BIOSOLIDS

Bahiagrass Production and Nutritive Value as Affected by Domestic Wastewater Residuals

Martin B. Adjei* and Jack E. Rechcigl

ABSTRACT

Approximately 70% of Florida's biosolids is land-applied with little supporting agronomic information. This experiment was conducted on bahiagrass (*Paspalum notatum* Flugge), on Pomona fine sand soil (sandy, siliceous, hyperthermic Ultic Alaquods), to compare the agronomic value of aerobically digested slurry biosolid, lime-stabilized slurry biosolid, lime-stabilized cake biosolid, and ammonium nitrate all applied to supply 90 or 180 kg N ha^{-1} vs. an unfertilized control. Forage production (3–5 Mg ha^{-1} yr^{-1}) was similar for the ammonium nitrate and the slurries in 1998 and 1999, highest for the lime-stabilized slurry in 2000, but always 30% lower for the cake biosolid due to the cake's lower N availability. The slurries and ammonium nitrate gave 50% or more forage and higher spring crude protein (CP) concentration (100–170 g kg^{-1}) than the control (75–110 g kg^{-1}). The CP was improved with ammonium nitrate in early spring, after which, there were no consistent differences in CP or in vitro organic matter digestion (460–600 g kg^{-1}) among N sources. Tissue P (2.0–3.5 g kg^{-1}), Ca (3.0–8.0 g kg^{-1}), and Fe (40–250 mg kg^{-1}) were increased by both biosolid slurries in the spring, whereas tissue Cu (6–15 mg kg^{-1}) and Mn (10–100 mg kg^{-1}) were elevated periodically only by the aerobically digested slurry. Forage was deficient in K and Mn in summer across treatments. Lime-stabilized biosolid could boost bahiagrass production in Florida because it is lower in pathogens, inexpensive, and provides lime and organic matter.

THE CONCEPT of using organic wastes as fertilizer is not new. Before the industrial age in the 1940s, when synthetic N fertilizer became widely available, animal manure and human waste were the primary amendments to agricultural soils for improving crop yields around the world.

Crop fertilization with organic waste has received renewed interest as municipalities face increasing disposal problems. A survey by the USEPA (1990) revealed that in 1990 the USA generated 8.5 million Mg of sewage sludge, and predicted that by 2000, 12 million Mg yr^{-1} will be generated because of increased population and advanced sewage treatment processes. Florida's human population growth from 4 million in 1955 to 16 million in 2000 is among the highest in the nation. Prohibition of waste dumping in streams and oceans, diminishing landfill space, skyrocketing landfill costs, and concerns over air pollution from incineration of waste have contributed to a strong public interest in finding alternative, environmentally sound solutions to waste disposal.

Federal and state laws require that domestic wastewater be treated through a two- or three-step process with the end products being sewage effluent and biosolids. Sewage effluent is essentially clear water that contains low concentrations of plant nutrients and traces of organic matter. It is chlorinated to destroy any pathogens. The solid material remaining after sewage treatment is referred to as *biosolids*, *domestic wastewater residuals*, or *sewage sludge* (Kidder, 2001). Wastewater residuals contain substantial amounts of plant nutrients, traces of heavy metals, and some pathogens (Table 1). Fresh residuals contain 30 to 50 g solids kg^{-1} but may contain 200 g solids kg^{-1} or more if the material has been dewatered or dried. For our discussion in this paper, the residuals with 95% or higher water content are referred to as *slurry biosolid* and the drier material as *cake biosolid*.

The cow–calf (*Bos taurus*) industry in Florida depends almost totally on grazed pastures. Seventy-five percent of the 1 million ha of improved pastures in Florida contain bahiagrasses. Nitrogen is the most limiting nutrient for pasture production so annual inputs of N from organic and inorganic sources are needed to produce adequate forage. Biosolids are applied to large areas in Florida. In 1995, 66% of the slurry and cake biosolids from Florida's population were land applied, 17% were land filled, and 8% were incinerated (Kidder, 2001). Land application of biosolids returns essential plant nutrients to the soil, releases them slowly to the crop, improves the organic matter content of the soil, and acts as liming material if it has been previously lime-stabilized.

Many livestock producers apply biosolids to their pasture to reduce cost of fertilizer and lime, but land owners are justifiably concerned about potential negative effects of applying such waste to the land. In decreasing order of importance, the potential for pathogen spread, heavy metal accumulation on agricultural land, excessive loading or volatilization of plant nutrients with nonpoint source pollution potential, and odor to the neighborhood are contentious issues regarding the use of biosolids for crop production.

Over the past 30 yr, the USEPA has developed guidelines for the application and use of biosolids on agricultural lands in answer to these concerns and to improve environmental safety. The USEPA guidelines (1993), as reinforced by Florida Department for Environmental Protection State Administration code 62-640 (Florida Dep. of Environ. Prot., 1996), stipulate pathogen and odor reduction procedures, limits on specific heavy metal concentrations in the biosolids and loading in the soil, nutrient application rates, minimum setbacks from

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Univ. of Florida, Range Cattle Res. and Educ. Center, Ona, FL 33865. Florida Agric. Exp. Stn. Journal Series no. R-08333. Received 15 Jan. 2002. *Corresponding author (mbadjei@mail.ifas.ufl.edu).

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Abbreviations: AM, ammonium nitrate; CB, cake biosolid; Cont, control of no fertilizer; CP, crude protein; SB7, slurry biosolid of pH 7; SB 11, slurry biosolid of pH 11.

Table 1. Mean bacteriological and chemical composition of biosolids used for the experiment in relation to USEPA ceiling concentrations for land application.

Parameter	Liquid sludge pH 7	Liquid sludge pH 11	Cake biosolid	USEPA pollutant concentration limit¶
pH	7.1	11.3	8.5	–
Fecal coliform, CFU kg^{-1}†	33.3×10^6	0.148×10^6	177.5×10^6	$<2\,000.0 \times 10^6$
Total solids, mg L^{-1}	47 000	20 500	500 000	–
Total P‡	25	22	33	–
Total N‡	48	40	39	–
Total K‡	2.5	2.6	3.1	–
As§	6.1	2.8	7.5	41
Cu§	362	301	532	1 500
Cd§	2	10	4	39
Cr§	6.5	34	48	1 200
Mo§	7.7	8.0	10	18
Pb§	15.3	35	46	300
Zn§	1 022	973	1 590	2 800
Hg§	1.1	0.24	0.66	17
Ni§	18.3	38	44.6	420

† Colony forming units kg^{-1} of residuals.
‡ g kg^{-1} of solids in residuals.
§ mg kg^{-1} of solids in residuals.
¶ Pollutant concentration limits as defined in USEPA (1993).

surface and ground water bodies, and waiting time intervals after application before crop utilization by humans and livestock.

There is little information available that confirms or disputes the beneficial use of biosolids for forage production. The objective of this study was to compare the effects of organic sources of N with inorganic sources on bahiagrass establishment, forage production, and nutritive value.

