

Municipal Biosolids as an Alternative Nutrient Source for Bioenergy Crops: II. Decomposition and Organic Nitrogen Mineralization

Miguel S. Castillo, Lynn E. Sollenberger,* João M.B. Vendramini, Kenneth R. Woodard, John T. Gilmour, George A. O'Connor, Yoana C. Newman, Maria L. Silveira, and Jerry B. Sartain

ABSTRACT

High-yielding biomass crops remove significant quantities of soil nutrients, and nutrient replacement using inorganic fertilizers may not be sustainable. Municipal biosolids (MBS) are an alternative nutrient source. Organic N is the primary N form in MBS, and patterns of N mineralization can determine the effectiveness of MBS as an N source. The objectives of this experiment were to: (i) determine the effect of season of application on organic N mineralization rate and dry matter (DM) decomposition of Class A MBS measured in the field with litter bags and (ii) compare N mineralization measured using a field-based technique with that predicted from the DECOMPOSITION model. Treatments were season of MBS application (spring and summer) during 2 yr. Organic N mineralization measured using litter bags followed the same pattern and arrived at a similar endpoint as predicted by the DECOMPOSITION model in three of four seasons. Lower spring temperatures and rainfall were associated with lower rates of N mineralization and DM decomposition during the 50 d following spring vs. summer application of MBS. When MBS were applied in summer, organic N mineralization leveled off approximately 50 d after application compared with 150 to 250 d following spring application. Seasonal weather conditions and N mineralization patterns should be considered when determining whether to apply MBS as the source of N, the timing of MBS application, and if single or split applications are best.

PLANT BIOMASS PRODUCTION is affected by soil nutrient quantity and availability. High-yielding bioenergy crops like elephantgrass (*Pennisetum purpureum* Schum.) remove relatively large amounts of nutrients at harvest (Castillo et al., 2010). If biomass production systems are to be sustainable, nutrient replenishment must occur in a manner that minimizes environmental impact and production costs. Land application of MBS represents an opportunity to recycle an existing by-product of municipal sewage sludge treatment plants while providing nutrients for biomass production.

Typical concentrations of total N and P in biosolids range from 35 to 68 g kg⁻¹ and 18 to 39 g kg⁻¹, respectively (USEPA, 1999), but the nutrient of greatest agronomic interest often is N. The forms of N in MBS are primarily organic, thus the main factor controlling availability of N to the subsequent crop is the mineralization/immobilization process. Plant-available N (PAN) in MBS is a function of the initial inorganic N concentration (NH₄–N and NO₃–N) and the proportion of organic N that mineralizes over a specific period of time (Gilmour and Skinner, 1999).

M.S. Castillo, L.E. Sollenberger, K.R. Woodard, and Y.C. Newman, Agronomy Dep., Univ. of Florida, Gainesville, FL 32611-0500; J.M.B. Vendramini and M.L. Silveira, Range Cattle Research and Education Center, Ona, FL 33865; J.T. Gilmour, John Gilmour Inc., P.O. Box 1109, Fayetteville, AR 72702; G.A. O'Connor and J.B. Sartain, Soil and Water Science Dep., Univ. of Florida, Gainesville, FL 32611. Received 11 March 2010. *Corresponding author (lesollen@ufl.edu).

Published in Agron. J. 102:1314–1320 (2010) Published online 7 June 2010 doi:10.2134/agronj2010.0107

Copyright © 2010 by the American Society of Agronomy, 5585 Guilford Road, Madison, WI 53711. All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher.



Significant research effort has been devoted to estimating the N mineralization rates of organic amendments (Sommers et al., 1981; Hanselman et al., 2004). Laboratory estimates of N mineralization may not adequately represent results in the field, however, due to dynamic and site-specific factors like drying and rewetting events and temperature changes (Goncalves and Carlyle, 1994; Gilmour and Skinner, 1999; Hanselman et al., 2004). As a result, in situ methods of assessing organic N mineralization are needed. Results using these methods should be compared to existing models describing N mineralization, both as a means of validating the model and assessing the merit of the field-based technique.

