COMMUN. SOIL SCI. PLANT ANAL., 32(9&10), 1589–1605 (2001)

MINERALIZATION OF COMPOSTED MUNICIPAL SLUDGE UNDER FIELD CONDITIONS

K. S. Balkcom, J. F. Adams,* D. L. Hartzog, and C. W. Wood

Agronomy and Soils Department, Auburn University, Auburn, AL 36849

ABSTRACT

Mineralization of nutrients from composted municipal sludge may vary due to sludge type and composting material. This study determined mineralization and release of selected elements from composted municipal sewage sludge to evaluate optimal land application rate under field conditions. Composted municipal sludge was studied in two on-farm experiments, at rates of 0.0, 2.0, 4.0, and 8.1 Mg ha^{-1} (dry wt. basis) applied to peanuts and another field incubation study consisting of 0.0 and 4.0 Mg ha^{-1} sludge rate (dry wt. basis). The on-farm studies were used to determine release of selected elements over a growing season, while third field experiment measured nutrient release periodically for an entire year. The on-farm studies used soil cores with resin bags placed on the bottom to trap any leached nutrient, while the soil in the PVC core was extracted to determine nutrient release. In the latter study, decomposition bags with soil cores and resins were utilized to help

* Corresponding author. E-mail: jadams@acesag.auburn.edu

determine the rate of nutrient release from the sludge. Nitrogen (N) was immobilized, while phosphorus (P) was mineralized at Site A from municipal sludge, but the opposite occurred at Site B. Net release of calcium (Ca), magnesium (Mg), and zinc (Zn) into the soil from sludge occurred after 1 yr. Greatest increase was Ca, at 16 mg kg^{-1} followed by Mg and Zn at 2 and 0.8 mg kg^{-1}, respectively. There was an initial release for all nutrients studied from sludge during the first 2 weeks after soil incorporation. Results show that under field conditions, nutrients from these organic amendments can be readily immobilized, but not supply selected elements in concentrations that would support annual crop growth.

INTRODUCTION

Agriculture has long recognized the benefits of waste materials as a nutrient source and as an amendment to improve the physical and chemical properties of soils. Land application of sludge provides an opportunity for recycling of nutrients and reducing the amount of sludge disposed in landfills. Approximately 4.5 million Mg of sludge are produced in the United States annually (1) and a survey conducted in 1995 reported that approximately 41 thousand Mg of sludge are produced annually in Alabama (2). These amounts are overburdening our landfills and disposal in landfills costly.

Municipal sludge application to agricultural land can supply needed nutrients, such as N, P, and potassium (K). However, with the exception of K, these nutrients are usually bound by organic matter and are not readily available to plants. However, the organic bound nutrients are slowly mineralized by microorganisms which makes them less susceptible to losses through leaching and surface runoff. The slow release characteristic of the potentially environmental damaging nutrients can be advantageous to the environment.

Sludges do not contain the quantity of nutrients as does inorganic fertilizers. Generally, about five times as much sludge would have to be applied to get the same agronomic response as would be expected with inorganic fertilizer (3). For determining maximum loading rate, N concentration is usually the controlling factor (4). If a particular sludge contains elevated levels of heavy metals, the metals would be the limiting factor. The objective of this study was to determine the release rates of selected plant nutrients in field conditions.

MATERIALS AND METHODS

Composted municipal sludge was applied on farm fields in Barbour (Site A) and Henry (Site B) counties (31°45′N, 85°28′W, and 31°32′N, 85°11′W) in

South Alabama. Climates at both sites were classified as subtropical with no dry season with a mean annual rainfall of 127 cm, and mean annual temperature of 19°C (5).Composted municipal sludge was applied and incorporated approximately 20 cm deep one month before planting of a peanut crop. Sludge rates were 0, 2.0, 4.0, and 8.1 Mg ha^{-1}. The municipal sludge was from Dothan, AL and was previously composted with wood chips.

Soils at the study sites were Troup loamy sand (loamy, siliceous, thermic, Grossarenic, Paleudult) and Bonifay loamy sand (loamy, siliceous, thermic, Grossarenic Plinthic, Paleudult) for Sites A and B, respectively (Table 1). Initial soil test values for Ca, K, Mg, and P were measured using the Mehlich 1 extract. Initial pH and soil test ratings were determined by the Auburn University Soil Testing Laboratory (6) (Table 1). Composted municipal sludge was dried at 50°C for 48 hrs., ground in a Retch high speed grinder and analyzed for selected properties (Table 2). Total carbon (C) and N were determined using a LECO-CHN 600 (LECO Corp., St. Joseph, MI). A 0.5-g sample was dry ashed in a muffle furnace at 450°C for at least 4 hrs to determine percent ash. Another 0.5-g sample was digested in a 70 : 30 mixture of nitric and perchloric acid overnight (7) and analyzed for P, K, Ca, Mg, copper (Cu), manganese (Mn), leaf (Pb), and Zn, using an inductively coupled argon plasma spectrophotometer (ICAP) (Jarrel-Ash Division/Fisher Scientific Co., Waltham, MA). Cadmium and nickel (Ni) were analyzed with a graphite furnace and found to be 3 and 6 mg kg^{-1}, respectively.