MATERIALS AND METHODS

The field experiment was conducted at the University of Florida Agricultural Research and Education Center, Ona, FL (27°26′ N, 82°55′ W) on a Pomona fine sand soil (Table 2). The experimental design was three randomized complete blocks with nine N source treatments: ammonium nitrate (AM), slurry biosolid of pH 7 (SB7) or pH 11 (SB11), lime-stabilized cake biosolid (CB), each applied to supply 90 or 180 kg total N ha^{-1}, and a nonfertilized control. All biosolids used in this study were of class B in terms of USEPA's pathogen and vector attraction reduction standards (Table 1). The SB7 was obtained from a county processing facility where domestic septage was stabilized by aerobic digestion in large recirculating tanks before land application and incorporation into the soil. The SB11 and CB came from a separate facility which, following anaerobic digestion, raises the initial pH of residuals to 12 with calcium hydroxide and maintains it at that pH for at least 2 h to kill pathogens and suppress odor. As a requirement, the pH of SB11 was maintained above 11 with additional hydrated lime as needed before land application. The lime-stabilized slurry was conditioned with polymer and dewatered by belt filter presses to produce the CB. The pH of CB declined to 8.5, probably due to a combination of organic acid production from further decomposition and the establishment of equilibrium between the Ca^{2+} and atmospheric CO_2 into $CaCO_3$.

Each plot was 6.25 by 6.25 m, with a 6.25 m wide border maintained free of vegetation by monthly roto-tillage during the growing season. In May 1997, plots were delineated after the preparation of a seed bed, and soil pH was raised from 4.6 to approximately 5.0 with dolomitic lime. Nitrogen source amendments were applied in May and roto-tilled into the soil just before broadcast seeding of bahiagrass at 30 kg ha^{-1}. The AM and nonfertilized treatments received a one-time application of 10 kg P ha^{-1} and 37 kg K ha^{-1} at seeding to partially compensate for the presence of these nutrients in the biosolids and encourage seedling establishment. Once fully

Table 2. The initial (1997) and final (2000) soil pH and fertility status as affected by N source treatment.

Treatment	pH	P†	K‡	Ca	Mg§	Zn¶	Fe	Cu††	Mn‡‡	OM
		mg kg^{-1}								g kg^{-1}
Initial (all treatments)	5.2	14	20	221	45	0.32	18	0.15	0.18	1.2
Final										
AM-90	5.0	16	3	95	18	0.35	34	0.05	0.05	1.9
AM-180	5.0	25	2	150	31	0.22	70	0.10	0.08	2.0
SB7-90	4.9	17	5	107	21	0.92	30	0.22	0.55	2.4
SB7-180	5.0	20	4	115	25	1.40	18	0.39	0.87	2.5
SB11-90	5.1	17	4	135	26	0.44	24	0.17	0.06	2.2
SB11-180	5.3	26	8	183	24	1.05	47	0.21	0.14	2.6
CB-90	5.2	14	7	171	24	0.39	20	0.14	0.15	2.4
CB-180	5.1	20	9	253	35	0.59	40	0.14	0.23	2.8
Cont	5.1	12	12	135	39	0.28	12	0.10	0.17	1.8
LSD $P = 0.05$§§	NS	NS	8	83	17	0.45	NS	0.15	0.36	0.6

† <10 mg P kg^{-1} soil, very low; 10–15, low; 16–20, medium; 31–60, high (Kidder et al., 2000).
‡ <20 mg K kg^{-1} soil, very low; 20–35, low, 36–60, medium; >60, high.
§ <15 mg Mg kg^{-1} soil, low; 15–30, medium; >30, high.
¶ 0.5 mg Zn kg^{-1} soil, test level below which there may be a crop response to applied Zn (Kidder, 1983).
†† 0.1–0.3 mg Cu kg^{-1} soil, test level below which there may be a crop response to applied Cu.
¶¶ 3–5 mg Mn kg^{-1} soil, test level below which there may be a crop response to applied Mn.
§§ For treatment comparisons at the final evaluation.

established, the bahiagrass root system is known to absorb adequate P and K nutrients from the subsoil and recycled nutrients from manure under grazing conditions (Rechcigl et al., 1992; Adjei et al., 2000) but not under a hay clipping operation (Stanley and Rhoads, 2000). For this initial study, it was decided to evaluate N sources without additional P and K input after the first year establishment.

Bahiagrass plots were cut to a 5-cm stubble on 19 Sept. 1997 and harvested to the same stubble height on 9 Oct. 1997. The dry matter (DM) yield of this first harvest was used to determine the effect of treatment on grass establishment. Plots were not cut from November to March each year. In early April 1998, 1999, and 2000, plots were mowed to 5-cm stubble and treated with the respective N source amendments. Amendment rates were calculated based on the concentrations of total solids in materials as determined by the American Public Health Association SM 2540G (1989) method and N in solids (EPA 351.2 and 353.1). Materials were weighed in buckets and uniformly applied.

Plant Sampling and Nutritive Value Analysis

Following the application of N source treatments in April, grass regrowth was harvested at approximately 30-d intervals (Mislevy et al., 1991) to estimate forage DM yield in 1998, 1999, and 2000 growing seasons. Forage was harvested on 139, 169, 203, 245, 273, and 307 d of year (DOY) in 1998; 125, 147, 174, 202, 230, 257, and 286 DOY in 1999; and 179, 209, 241, 270, and 301 DOY in 2000. At each harvest, forage was clipped to a 5-cm stubble with a 0.5 m wide rotary mower from a 3-m length, randomly selected site inside a plot. After a harvest, the entire plot was cleaned to 5-cm stubble and allowed to regrow for the next harvest. The mower had a basket to hold harvested forage. Total green harvested forage was weighed. Harvested forage subsamples were weighed, oven-dried at 60°C to constant weight, and ground to pass through a 1-mm mesh screen in a Wiley mill. Ground 1998, 1999, and 2000 forage was analyzed for CP (Hambleton, 1977; Gallaher et al., 1976) and in vitro organic matter disappearance (IVOMD) (Moore and Mott, 1974). Ground forage samples from 1998 and 1999 were analyzed for tissue P, K, Ca, Mg, Fe, Zn, Cu, and Mn concentrations using inductive coupled argon plasma spectroscopy at the University of Florida Analytical Research Lab (ARL). The model Spectrociros CCD-Thermo Jarrell, manufactured by Spectro Analytical Instrument, Fitchburg, MA, was used. Forage was predigested in a mixture of nitric and perchloric acids using standard methods of the University of Florida ARL (Hanlon and Devore, 1989).

Statistical Analysis

Forage data were initially subjected to analysis of variance using the Proc Mixed procedure in SAS (SAS Inst., 1999) with treatment, year, and the number of harvest as main plot, split, and split-split plot, respectively. As a result of significant treatment × harvest × year interactions for DM yield, CP, IVOMD, and tissue mineral responses, data were reexamined annually, with harvest DOY as a repeated measure. Treatment means were separated according to Fisher's Protected LSD, or Duncan's multiple range test at $P = 0.05$. The effect of DOY on forage cumulative dry matter yield was plotted with the graph wizard of SigmaPlot procedure (SPSS, 1997) and treatment means on each DOY were separated with Fisher's protected LSD at $P = 0.05$.

RESULTS AND DISCUSSION

Pathogen and chemical composition of the class B biosolids were in compliance with USEPA guidelines (Table 1). Liming of residuals to a pH 12 and maintaining it at that level for at least 2 h, followed by maintenance of pH > 11 before application was both an effective pathogen- and odor-reduction technique as indicated by the much lower fecal coliform counts for the SB11 compared with the SB7. Apparently, allowing the pH to drop to 8.5 during the drying process permitted coliform bacteria to build up in the lime-stabilized cake biosolid (Table 1). Concentrations of As, Cd, Cu, Pb, Hg, Mo, Ni, and Zn in these residuals were far below the national USEPA limits, partly because Florida has relatively little industrial base and partly because of successful efforts in preventing industrial sources of metals from contaminating sewage (Kidder, 2001).