Although the seasonal effects and synchrony of N release from cover crops to meet the demand of associated row crops has been explored thoroughly in the literature (Reeves et al., 1993), relatively little attention has been paid to season of application and advantages of single or split doses of MBS. Because of effects of environmental conditions on N mineralization, there may be advantages to MBS application during particular seasons to synchronize N release and plant N demand. This issue has significant ramifications for MBS management in biomass production systems because number of harvests may be limited to one or generally no more than two per year. Limited options for split applications imply that timing of MBS doses may be very critical. Thus, the objectives of this experiment were to: (i) determine the effect of season of application (spring or summer) on organic N mineralization rate and DM decomposition of Class A MBS measured in the field with litter bags and (ii) compare N mineralization measured using litter bags with that predicted from the DECOM-POSITION model.

Abbreviations: BDR, biosolids decomposition rate; DM, dry matter; MBS, municipal biosolids; NMR, nitrogen mineralization rate; PAN, plant-available N.



Fig. 1. Weekly total precipitation and average weekly maximum and minimum air temperatures at the Range Cattle Research and Education Center at Ona, FL during 2007 and 2008. Arrows indicate when treatments were applied. Spring and summer dates were 20 May and 3 Aug. 2007 and 4 Apr. and 8 Aug. 2008, respectively.

MATERIALS AND METHODS

Experimental Site

The experiment was conducted during 2007 and 2008 at the Range Cattle Research and Education Center at Ona, FL (27°26' N and 81°55' W). The soil at the experimental site was classified as Ona sand (sandy, siliceous, hyperthermic Typic Alaquods). Initial soil characterization of the Ap horizon (to a depth of 20 cm) showed an average soil pH of 6.0 and Mehlich-1 extractable P, K, Mg, and Ca of 10, 42, 230, and 1510 mg kg⁻¹, respectively. Average weekly maximum and minimum temperatures as well as precipitation during the 2 yr are shown in Fig. 1.

Treatments and Design

Polyester bags containing MBS were field-incubated on the soil surface in plots of elephantgrass PI 300086. The grass was one of six elephantgrass entries that were part of an experiment established in the early 1990s. The elephantgrass entries were arranged in four replicates of a randomized complete block design in the earlier study, and plots (experimental unit) were 9 by 16 m. For the current study, each original plot of PI 300086 served as a block and accommodated the two treatments.

Treatments were season of the year when bags were placed in the field (spring vs. summer) and were applied on 20 May and 3 Aug. 2007 and 4 Apr. and 8 Aug. 2008, respectively. Dates of treatment application correspond to times when a once per year application of MBS would be made (spring) or when split applications would be made (spring and summer). Spring weather conditions are characteristically warm and dry, and summer is hot, humid, and with high rainfall (Fig. 1). Treatments also represent the dates of MBS application in a companion experiment that evaluated elephantgrass biomass production response to MBS (Castillo et al., 2010). Treatments were arranged in four replicates of a randomized complete block design.

The MBS material was the result of blending anaerobically digested sludge and undigested waste-activated sludge. The mixture was fed to a belt press and ultimately sent to an

Table I. Composition of the Class A municipal biosolids used for the incubation study.⁺