Immediately after planting in May, soil samples from the A_p horizon were taken from control and 2.0 Mg ha^{-1} sludge plots, dried, ground to pass a 2-mm screen and extracted with 25 mL of 2 *M* KCl, for 30 min and filtered. The extracts were analyzed for NH_4-N and NO_3-N by a microscale colorimetric procedure developed by Sims et al. (8). Soil samples were also extracted with 20 mL of Mehlich 1 extract, for 5 min and filtered. These extracts were analyzed for inorganic P by modifying the microscale colorimetric procedure of Sims et al. (8).

A PVC cylinder (6.5 cm diameter x 20 cm long) was used to obtain an undisturbed soil core from within the plant row of the plots listed previously. The cylinders were placed in the field immediately after planting. The treatments were affected approximately one month prior to planting. Approximately 2 cm of soil was displaced from the bottom of the cylinder and replaced with a resin bag. Resin bags were assembled by putting a PVC ring in a nylon sock and filling with a mixed bed resin [10 g of both anion exchange resin (A-400) and cation exchange resin (C-100); Purolite Co., Bala Cynwyd, PA]. The cores were placed back in the row with the resin bags on the bottom. The PVC cylinder eliminated plant uptake of inorganic N and P, while the resin captured leached N or P. Cores and resins remained in the field until digging of peanuts in early October. Soil in the cores were analyzed for Mehlich-1 extractable P, K, Ca, Mg, Cu, Mn, Pb, and Zn (9). Soil pH was determined with a 1 : 1 soil water mixture and a glass electrode. Soils were also subjected to the same microscale procedure as initial samples. Resins were extracted with 2 *M* KCL and analyzed by the microscale procedure for

Table 1. Classification and Initial Soil Test Values of Field Soils

Series	Family	pH	Ca	K	Mg	P
			kg ha^{-1}			
	Site A					
Troup ls	Loamy, siliceous, thermic, Grossarenic, Paleudult	6.2	141 (L)[†]	40 (M)	20 (L)	29 (H)
	Site B					
Bonifay ls	Loamy, siliceous, thermic, Grossarenic Plinthic, Paleudult	6.5	986 (H)	56 (H)	43 (H)	16 (M)

[†] L, M, H: Low Medium or High Soil-Test Ratings as determined by Auburn University Soil Testing Lab.

Table 2. Analysis of Composted Municipal Sludge from Dothan, AL

Element	%	Element	mg/kg
Nitrogen	1.88	Copper	109.2
Phosphorus	0.62	Lead	24.8
Potassium	0.17	Manganese	420.4
Calcium	0.88	Molybdenum	12.3
Magnesium	0.11	Zinc	845.2
Ash	7.1	Cadmium	3.0
H_2O	55.0	Nickel	6.0
Carbon	43.4		
C : N Ratio	23.1		

NH_4-N, NO_3-N, and inorganic P. Values obtained from soil cores plus the amount on resins were added together. Initial values were subtracted from final numbers to yield net mineralization of NH_4-N, NO_3-N, and inorganic P.

To determine mineralization over a year and not a growing season, another experiment was conducted at the Alabama Agricultural Experiment Station Wiregrass Substation (31°24′N, 85°15′W) on a Dothan loamy sand (fine-loamy, siliceous, thermic Plinthic Paleudult) to determine the rate of release of elements present in the sludge material. Climate at the Substation was classified as subtropical with no dry season with a mean annual rainfall of 127 cm, and mean annual temperature of 19°C (5). On May 22, 1995, a 4.0 Mg ha^{-1} dry wt. sludge rate was applied to the soil and incorporated to an approximate depth of 20 cm. Plots were 5.4 by 15.2 m. An area 5.4 by 2.1 m did not receive any sludge material. This area served as the control. No crops were planted in the plots. Weeds were controlled with herbicide applications as needed.

Immediately after sludge incorporation, soil samples were taken to determine initial soil conditions. Soil samples were analyzed for Mehlich-1 extractable P, K, Ca, Mg, Cu, Mn, and Zn and pH identical to soil samples from the field study. Cores and resins were also placed at random in both plots. The soil and resin analyses administered were identical to the soils from the on-farm study, except inorganic P was not measured. Cores and resins were removed at time intervals of 2, 4, 8, 16, 32, and 52 weeks after application. Each time the cores and resins were removed, new ones were put in their place at a different location within the plots. Five cores were placed in the control and five in the treated areas at each sampling time. The soil from each core in the control and treated plots were analyzed for each time interval, just as the initial soil samples.

Decomposition bags were also utilized in this study. The bags were made of nylon and filled with an equivalent amount of sludge to produce a 4.0 Mg ha^{-1} sludge rate on a dry wt. basis for the area of the bag. The bags were sealed with a heat strip and a wire with a tag was attached to it. The bags were then buried between 10 and 20 cm depth within the treated plot. Forty bags were prepared and buried initially, to ensure that for every sampling time, five bags could be uncovered and obtained for analysis. The sludge that was obtained from each bag at each time interval was dried, ground and analyzed for total N, C, percent ash, P, K, Ca, Mg, Cu, Mn, and Zn using the methods discussed previously.

