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Research Article

Agronomic Efficiency of Biosolid as Source of Nitrogen to Banana Plants

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Sewage sludge (SS) or biosolid has been studied as source of nutrient for several different plant species. It also contributes to soil fertility recycling organic matter and plant nutrients. This followup work examines a three-year (2001–2004) field experiment designed to evaluate the response of banana plants (Cavendish subgroup) to the application of biosolid as source of nitrogen. The treatments consisted of control (mineral PK, no N), three rates of sludge, and two rates of mineral NPK fertilizer. Plant and soil N concentration, fruit yield, plant height, stem diameter, and foliar endurance index were measured. Fruit yield with mineral fertilization or sludge applications did not differ statistically ($P > 0.05$). Application of biosolid resulted in statistically significant higher agronomic efficiency ($P < 0.05$) in comparison to mineral fertilizers. The concentration of soil mineral nitrogen increased using mineral fertilizer or sludge until 0.80 m after three years of application. The effect of the source of N was smaller than the effect of the rate. Biosolid can be used as source of N for banana growers.

1. Introduction

Among the alternatives to dispose biosolid, recycling on agricultural land offers economic and environmental benefits. The key concept of land application of biosolid [1–3] is the return of organic matter and plant nutrients removed by crops. Some researchers have reported that biosolid application also improves soil physical properties [4–6]. Biosolids were effective to substituted mineral fertilizers as source of nitrogen (N) for ryegrass [7], sugarcane [1, 2, 8], sunflower [9], and maize [10, 11]. In all of these, there were no indications of environmental hazards due to biosolid addition in soils. In Brazil, as in many other places, there is a specific regulation about the application of biosolids in agricultural soils [12] and for agronomic purposes, the sludge rate must be calculated by using the sludge's N mineralization rate (N_{MR}) and the plant requirement.

Andrade et al. [11] pointed out that the successive application of biosolid can cause an increase of the potential mineralizable N, underestimating the soil capacity of providing N. Situations like that could represent environmental risks as the gradual increase of soil capacity to supply N should be coupled to a decrease in the rates of sludge applied as fertilizer preventing nitrate leaching [13, 14] and soil N_2O emissions [15, 16].

Besides the environmental concern, the use of biosolid as source of N for banana could be beneficial as the plant grows fast and requires high levels of nutrients to produce biomass and fruits. Literature review indicates that plant of banana producing around 50 t fruits ha^{-1} $year^{-1}$ demands from 198 to 388 kg ha^{-1} of N and 29 to 52 kg ha^{-1} of P [17]. Although the biosolid, as source of plant nutrients, has been evaluated for other plant species, there is a lack of knowledge about crops highly nutrient demanding.

In this study, we hypothesized that the biosolid was similar to mineral N fertilizer to supply the required nutrients to banana plants. The objectives of this work were to evaluate the banana response to the application of biosolid as source of N in terms of fruit yield, N uptake, and agronomic effectiveness of N usage.

2. Materials and Methods

2.1. Site Description. The experiment described in this paper is complementary to that reported by Teixeira et al. [18] which discussed only soil parameter modifications by sludge application. Here, fruit yield from three cropping cycles, the agronomic efficiency use of N from sludge, and the concentration of soil nitrogen (N-NO_3^- and N-NH_4^+) were presented. The experiment was carried out between September 2001 and December 2004 at the city of Pariquera-Açu, state of Sao Paulo, Brazil (24°39′S; 47°55′W). This region cropped around 38,500 hectares of land with banana, representing 70% of the total area planted with this specie in the state of Sao Paulo. Historical climatic records from 01/10/1992 to 31/12/2004 showed that the monthly averaged minimum/maximum air temperature ranged from 23.2°C (July) to 31.1°C (February); monthly rainfall averaged from 54.7 mm (August) to 298.6 mm (January). Climate data of experimental period and most relevant management practices performed during cropping period were presented in Figure 1.