ltem	Season of application					
	Spring 2007	Summer 2007	Spring 2008	Summer 2008		
pH‡	6.3 ± 0.2	6.4 ± 0.1	6.5 ± 0.0	6.6 ± 0.1		
		g k	g-I			
Dry matter	950 ± 2	990 ± I	980 ± 2	980 ± 1		
Total C§	352 ± 0.1	373 ± 0.1	338 ± 0.1	340 ± 0.1		
Total N¶	58 ± I	65 ± 0	54 ± 0	54 ± 0		
Organic N#	57	64	53	52.6		
C to N ratio	C to N ratio 6.1		6.2	6.3		
Total P††	20 ± 2	21 ± 1	20 ± 2	23 ± I		
К	1.6 ± 0	1.6 ± 0	1.5 ± 0	1.7 ± 0		
Ca	1.9 ± 0	3.1 ± 0	1.6 ± 0	2.2 ± 0		
Mg	1.8 ± 0	3.5 ± 0	2.4 ± 0	2.6 ± 0		
Na	0.6 ± 0	0.7 ± 0	± 0 0.5 ± 0			
Fe	17.6 ± 0.71	21.5 ± 0.92 19.0 ± 2.76		37.8 ± 1.13		
		⟨g−l				
Zn	709 ± 65.0	871 ± 17.7	525 ± 60.8	873 ± 0.7		
Cu	197 ± 6.4	184 ± 3.5	27 ± 4.	193 ± 3.5		
Mn	127 ± 5.7	117 ± 2.8	62 ± 6.4	100 ± 0.7		
Mo	14 ± 0.1	16 ± 0.6	± .2	17 ± 1.0		
NH ₄ N‡‡	881 ± 20.0	618 ± 0.1	966 ± 17.9	1317 ± 1.6		
NO ₃ –N	37 ± 0.6	9 ± 0.3	37 ± 0.6	28 ± 0.5		

 \dagger Data are means and standard deviations of two samples per batch, on a 100% dry matter basis.

 \ddagger pH determined using 15 g wet sample + 200 mL deionized water. Sample was stirred and allowed to stabilize for 5 min.

§ Total C determined by dry combustion (Nelson and Sommers, 1996) on a Thermo Flash EA1112- NC elemental analyzer.

¶ Total N determined using a micro-Kjeldahl method, a modification of the aluminum block digestion procedure (Gallaher et al., 1975) followed by semiautomated colorimetric determination (Hambleton, 1977). # Organic N calculated as: Total N- (NH₄-N + NO₃-N).

†† Minerals were determined by ashing samples and digesting using 6 M HCI. Analyzed using ICP spectrometer.

 $\ddagger NH_4-N$ and NO₃-N determined by shaking 2.5 g of biosolids with 25 mL of I M KCI for I h and analyzing concentrations with a Rapid Flow Analyzer (RFA, method A303-S020, Alpkem Corporation, 1989).

indirect drier system and dried to an average 950 g DM kg⁻¹ product (Hicks et al., 2007). The heat drying (150–200°C) serves as a "process to further reduce pathogens" (USEPA, 1995), and the resulting Class A biosolids are marketed as a slow-release soil amendment. The MBS used represented four different batches obtained from the municipality (two per year). Two composite subsamples from each batch were analyzed before it was placed in the litter bags (Table 1).

The polyester bags used for the incubation study were 75- μ m mesh and measured 15 by 20 cm. Bags made from this material have been used previously in studies of grass litter decomposition (Dubeux et al., 2006). Based on an application rate of 350 kg total N ha⁻¹ yr⁻¹ from MBS in a companion study (Castillo et al., 2010), 25 g of MBS were placed in each bag. Bags were collected at 10 and nine incubation times following placement in spring and summer, respectively. Incubation times were 3, 6, 12, 24, 48, 96, 144, 192, 240, and 336 d. The incubation times were chosen to provide information on the responses measured over the course of nearly 1 yr after placement in the field. The last date for collection would have interfered with the next year's experiment. Three complete sets of bags (sampling units) were included in each experimental unit. Thus, for each incubation

time there were a total of 12 observations (four replicates × three bags per replicate) per treatment. Also, at each incubation time, two control (empty) bags were collected.

The elephantgrass was clipped to a 10-cm stubble immediately before the beginning of each incubation period. Thus grass in spring plots was clipped 79 d into the incubation period in 2007 and 126 d into the incubation period in 2008, while grass in summer plots was not clipped until near the end of the incubation period. There was no inorganic fertilizer applied and no equipment traffic during the incubation period. The areas in the elephantgrass plots where bags were placed were caged with kennel wire to prevent disturbance by wildlife, and bags were turned weekly by hand to prevent root penetration. A preliminary lab study showed that hand turning of bags caused a loss of mass of less than 0.01 g per bag, indicating that this is an effective technique for avoiding root penetration.

