeated storm events.

2. Materials and methods

2.1. Compost materials

Three different ages of Grover Green Waste (GGW) compost were tested in this study at zero weeks (GGW0), 4 weeks (GGW4) and 9 weeks (GGW9). The composting process included a 15 d thermophilic period with frequent turning, moisture control and temperature monitoring. This was followed by windrowing and weekly turning to produce a finished compost product; Compost material subjected to this minimum curing time is denoted here as GGW0. Following that, an additional curing period of 4 and 9 weeks was provided, and those are denoted here as GGW4 and GGW9 respectively. Moisture content and volatile organic matter were determined gravimetrically for triplicate samples for each compost age. Dry bulk density of the compost was measured by taking a known volume of compost and weighing it; tests were performed in triplicate for each compost age.

Moisture content and volatile solids were measured gravimetrically by adding 50 g of compost to a tared metal tray. Weight loss after drying for 24 at 105 °C was assumed to be equal to the moisture content. Mass loss upon heating at 550 °C after another 24 h provided the volatile solids content.

Compost samples were prepared for analysis by adding 5 mL of concentrated nitric acid to 0.5 g of fine compost particles and left overnight. The next day, samples were sonicated for 1 h, diluted to 50 mL, and centrifuged prior to analysis.

2.2. Batch experiments

Batch compost-water equilibration experiments were conducted by adding 5 g of compost passing a 1.7 mm sieve to 50 mL of de-ionized (Milli-Q) water and mixing at 35 rpm for 72 h to allow equilibrium to be attained. After that the aliquot were filtered using a 0.45 μm filter and acidified. The samples were preserved at 4 °C until analysis. The test was done in triplicate for each compost age (GGW0, GGW4 and GGW9).

2.3. Rainfall simulation

Rain simulation was performed on three consecutive days (24 h period between each test) for the three compost samples (GGW0, GGW4 and GGW9) using a drop forming rainfall simulator designed and calibrated as described previously (Battany & Grismer, 2000). The test plot consisted of two 80 × 80 cm concrete slabs operated as duplicates and having a 2% slope. Test plots were lined with plastic lining and equipped with a 10 cm surrounding wall on three sides to contain the runoff. The last side was equipped with a v-shape channel for runoff collection. The weighed compost was applied in a 4–5 cm loose layer to the test plot surface. Because of the different dry bulk densities between the three compost ages, different compost masses were applied to cover each test plot for each compost age (GGW0, GGW4, and GGW9).

Rainfall intensity was measured by placing a cylindrical pan with a known area under the rainfall simulator for 1 h and measuring the volume of water collected. All simulations were conducted at a rainfall intensity of 55 ± 5 mm/h.

The time interval between starting the rain simulator and the collection of the first 50 mL of runoff was recorded and the first sample was designated as the time 0 sample. Subsequent samples were taken at different time intervals until nitrogen concentration in the runoff was minimal. The compost used had less than 1% of impurities such as plastic bags, paper, cloth tissues and stones. Each day, after the rain simulation ended the test plots were covered with a plastic cover to keep the compost moist. Runoff samples collected were analyzed within two hours of completing the rain simulations for total nitrogen (TN). Runoff samples collected for other analyses were acidified and stored at 4 °C.

2.4. Analytical methods

All nitrogen species were measured by colorimetric methods using appropriate HACH test kits and a HACH DR/890 colorimeter. Samples were analyzed for total nitrogen (TN) using method 10071 following 10-fold dilution. All nitrogen species are converted to nitrate by the alkaline persulfate digestion method. To minimize halogen oxide interferences, sodium metabisulfite was added after digestion. Chromotropic acid then reacts with nitrate to form a yellow complex (absorbance near 420 nm). The method has a detection range of 0 to 25 mg N/L.

Total Inorganic Nitrogen (TIN) concentration in samples was measured using method 10021 following 10-fold dilution. Nitrite and nitrate are reduced by titanium (III) to ammonia in a basic environment. After removing the solids, the ammonia reacts with chlorine and forms monochloramine, which reacts with salicylate to form 5-aminosalicylate. The sodium nitroprusside catalyst oxidizes the 5-aminosalicylate to form a blue compound; this blue color gets mixed with the yellow color from the excess reagent to result in a final green color solution. The method has a detection range of 0 to 25 mg N/L.

Nitrate-Nitrite concentration in samples was measured using method 10020 with no dilution. Chromotropic acid reacts with the nitrate under a strong acidic condition producing a yellow compound. The method has a detection range of 0 to 30 mg N/L.

Ammonia-Ammonium concentration in samples was measured using method 10023 following 10-fold dilution.