RESULTS AND DISCUSSION

A mineralization study was conducted at two on-farm sites. Treatments were applied one month before the cores were placed in the field. Due to continued land preparation by farmers, cores could not be placed until planting, and initial samples were not collected until planting. There was no expected N loss between application and installation of soil cores because of immobilization. Sludge composted with wood chips do not mineralize rapidly and often show immobilization of N for several weeks after application (10,11,12). These authors reported C:N ratios of 17, 18, and 33, respectively. The C:N ratio of the composted sludge in this study was 23 : 1 (Table 2). Initial and final soil NH_4^+ and NO_3^- and resin NH_4^+ and NO_3^- were measured to determine total mineralized N and net N mineralization.

At Site A, the initial inorganic N level in the soil was higher than in the soil plus resins within the core after 21 weeks. Since the core excluded N uptake by the plant, the decrease in inorganic N over the growing season was most likely due to immobilization or possible denitrification (Table 3). No data were collected on rainfall at either site, but heavy rains occurred shortly after planting. These saturating rains could have promoted denitrification across all treatments. Extractable NH_4^+ in the soil was not different between the sludge and control plots at the end of the study, but soil NO_3^- was higher with sludge. The NH_4^+ and NO_3^- extracted from the resins did not differ among treatments. Ammonium in the resins was much lower than in the soil above the resin, which suggest that leaching was not a problem during the growing season. Nitrate levels were higher in the sludge treated soils than in the control. If denitrification was a problem during the growing season, higher NO_3^- levels in the sludge treated soils would suggest that the slow mineralization process with the sludge helped lower N losses from denitrification.

Initial inorganic N at Site B followed the same trend as at Site A. The soil NO_3^- for Site B was higher for the control than the composted sludge, just the opposite at Site A. The probable reason was that at this site there was not excessive rainfall to promote denitrification. The higher soil NO_3^- in the control plots at Site B accounted for the difference in total N at the end of the study. There was no previous crop at Site B and this site was cleared of a well established hardwood forest in 1991 and planted to bahiagrass (*Paspalum notatum* Fluegge). The

Marcel Dekker, Inc.
270 Madison Avenue, New York, New York 10016

Table 3. Inorganic N and P Release from Composted Sludge Applied at 2 Mg ha^{-1} at Two On-Farm Sites

		Soil		Resin						
Treatment	Initial N†	NH_4^+	NO_3	NH_4^+	NO_3^-	Total N†	Initial P‡	Soil P	Resin P	Total P
	kg ha^{-1}									
					Site A					
Control	36.2	15.2	8.7	0.42	3.7	28.0	18.8	40.5	0.04	40.5
Sludge	36.0	15.2	11.4	0.54	4.0	31.0	24.7	53.8	0.05	53.9
Contrast				P>F					P>F	
C vs. S§		0.98	0.02	0.32	0.68	0.13		0.01	0.54	0.01
					Site B					
Control	40.2	19.30	11.7	0.30	13.9	45.2	9.5	7.2	0.04	7.2
Sludge	37.7	19.83	6.3	0.46	10.7	37.2	24.9	6.8	0.05	6.9
Contrast				P>F					P>F	
C vs. S		0.83	0.08	0.32	0.44	0.07		0.62	0.54	0.70

† Inorganic nitrogen.
‡ Inorganic phosphorus.
§ Probability of a greater F value.

positive mineralization for the control could have resulted from a release of organic N present from the forest and pasture. This study did not compare forest and row-crop soils, but it helps explain why the control at Site B had the highest N mineralized.

Phosphorus was measured in the same manner as N with soil cores and resin bags. Extractable soil P increased with composted sludge application at Site A with no appreciable P extracted from the resin indicating that there was no downward P movement, as would be expected. Thus, soil core P and total P are essentially the same. The sludge treatment had a larger net P mineralization or release at Site A, while Site B had net negative P mineralization, indicating P fixation. The topsoil at Sites A and B are very similar and should have similar buffering capacities assuming Langmuir adsorption characteristics. The lower soil test P at Site B (Table 1) would indicate that more P could be fixed and result in minimal change in extractable P with added sludge where as the 2.0 Mg ha^{-1} rate had a significant increase in extractable P at Site A.