Following collection, the bags were immediately dried in a forced-air oven at 60°C for 72 h. Before weighing the dried bags, the outside of each bag was lightly brushed to remove extraneous material. Each bag was weighed and weights were recorded individually. Final weights were corrected by the weight of the control bags. The contents of all three bags from a single collection date in a given experimental unit were composited and stored in Ziploc bags at room temperature awaiting subsequent analysis.

Chemical Analysis

Before laboratory analysis, particle size homogenization of the collected MBS samples was achieved by grinding the samples using a mortar and pestle. Total N was determined using a micro-Kjeldahl method, a modification of the aluminum block digestion procedure (Gallaher et al., 1975), followed by semi-automated colorimetric determination (Hambleton, 1977). Extractable NH_4 –N and NO_3 –N were determined by shaking 2.5 g of biosolids with 25 mL of 1-M KCl for 1 h and analyzing concentrations of NH_4 –N and NO_3 –N with a Rapid Flow Analyzer (RFA, method A303-S020, Alpkem Corporation, 1989).

Response variables calculated were biosolids decomposition rate (BDR) and organic nitrogen mineralization rate (NMR). The BDR was calculated as

$$BDR = [(W_0 - W_y)/(W_0)] \times 100$$

with W_0 equal to initial weight of MBS and W_x equal to the weight of MBS at a specific incubation time x. The final weights were corrected by the weights of the control bags. The NMR was calculated as

with N₀ equal to the initial weight of organic N and N_x equal to the weight of organic N at a specific incubation time x and where Organic N = Total N – (NH₄–N + NO₃–N).

The approach was based on the work of He et al. (2000), who evaluated several techniques to measure organic N mineralization and transformations from MBS in a field incubation study. These authors concluded that the organic N decrease method was a useful method for estimating N mineralization potential of compost and biosolids under field conditions because it estimated total N mineralization including mineralized N lost through leaching, volatilization, and denitrification.

Statistical Analysis and Model Description

The data were subjected to repeated measures analysis using mixed-model procedures (SAS Institute, 1996; Littell et al., 1998). Incubation period was used in the repeated statement with correlation modeled via replicates within season. All means reported are least squares means. Treatment effects were considered significant if $P \le 0.05$.

The nonlinear mixed models procedure (PROC NLMIXED) (Kratzer and Littell, 2006) was used to fit equations to the data describing organic N mineralization and MBS DM remaining. Organic N mineralization was described using the following equation (Stanford and Smith, 1972; Epstein et al., 1978; Weider and Lang, 1982):

$$N_{min} = N_0 \left[1 - \exp(-kt)\right]$$

where N_{min} = amount of N mineralized at a specific time (*t*); N₀ = constant that represents mineralizable organic N (asymptote); and *k* = rate constant. Municipal biosolids DM remaining was described as follows (Weider and Lang, 1982):

$$X = a + (1000 - a) \exp(-kt)$$

where X = amount of MBS mass remaining at a specific time (*t*) and *a* = constant.

Organic N mineralization results using the litter bag technique were compared to those estimated by the DECOMPOSI-TION simulation model (Gilmour and Clark, 1988; Gilmour, 1998). The model employs first-order kinetics to estimate rates of C and N transfer among biosolids (rapid and slow fractions), microbial biomass (indigenous, new), and soil organic matter (decomposable, recalcitrant) pools (Gilmour et al., 2003). Model inputs are mean temperature, rainfall, and pan evaporation; MBS loading rate, total N, total C, and inorganic N; and initial soil organic matter and inorganic N concentrations.

RESULTS AND DISCUSSION Organic Nitrogen Mineralization

There was season \times year interaction for organic N mineralization; therefore, data were analyzed by year. Within year, season \times incubation period interaction was significant; thus, data were analyzed by incubation period.

The amount of organic N mineralized followed a generally similar pattern of response during 2007 and 2008. When data were analyzed by incubation period, mineralization of N was greater for summer than spring application for all periods in 2007, and in 2008 there were differences favoring summer for Days 12 through 96 (Table 2). In 2007, the amount of organic N mineralized after 240 d was greater for summer vs. spring application, 374 and 289 g kg⁻¹, respectively. In contrast, after 240 d in 2008 total organic N mineralized was not different for the two seasons (average of 429 g kg⁻¹).