2.5. Nitrogen release model

2.5.1. Intra-storm nitrogen release model

The model used here to describe nitrogen release at different times within a single storm (intra-storm model) was originally developed to predict the release of pathogens from manure into the aqueous phase (Bradford & Schijven, 2002). The same model was later applied by Guber, Shelton, Pachepsky, Sadeghi, and Sikora (2006) and compared with two other existing models to predict the release of Phosphorous from manure. In their study, the Bradford and Schijven model performed well, and it was recommended because of the stability of its parameters (Guber et al., 2006).

$$N(t) = \frac{dN_w}{Qdt} = \frac{C_{0j}\alpha N_{0i}}{Q}(1+\alpha\beta t)^{-(1+1/\beta)} \tag{1}$$

Where $N(t)$ is the concentration of nitrogen in runoff at time t

(mg N/L), N_w is the cumulative nitrogen mass released into the aqueous phase (kg), Q is the aqueous phase flow rate ($Q = 0.587\ L\ min^{-1}$ in all experiments), C_{0j} is the mass (kg) of the jth compost (j=GGW0, GGW4, GGW9) at the beginning of the first rainfall event with each compost age, N_{0i} is the mass of nitrogen per mass of compost (mg N/kg) at the beginning of the i^{th} storm event (i=days1, 2, and 3), and α (min^{-1}) and β are fitting parameters that define the shape of the nitrogen release curve.

2.5.2. Inter-storm nitrogen release model

A first-order kinetic model has been used previously to simulate nitrogen immobilization and mineralization across multiple storms (Chaves et al., 2005, 2007; De Neve & Hofman, 1996). A typical form of this inter-storm model is:

$$N_{rel}(t) = N_0(1 - e^{-k \cdot t}) \tag{2}$$

Where: $N_{rel}(t)$ is the total N (kg) that has been released at time (t), N_0 is the total mass of N available for release (kg) at the beginning of a simulated storm event (t=0), k is the rate constant for N immobilization and t is the time from the start of incubation.

In this work we are interested in both the N released at a particular time (N_{rel} (t)) and in the amount remaining for release at that time (N_{rem} (t)). These two terms are related by:

$$N_0 = N_{rem}(t) + N_{rel}(t) \tag{3}$$

Comparing (Eqs. (2) and 3) reveals that:

$$N_{rem}(t) = N_0 \quad (e^{-k \cdot t}) \tag{4}$$

In practice it is difficult to define the fraction of total N that is available for leaching and logarithmic fits of Eq. (4) do not always pass through the origin. The intercept on such a plot represents the amount of N apparently available for leaching. One way to fit such data is:

$$N_{rem}(t) = N_0(e^{-k \cdot t \ + \beta}) \tag{5}$$

Where: β is an empirical constant and e^{β} is the fraction of N available for runoff.

Eq. (5) was used to model the nitrogen remaining at each time point during each simulated storm on three consecutive days for each of the three compost ages. Eq. (5) was also used to model the change in nitrogen remaining for each compost age after each simulated rain event.

Event mean concentrations (EMC) of nitrogen in runoff water were calculated using the following equation:

$$C_{avg.} = \frac{\sum (C_t \times \Delta t)}{\sum \Delta t} \tag{6}$$

Where: C_{avg} is the event mean concentration (mg N/L), C_t is the nitrogen concentration in runoff at time (t) and Δt is the time segment duration (t_2-t_1) in minutes.

3. Results and discussion

3.1. Compost characteristics

Physical and chemical characteristics of the three different ages of compost used (GGW0, GGW4; and GGW9) are presented in Table 1.

The N content of the compost increased slightly (~10%) with compost age while the C content, NH_4-N and carbon-nitrogen ratio decreased with the increase in the compost age. The reductions were not significant for the C content and carbon-nitrogen ratio between GGW4 and GGW9, while a significant reduction is apparent for NH_4-N which declined by a factor of 3.3 and 9.8 in going from 0 to 4 and 4 to 9 weeks of age. Volatile solids content also decreased with age. As compost age increased the C/N ratio decreased. A significant drop can be seen between GGW0 and GGW4, while not much difference was noticed between GGW4 and GGW9.

3.2. Batch test results

The results of batch experiments for nutrients release conducted on compost of three ages are presented in Table 2.