The soil was classified by Sakai and Lepsch [19] as a clayey texture (34.0% of clay, 0.9% of silt and 57.0% of sand) A horizon alic Yellow Oxisol (Pariquera Unit-I). Before trial installation, soil chemical characteristics were evaluated according Raij et al. [20] in composite samples ($n = 6$) collected from depths of 0–0.20 and 0.20–0.40 m resulting in values of pH $CaCl_2$ = 4 and 4; soil organic carbon = 23 g dm^{-3} and 18 g dm^{-3}; K^+ = 1.6 mmol$_{(+)}$ dm^{-3} and 1.2 mmol$_{(+)}$ dm^{-3}; Ca^{2+} = 8 mmol$_{(+)}$ dm^{-3} and 7 mmol$_{(+)}$ dm^{-3}; Mg^{2+} = 2 mmol$_{(+)}$ dm^{-3} and 2 mmol$_{(+)}$ dm^{-3}; H + Al^+ = 90 mmol$_{(+)}$ dm^{-3} and 92 mmol$_{(+)}$ dm^{-3}; and base saturation index as (K + Ca + Mg)/CEC = 12.3% and 10%, respectively. Based in this data, soil received dolomitic limestone (effective calcium carbonate equivalent = 67%) in order to increase the base saturation index (V) to 60%. Soil preparation consisted of disc plowing, harrowing and furrowing until the depth of 0.35 m.

2.2. Sludge and Application Rates. Biosolid was produced by the sewage treatment plant of the city of Mongagua, located 170 km far north of the experimental site. This plant processes municipal sewage by using the method of Sequencing Batch Reactor (SBR) or "Fill and Draw System" with hydraulic retention time of around 6-7 hours. Selected characteristics of the sludge, on different years, are in Table 1. Sludge available N was quantified according CETESB [21]. Organic carbon (OC) and nitrogen forms (Kjeldahl-N, NH_4-N, (NO_3 + NO_2)-N) were determined according Raij et al. [20]. Nutrients and heavy metals were extracted according to the 3051 US-EPA method [22] and quantified by inductively coupled plasma atomic emission spectroscopy (ICP-AES). Sludge pH was determined at 1 : 10 water extract (m/v); humidity and volatile solids (VS) by mass loss at 60°C and 500°C, respectively.

Sludge rate was calculated to match the theoretical banana requirement for nitrogen. In the state of Sao Paulo, N fertilizer recommendation to produce 50–60 t ha^{-1} of fruits is 430 kg N ha^{-1} [23]. Therefore, rates equivalent to 0.5, 1.0 and 2 times of the mentioned N rate were applied. For first growing season, sludge rates were equal to T_{L1} = 219 kg ha^{-1} N; T_{L2} = 400 kg ha^{-1} N and T_{L3} = 870 kg ha^{-1} N (Table 2). For the subsequent two growing seasons the nitrogen rate were reduced by half (i.e., T_{L1} = 100 kg ha^{-1} N; T_{L2} = 200 kg ha^{-1} N and T_{L3} = 400 kg ha^{-1} N) in all treatments (Table 2). This modification on sludge rate was necessary because, in an unexpected way, fruit production reached 50–60 t ha^{-1} in the first growing season. As the nitrogen mineralization rate of the biosolid was determined as 30% we supposed the full response of fruit yield would occur only in the second or third season, when most of the N was mineralized. Therefore, facing to the high productivity in the first cropping season and to prevent plant toxicity or environmental concerns we adopted a reduced rate of the sludge. This occurred because for normal agricultural practices in Sao Paulo State, the recommendation for N application is based on expected productivity.