At the end of the growing season all plots were soil sampled to determine pH and Mehlich I extractable Ca, K, Mg, P, Cu, Mn, and Zn (Table 4). Since there were only three cores were placed in the control and the 2.0 Mg ha^{-1} rate, soil samples were taken in all plots with about 20 subsamples to plow depth per plot and composited by rep for each treatment to give a more accurate soil analysis. Extractable P, Cu, and Zn significantly increased with sludge application rate at

Table 4. Mehlich 1 Extracts for Site A and B

Rate		Mehlich 1 Extractable						
		Ca	K	Mg	P	Cu	Mn	Zn
Mg ha^{-1}	pH	kg ha^{-1}						
					Site A			
0	6.11	109	15	13	22 c	0.71 b	26	2.2 c
2.0	6.26	154	16	15	27 b	0.73 b	25	2.7 bc
4.0	6.01	121	18	14	31 b	0.81 ab	26	3.4 ab
8.1	6.12	154	17	16	40 a	0.85 a	24	4.3 a
P>F	0.27	0.54	0.70	0.65	>0.01	0.09	0.99	0.03
					Site B			
0	6.35	1100 ab	25	45	13 b	0.36 b	31	2.1 b
2.0	6.42	970 b	24	50	14 b	0.43 b	39	2.4 b
4.0	6.32	1080 b	25	46	18 b	0.43 b	29	2.5 b
8.1	6.57	1420 a	22	53	28 a	0.65 a	34	4.6 a
P>F	0.23	0.12	0.54	0.85	0.01	0.04	0.21	0.02

Site A, while sludge had no effect on pH, Ca, K, Mg, or Mn. Phosphorus increase reflected the similar results as core soil sampling for Site A. There were also increased extractable P, Cu, and Zn at Site B, but only at the highest sludge rate. The soil data from all plots at Site B indicates that the soil at Site B is more buffered than at Site A. For example, at Site B only the highest rate of sludge (8.1 Mg ha^{-1}) increased extractable P, Cu, and Zn above the control. The extractable soil data indicates that low initial soil P at Site B required a higher sludge rate than the 2.0 Mg ha^{-1} to show an increase in soil test P.

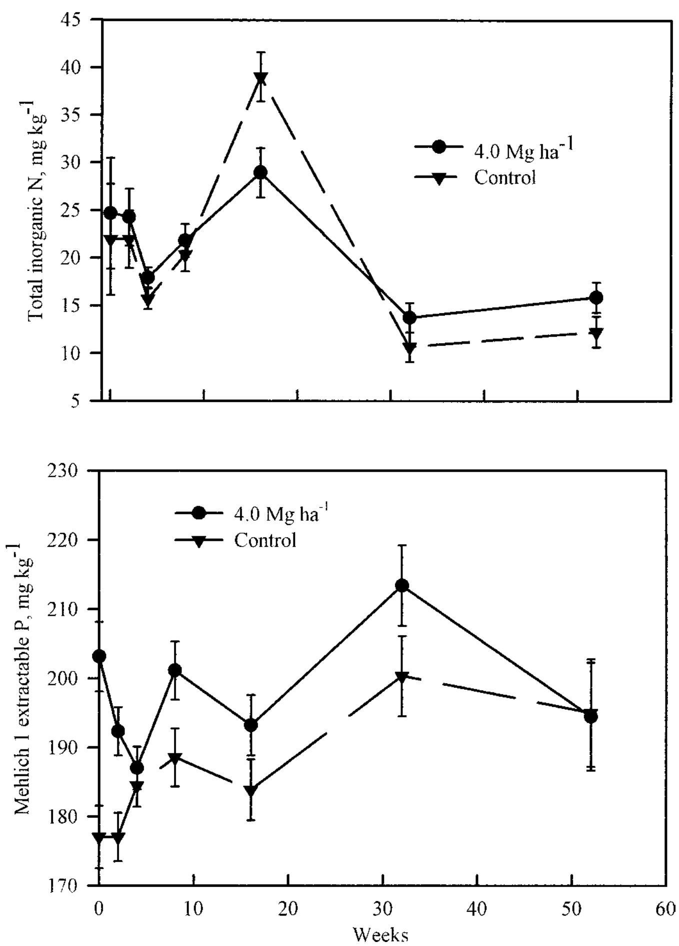

Figure 1. Total inorganic N and Mehlich 1 extractable P measured during incubation study at Wiregrass Substation.

A second mineralization study was conducted at the Wiregrass Substation. Composted municipal sludge was applied at a rate of 0 and 4.0 Mg ha^{-1} (dry wt. basis). Selected elements were measured for 1 year utilizing soil cores and resin bags as in the on-farm studies. Decomposition bags were also used to estimate the amounts of nutrients supplied by municipal sludge. Unlike the previous study, measurements of initial mineralization were possible.

Total inorganic N in the sludge treated soil and control were about the same throughout the year, except for a slightly higher level in the control soil at wk 16 (Fig. 1). A lower N with than without sludge may be due to immobilization caused from the high C : N ratio in the sludge. Inorganic N levels were lower after 1 year for both treatments. This test site had been planted to field peas in prior years, resulting in high residual soil N. Leaching losses would not be a problem because there was no N found in the resin layer. However, losses could be due to denitrification because of saturating rains that occurred at various times during the year (Table 5) and/or immobilization.