As compost age increases, the concentration of total nitrogen (TN), total inorganic nitrogen (TIN), organic nitrogen (N_{org}) and NH_3 leaching out of the compost decreases, as expected from previous research (Claassen & Carey, 2007). As compost age increases the concentration of total nitrogen (TN), total inorganic nitrogen (TIN), organic nitrogen (N_{org}) and NH_3 leaching out of the compost decreases, as expected from previous research by others. Nitrifying bacteria are likely responsible for much of the decrease in available ammonia as the compost ages with a corresponding production of nitrate. Nitrate concentration leached from the compost did increase as the compost aged, as expected, but the increase was small compared with the decline in ammonia concentration. It is unclear whether this is because species other than nitrate were produced or because the nitrate produced was not efficiently leached during the batch experiments.

3.3. Rain simulation

Total nitrogen concentrations in runoff for the three simulated storms for each of the three compost ages are summarized in Fig. 1. This plot also includes model fits described further below.

Dry compost is expected to absorb water. For the day 1 storm, compost retained water for the first two minutes, which was the time required until the first 50 ml of runoff was collected from the test plot.

All parameters presented in Table 3 followed the same behavior as the TN for each individual storm and also for the three consecutive storms for each compost age.

Event mean concentrations for a 55 ± 5 mm/h intensity storm with one hour duration, on three consecutive days for each of the three compost ages are presented in Table 3. The results

Table 1
Physical and chemical characteristics of compost.

Compost	Chemical					Physical		
	N content (%)	C content (%)	C/N ratio	NH_4-N (mg/kg)	NO_3^--N (mg/kg)	Moisture content (%)	Volatile solids (%)	Dry bulk density (kg/m^3)
GGW0	1.20	32.05	26.82	636.55	13.30	5.76	73.37	119.75
GGW4	1.31	26.10	19.92	192.70	1.70	7.44	63.11	129.71
GGW9	1.34	26.05	19.51	19.60	65.55	6.72	55.05	202.28

Table 2
Nutrients batch concentration.

Compost	Parameter soluble concentration (mg/L)						
	TN[a]	TIN[a]	N_{org}[a]	NH_3[a]	NO_3^-[a]	P	K
GGW0	171.9	47.8	124.1	43.8	4.0	13.1	254.3
GGW4	127.0	23.9	103.1	16.8	5.8	6.1	204.5
GGW9	60.6	7.6	53.0	1.0	6.6	1.4	216.9

[a] concentration in mg N/L.

presented in Table 3 are valuable for understanding and modeling the release behavior of nutrients for each compost age, under three consecutive simulated storms. For any compost age, a more significant difference in concentrations between the first day and second day storms is expected in comparison with the difference between the second day storm and the third day storm, since some nutrients will be washed off in each storm and the most labile forms will be removed first. Results presented in Table 3 show that for all nitrogen species, event mean concentrations decreased each day. The concentration values of the different elements presented in Table 3 also show more significant differences between day 1 and day 2 values than that between day 2 and day 3 for all three ages of compost as expected.

3.4. Nitrogen release model

3.4.1. Intra-storm nitrogen release model

The values of the input parameters required in Eq. (1) are presented in Table 4. The values of N_{0i} for Day 1 were calculated from the values presented in Table 1 for N content (%) for each compost. The values of N_{0i} for day 2 were obtained by subtracting the amount of TN released on day 1 (event mean concentration multiplied by the flow rate and duration of the storm event and then divided by the weight of the compost) from the value of N_{0i} on day 1. The same procedure was used to obtain the values of C_{0j} of day 3.

Values for the parameters α and β were obtained by fitting Eq. (1) to the measured concentration of nitrogen released in the runoff from the designated compost at the three different simulated storm events using nonlinear regression (Table 5). The model fits rather well for most of our trials, with R^2 values varying for GGW0 from 0.954 (day 1) to 0.992 (day 3), for GGW4 from 0.998 (day 1) to 0.987 (day 3) and for GGW9 from 0.971 (day 1) to 0.991 (day 2).

It can be seen from Table 5 that as compost age increases and compost becomes more mature and stable, the magnitude of β generally increased (except for the GGW9 day 3 value). No specific trend was observed for α values as compost age increased; however, the values of α decreased gradually on the three consecutive simulated storm events for each of the three compost ages. It can