Sewage sludge rate (SS_R) was calculated considering the amount of N required by the plants (N_{RP}), the content N available on the residue (SS_N) (Table 1) by using (1).

$$SS_R, \text{kg ha}^{-1} = N_{RP} \times SS_N. \tag{1}$$

The nitrogen mineralization rate (N_{MR}) was determined in a laboratorial trial (data not shown) and was equal to 30% of total N. For planting (2) and growing seasons 2 and 3 (3) amendments two different equations to estimate SS_N were used:

$$\begin{aligned} SS_N = {} & \left(\frac{N_{MR}}{100}\right) \times (\text{Kjeldahl}_N - NH_3\text{-N}) \\ & + NH_3\text{-N} + NO_3^{-}\text{-N} + NO_2^{-}\text{-N} \end{aligned} \tag{2}$$

$$\begin{aligned} SS_N = {} & \left(\frac{N_{MR}}{100}\right) \times (\text{Kjeldahl}_N - NH_3\text{-N}) \\ & + 0.5 \times [NH_3\text{-N} + NO_3^{-}\text{-N} + NO_2^{-}\text{-N}], \end{aligned} \tag{3}$$

where Kjeldahl-N = total nitrogen (mg kg^{-1}); NH_4^+-N = nitrogen as ammonia (mg kg^{-1}); NO_3^--N = nitrogen as nitrate (mg kg^{-1}); NO_2^--N = nitrogen as nitrite (mg kg^{-1}).

This was necessary because in 2002 and in 2003, biosolid was manually side-dressed without incorporation into the soil, over a one meter-wide strip alongside the plant rows.

2.3. Orchard Planting, Management and Sampling. Experiment consisted of plots with 100 m^2 (10 × 10 m) distributed in a complete randomized design, with five replicates (n = 5). Twenty banana plantlets per plot were planted (2.5 × 2.0 m spacing) by using *in vitro* micropropagated Grand Naine cultivar (AAA group, Cavendish subgroup) material. By the time of the orchard establishment the plantlets presented, in average (n = 50), 4.4 leaves and 0.221 m height.

In 2001, biosolid was applied into the furrows, between the planting holes, and carefully incorporated to the soil. Fertilizer phosphorus was applied in all plots, twice during

Table 1: Chemical composition of the municipal biosolid applied to a banana plantation in the city of Pariquera-Açu as source of nitrogen over three crop seasons.

Parameter	Unit	Growing season			Parameter	Unit	Growing season		
		2001	2002	2003			2001	2002	2003
P	$g\,kg^{-1*}$	15.4	11.6	8.7	OC	$g\,kg^{-1*}$	222.7	302.8	172.4
K	$g\,kg^{-1*}$	0.9	0.8	1.0	pH		9.9	12.7	12.6
Na	$g\,kg^{-1*}$	0.6	0.8	0.4	Humidity	% (m/m)	71.2	64.3	62.9
As	$mg\,kg^{-1*}$	<0.1	<0.1	<0.1	Volatile solids	% (m/m)*	52.5	43.9	35.1
Cd	$mg\,kg^{-1*}$	10.3	1.2	0.5	Kjeldahl-N	$g\,kg^{-1*}$	32.0	31.1	21.5
Pb	$mg\,kg^{-1*}$	83.6	115.6	21.0	NH_4-N	$mg\,kg^{-1**}$	1941.5	806.7	591
Cu	$mg\,kg^{-1*}$	139.6	115.6	67.2	$(NO_3 + NO_2)$-N	$mg\,kg^{-1**}$	47.1	42.0	33.5
Cr	$mg\,kg^{-1*}$	43.8	19.3	14.5	S	$g\,kg^{-1*}$	7.7	7.0	6.74
Hg	$mg\,kg^{-1*}$	ND	ND	ND	Mn	$mg\,kg^{-1*}$	778.5	539.4	342.8
Mo	$mg\,kg^{-1*}$	ND	ND	ND	Fe	$g\,kg^{-1*}$	106.4	50.9	54.7
Ni	$mg\,kg^{-1*}$	22.2	12.7	9.9	Mg	$g\,kg^{-1*}$	5.9	4.8	3.8
Se	$mg\,kg^{-1*}$	ND	ND	ND	Al	$g\,kg^{-1*}$	7.0	6.7	5.5
Zn	$mg\,kg^{-1*}$	573.4	449.8	281.6	Ca	$g\,kg^{-1*}$	173.6	359.6	193.7
B	$mg\,kg^{-1*}$	22.9	13.9	7.4	Available-N	$g\,kg^{-1**}$	2.96	3.41	2.32

*On dry matter basis; **determined on biosolid with natural moisture content.