Generalizations about treatment responses were made based on the first order kinetics equations fitted to treatments (Fig. 2). This follows work by Sommers et al. (1981) showing that the first order kinetics model described appropriately C and N

Table 2. Organic N mineralization from municipal biosolids incubated in the field following application in spring and summer 2007 and 2008.

Days of	2	2007†	2008†		
incubation	S pring	Summer Spring		Summer	
d		g kg ⁻¹			
3	5.0 b‡	102 a	104 a	97 a	
6	2.3 b	202 a	116 a	115 a	
12	63 b	218 a	90 b	228 a	
24	168 b	281 a	125 b	261 a	
48	221 b	349 a 194 b		301 a	
96	268 b	347 a	332 b	379 a	
144	14 289 b		400 a	366 b	
196	96 313 b		420 a	427 a	
240	2 89 b		428 a	429 a	
336	36 320		496	ND§	
Mean	n 180 288		223	272	

† Standard error of a season mean in 2007 is 11 and in 2008 ranged from 14 to 15. ‡ Season means within a row and year followed by different letters are different ($P \le 0.05$).

§ ND = Bags not placed in the field (Summer 2007 and 2008).

mineralization. The maximum amount of organic N mineralized, as estimated by the models, was 305 and 469 for spring 2007 and 2008, and 353 and 390 g kg⁻¹ for summer 2007 and 2008, respectively (Table 3). In 2007, the total organic N mineralized in spring did not reach the total in summer, contrary to what occurred in 2008. When MBS were applied in summer, organic N mineralization leveled off approximately 50 d after placement in the field in both years (Fig. 2). When MBS were applied in spring, N mineralization reached its maximum after ~150 d in 2007 and 250 d in 2008. Part of the year difference in number of days to maximum can be attributed to MBS application 47 d earlier in 2008 (20 May 2007 vs. 4 Apr. 2008), resulting in a longer period of cool, dry conditions in 2008 than 2007.

Despite this, during the first 144 d there was greater total N mineralization in 2008 than 2007 (400 vs. 289 g kg⁻¹ in 2008 and 2007, respectively). This may be due to the fact that although significant rainfall did not occur until later in the 2008 incubation period, once rains began in June 2008 there was greater uniformity of weekly rainfall and fewer dry weeks compared to 2007.

In general, as temperature and moisture increase, microbial activity increases. Soil microorganisms are primarily mesophyllic and prefer moderate temperatures, with optimum activity between 25 and 37°C (Goncalves and Carlyle, 1994; Jarvis et al., 1996). During the first 24 d of incubation, total rainfall and average temperatures (Table 4) were similar when MBS were applied in summer of 2007 and 2008 (average daily temperature was 27°C for both years and total rainfall was 140 and 195 mm for 2007 and 2008, respectively). Organic N mineralization followed similar patterns during this 24-d period in both years (Fig. 2), with total amounts of N mineralized during the period of 281 and 261 g kg⁻¹ for 2007 and 2008, respectively. In contrast, when MBS were applied in spring, average daily temperatures during the first 24 d were 24°C in 2007 and 20°C in 2008, and total rainfall was 88 and 8 mm for 2007 and 2008, respectively (Table 4). Further, the lowest temperature recorded during the first 24 d was 12°C in 2007 vs. 4°C in spring 2008. These values were considerably less than period lows of 20 and 21°C during summer of the 2 yr. Weather conditions likely explain differences in mineralization

Table 3. Regression coefficients for organic N mineralization estimated using NLMIXED procedures. †

	Year					
	20	07	2008			
Season	N ₀ k		N ₀	k		
	g kg ⁻¹	d-I	g kg ⁻¹	d-I		
Spring	305	0.0250	469	0.01307		
Summer	353	0.0973	390	0.05651		
SE	9.3	0.009	20.3	0.007		
P value	0.0003	<0.0001	0.0005	<0.0001		

 $+ N_{min} = N_0 [\overline{1 - \exp(-kt)}]$ where $N_{min} =$ amount of N mineralized at a specific time (t) and N_0 and k are regression coefficients.