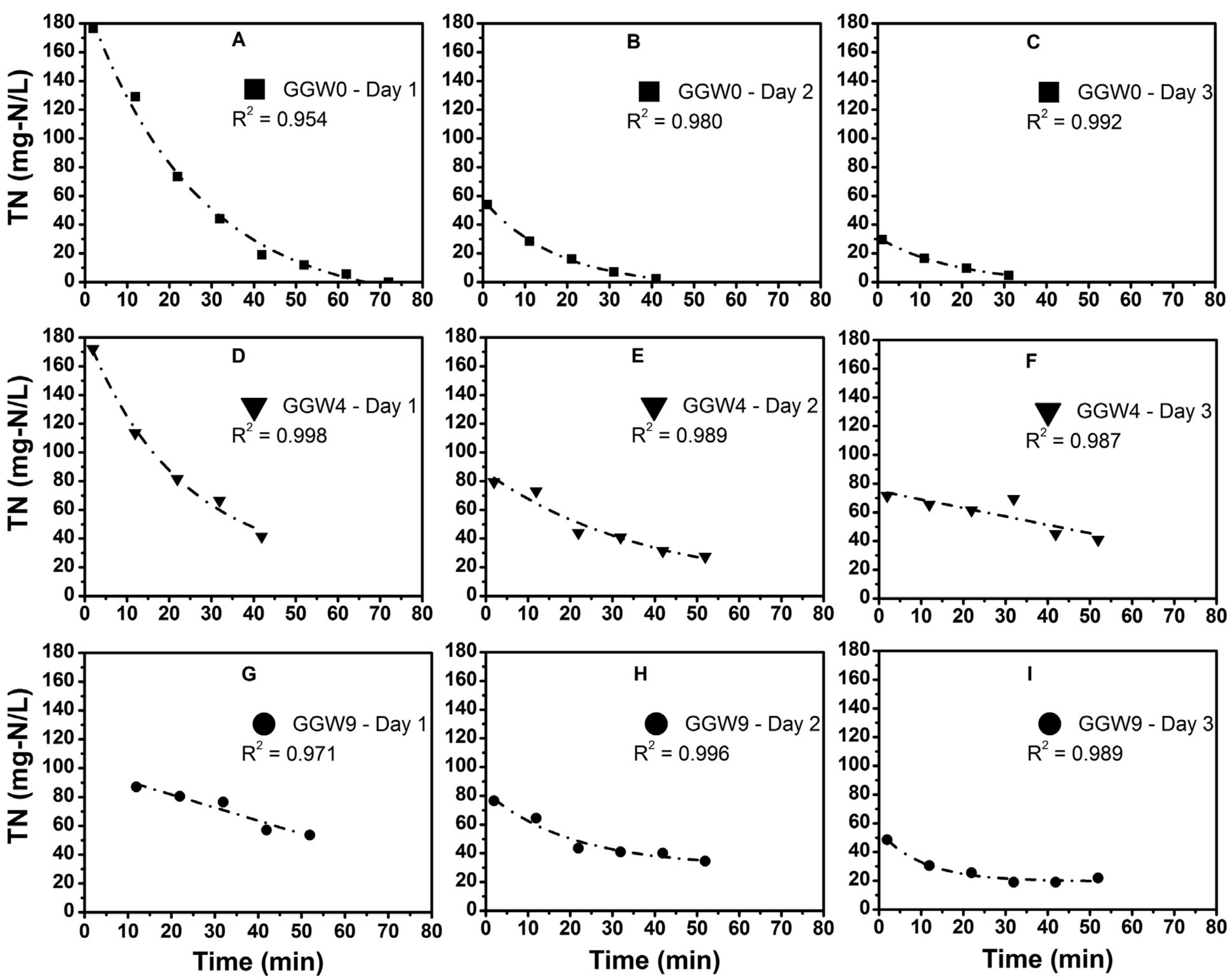

Fig. 1. Measured (data points) and predicted (dashed line) values for total nitrogen concentration in runoff for the three compost types during the three consecutive simulated storm events. Results for GGW0 for storm days 1, 2, and 3 are presented in sub-figures A, B, and C respectively. Similarly for GGW4 storm days 1, 2, and 3 are presented in sub-figures D, E, F, and for GGW9 storm days 1, 2, and 3 are presented in sub-figures G, H, and I.

Table 3
Event mean concentrations for nutrients in rainfall simulation.

	Compost								
	GGW0			GGW4			GGW9		
	Day			Day			Day		
	1	2	3	1	2	3	1	2	3
Parameter	Soluble concentration (mg/L)								
TN [a]	53.00	16.20	11.40	84.60	55.00	42.70	66.80	45.20	24.00
N_{org} [a]	19.40	1.30	0.80	18.50	9.50	5.40	11.20	5.40	4.60
TIN [a]	33.60	14.90	10.60	66.10	45.50	37.30	55.60	39.80	19.40
NH_3 [a]	32.80	14.40	10.30	65.10	44.90	36.80	52.80	38.70	18.70
NO_3^- [a]	0.80	0.50	0.30	1.00	0.60	0.50	2.80	1.10	0.70
P	16.00	2.40	2.00	12.40	5.90	3.50	4.60	4.30	3.60
K	302.20	81.90	39.20	890.90	316.30	156.00	1596.30	460.30	239.30
TOC [b]	1007.70	139.60	43.20	384.00	130.80	58.90	261.40	124.00	52.50

[a] concentration in mg N/L.
[b] TOC: total organic carbon.