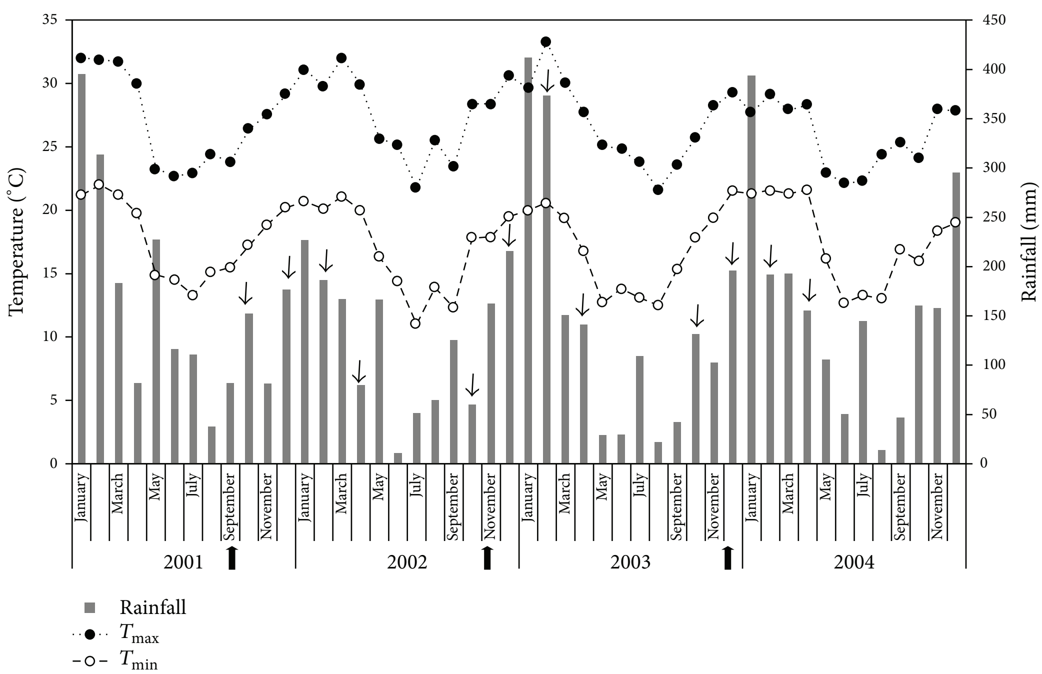

Figure 1: Climatic parameters over the period of 2001–2004 in the city of Pariquera-Açu at Sao Paulo State, Brazil. Upward fulfilled black arrows indicate the sludge application dates. Mineral fertilizer application was split in four events (25% each) within the same crop season and was represented by the downward arrows.

the trial: 150 kg ha^{-1} of P_2O_5, into the furrows by the planting (in 2001) and 200 kg ha^{-1} of P_2O_5 was broadcasted on soil surface in 2003. The source of P was phosphate (41% P_2O_5). Potassium was yearly applied at a rate of 342 kg ha^{-1} $year^{-1}$ of K as KCl, and nitrogen as NH_4NO_3 (32% N) according to each treatment (Table 2). Fertilization with potassium and nitrogen was split in four events during the crop cycle (Figure 1).

Due to its own biological characteristics, as banana plant grows new suckers from its rhizome comes out. The management of the plants consisted of pruning and keeping a clump formed by three plants (parent plant, first and second