The initial soil pH averaged 5.2 after lime application and P, K, and micronutrients were low (Table 2) but, to simulate current producer practices, N source treatments were expected to provide some of these nutrients in our first trial.

Forage Establishment

Best bahiagrass establishment was obtained with treatments SB11-180 and AM-180, each of which produced 1.0 Mg DM ha^{-1} at the 9 Oct. 1997 harvest (data not shown). This was probably due to the higher concentration of readily available N from those sources in addition to the liming property of the SB11 treatment. Yields on this date were intermediate for the remaining treatments (0.4–0.7 Mg ha^{-1}) and lowest for the control (0.3 Mg ha^{-1}).

Forage Dry Matter Yield

Rainfall varied between years (Table 3), which caused the initial forage harvest date and number of annual harvests to differ. For example, in 1998 the first and last forage harvests occurred on 19 May and 3 November, and there were a total of six harvests. There were seven harvests in 1999 between 5 May and 13 October, and five harvests in 2000 between 6 June and 27 October.

Forage Growth Rate

Response of forage yield to N source treatments varied within harvest dates and years. In 1998, forage yield was greatest ($P < 0.01$) for the AM-180 and the SB11-180 treatments, but lowest for the CB at both N rates and the nonfertilized control on 139 DOY harvest (Fig. 1). Both slurry biosolids and AM treatment maintained their superior growth rate over the other treatments through the second harvest on 169 DOY in 1998. During the peak summer growth between 203 and 245 DOY, however, the rate at which forage DM accumulated (approximately 0.02 Mg ha^{-1} d^{-1}) was about equal for all treatments. In the fall of 1998 season (245–307 DOY), DM accumulated at a highest rate (approximately 0.02 Mg ha^{-1}) with slurry biosolids applied at 180 kg N Mg ha^{-1}, intermediate rate (0.016 Mg ha^{-1}

Table 3. Mean monthly minimum and maximum temperatures and total monthly rainfall at Range Cattle Research and Education Center, Ona, FL, for 1997–2000.

	Temperature								Total rainfall				
	1997		1998		1999		2000						
Month	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	1997	1998	1999	2000	59-yr mean
	°C								mm				
Jan.	28.9	−5	28.9	3.9	28.9	−1.7	27.8	−1.1	34.7	108.3	112.8	54.8	56.50
Feb.	31.1	1.1	28.9	5.6	27.8	3.3	29.4	1.1	19.8	239.8	17.5	9.3	63.75
Mar.	31.1	11.7	30	3.3	29.4	3.9	30.6	7.2	38.5	333.5	38.5	36.5	80.00
Apr.	30.6	3.9	31.1	8.3	33.9	6.7	31.1	3.3	214.0	10.3	103.3	64.8	63.00
May	33.3	13.3	35	11.7	33.3	10	36.1	10	61.0	54.5	195.8	1.3	94.30
June	34.4	16.1	36.7	20	34.4	19.4	36.7	17.2	114.3	151.0	194.8	94.5	208.3
July	35.6	20	35.6	21.7	35.6	21.1	35.7	20	311.0	188.5	90.8	112.5	210.8
Aug.	35.6	19.4	35.6	20.6	36.7	20.6	35	18.3	135.5	193.3	146.8	133.8	199.0
Sept.	33.9	18.3	34.4	20.6	33.9	11.1	34.4	18.9	211.8	260.3	137.8	200.8	178.3
Oct.	32.2	10	33.9	13.9	33.9	8.9	37.7	8.3	59.5	72.8	117.8	55.8	79.00
Nov.	29.4	8.3	30.6	11.1	28.9	6.7	30.6	−1.7	280.5	103.3	23.0	8.5	48.25
Dec.	28.3	4.4	28.9	3.9	28.3	2.8	30	−2.2	215.3	19.0	74.3	28.3	47.80
Total									1695.0	1709.0	1253.0	800.8	1329

d^{-1}) with the AM-180, and lowest rate (0.01 Mg ha^{-1} d^{-1}) with the remaining N source treatments (Fig. 1). The orthogonal contrast between 90 and 180 kg N ha^{-1} rates was significant ($P < 0.05$) only for the first harvest yield on 139 DOY, but the 0 vs. 90 kg N ha^{-1} rates were different for DM yields on 139, 169, and 203 DOY.

In 1999, the greater rate of initial (125 DOY) forage DM accumulation (approximately 0.02 Mg ha^{-1} d^{-1}) for the AM-90-180, SB11-180, and SB7-180 was maintained through the second harvest on 147 DOY (Fig. 1). After 147 DOY, forage DM accumulated at a rate >0.03 Mg ha^{-1} d^{-1} for AM-180, SB11-180, and SB7-180; at a rate >0.02 Mg ha^{-1} d^{-1} for the AM-90, SB11-90, CB-180, and SB7-90; and at a rate <0.02 Mg ha^{-1} d^{-1} for the CB-90 and Cont. treatments (Fig. 1). With the exception of the second harvest on 147 DOY, the contrasts ($P < 0.05$) between 90 and 180 kg N ha^{-1}, and between the 0 and 90 kg N ha^{-1} on each DM harvest was always significant in 1999.

The spring and early summer 2000 was characterized by a 40-yr record drought in south-central Florida (Table 3). This drought resulted in a delay of the initial harvest until 179 DOY, at which time we obtained about three times as much forage with SB11-180 and about twice as much forage with AM-180 as the average yield of the remaining treatments (Fig. 1). Also as a consequence of the drought, forage production for the season was measured from summer to fall when the rate of DM accumulation normally is on the decline. For the 2000 season, yield from the SB11-180 treatment at each harvest was always greater than the control, but there was little difference among the remaining treatments in rate of forage accumulation after the first harvest.

The major processes for the release of organic N into inorganic forms when wastewater residuals are applied to the soil are well understood (Stevenson, 1982, 1986; Keeney, 1983; Petrovic, 1990)–mineralization (transformation of organic N to inorganic N, primarily NH_4), and nitrification (conversion of NH_4 to NO_3). On the other hand, NH_4–based fertilizers are readily available for plant absorption, but the NH_4 may be nitrified to NO_3, under proper pH, moisture, aeration, and temperature. According to Boswell et al. (1985), several physical, chemical, and biological factors that interact with each other and the environment, determine the rate and fate of the N that is released in the soil–plant system. In our study, the N in the AM fertilizer was in readily soluble and available forms (NH_4 and NO_3) for immediate crop uptake as shown by the rapid yield response. Since moisture and aeration are necessary ingredients for both N mineralization and crop uptake, nutrients in the slurry biosolids also became immediately available in our