Table 4
Model input summary.

Compost	Days	C_{0j} (kg)	N_{0i} (10^3 mg N/kg)	C_{0j} * N_{0i}/Q (10^3 mg N/L) min
GGW0	1	3.832	11.95	78.06
	2	3.832	11.39	74.37
	3	3.832	11.26	73.57
GGW4	1	4.151	13.10	92.69
	2	4.151	12.41	87.80
	3	4.151	12.06	85.36
GGW9	1	6.473	13.35	147.30
	2	6.473	13.03	143.73
	3	6.473	12.80	141.29

Table 5
Model results summary.

Compost	Parameter	Day		
		1	2	3
GGW0	$\alpha \times 10^3$	2.86	0.68	0.23
	β	−37.10	−224.00	−509.00
GGW4	$\alpha \times 10^3$	7.08	1.02	0.53
	β	−22.40	−36.10	−20.60
GGW9	$\alpha \times 10^3$	1.04	0.95	0.36
	β	−3.08	−28.50	−115.00

be seen from Fig. 1 that there is no specific effect of compost age on the regression R^2 values.

There is a strong relationship between the C/N ratio and the release of nitrogen from organic material. As the C/N ratio increases the nitrogen release decreases, organic material with high C/N ratios are known as immobilizers of nitrogen, while others with low C/N ratio are known as mineralizers (Chaves et al., 2005; De Neve, Sáez, Daguilar, Sleutel, & Hofman, 2004). Another factor that could affect the nitrogen release is the polyphenol content, which is considered to be a nitrogen immobilizer (Chaves et al., 2005; De Neve et al., 2004). This is due to the toxicity of polyphenolic compounds for bacteria and other microorganisms that mineralize the nitrogen from the organic compounds, in addition to its strong affinity to amide groups and its strong protein binding capacity (Chaves et al., 2005; Scalbert, 1991). On the other hand it was found that the presence of molasses can increase the nitrogen release (Rahn, Bending, Turner & Lillywhite, 2003). The first data point for GGW9 on day 1 was ignored due to a human error in sample collection. Moreover, by comparing the results from days 2 and 3 for the three compost ages, it can be seen that the total nitrogen released from GGW4 and GGW9 was higher than that for GGW0 (data presented in Fig. 2 and Table 7). One possible explanation for that is the lower C/N ratio (presented in Table 1) in GGW4 and GGW9 when compared to the high C/N value in GGW0. When comparing GGW4 and GGW9 it can be seen that GGW4 had a higher nitrogen release than that for GGW9, although not much difference was found in their C/N value. This could be due to their polyphenol content, or a higher microorganism activity in GGW4.

Table 6
Input values used in fitting intra-storm N release model for GGW0 on day 1.

	GGW0 Day 1			
Time (min)	TN (mg/L)	TN_{avg} (mg/L)	Δt (min)	$TN_{avg}{}^*\Delta t$ (mg.min/L)
1.83	176.5			
11.83	129.0	152.75	10	1527.5
21.83	73.5	101.25	10	1012.5
31.83	44.0	58.75	10	587.5
41.83	19.0	31.50	10	315.0
51.83	12.0	15.50	10	155.0
61.83	5.5	8.75	10	87.5
71.83	0.0	2.75	10	27.5
Σ			70	3712.5

3.4.2. Inter-storm nitrogen release model

Values of TN_{avg} represent the average of two consecutive TN values. The storm event mean concentration (C_{avg}) for GGW0 on the first day rain simulation was calculated using Eq. (6). Using the values presented in Table 6, and by dividing the summation of $TN_{avg}{}^*\Delta t$ over the summation of Δt, C_{avg} was found to be 53.04 mg N/L. Event mean concentrations for each compost age for the three consecutive days of rain simulation were calculated