Extractable soil P in the sludge treatment decreased initially until wk 4. The sludge treatment had significantly higher soil P than the control for weeks 8, 16, and 32 (Fig. 1). Here again, this corresponds to the increased P found in the previous on-farm study. The maximum extractable P occurred at week 32. McCoy et al. (13) found only 3 to 5% of P in sludge composts were in the organic form as a result of tertiary treatment and low organic P fractions would not contribute

Table 5. Total Rainfall by Month and Average Soil Temperature at Wiregrass Substation for One Year

Month	Total Rainfall cm	10 cm Average Soil Temperature C°
May, 1996	7.2	23.3
June	9.7	25.4
July	13.4	27.4
August	13.1	27.6
September	4.3	25.6
October	15.4	22.2
November	11.3	11.5
December	6.1	8.7
January, 1996	13.4	6.1
February	11.8	8.8
March	17.7	11.4
April	11.8	15.6
May	5.6	24.7

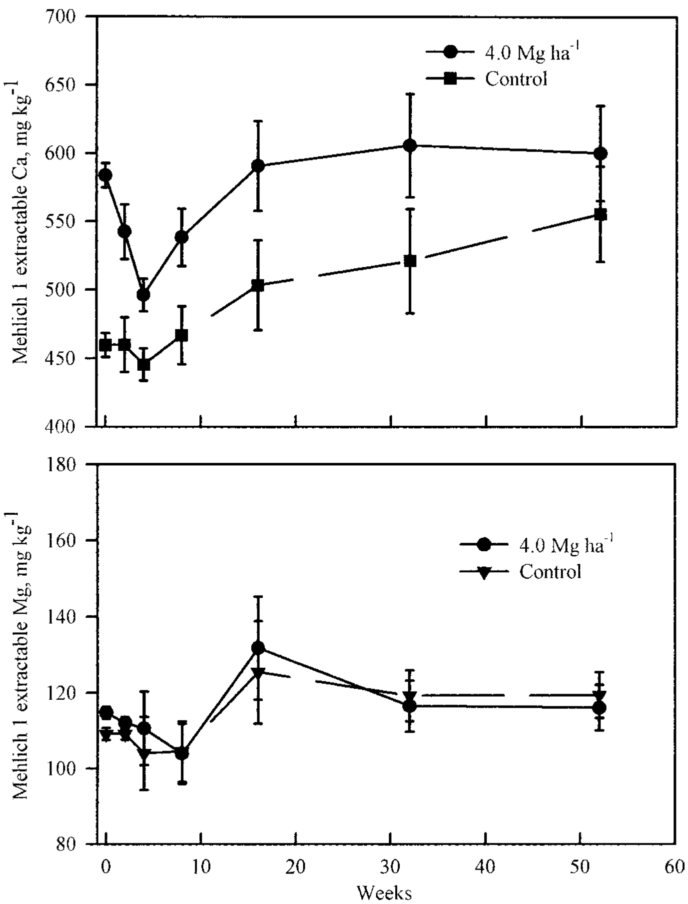

Figure 2. Mehlich 1 extractable Ca and Mg measured during incubation study at Wiregrass Substation.

much to plant available P via mineralization. This sludge did not receive tertiary treatments and thus the P is expected to be associated with the organic fraction. The maximum extractable soil P concentration at wk 32 was a 10 mg kg^{-1} increase over the initial soil concentration. Sludge supplied 11 mg P kg^{-1} (Table 3) at the selected rate. This corresponds to over 91% of the total P in the sludge as being plant available. This is much higher than 25 to 40% reported by Sikora et al. (14). However, this soil was rated "extremely high" by the Auburn University Soil Testing Laboratory (6) and would probably not (or slowly) fix or adsorb any

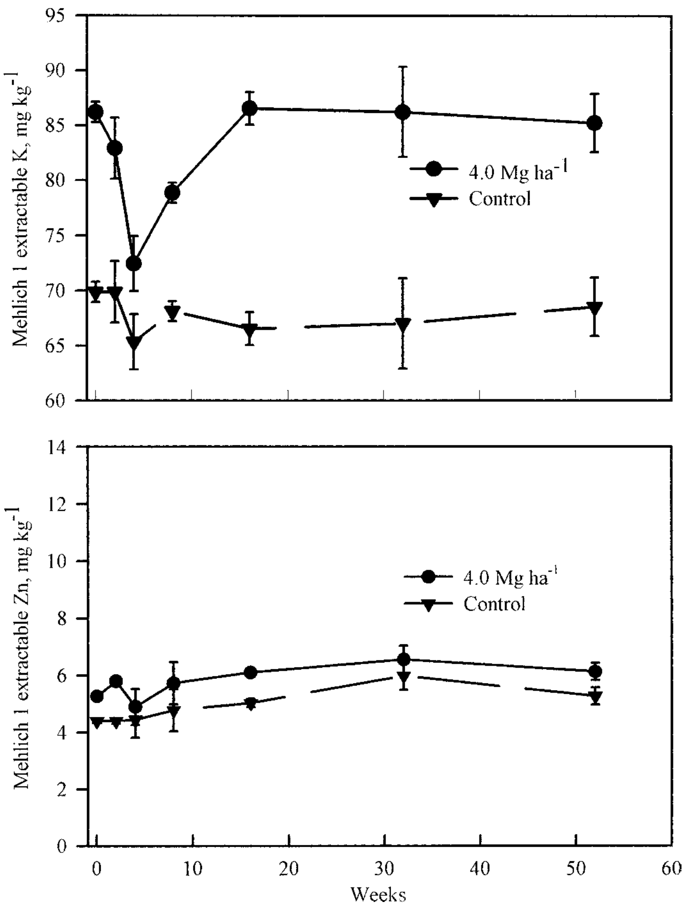

Figure 3. Mehlich 1 extractable K and Zn measured during incubation study at Wiregrass Substation.