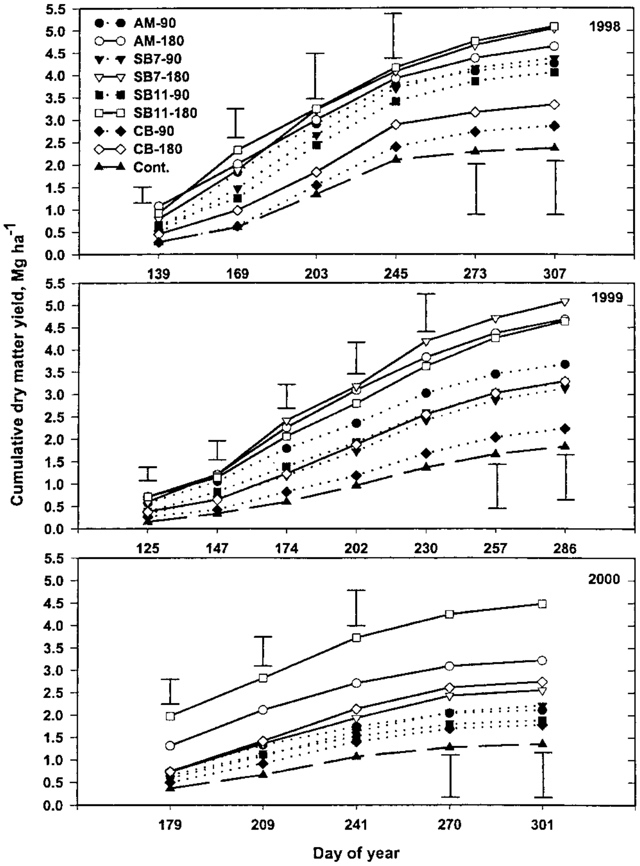

Fig. 1. The effect of treatment × year × harvest date on cumulative forage dry matter yield. Ammonium nitrate (AM); slurry biosolids of pH 7 (SB7), of pH 11 (SB11); cake biosolid (CB); nonfertilized control (Cont.).

sandy soil for plant root uptake and forage growth than those in the CB. Considerable amount of water accompanied the application of slurry biosolids. For example, the weight of total dry solids applied from organic materials ranged from 2.1 to 4.8 Mg ha^{-1} depending on N rate of application, and the concentrations of solids and N in the materials. The associated weight of water applied with materials ranged from 2.3 to 4.6 Mg ha^{-1} (2.3–4.6 m^3 ha^{-1}) for the CB; 40.6 to 81.2 Mg ha^{-1} (40.6–81.2 m^3 ha^{-1}) for the SB7, but 110 to 220 Mg ha^{-1} (110–220 m^3 ha^{-1}) for the SB11. The water probably also aided infiltration of nutrients into the root zone for the slurry treatments. Additionally, dewatering and drying of the CB could have increased fiber N and decreased plant-available N in that material. Furthermore, the liming effect from the SB-11 treatment was advantageous. Differences in N solubilities and moisture levels of N sources probably accounted for the rapid bahiagrass yield response to the AM and SB materials but the slower response to the CB material until adequate moisture became available in the summer. These differences were probably the underlying cause for the N source × harvest DOY interaction on forage yield each year. The control treatment depended exclusively on N soil mineralization of native organic matter (Table 2) in summer and was always lowest in forage production per harvest.

Forage Total Yield

Cumulative annual forage yield was similar for the slurry biosolids and AM treatments at equivalent N rates in both 1998 and 1999 (Table 4). As discussed earlier, greater forage production with the 180 kg N ha^{-1} compared with the 90 kg N ha^{-1} occurred only at the beginning of the 1998 season (a normal wet year, Table 3) but also throughout most of the 1999 and 2000 seasons (dry years), an indication that N leaching might have occurred and contributed to the lack of N rate effect in the range of 90 to 180 kg N ha^{-1} on cumulative DM yield in 1998. In 2000, cumulative forage yield ranged from 1.8 to 4.5 Mg ha^{-1} and was generally lower for all treatments because of drought, except for the SB11-180 which, due to the inherent high moisture content, yielded 4.5 Mg ha^{-1} (Table 4). Over the 3-yr period, annual yield for the CB treatment was 65 to 70% the yield for the other N sources, at comparable N rates. Muchovej and Rechcigl (1997) estimated a minimum N recovery rate from biosolids by bahiagrass crop of 70% in 2 yr with the remaining 30% becoming available with additional time. King and Morris (1972) reported a linear increase in bermudagrass N uptake to land application of liquid sludge, whereas Tester et al. (1982) observed the same effect on tall fescue using composted sewage sludge. McCaslin et al. (1987) showed that gamma-irradiated, anaerobically digested sludge improved yield and corrected Fe chlorosis in grain sorghum grown on calcareous Fe-deficient soils in New Mexico. Nitrogen is the most limiting nutrient for grass production on Florida's spodic sandy soils as evidenced by the lowest cumulative yield for the nonfertilized control compared with the N-fertilized treatments. The control yielded approximately 50% of the AM-90 treatment each year (Table 4).

Table 4. Bahiagrass annual forage dry matter yield as influenced by N-source treatment.

	Year			
N source	**1998**	**1999**	**2000**	**Mean**
		Mg ha^{-1}		
AM-90	**4.3ab†**	**3.7b**	**2.1cd**	**3.3**
AM-180	**4.7a**	**4.7a**	**3.2b**	**4.2**
SB7-90	**4.4ab**	**3.1b**	**2.2bcd**	**3.2**
SB7-180	**5.0a**	**5.1a**	**2.6bc**	**4.2**
SB11-90	**4.1abc**	**3.3b**	**1.9cd**	**3.1**
SB11-180	**5.1a**	**4.6a**	**4.5a**	**4.7**
CB-90	**2.9cd**	**2.2c**	**1.8cd**	**2.3**
CB-180	**3.3bcd**	**3.3b**	**2.7bc**	**3.1**
Cont.	**2.4d**	**1.8c**	**1.4d**	**1.9**
N contrasts				
90 vs. 180	**NS‡**	**	*	
0 vs. 90	**	**	**	

*** Significant N effect at $P = 0.05$.**
**** Significant N effect at $P = 0.01$.**
† Values in each column followed by the same letter are not different ($P > 0.05$) according to the Duncan's multiple range test.
‡ NS, no significant N effect.

The DM yields at each harvest and annual yields obtained for 1998 and 1999 in this study are typical of bahiagrass production in Florida with a one-time spring N application and similar frequency of harvest (Muchovej and Mullahey, 2000; Stanley and Rhoads, 2000). Blue (1974) investigated the efficiency of five inorganic sources of N for bahiagrass production during 10 yr and reported slightly better mean forage yields of 3.5, 6.8, and 11.3 Mg DM ha^{-1} for the 0, 112, and 224 kg N ha^{-1} rates, respectively. Higher bahiagrass yields are possible with a multiple split N application and less frequency of harvest (Adjei et al., 1989; Mislevy et al., 1996, 2000) and with irrigation (Mislevy and Everett, 1981).

Forage Crude Protein and Digestibilty

Forage crude protein concentration ranged from 80 to 170 g kg^{-1} in 3 yr. Highest CP concentration in forage, in excess of 130 g kg^{-1}, occurred in the first harvests of 1998 and 1999 for the AM fertilizer treatment (Table 5), probably due to a rapid N release rate. Subsequent CP concentrations in forage for all treatments showed a decline during the peak summer regrowth and an increase toward the fall, with little difference between treatments including the control (Table 5). The variation of CP concentration in 2000 was different compared with the first 2 yr. An increase in forage CP occurred between the first and second harvests, due probably to the drought in June of that year (Table 3). This increase was followed by a steep decline at the onset of summer rains. In 2000, the SB7-180 and the AM-180 CP levels were greatest at most harvests (Table 5), probably due to the lower DM dilution effect.