Fig. 2. Effect of season of application (spring vs. summer) of municipal biosolids on organic N mineralization patterns in 2007 and 2008 at the Range Cattle Research and Education Center, Ona, FL.

responses early in spring and summer incubation periods, and may explain the differences that occurred during the first 24 d of spring 2007 vs. 2008 (168 vs. 125 $g kg^{-1}$).

From Day 25 to 48 of incubation following spring application, rainfall was more than twice as great in 2007 (182 mm) than 2008 (71 mm). Although average daily temperatures during this period were similar (26°C in 2007 and 24°C in 2008), the lowest spring temperature was 17°C in 2007 compared to 8°C in 2008. These factors may explain in part why mineralization during Days 25 to 48 of 2008 (221 vs. 194 g kg⁻¹ for 2007 and 2008, respectively) did not compensate for the slower mineralization during Days 0 through 24 of that year. From

Day 25 to 48 of summer incubation, average temperatures were nearly the same in 2007 (26°C) and 2008 (27°C), but rainfall was 37 mm greater in 2007 than in 2008, possibly explaining greater organic N mineralization from Day 25 to 48 in 2007 vs. 2008 (68 and 43 g kg⁻¹, respectively). The total amounts of organic N mineralized after 48 d of summer incubation in the field were 349 g kg⁻¹ in 2007 and 301 g kg⁻¹ in 2008.

When DECOMPOSITION model estimates were compared with field data, observed and predicted values described the same general pattern and endpoint of mineralization for three of four MBS application dates (Fig. 3). Model estimates of organic N mineralization were nearly identical to the final observed values for spring (497 vs. 496 g kg⁻¹) and summer 2008 (432 vs. 429 $g kg^{-1}$) and very similar for summer 2007 (421 vs. 374 vs. g kg⁻¹). The exception to similar predicted vs. observed responses occurred spring 2007 when organic N mineralization at the end of incubation was estimated to be 530 g kg⁻¹ while observed mineralization was 320 g kg⁻¹. Reasons for this disparity are not completely clear, but when looking at rainfall data (Fig. 1) it is noticeable that the portion of the incubation period during which the model overestimated N mineralization in 2007 (~Day 75 and following; Fig. 2) was a period of large variability in

Table 4. Weather conditions during Days 0 to 24 and 25 to 48 following application of municipal biosolids at the Range Cattle Research and Education Center, Ona, FL, in 2007 and 2008.

	0 to 24 d			25 to 48 d				
-	2007		2008		2007		2008	
ltem	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer
Rainfall, mm	88	140	8	195	182	173	71	136
Temperature, °C								
Avg. low	18	22	12	23	20	22	16	22
Avg. high	31	34	28	32	33	33	32	33
Avg. daily	24	27	20	27	26	26	24	27
Period low	12	20	4	21	17	20	8	16
Period high	35	37	32	35	35	35	34	36



Fig. 3. Observed vs. predicted (DECOMPOSITION model) organic N mineralized from municipal biosolids applied in spring and summer seasons of 2007 and 2008 at the Range Cattle Research and Education Center, Ona, FL.

weekly rainfall patterns. Some weeks had in excess of 100 mm whereas others had <10 mm, and this is in contrast to 2008 when minimum rainfall amounts per week rarely were <20 mm.

Biosolids Dry Matter Decomposition

Decomposition of DM, expressed as percentage MBS mass remaining (Fig. 4), followed the same patterns as organic N mineralization when MBS were applied in spring and summer 2007. In 2008, there was a lag period during the first 48 d when MBS were applied in spring, which also occurred when measuring organic N mineralization. The response can be attributed to lower rainfall (86 mm lower) and lower air temperatures during the first 48 d of incubation when MBS were applied in spring vs. summer (period lowest temperature was 4°C for spring vs. 16°C for summer in 2008). In a laboratory study conducted for 32 wk with soils from the northern hardwood forest in the Great Lakes region, MacDonald et al. (1995) reported that microbial respiration (CO_2) release) and net N mineralization nearly doubled when temperatures increased from 15 to 25°C.