additional P. After 1 year, an increase of 18 mg kg^{-1} occurred in the control soil and the amount in the control was equal to the amount when sludge was applied. This could be a result of the high P present in the soil and the lack of P removal by plants.

Extractable soil Ca (Fig. 2) and K (Fig. 3) was increased by the sludge application. For both extractable Ca and K there was an initial increase immediately following application and then a quick decrease during the first few weeks after application and then followed by another rapid increase which tended to level at week 20. It appears that the total impact of the sludge application on Ca and K will occur within the 20 weeks after application. The low amount of Mg applied

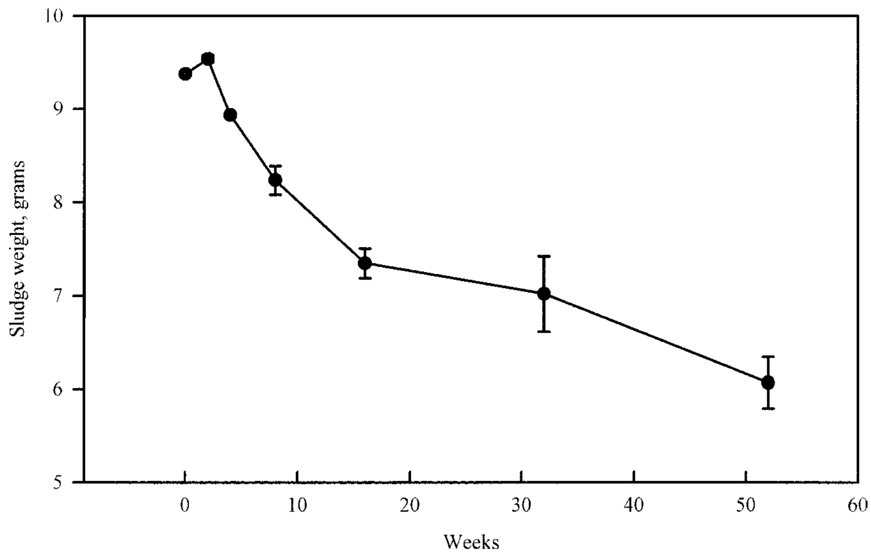

Figure 4. Average weight of sludge contained in decomposition bags for each sample period.

with the sludge did not increase extractable Mg and its variation during the year may be due to environmental factors.

Extractable Zn concentration increased immediately, but dropped slightly at week 4, before increasing again in the treated soil (Fig. 3). Zinc had the highest concentration of the micronutrients in the sludge (Table 2), but only 1.5 mg kg^{-1} was supplied by the selected rate. The concentration dropped at week 4, but increased to a maximum at week 32. After 1 yr. extractable Zn had increased nearly 1 mg kg^{-1} (Fig. 3). The extractable Zn remained constant until week 4, for the control, but gradually increased until week 32. Extractable soil Zn concentration with the control remained the same after 1 year. Tentative critical values for Zn toxicity in peanut production have been set at 12 mg kg^{-1} for soil (acid-extractable) (15). The prolonged use of this sludge may pose a potential production problem and should be monitored.

The elements that were examined (Ca, K, Mg, P, Zn, and N) only four showed an increase over the initial concentration after 1 year. Of those four (Ca, Mg, and Zn) the greatest increase was Ca, at 16 mg kg^{-1} followed by Mg and Zn at 2, and 0.8 mg kg^{-1}. The increases would not be sufficient to affect peanut production.

Sludge contained in decomposition bags decreased with time due to the breakdown of the material (Fig. 4). The most rapid decrease was from week 2 to week 16.