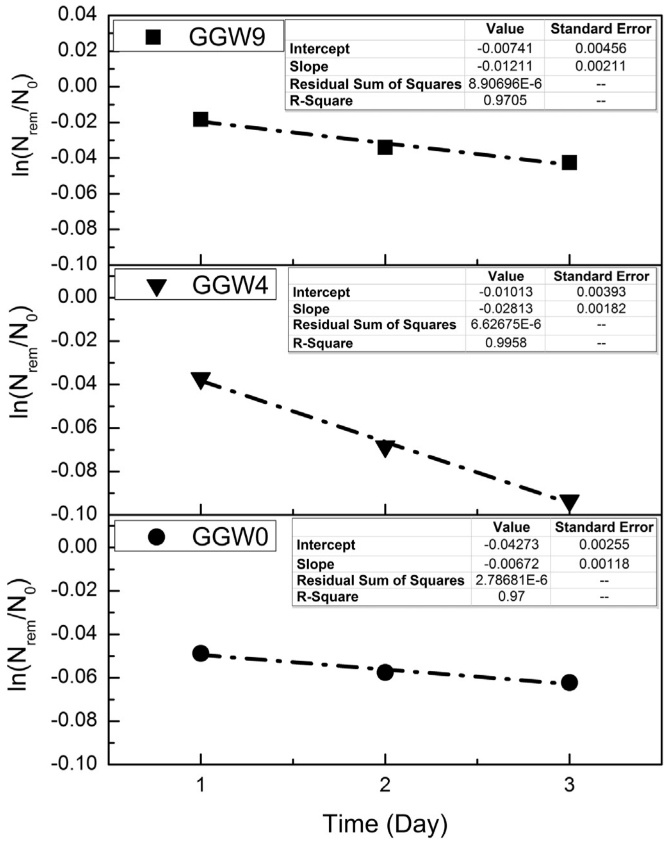

Fig. 2. The values for the nitrogen release rate constant (k, − slope of plot), their related correlation (R^2), and β values (y-intercept) obtained for the three days of rain simulations applied on each of the three compost ages GGW0, GGW4 and GGW9 for the inter-storm model.

Table 7
Inter-storm events mean concentrations.

Day	C_{avg} (mg N/L)		
	GGW0	GGW4	GGW9
1	53.04	84.60	66.75
2	16.20	54.98	45.23
3	11.44	42.68	23.97

following the same procedure and the results are presented in Table 7.

Using the values of C_{avg} presented in Table 7 for GGW0, Table 8 was obtained.

Table 8 represents a sample calculation for GGW0 on the three simulated storm events. To obtain the values for the model parameters k and β, Eq. (5) was rearranged and the linear relationship between the values of $\ln(N_{rem}/N_0)$ and time in days were plotted as shown in Fig. 2.

Nitrogen release rate constants (k) were the highest for GGW4, GGW9 and GGW0 respectively. High R^2 values ($R^2 > 0.97$) were