Fig. 4. Municipal biosolids (MBS) dry matter mass remaining during incubation periods that started in spring and summer 2007 and 2008 at the Range Cattle Research and Education Center, Ona, FL.

Total DM mass loss was 188 and 156 for spring and summer 2007 and 253 and 160 g kg⁻¹ for spring and summer 2008. At the end of 1 yr of MBS incubation under field conditions at Fort Pierce, FL, He et al. (2000) reported total mass loss of 250 g kg⁻¹ of dry weight from biosolids with an initial C/N ratio similar to those used in the current study (~6).

SUMMARY AND CONCLUSIONS

Organic N mineralization measured using a litter bag technique in the field followed the same pattern and arrived at a similar endpoint as results predicted by the DECOMPOSI-TION simulation model in three of four season × year combinations evaluated. The reason for the overestimation of N mineralization by the model in Spring 2007 is not totally clear.

Lower temperature and rainfall during the first 50 d of incubation were associated with lower rates of N mineralization and DM decomposition during that period for spring- vs. summerapplied MBS. When MBS were applied in summer, organic N mineralization leveled off approximately 50 d after application during 2007 and 2008, with total N mineralization of 353 and 380 g kg⁻¹ in the 2 yr, respectively. In contrast, when MBS were applied in spring, organic N mineralization did not stabilize until approximately 150 d after incubation was initiated in 2007 and 250 d in 2008, in part due to slow mineralization early in the incubation period. Total organic N mineralization was greater in summer than spring 2007 but did not differ due to season in 2008. These data show that the temperature and rainfall conditions following MBS application have a significant impact on timing of N mineralization and N availability to the crop. When deciding the timing of MBS application and whether single or split doses are best, these mineralization patterns and their synchrony with crop N demand should be considered. Specifically, limited N mineralization from MBS in cool, dry spring conditions suggest advantages to use of inorganic N during that season followed by application of MBS later in the year when temperature and rainfall patterns favor more rapid N mineralization.

ACKNOWLEDGMENTS

The authors would like to express their appreciation to the City of Ocala Water and Sewer Department, Jeff G. Halcomb, Director, for providing the batches of MBS used in the study.

REFERENCES

- Alpkem Corporation. 1989. RFA methodology for ammonium nitrogen. A303–S020. Alpkem Corp., Clackamas, OR.
- Castillo, M.S., L.E. Sollenberger, J.M.B. Vendramini, K.R. Woodard, G.A. O'Connor, Y.C. Newman, M.L. Silveira, and J.B. Sartain. 2010. Municipal biosolids as an alternative nutrient source for bioenergy crops: I. Elephantgrass biomass production and soil responses. Agron. J. 102:1308–1313 (this issue).
- Dubeux, J.C.B., Jr., L.E. Sollenberger, S.M. Interrante, J.M.B. Vendramini, and R.L. Stewart, Jr. 2006. Litter decomposition and mineralization in bahiagrass pastures managed at different intensities. Crop Sci. 46:1305–1310.