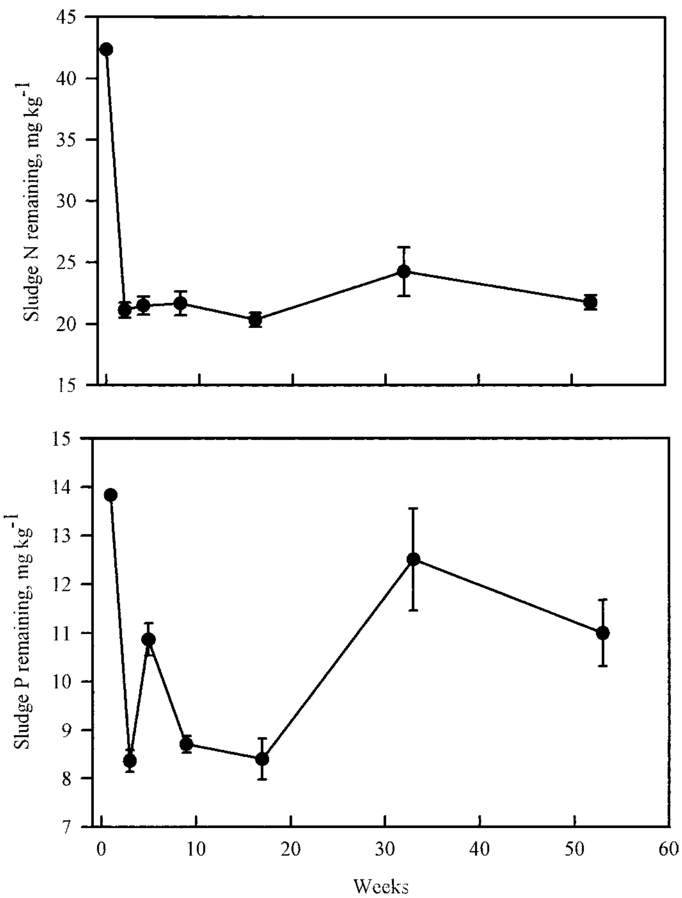

Figure 5. Total N and P present on a dry weight basis in sludge from decomposition bags at each sample period.

There appeared to be an easily mineralizable N fraction in the composted municipal sludge, then the N content remained essentially the same in the sludge after its initial release (Fig. 5). Phosphorus also appeared to have some soluble P but the P concentration increased in the sludge as sludge weight decreased from decomposition, apparently associated with more stable organic matter. No tests were performed to determine the percentage of inorganic and organic P fractions within the sludge compost. Sludges that receive a tertiary treatment have inorganic P as the dominant form of P present (16). McCoy et al. (13) concluded

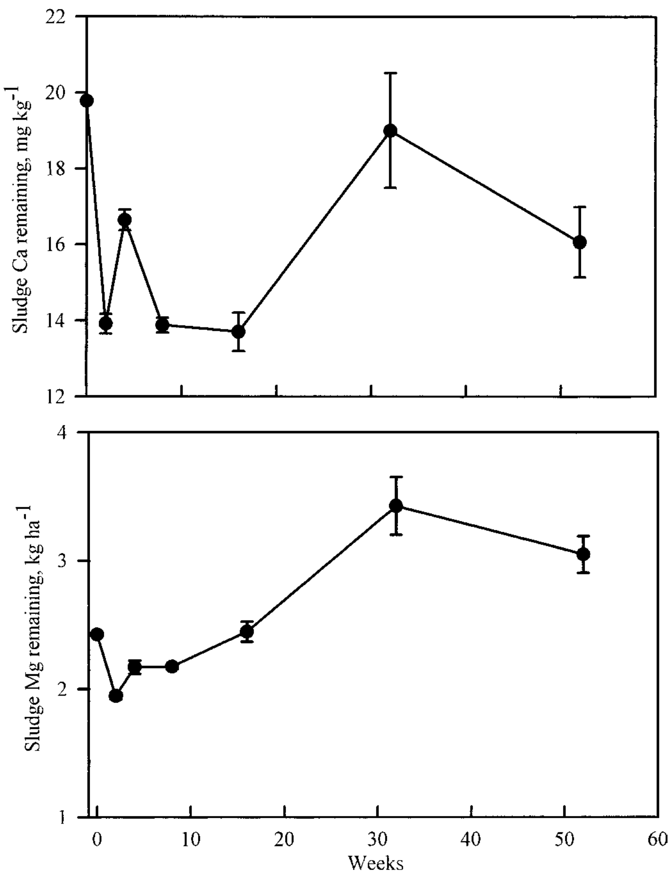

Figure 6. Total Ca and Mg on a dry weight basis remaining in sludge from decomposition bags for each sample period.

that due to these tertiary treatments [iron (Fe) and aluminum (Al) to precipitate P], the sludge composts were insufficient P sources for plant growth. This sludge did not receive any tertiary treatments creating insoluble P precipitates, but still appeared to be a poor source of P as demonstrated by the field and incubation studies.

Calcium concentration in sludge was lower after 1 yr., while Mg was higher (Fig. 6). Calcium showed some initial release but Mg did not. The concentration trends associated with the more microbial resistant organic matter. Zinc behaved much like Ca with an initial release and the increasing concentration in the sludge with time (Fig. 7).