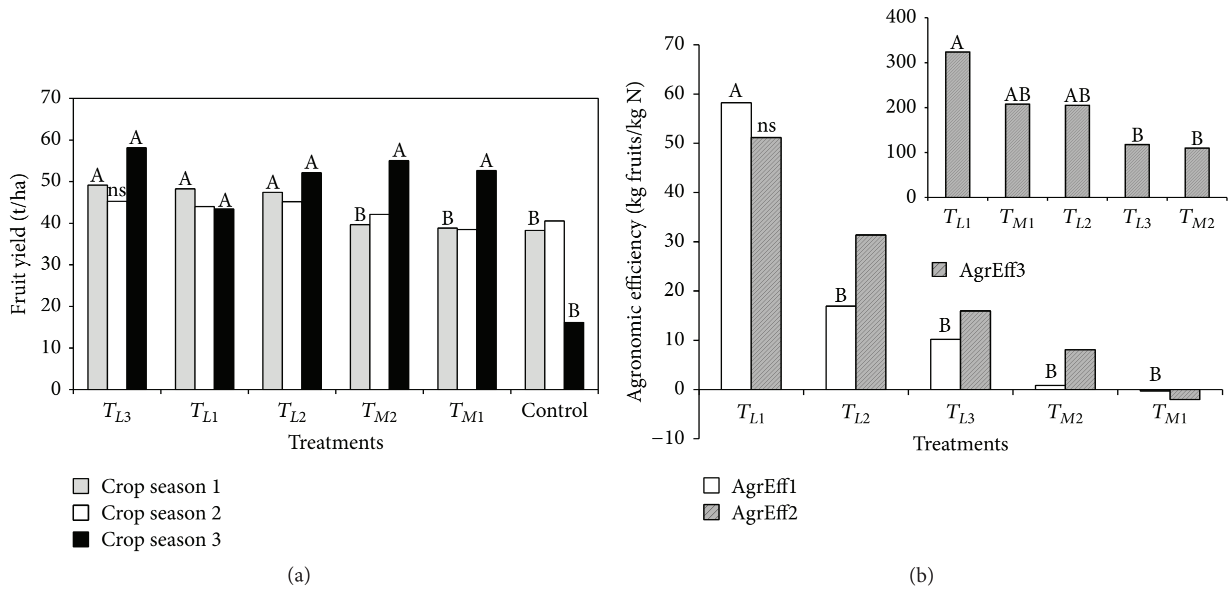

Figure 2: Biosolid and mineral fertilizer application on fruit yield (a) and agronomic efficiency index (b). Columns, within the same crop season, labelled with different letters on top are significantly different ($P < 0.05$). ns = not significant ($P > 0.05$). In (b) observe the difference of scale on y-axis. T_{L1}, T_{L2}, and T_{L3} correspond to the equivalent amount of approximately 100, 200, and 400 kg ha^{-1} year^{-1} of N applied as SS. T_{M1} and T_{M2} were equivalent to the application of 200 and 400 kg ha^{-1} year^{-1} of N as NPK mineral fertilizer.

suckers). Only the parental plant of each plot was used to record fruit yield, plant height, pseudo-stem diameter and to collect leaf samples. Soil sampling was done yearly, after the fruit harvesting, in 2002, 2003, and 2004. In 2002 and 2003 soil samples were taken from depths of 0–0.2, 0.2–0.4, 0.4–0.6 m. In 2004 the layer of 0.60–0.80 m was also collected. Fresh soil samples were analyzed for N-NO_3^- and N-NH_4^+ after extraction with 2 mol L^{-1} KCl solution according to Raij et al. [20]. Fertility parameters were evaluated in 2 mm sieved air-dried soil samples and processed according Raij et al. [20].

To evaluate the effect of sludge and fertilizer applications on soil organic matter variations from the initial condition, before the application of sludge or fertilizer, were calculated every year as $\Delta_{\text{SOM}} = \text{SOM}_{\text{year}} - \text{SOM}_{\text{initial}}$. Thus, a positive Δ_{SOM} indicates accumulation of carbon for a specific treatment, depth and time.

Plant nutrition was evaluated by using the chemical leaf tissue analysis [24] prepared according to procedures described by Bataglia et al. [25].

The agronomic efficiency index (AgrEff) was calculated according to (4):

$$\text{AgrEff} = \frac{(Y_{\text{fert}} - Y_{\text{unfert}})}{Q_{\text{NA}}}, \tag{4}$$

where AgrEff = agronomic efficiency index in kg fruits kg^{-1} of N applied; Y_{fert} = Production of harvested biomass (Fruits + peduncle) with N, kg ha^{-1}; Y_{unfert} = Yield without N, kg ha^{-1} (Control); Q_{NA} = Amount of N applied, kg ha^{-1}.