- Epstein, E., D.B. Keane, J.J. Meisinger, and J.O. Legg. 1978. Mineralization of nitrogen from sewage sludge and sludge compost. J. Environ. Qual. 7:217–221.
- Gallaher, R.N., C.O. Weldon, and J.C. Futral. 1975. An aluminum block digester for plant and soils analysis. Soil Sci. Soc. Am. Proc. 39:803–806.
- Gilmour, J.T. 1998. Carbon and nitrogen mineralization during co-utilization of biosolids and compost. p. 89–112. *In* S. Brown et al. (ed.) Beneficial coutilization of agricultural, municipal and industrial by-products. Kluwer Academic Publ., Dordrecht, the Netherlands.
- Gilmour, J.T., and M.D. Clark. 1988. Nitrogen release from wastewater sludge: A site-specific approach. J. Water Pollut. Control Fed. 60:494–498.
- Gilmour, J.T., C.G. Cogger, L.W. Jacobs, K.G. Evanylo, and D.M. Sullivan. 2003. Decomposition and plant-available nitrogen in biosolids: Laboratory studies, field studies, and computer simulation. J. Environ. Qual. 32:1498–1507.
- Gilmour, J.T., and V. Skinner. 1999. Predicting plant available nitrogen in land-applied biosolids. J. Environ. Qual. 28:1122–1126.
- Goncalves, J.L.M., and J.C. Carlyle. 1994. Modelling the influence of moisture and temperature on net nitrogen mineralization in a forested sandy soil. Soil Biol. Biochem. 26:1557–1564.
- Hambleton, L.G. 1977. Semiautomated method for simultaneous determination of phosphorus, calcium and crude protein in animal feeds. J. Assoc. Off. Anal. Chem. 60:845–852.
- Hanselman, T.A., D.A. Graetz, and T.A. Obreza. 2004. A comparison of in situ methods for measuring net nitrogen mineralization of organic soil amendments. J. Environ. Qual. 33:1098–1105.
- He, Z.L., A.K. Alva, P. Yan, Y.C. Li, D.V. Calvert, P.J. Stofella, and D.J. Banks. 2000. Nitrogen mineralization and transformation from composts and biosolids during field incubation in a sandy soil. Soil Sci. 165:161–169.
- Hicks, H., W.M. Litvany, P.M.E., and J.H. Herndon. 2007. How Ocala's biosolids reuse program controls costs, meets regulations, and is safe for the environment. Available at http://www.fwrj.com/TechArticle07/0507%20FWRJ_t3.pdf (verified 21 May 2010). Florida Water Resource Conf., Clermont, FL.
- Jarvis, S.C., E.A. Stockdale, M.A. Shepherd, and D.S. Paulson. 1996. Nitrogen mineralization in temperate agricultural soils: Processes and measurement. Adv. Agron. 57:187–235.
- Kratzer, D.D., and R.C. Littell. 2006. Appropriate statistical methods to compare dose responses of methionine sources. Poult. Sci. 85:947–954.
- Littell, R.C., P.R. Henry, and C.B. Ammerman. 1998. Statistical analysis of repeated measures data using SAS procedures. J. Anim. Sci. 76:1216–1231.
- MacDonald, N.W., D.R. Zak, and K.S. Pregitzer. 1995. Temperature effects on kinetics of microbial respiration and net nitrogen and sulfur mineralization. Soil Sci. Soc. Am. J. 59:233–240.
- Nelson, D.W., and L.E. Sommers. 1996. Total carbon, organic carbon, and organic matter. p. 961–1010. *In* D.L. Sparks (ed.) Methods of soil analysis. ASA and SSSA, Madison, WI.
- Reeves, D.W., C.W. Wood, and J.T. Touchton. 1993. Timing nitrogen applications for corn in a winter legume conservation-tillage system. Agron. J. 85:98–106.
- SAS Institute. 1996. SAS statistics user's guide. Release version 6. SAS Inst., Cary, NC.
- Stanford, G., and S.J. Smith. 1972. Nitrogen mineralization potentials of soils. Soil Sci. Soc. Am. J. 36:465–472.
- Sommers, L.E., C.F. Parker, and G.J. Meyers. 1981. Volatilization, plant uptake and mineralization of nitrogen in soils treated with sewage sludge. Technical Rep. 133. Purdue Univ., Water Resources Res. Ctr., West Lafayette, IN.
- USEPA. 1995. Process design manual: Land application of sewage sludge and domestic septage. EPA/625/R-95/001. Office of Res. and Development, Cincinnati, OH.
- USEPA. 1999. Biosolids, generation, use and disposal in the United States. EPA530-R-99-009. USEPA, Washington, DC.
- Weider, R.K., and G.E. Lang. 1982. A critique of the analytical methods used in examining decomposition data obtained from litter bags. Ecology 63:1636–1642.