The effect of treatments on forage IVOMD was erratic over harvest DOY (Table 6) because a treatment could be of the highest forage IVOMD in one harvest and the lowest in the next harvest. In addition, treatment differences in forage IVOMD were less defined than in CP concentration since most treatments produced the

Table 5. The effect of treatment × year × harvest date on bahiagrass forage crude protein concentration.

	1998 harvest day of year							
N source†	139	169	203	245	273	307		Mean
	g kg^{-1}							
AM-90	145b‡	102abc	100a	72ab	82bc	88b	–	98ab
AM-180	172a	104ab	83a	77ab	92ab	95ab	–	103a
SB7-90	102d	83bcd	86a	73ab	79c	92ab	–	86cd
SB7-180	122c	116a	83a	83a	96a	101a	–	100ab
SB11-90	112cd	73d	89a	70ab	79c	89ab	–	85cd
SB11-180	126c	79bcd	86a	77ab	86abc	98ab	–	92bc
CB-90	95d	79bcd	80a	68b	77c	87b	–	81d
CB-180	106d	97abcd	81a	71ab	86abc	97ab	–	90bcd
Cont.	96d	75cd	82a	72ab	84abc	92ab	–	83cd
N contrasts								
90 vs. 180	**	NS	NS	NS	NS	NS		
0 vs. 90	*	NS	NS	NS	NS	NS		
	1999 harvest day of year							
N source	125	147	174	202	230	257	286	
AM-90	103b	116ab	55b	79ab	81a	95a	104b	94bc
AM-180	142a	121a	89a	85a	87a	96a	115ab	105a
SB7-90	92de	109bc	82ab	75ab	90a	97a	117ab	95bc
SB7-180	109c	116ab	89a	76ab	86a	102a	122a	100ab
SB11-90	98d	101cd	83ab	77ab	90a	100a	111ab	94bc
SB11-180	96d	106bcd	84ab	77ab	87a	103a	111ab	95bc
CB-90	83e	100cd	74ab	70ab	83a	95a	106b	87c
CB-180	91de	102de	78ab	67b	87a	96a	109ab	90bc
Cont.	91de	96d	77ab	69ab	81a	97a	111ab	89c
N contrasts								
90 vs. 180	*	NS	NS	NS	NS	NS	NS	
0 vs. 90	NS	NS	NS	NS	NS	NS	NS	
	2000 harvest day of year							
N source	179	209	241	270	301			
AM-90	101ab	116bcd	93bc	93b	106a	–	–	102bc
AM-180	121ab	126ab	102ab	101ab	109a	–	–	112ab
SB7-90	102ab	124abc	91c	102ab	109a	–	–	106bc
SB7-180	138a	136a	104a	114a	119a	–	–	122a
SB11-90	111ab	119abcd	92bc	96b	111a	–	–	106bc
SB11-180	92b	121abcd	89cd	99b	112a	–	–	103bc
CB-90	80b	105d	79d	93b	113a	–	–	94c
CB-180	93b	123abcd	82cd	93b	108a	–	–	99bc
Cont.	90b	107cd	85cd	94b	112a	–	–	98bc
N contrasts								
90 vs. 180	NS	NS	NS	NS	NS			
0 vs. 90	NS	NS	NS	NS	NS			

† Ammonium nitrate (AM), slurry biosolid of pH 7 (SB7), slurry biosolid of pH 11 (SB 11), Cake biosolid (CB), nonfertilizer control (Cont.).

‡ Values for a harvest date or means followed by the same letter are not different ($P > 0.05$) according to the Duncan's multiple range test.

same forage IVOMD as the control. Nonetheless, the general summer decline followed by a fall increase in IVOMD was still prevalent in most years.

The ranges of forage CP concentration (80–170 g kg^{-1}) and IVOMD (440–600 g kg^{-1}) were also in agreement with work reported on bahiagrass in Florida (Adjei et al., 2000; Mislevy et al., 2000; Muchovej and Mullahey, 2000). Low forage CP concentration and IVOMD during the rapid summer regrowth is a phenomenon well documented on warm-season grasses in Florida (Adjei et al., 2000; Muchovej and Mullahey, 2000; Mislevy and Everett, 1981) and neither organic nor inorganic N source treatments were able to prevent this response.

Forage Tissue Mineral Concentrations

Tissue K and Zn varied over harvest date ($P < 0.001$) with a year × harvest date interaction ($P < 0.001$) but, while tissue K at each harvest was never affected ($P > 0.10$) by N source treatment, tissue Zn at each harvest was affected the same way by N source treatment for 2 yr.

Potassium concentration in forage tissue ranged from 4.6 to 7.9 g kg^{-1} in 1998 with 203 and 307 harvest DOY providing the highest and lowest concentrations, respectively. Corresponding K tissue concentrations in 1999 were 6.0 and 7.4 g kg^{-1} for 147 and 203 DOY, respectively.

Apparently, aerobic digestion of wastewater residuals increased Zn availability to bahiagrass to a greater extent than anaerobically digested, lime-stabilized residuals. During 1998 and 1999, Zn concentration in forage tissue was affected by N source treatments in a similar manner for each harvest date because concentration for SB7-180 (43 mg kg^{-1}) was always greater than the mean for the other treatments (30 mg kg^{-1}).

Tissue P, Mg, and Cu concentrations were affected differently by N source treatments over harvest dates, but in a similar manner for 1998 and 1999, hence 2-yr means are presented. Tissue P tended to be highest for

Table 6. The effect of treatment × year × harvest date on bahiagrass forage in vitro organic matter digestion.

	1998 harvest day of year							
N source†	139	169	203	245	273	307		Mean
	g kg^{-1}							
AM-90	580ab‡	526a	440b	470ab	478ab	497a	–	499ab
AM-180	595a	505ab	462ab	432bc	479ab	518a	–	499ab
SB7-90	575ab	508ab	491a	447abc	452c	500a	–	480d
SB7-180	581ab	522ab	484a	427c	486a	514a	–	502ab
SB11-90	583ab	516ab	480a	467ab	471abc	522a	–	507a
SB11-180	590a	488b	472ab	445abc	484a	533a	–	502ab
CB-90	542cd	509ab	484a	472ab	457bc	488a	–	492abcd
CB-180	552bc	517ab	468ab	445abc	472abc	514a	–	495abc
Cont.	511d	494ab	474ab	478a	455bc	493a	–	483cd
N contrasts								
90 vs. 180	NS	NS	NS	NS	NS	NS		
0 vs. 90	NS	NS	NS	NS	NS	NS		
	1999 harvest day of year							
N source	125	147	174	202	230	257	286	Mean
AM-90	550ab	545ab	482a	490ab	492b	506b	523a	512ab
AM-180	572a	562a	478a	512a	506ab	537a	533a	529a
SB7-90	504cd	552ab	508a	488ab	505ab	540a	530a	518ab
SB7-180	525bc	542ab	479a	462b	492b	507b	525a	504b
SB11-90	504cd	499b	491a	506a	535a	530ab	537a	515ab
SB11-180	515bcd	538ab	494a	500a	516ab	527ab	526a	517ab
CB-90	476d	535ab	490a	489ab	520ab	538a	521a	510ab
CB-180	511bcd	545ab	487a	503a	506ab	538a	535a	518ab
Cont.	478d	545ab	500a	510a	513ab	528ab	520a	513ab
N contrasts								
90 vs. 180	NS	NS	NS	NS	NS	NS	NS	
0 vs. 90	NS	NS	NS	NS	NS	NS	NS	
	2000 harvest dates							
N source	179	209	241	270	301			Mean
AM-90	483abc	542abc	540a	543a	565a	–	–	532a
AM-180	472bc	536cd	534a	547a	550ab	–	–	528a
SB7-90	507abc	566ab	527a	508a	560ab	–	–	533a
SB7-180	525a	541cd	486b	535a	564ab	–	–	530a
sB11-90	513ab	531d	420a	521a	544ab	–	–	526a
SB11-180	464c	535cd	517a	544a	536b	–	–	519a
CB-90	501abc	557abcd	528a	557a	546ab	–	–	538a
CB-180	504abc	559abc	531a	538a	537ab	–	–	534a
Cont.	529a	570a	536a	522a	546ab	–	–	541a
N contrasts								
90 vs. 180	NS	NS	NS	NS	NS			
0 vs. 90	NS	NS	NS	NS	NS			