Pseudo-stem diameter was measured at the height of 0.30 m from the soil surface and the plant height was measured from soil surface to the insertion point of youngest leaf. In addition, the leaf endurance index (LEI), which is the number of active leaves at the harvesting divided by the number of active leaves at bunch emission, was calculated. "*LEI*" represents the maintenance of active leaves by plants and the practical experience of the researches involved in this paper has showed that there was a direct and positive relationship between LEI and yield.

2.4. Statistical Calculations and Data Analysis. Data were analyzed using analysis of variance (ANOVA) for randomized complete block designs to test the effect of treatments. Means were compared by using Tukey's HSD test. All calculations considered the level of significance of $P = 0.05$ and were performed in Minitab v.16.

3. Results and Discussion

As said at the beginning, this paper continues to explore the experiment previously reported by Teixeira et al. [18]. Also, data of first fruit yield became available after the publication of the soil parameters [18], allowing to consider that these was partially resulted from the sludge application in 2001. In this way, some information about the soil from the first growing season already presented by Teixeira et al. [18] is been showed again to facilitate discussions.

3.1. Fruit Productivity and Agronomic Efficiency. In the first growing season, treatments that received sludge produced higher amounts of fruits (Figure 2(a)). Unlikely, plants cultivated with the similar N rate, but applied as mineral fertilizer (T_{M2}), did not respond in the same way (Figure 2(a)). Besides the addition of sludge increases the availability of nitrogen and phosphorus other factors should be improving the biomass production.