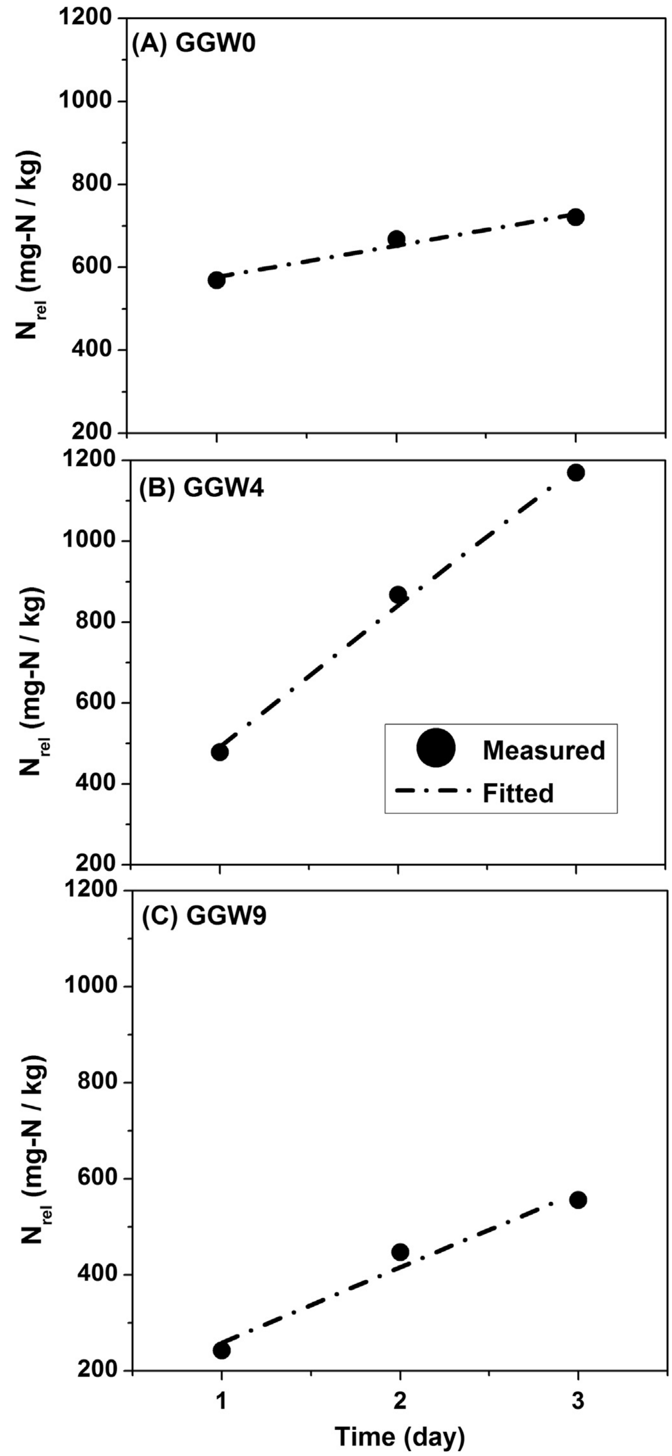

Fig. 3. Measured (data points) and predicted (dashed line) values of total nitrogen release for the three compost types on the three consecutive simulated storm events. Inter-storm results for GGW0, GGW4 and GGW9 are presented in sub-figures A, B, and C, respectively.

Table 8
Sample calculation for the fitting parameters of the (inter-storm) nitrogen runoff model for GGW0.

Time (day)	C_{avg} (mg-N/L)	Duration (min)	Flow (L/min)	Runoff Vol. (L)	N_{rel} (mg)	Compost (Kg)	(mg N/kg-compost) N_{rel}	N_{rel} (t)	N_{rem}	N_0	$\ln(N_{rem}/N_0)$
1	53.04	70.00	0.59	41.09	2179.41	3.832	568.74	568.74	11381.26	11950	−0.0488
2	16.20	40.00	0.59	23.48	380.38	3.832	99.26	668.00	11282.00	11950	−0.0575
3	11.44	30.00	0.59	17.61	201.46	3.832	52.57	720.58	11229.42	11950	−0.0622

obtained for the three compost ages. The y-intercept (-β) value was decreasing with the increase of the compost age.

The first order kinetic model has advantages over more complicated models used in some previous research. It does not require initial estimates for the parameters, a limited number of data points can be used, and the model will still converge at high data variabilities. It can be seen from Fig. 3 that GGW4 had the highest values of nitrogen release per kg of compost among the three compost ages, which was followed by GGW0 and GGW9 respectively. The real mechanism behind that is not well understood. There is a variation in nitrogen release behavior among the same compost type at three different ages, with no clear relation between the age of compost and its nitrogen release. This shows that it was important to investigate these different ages of compost. This difference in nitrogen release could be a result of differences in their polyphenol content and/or due to different microbial populations and/or activity in the three types of compost. The model performed quite well in predicting the amount of nitrogen released for the three ages of compost at the three consecutive simulated storm events. It is difficult to assess the performance of the model in predicting nitrogen release for longer durations. The three consecutive storm events were one day apart from each other and prior to subjecting the compost material to any previous rain events. Although the model used to predict the nitrogen release was exponential, the results obtained seemed to be linear, possibly because we were operating in the first three days of storms which falls in the linear portion of the exponential curve.

4. Conclusions

Aging of the green waste compost studied here by an additional 4 or 9 weeks beyond a typical curing period used in commercial green waste composting operations led to some significant changes in the characteristics of the compost and the amounts, forms and timing of constituent release during stormwater runoff. Nitrogen content (%) and bulk density of compost increased with the increase in compost age, while the carbon content (%) and volatile solids content (%) decreased as compost age increased. Total nitrogen release during simulated storms declined in the order 4 week > 9 week > 0 week, while total phosphorous release consistently declined with aging time. Inorganic nitrogen, mostly in the form of ammonium ion, was the predominant species of nitrogen released in all storms and for all aging times. Small increases in the NO_3^- concentrations were observed with the increase in compost age, presumably due to nitrification. The three rain simulations (storms) performed on each of the three compost ages show that nitrogen release declined each day of the repeated daily storms. The event mean concentrations for both N and P were much more consistent across the three simulated storms than for the 0 week aging period, suggesting that more sustained nutrient release was available from the aged materials; in addition to its benefits for plant health, these sustained release values may also avoid watershed impacts arising from large "pulse inputs" of nutrients from non-point sources. A first-order kinetic model can be used to estimate the amount of nitrogen released from compost after several storms, with a good correlation (R^2) ranging from 0.954 to 0.997, and such models can inform decisions about the acceptability of the extent and rate of nutrient release for various compost ages and source materials.