† Ammonium nitrate (AM), slurry biosolid of pH 7 (SB7), slurry biosolid of pH 11 (SB 11), Cake biosolid (CB), nonfertilizer control (Cont.).

‡ Values for a harvest date or means followed by the same letter are not different ($P > 0.05$) according to the Duncan's multiple range test.

the slurry biosolids (2.5–3.5 g kg^{-1}), intermediate for the cake biosolid (2.0–2.5 g kg^{-1}), and lowest for the inorganic fertilizer and the nonfertilized control (<2.2 g kg^{-1}) during the first three (spring) harvests of each season (Table 7). During the rapid summer growth, there was little effect of treatments on tissue P, which persisted through the fall harvests. The lowest tissue P during midsummer was under AM-180 treatment (1.6 g kg^{-1}), and the highest tissue P concentration of 3.6 g kg^{-1} was in a spring harvest for the SB7-180 treatment (Table 7).

Forage tissue Mg tended to be lower (<4.0 g kg^{-1}) for the lime-stabilized biosolids (SB11 and CB), intermediate for the control, and highest (>5.0 g kg^{-1}) for the AM and SB7 treatments during the first three harvests (Table 7), a plausible outcome of Ca vs. Mg antagonism (Tables 7 and 8). Tissue Mg levels were practically the same for all treatments during summer and fall harvests, but there was an overall increase in tissue Mg (>4.0 g kg^{-1}) toward the end of 1999. Despite the Ca antagonism, tissue Mg was always in or above the sufficiency range of 2.0 to 3.0 g kg^{-1} set by Kincheloe et al. (1987). Tissue Cu concentration was also reduced by lime stabilization incrementally from spring through summer, but no differences among treatments were observed in the fall when all tissue Cu concentrations increased beyond 10 mg kg^{-1} (Table 7). Tissue Cu was also sufficient (4.0–10.0 mg kg^{-1}) according to Kincheloe et al. (1987).

Kincheloe et al. (1987) and Rechcigl et al. (1992) showed that adequate production of bahiagrass is achieved with a tissue P concentration of approximately 2.0 g kg^{-1}, which was nearly always exceeded using the organic wastes in our study. Hence, ranchers on Florida's flatwoods soils do not have to worry about applying additional P fertilizer when using biosolids on their bahiagrass pastures. To the contrary, producers should be concerned about overapplication of P. Approximately 75 to 100 kg P ha^{-1} was applied to the soil from biosolid treatments. Repeated use of biosolids may result in either increased soil P accumulation or P sur-

Table 7. The effect of treatment × harvest date on 2-yr (1998 and 1999) mean bahiagrass forage tissue concentrations of P, Mg and Cu.

	Harvest no.							
N source†	1	2	3	4	5	6	7‡	Mean
				g kg^{-1}				
				P				
AM-90	2.0cd§	2.2cd	1.9de	2.1a	2.4a	2.4ab	3.0a	2.2bc
AM-180	1.8d	1.6e	1.6e	1.7a	2.0a	2.3ab	2.6a	1.9d
SB7-90	2.7b	2.9b	2.8ab	2.6a	2.1a	2.5ab	3.4a	2.7a
SB7-180	3.3a	3.6a	3.0a	2.2a	2.3a	2.8a	2.9a	2.8a
SB11-90	2.5b	2.8b	2.5bc	2.6a	2.6a	2.1b	2.8a	2.6ab
SB11-180	2.5b	2.7b	2.5bc	2.6a	2.3a	2.3ab	3.1a	2.5ab
CB-90	2.0cd	2.6bc	2.3cd	2.6a	2.2a	1.9b	2.5a	2.3bc
CB-180	2.3bc	2.6bc	2.2cd	2.4a	2.2a	2.1b	2.5a	2.3bc
Cont.	1.9d	2.1d	1.8e	2.4a	2.3a	2.3ab	3.0a	2.2cd
				Mg				
AM-90	4.2ab	5.5abc	4.2ab	4.2a	3.7ab	3.6a	5.5a	4.3a
AM-180	5.5a	6.7a	5.1a	4.6a	3.1ab	3.6a	5.6a	4.8a
SB7-90	3.7ab	4.3bc	3.9ab	4.7a	4.2ab	3.1a	5.7a	4.1a
SB7-180	4.9ab	5.9ab	4.7ab	4.8a	4.6ab	3.7a	5.3a	4.9a
SB11-90	3.4ab	3.7bc	3.2ab	5.0a	4.8a	4.0a	4.7a	4.1a
SB11-180	3.2b	3.4c	3.2ab	3.3a	2.8b	3.0a	4.5a	3.3a
CB-90	3.1b	3.3c	3.1ab	3.5a	2.9ab	3.3a	4.5a	3.3a
Cb-180	3.0b	3.1c	2.7b	3.1a	3.5ab	2.8a	5.5a	3.2a
Cont.	3.6ab	3.6bc	3.3ab	4.4a	3.2ab	3.5a	5.2a	3.7a
				Cu				
				mg kg^{-1}				
AM-90	7.0cd	10.7ab	7.0ab	7.0ab	6.5b	11.0a	11.3a	8.4b
AM-180	9.0c	11.3ab	10.7ab	6.3b	6.2b	13.2a	11.7a	9.6ab
SB7-90	11.7b	10.8ab	6.8ab	6.5ab	6.3b	10.7a	11.7a	8.8ab
SB7-180	14.7a	13.0a	11.3a	6.8ab	8.8a	10.5a	11.7a	10.6a
SB11-90	7.8cd	10.8ab	9.0ab	7.3ab	7.3ab	11.7a	12.0a	9.2ab
SB11-180	7.7cd	9.7b	6.5b	7.0ab	6.5b	11.0a	10.3a	8.2b
CB-90	6.2d	8.3b	6.5b	6.8ab	6.2b	9.8a	10.0a	7.5b
CB-180	7.5cd	9.0b	6.7ab	6.0b	6.3b	12.5a	11.3a	8.3b
Cont.	6.0d	8.8b	6.3b	8.8a	6.8b	12.0a	10.7a	8.5b

† Ammonium nitrate (AM), slurry biosolid of pH 7 (SB7), slurry biosolid of pH 11 (SB 11), Cake biosolid (CB), nonfertilizer control (Cont.).
‡ Harvest 7 data is for 1999 only.
§ Values for a harvest date or means followed by the same letter are not different ($P > 0.05$) according to the Duncan's multiple range test.