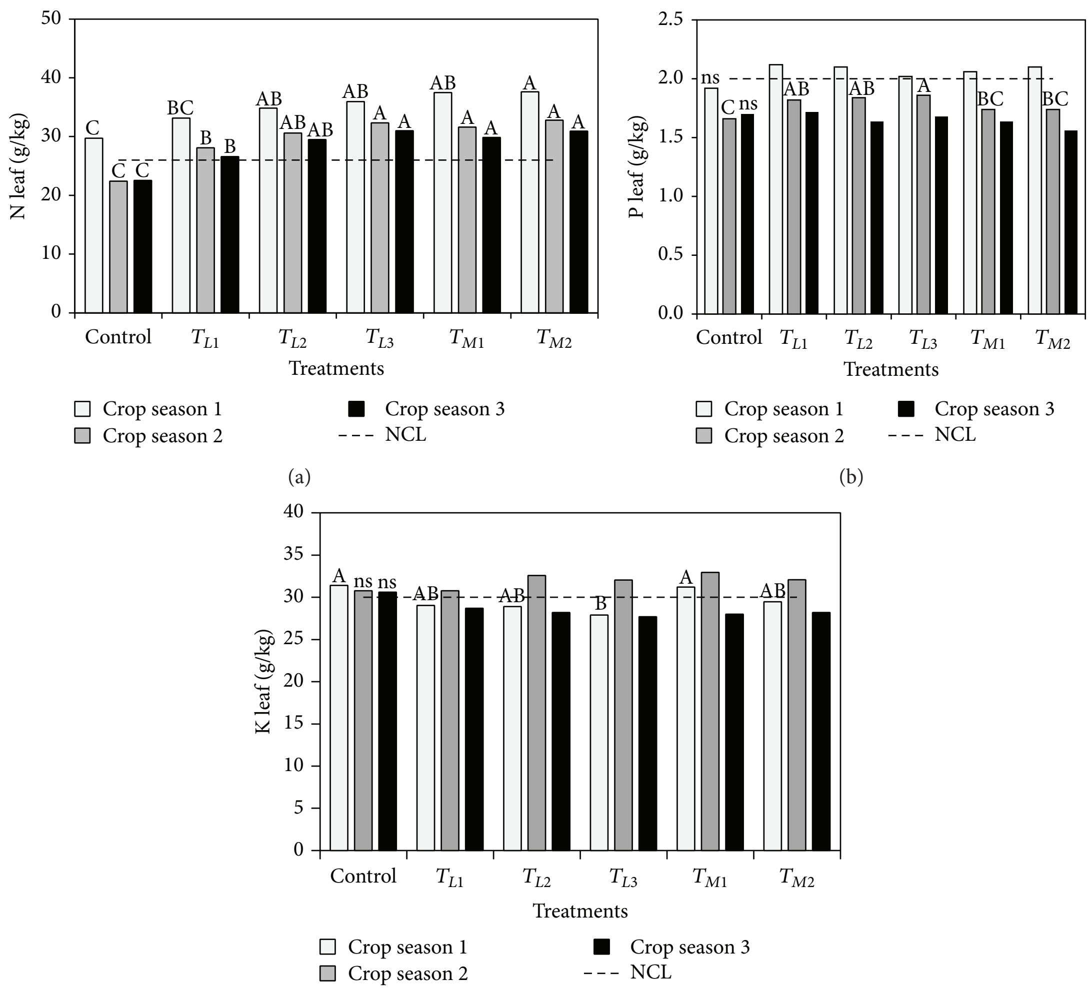

FIGURE 3: Nitrogen (a), phosphorus (b), and potassium (c) concentrations in banana leaves with sewage-sludge (T_L) and mineral fertilizer (T_M). Columns with the same letter on top, within crop season, indicate that the mean does not differ by Tukey's HSD test ($P > 0.05$). ns = ANOVA F test is not significant for treatments effects ($P > 0.05$). Dashed line represents the nutrient critical level (NCL) according to Raij et al. [37].

The precise contribution of sludge is difficult to measure comparing the yield from Control to amended treatments. Control also received P and K; thus part of the variation observed was caused by the supply of N. Besides, yield in first two growing seasons did not differentiated among treatments with biosolid rates.

The highest yield obtained with sludge amendment can be due to double effect of the organic material supplying nutrients and improving soil physical parameters as well [4, 5]. Unfortunately, soil physical properties were not measured in this work and more considerations cannot be made.

Absence of plant response in mineral fertilized treatments in comparison to the Control can be partially input to natural soil fertility. Although N supply is used as indicator to sludge rate application, there was no agreement about soil N evaluation. More about soil N is shown in Section 3.2 of this paper.

Fruit production in the Control treatment without N at similar levels to plants amended with mineral fertilizer (T_{M1} and T_{M2}) reinforces this statement.

The data from the third growing season (AgrEff3) were considered without influence of the natural soil fertility and analyzed with more detail (Figure 2(b)). It reflected the data of fruit yield but showed that the application of the smallest rate of sludge (T_{L1}) was the most effective then the mineral amendment. This reinforces the observation that biosolid is not a pure source of nutrients but also affects other soil parameters resulting in a more efficient use of them.

Furthermore, in general, biosolid increased the AgrEff within growing seasons, but the ratio of AgrEff between biosolid to fertilizer (AgEff_T_L/AgEff_T_M) diminished from 103.5 (growing season 1) to 10.77 (growing season 2) and 1.36 (growing season 3). Probably the biosolid re-application is increasing the amount of N potentially mineralizable and therefore, reducing the proportion of fruits per kilogram of applied N as postulated by others [11, 26].

3.2. Plant Nutrition. Foliar N and P contents agreed with the yield data (Figure 3). For the three crop cycles the N concentrations for Control treatment were lower than the observed

Table 2: Description of treatment and additional information.