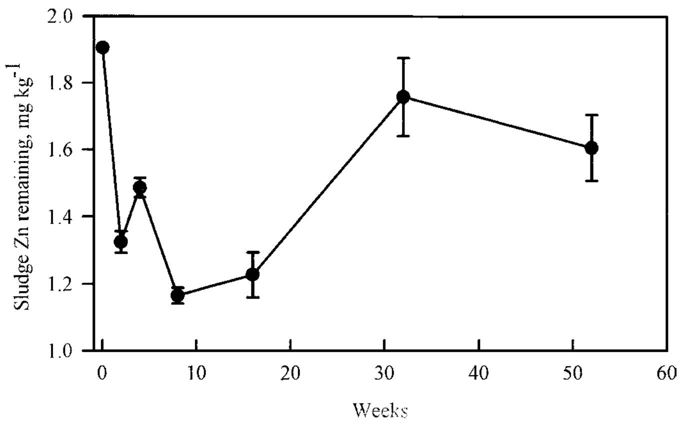

Figure 7. Total Zn on a dry weight basis remaining in sludge from decomposition bags for each sample period.

CONCLUSIONS

Composted municipal sludge was evaluated in an incubation study, involving soil cores, resin bags, and decomposition bags, to determine release of selected elements within the sludge. The following conclusions were determined from the results of these studies:) Of the seven elements examined (N, P, K, Ca, Mg, and Zn) only four resulted in higher soil concentrations after 1 year; ii) Ca was the greatest at 16 mg kg^{-1} followed by Mg and Zn at 2 and 0.8 mg kg^{-1}; iii) decomposition bags showed that mineralization or release of selected elements occurred during the first 2 weeks after soil incorporation; and iv) the total nutrient levels released from the municipal sludge were all low. In a crop production system, the levels released would be inadequate for deficient soils. Previous on-farm studies appear to reflect the same nutrient availabilities found in the incubation study.

REFERENCES

1. Barkenbus, J.N. Overview of the Solid Waste Management Situation: Federal Framework and State Initiatives. In *Economics of Solid Waste Management in the 90s*; Reddy, R.C., Pagoulatos, A., Park, W.M., Eds.; Southern Rural Development Center: Mississippi State, MS, 1993; 1–8.
2. Cummings, B.S. *Analysis of Sewage Sludge Treatment and Use/disposal Practices of Alabama Treatment Works*. Auburn University: Auburn, AL, 1995; M.S. Thesis.

3. Dean, R.B.; Smith, J.E., Jr. The Properties of Sludges. In *Proceedings of the Joint Conference on Recycling Municipal Sludges and Effluents on Land*, Champaign, IL, July 9–13, 1973; 39–47.
4. Raun, W.R.; Johnson, G.V. Crop Production and Plant Soil Relationships. In *Land Application of Biosolids*; Basta, N.T., Ed.; Oklahoma Agricultural Experiment Station: Stillwater, OK, 1995; B-808.
5. Shaw, R.H. Climate of the United States. In Handbook of Soils and Climate in Agriculture; Kilmer, V.J., Ed.; CRC Press: Boca Raton, FL, 1982; 1–101.
6. Adams, J.F.; Mitchell, C.C.; Bryant, H.H. *Soil Test Fertilizer Recommendations for Alabama Crops*; Auburn University: Auburn, AL, 1994; Agronomy and Soils Dept. Series 178.
7. Hue, N.V.; Evans, C.E. Procedures Used for Soil and Plant Analysis by the Auburn University Soil Testing Laboratory; Alabama Agricultural Experiment Station: Auburn AL, 1986; Agronomy and Soils Dept. Series 106.
8. Sims, G.K.; Ellsworth, T.R.; Mulvaney, R.L. Microscale Determination of Inorganic Nitrogen in Water and Soil Extracts. Commun. Soil Sci. Plant Anal. 1995, 26, 303–316.
9. Mehlich, A. Determination of P, Ca, Mg, K, Na, and NH_4 by North Carolina Soil Testing Laboratories; North Carolina State University, Raleigh, NC, 1953.
10. Tester, C.F.; Sikora, L.J.; Taylor, J.M.; Parr, J.F. Decomposition of Sewage Sludge Compost in Soil: I. Carbon and Nitrogen Transformation. J. Enivorn. Qual. 1977, 6, 459–463.
11. Epstein, E.; Keane, D.B.; Meisinger, J.J.; Legg, J.O. Mineralization of Nitrogen from Sewage Sludge and Sludge Compost. J. Environ. Qual. 1978, 7, 217–221.
12. Sims, J.T. Nitrogen Mineralization and Elemental Availability in Soils Amended with Composted Sewage Sludge. J. Environ. Qual. 1990, 19, 669–675.
13. McCoy, J.L.; Sikora, L.J.; Weil, R.R. Plant Availability of Phosphorus in Sewage Sludge Compost. J. Environ. Qual. 1986, 15, 403–409.
14. Sikora, L.J.; Tester, C.F.; Taylor, J.M.; Parr, J.F. Phosphorus Uptake by Fescue from Soils Amended with Sewage Sludge Compost. Agron. J. 1983, 74, 27–33.
15. Keilsing, T.C.; Lauer, D.A.; Walker, M.E.; Henning, R.J. Visual, Tissue, and Soil Factors Associated with Zn Toxicity of Peanuts. Agron. J. 1977, 69, 765–769.
16. McLaughlin, M.J. Land Application of Sewage Sludge: Phosphorus Considerations. S. Afr. J. Plant Soil **1984**, *1*, 21–29.