Table 8. The effect of treatment × year × harvest date on bahiagrass forage tissue concentration of Ca.

	Harvest no.							
N source†	1	2	3	4	5	6	7	Mean
				g kg^{-1}				
				1998 Ca				
AM-90	7.9a‡	3.6b	3.4ab	3.5a	3.2abc	4.6abc	–	4.3ab
AM-180	6.2a	3.2b	3.1ab	3.3a	2.5c	4.6abc	–	3.7bc
SB7-90	8.0a	5.0a	3.7ab	2.9a	2.7bc	3.9bc	–	3.7bc
SB7-180	6.4a	4.9a	3.4ab	3.0a	2.9abc	3.8bc	–	4.5ab
SB11-90	8.3a	4.3ab	3.9a	3.9a	4.0a	5.1ab	–	5.0a
SB11-180	6.5a	3.6b	3.8ab	3.9a	3.7ab	5.4a	–	4.6ab
CB-90	8.2a	4.0ab	3.9a	2.9a	3.3abc	4.2abc	–	4.2ab
CB-180	5.9a	4.2ab	3.4ab	2.8a	3.7abc	4.1abc	–	4.0bc
Cont.	5.1a	3.2b	2.8b	3.3a	2.6bc	3.5c	–	3.2c
				1999 Ca				
AM-90	4.8c	4.9bc	2.6de	4.4a	5.2a	3.1a	4.0a	4.2abc
AM-180	5.1c	4.5c	2.5e	3.5a	3.8b	4.1a	4.0a	3.9c
SB7-90	5.4c	4.2c	3.2bcd	4.1a	4.0ab	4.3a	5.2a	4.3abc
SB7-180	5.5c	4.4c	2.9cde	2.4a	3.8b	4.1a	4.4a	4.0bc
SB11-90	6.7ab	6.1a	3.8a	4.3a	4.3ab	3.6a	4.9a	4.8a
SB11-180	7.3a	5.8ab	3.8a	4.2a	4.1ab	3.7a	4.5a	4.7ab
CB-90	5.4c	5.1bc	3.3abc	4.4a	3.6b	3.7a	4.4a	4.3abc
SB-180	6.4b	4.5c	3.6ab	4.2a	3.8b	4.1a	4.5a	4.4abc
Cont.	5.2c	4.2c	2.8cde	4.5a	4.9ab	3.8a	3.9a	4.2abc

† Ammonium nitrate (AM), slurry biosolid of pH 7 (SB7), slurry biosolid of pH 11 (SB 11), Cake biosolid (CB), nonfertilizer control (Cont.).
‡ Values for a harvest date or means followed by the same letter are not different ($P > 0.05$) according to the Duncan's multiple range test.

face water runoff, which could pose potential eutrophication problems for sensitive water bodies such as the Lake Okeechobee Basin (Reddy and Flaig, 1995; Walker and Havens, 1995).

In their study to compare the P and K value of biosolids with inorganic P and K for seven consecutive barley (*Hordeum vulgare* L.) crops, Christie et al. (2001) reported that alkaline biosolids acted as slow-release P fertilizer, which was at least as available to crops as inorganic fertilizer P. Tissue P concentration in the pres-

Table 9. The effect of treatment × year × harvest date on bahiagrass forage tissue concentration of Fe.

	Harvest no.							
N source†	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Mean**
	mg kg^{-1}							
				1998 Fe				
AM-90	**93.3b‡**	**50.7b**	**46.3b**	**5.63a**	**47.7ab**	**59.7a**	**–**	**56.4bc**
AM-180	**100.0b**	**50.3b**	**61.7ab**	**61.0a**	**38.0b**	**78.0a**	**–**	**60.1bc**
SB7-90	**250.0a**	**127.3a**	**70.3ab**	**47.3a**	**46.7ab**	**65.0a**	**–**	**66.1b**
SB7-180	**211.0a**	**140.3a**	**94.0a**	**65.3a**	**59.3a**	**64.7a**	**–**	**83.1a**
SB11-90	**217.3a**	**76.3b**	**69.7ab**	**72.0a**	**63.0a**	**78.7a**	**–**	**91.3a**
SB11-180	**196.3a**	**51.0b**	**65.7ab**	**69.7a**	**56.3ab**	**72.0a**	**–**	**81.7a**
CB-90	**69.7b**	**56.3b**	**56.7b**	**41.7a**	**44.0ab**	**61.3a**	**–**	**49.8c**
CB-180	**66.3b**	**53.0b**	**58.0b**	**41.0a**	**58.0ab**	**57.7a**	**–**	**52.3bc**
Cont.	**55.5b**	**75.3b**	**53.7b**	**68.0a**	**44.0ab**	**72.0a**	**–**	**56.4bc**
				1999 Fe				
AM-90	**85.0cd**	**83.7a**	**61.7b**	**76.0a**	**82.7ab**	**65.7b**	**72.7a**	**75.3c**
AM-180	**86.3cd**	**84.7a**	**69.3b**	**69.3a**	**71.0b**	**75.7ab**	**70.0a**	**75.0c**
SB7-90	**95.0c**	**78.7a**	**65.3b**	**72.3a**	**94.7a**	**74.3ab**	**72.7a**	**79.0bc**
SB7-180	**114.3b**	**83.7a**	**70.3ab**	**71.3a**	**93.3ab**	**94.7a**	**82.7a**	**87.2a**
SB11-90	**123.0b**	**89.0a**	**79.0a**	**75.3a**	**77.0ab**	**70.3ab**	**70.3a**	**83.4ab**
SB11-180	**154.0a**	**89.3a**	**68.7b**	**70.7a**	**76.3ab**	**68.7b**	**73.0a**	**85.9ab**
CB-90	**74.0de**	**85.0a**	**61.3b**	**81.0a**	**78.7ab**	**71.0ab**	**70.0a**	**74.4c**
CB-180	**87.3cd**	**80.7a**	**67.7b**	**73.3a**	**76.7ab**	**67.3b**	**72.3a**	**75.0c**
Cont.	**64.5e**	**93.3a**	**64.3b**	**74.0a**	**76.7ab**	**86.3ab**	**68.0a**	**75.9c**

† Ammonium nitrate (AM), slurry biosolid of pH 7 (SB7), slurry biosolid of pH 11 (SB 11), Cake biosolid (CB), nonfertilizer control (Cont.).
‡ Values for a harvest date or means followed by the same letter are not different (*P* > 0.05) according to the Duncan's multiple range test.

ent study was suboptimal for the AM and control treatments in early to midsummer while the biosolids maintained a significantly higher tissue P levels beyond the 2.0 g kg^{-1} threshold in spring and fall.