Author contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

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References

Battany, M. C., & Grismer, M. E. (2000). Development of a portable field rainfall simulator for use in hillside vineyard runoff and erosion studies. Hydrological Processes, 14 (August 1999), 1119–1129. Retrieved from http://onlinelibrary.wiley.com. doi:http://dx.doi.org/10.1002/(SICI)1099-1085(20000430)14:6 < 1119::AID-HYP8 > 3.0.CO;2-O/abstract.

Bradford, S. A., & Schijven, J. (2002). Release of Cryptosporidium and Giardia from dairy calf manure: impact of solution salinity. *Environmental Science and Technology*, *36*(18), 3916–3923. http://dx.doi.org/10.1021/es025573l.

Chaves, B., De Neve, S., Boeckx, P., Van Cleemput, O., & Hofman, G. (2005). Screening organic biological wastes for their potential to manipulate the N release from N-rich vegetable crop residues in soil. *Agriculture, Ecosystems & Environment*, *111*(1–4), 81–92. http://dx.doi.org/10.1016/j.agee.2005.03.018.

Chaves, B., De Neve, S., Boeckx, P., Van Cleemput, O., & Hofman, G. (2007). Manipulating nitrogen release from nitrogen-rich crop residues using organic wastes under field conditions. *Soil Science Society of America Journal*, *71*(4), 1240.

Claassen, V. P., & Carey, J. L. (2007). Comparison of slow-release nitrogen yield from organic soil amendments and chemical fertilizers and implications for regeneration of disturbed sites. *Land Degradation and Development*, *132*, 119–132. http://dx.doi.org/10.1002/ldr.

Cogger, C. G. (2005). Potential compost benefits for restoration of soils disturbed by urban development potential compost benefits for restoration of soils disturbed by urban development. *Compost Science & Utilization*, *13*(4), 243–251. http://dx.doi.org/10.1080/1065657X.2005.10702248.

De Neve, S., & Hofman, G. (1996). Modelling N mineralization of vegetable crop residues during laboratory incubations. *Soil Biology and Biochemistry*, *28*(10–11), 1451–1457. http://dx.doi.org/10.1016/S0038-0717(96)00154-X.

De Neve, S., Sáez, S. G., Daguilar, B. C., Sleutel, S., & Hofman, G. (2004). Manipulating N mineralization from high N crop residues using on- and off-farm organic materials. *Soil Biology and Biochemistry*, *36*(1), 127–134. http://dx.doi.org/10.1016/j.soilbio.2003.08.023.

Faucette, L. B., Risse, L. M., Nearing, M. A., Gaskin, J. W., & West, L. T. (2004). Runoff , erosion , and nutrient losses from compost and mulch blankets under simulated rainfall. *Journal of Soil and Water Conservation*, *59*(4), 154.

Glanville, T. D., Persyn, R. A., Richard, T. L., Laflen, J. M., & Dixon, P. M. (2004). Environmental Effects of Applying Composted Organics to New Highway Embankments: Part 2. Water Quality. *American Society of Agricultural Engineers*, *47*(2), 471–478.

Guber, A. K., Shelton, D. R., Pachepsky, Y. A., Sadeghi, A. M., & Sikora, L. J. (2006). Rainfall-induced release of fecal coliforms and other manure constituents: comparison and modeling. *Applied and Environmental Microbiology*, *72*(12), 7531–7539. http://dx.doi.org/10.1128/AEM.01121-06.

Rahn, C. R., Bending, G. D., Turner, M. K., & Lillywhite, R. D. (2003). Management of N mineralization from crop residues of high N content using amendment materials of varying quality. *Soil Use and Management*, *19*(3), 193–200. http://dx.doi.org/10.1079/SUM2003188.

Royse, D. J. (2010). Effects of fragmentation, supplementation and the addition of phase II compost to 2nd break compost on mushroom (*Agaricus bisporus*) yield. *Bioresource Technology*, *101*(1), 188–192. http://dx.doi.org/10.1016/j.biortech.2009.07.073.

Scalbert, A. (1991). Antimicrobial properties of tannins. *Phytochemistry*, *30*(12), 3875–3883. http://dx.doi.org/10.1016/0031-9422(91)83426-L.

Zougmoré, R., Mando, A., Stroosnijder, L., & Guillobez, S. (2004). Nitrogen flows and balances as affected by water and nutrient management in a sorghum cropping system of semiarid Burkina Faso. *Field Crops Research*, *90*(2–3), 235–244. http://dx.doi.org/10.1016/j.fcr.2004.03.006.