The biosolids used by Christie et al. (2001) contained some cement kiln dust and much higher K concentrations (12–22 g K kg^{-1}) than the biosolids (2.5–3.0 g K kg^{-1}) used in our study. They observed that biosolid K was as available as fertilizer K. However, due to the deficiency of K relative to the concentrations of N and P in our biosolids (Table 1), our forage tissue K concentration (4.6–7.9 g kg^{-1}) was below the 10.0–12.0 g kg^{-1} critical level suggested for optimum warm season grass growth (Snyder and Kretschmer, 1986; Rechcigl et al., 1992) and was probably a constraint to forage production. Tissue K responded positively (9.0–14.0 g kg^{-1}) to K application (0–56 kg K ha^{-1}) in a grazing study on warm-season grasses, but forage yield did not (Adjei et al., 2000). However, both bahiagrass yield and tissue K responded to K fertilizer between 56 and 112 kg K ha^{-1} in a clipping study (Stanley and Rhoads, 2000). Supplemental K may therefore be beneficial to grass hay production when using straight domestic wastewater residuals as a source of N if initial K soil test is low.

Within each year and harvest date, tissue Ca, Fe, and Mn were affected differently ($P < 0.01$) by N source treatments (Tables 8–10). For the initial 1998 harvest, the 90 kg N ha^{-1} led to a higher tissue Ca than the 180 kg N ha^{-1}, regardless of N source, and tissue Ca for the control was lowest. During the summer harvests, no

Table 10. The effect of treatment × year × harvest date on bahiagrass forage tissue concentration of Mn.

	Harvest no.							
N source†	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Mean**
	mg kg^{-1}							
				1998 Mn				
AM-90	**30.3b‡**	**18.3c**	**15.3c**	**13.3d**	**12.7b**	**15.3b**	**–**	**17.9e**
AM-180	**30.3b**	**18.0c**	**18.3bc**	**15.0cd**	**9.7b**	**13.7b**	**–**	**19.5de**
SB7-90	**89.0a**	**38.3b**	**30.7ab**	**24.0abc**	**32.0a**	**72.0a**	**–**	**30.6b**
SB7-180	**65.0a**	**58.7a**	**41.7a**	**30.7a**	**34.7a**	**66.7a**	**–**	**40.8a**
SB11-90	**33.7b**	**20.0c**	**22.0bc**	**19.3bcd**	**17.0b**	**21.7b**	**–**	**24.7c**
SB11-180	**27.7b**	**15.0c**	**17.0bc**	**14.3d**	**11.0b**	**14.7b**	**–**	**19.6de**
CB-90	**32.7b**	**23.7c**	**21.0bc**	**15.7cd**	**12.7b**	**15.7b**	**–**	**21.4cde**
CB-180	**31.3b**	**26.3c**	**21.0bc**	**16.0cd**	**12.7b**	**13.0b**	**–**	**22.1cde**
Cont.	**32.0b**	**20.0c**	**21.3bc**	**26.3ab**	**19.3b**	**27.0b**	**–**	**23.1cd**
				1999 Mn				
AM-90	**21.0b**	**27.7bc**	**17.7b**	**15.0a**	**18.3a**	**71.7ab**	**76.3a**	**35.4bc**
AM-180	**17.3b**	**20.0c**	**12.0b**	**12.0a**	**28.7a**	**47.0abc**	**52.7a**	**27.1bc**
SB7-90	**91.0a**	**71.0a**	**78.3**	**35.7a**	**21.3a**	**15.3bc**	**57.3a**	**52.9ab**
SB7-180	**98.0a**	**53.0ab**	**92.3a**	**36.7a**	**61.3a**	**98.7a**	**59.0a**	**70.0a**
Sb11-90	**23.3b**	**26.3bc**	**24.3b**	**39.0a**	**86.7a**	**22.3bc**	**29.7a**	**36.0bc**
SB11-180	**13.3b**	**17.3c**	**14.9b**	**38.7a**	**35.0a**	**44.3abc**	**52.3a**	**30.7bc**
CB-90	**17.7b**	**21.7c**	**19.3b**	**29.3a**	**34.3a**	**18.0bc**	**19.7a**	**22.9c**
Cb-180	**21.0b**	**19.3c**	**13.3b**	**27.3a**	**22.3a**	**9.3c**	**14.3a**	**18.1c**
Cont.	**31.5b**	**36.0bc**	**29.0b**	**15.7a**	**21.0a**	**39.0abc**	**33.0a**	**29.2bc**

† Ammonium nitrate (AM), slurry biosolid of pH 7 (SB7), slurry biosolid of pH 11 (SB 11), Cake biosolid (CB), nonfertilizer control (Cont.).
‡ Values for a harvest date or means followed by the same letter are not different (*P* > 0.05) according to the Duncan's multiple range test.

noticeable differences were observed among treatments, but toward the fall of the 1998 season and for the spring of 1999 season tissue Ca was elevated with lime-stabilized biosolids treatments (Table 8). Iron concentration in forage tissue was greatest ($P < 0.001$) for the slurry biosolids only in spring harvests, after which tissue Fe concentrations stabilized at approximately 75 mg kg^{-1} for the remainder of the season each year (Table 9). Tissue Mn was noticeably higher ($P < 0.0001$) for the SB7 treatment than most of the other treatments in nearly all harvests during the 2 yr (Table 10).

Rechcigl et al. (1992), while evaluating the effect of reduced P application on bahiagrass production and quality, also reported average tissue concentrations of 4.0 g kg^{-1} for Ca, 3.0 g kg^{-1} for Mg, 2.5 mg kg^{-1} for Cu, 40 mg kg^{-1} for Mn, and 12 mg kg^{-1} for Zn, all of which were in the sufficiency range for bahiagrass (Kincheloe et al., 1987). These tissue concentrations of nutrients are also supported by results from a micronutrient and S study on bahiagrass (Kalmbacher, 2001) where mean tissue Cu concentration of 3.0 mg kg^{-1}, tissue Zn of 20 to 41 mg kg^{-1}, tissue Fe of 28 to 39 mg kg^{-1}, and tissue Mn of 36 to 116 mg kg^{-1} in response to micronutrients application were reported. An increasing soil pH from alkaline biosolid application was responsible for a lower shoot Mn concentration (Christie et al., 2001). Our study shows that biosolids can support adequate tissue concentrations of micronutrients except Mn. The initial Mn status of our soil was low but we did not measure Mn concentration in our biosolids. Tissue Mn below 20 mg kg^{-1}, as observed in our study, was suboptimal for grass growth and may need to be rectified in the future.

CONCLUSIONS

Slurry biosolids supported bahiagrass forage production at a similar rate and to the same extent as the inorganic AM fertilizer, but the lime-stabilized CB was only 70% as effective. All N sources gave better forage production than the nonfertilized control. Apart from the early spring season when CP was improved with inorganic N, there was practically no consistent difference in forage quality (CP and IVOMD) between organic and inorganic N sources. Tissue P and Ca were elevated by both lime-stabilized and aerobically digested slurry biosolid in spring and fall, whereas tissue Fe, Mn, and Cu were elevated in spring or spring and fall only by aerobically digested slurry biosolid. Both the organic and inorganic sources of N used appeared lacking in K and Mn nutrients during rapid summer forage growth, which may need to be corrected in the future to optimize forage yield and tissue levels of these nutrients. Considering that only 50% of the 1 million ha of bahiagrass pastures in Florida are given inorganic N yearly, lime-stabilized liquid sludge, if processed and applied according to USEPA rules, has a potential to boost forage production in Florida because it is inexpensive, environmentally safe (Adjei and Rechcigl, 2002), and could act as liming and organic matter amendment as well. But careful attention should be paid to the P loading factor in ecologically sensitive areas.

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