Treatment	Fertilization	Biosolid rate $t\,ha^{-1}$ (dry base)	Nitrogen $kg\,ha^{-1}$
	2001		
Control	No N + mineral fertilization (P + K)	—	—
T_{L1}	Biosolid rate 1 + K	21.3	219
T_{L2}	Biosolid rate 2 + K	42.6	435
T_{L3}	Biosolid rate 3 + K	85.2	870
T_{M1}	Mineral N (rate 1) + P + K	—	400
T_{M2}	Mineral N (rate 2) + P + K	—	800
	2002		
Control	No N + mineral fertilization (P + K)	—	—
T_{L1}	Biosolid rate 1 + K	10.7	100
T_{L2}	Biosolid rate 2 + K	21.4	200
T_{L3}	Biosolid rate 3 + K	42.8	400
T_{M1}	Mineral N (rate 1) + P + K	—	200
T_{M2}	Mineral N (rate 2) + P + K	—	400
	2003		
Control	No N + mineral fertilization (P + K)	—	—
T_{L1}	Biosolid rate 1 + K	13.9	100
T_{L2}	Biosolid rate 2 + K	27.8	200
T_{L3}	Biosolid rate 3 + K	55.5	400
T_{M1}	Mineral N (rate 1) + P + K	—	200
T_{M2}	Mineral N (rate 2) + P + K	—	400

in T_L and T_M treatments. In terms of foliar phosphorus concentration, biosolid presented similar effectiveness than mineral fertilizer amendments (Figure 3(b)) although no difference between T_{L1} and T_{L3} rates were observed.

These results agree with the observed for other species in which a significant amount of P was released by the biosolid [2, 27–32]. Also it is important consider that the establishment of biosolid application rate based on N availability, in this case, resulted in high amounts of P being added to soil ranging from 1278 $kg\,ha^{-1}$ (T_{L3}—in 2001) to 121 $kg\,ha^{-1}$ (T_{L1}—in 2003).

Statistical significant effect of treatments on potassium foliar concentrations was found only in the data of the first growing season (Figure 3(c)). Some can highlight the difference of K content between T_{L3} and T_{M1} but is important to observe that the treatment T_{M2} presented similar values. Because potassium was applied to all treatments and as there was no consistent alterations of foliar concentration with biosolid rates increase, further considerations about this nutrient are difficult to be made.

These results support the conclusion of Teixeira et al. [18] about the capacity of the biosolid to supply N to banana and also P. These results are important because practically there were no others references about the usage of biosolid as source of plant nutrients in banana orchards. More studies considering fruit quality parameters as well are encouraged.

Table 3: Leaf endurance index, N/K relationship in the shoots, plant height, and banana stem diameter due to biosolid or mineral fertilizer application.

Treatment	LEI, %	Foliar N/K	Plant height, m	Stem diameter, m
		2002		
Control	39 ab	0.95 b	2.21 abc	0.19 ab
T_{L1}	33 bc	1.14 a	2.29 a	0.21 a
T_{L2}	32 cd	1.20 a	2.26 ab	0.20 a
T_{L3}	26 d	1.29 a	2.26 ab	0.21 ab
T_{M1}	39 ab	1.20 a	2.16 bc	0.19 b
T_{M2}	40 a	1.28 a	2.10 c	0.19 b
$P_{F5,4}$	<0.0001	<0.0001	<0.0001	<0.0001
		2003		
Control	49 a	0.74 b	2.42 b	0.23 ab
T_{L1}	37 b	0.91 a	2.60 ab	0.23 ab
T_{L2}	34 bc	0.95 a	2.63 ab	0.23 ab
T_{L3}	28 c	1.02 a	2.71 a	0.23 a
T_{M1}	39 b	0.96 a	2.48 ab	0.21 b
T_{M2}	38 b	1.03 a	2.59 ab	0.21 ab
$P_{F5,4}$	<0.0001	<0.0001	0.023	0.012
		2004		
Control	63	0.74 c	2.74	0.25
T_{L1}	61	0.92 b	2.96	0.26
T_{L2}	59	1.05 ab	2.95	0.26
T_{L3}	65	1.12 a	2.92	0.26
T_{M1}	67	1.07 ab	2.83	0.24
T_{M2}	62	1.10 a	2.89	0.25
$P_{F5,4}$	0.105	<0.0001	0.44	0.092

LEI: leaf endurance index; $P_{F5,4}$: significance of F test for treatment effects at 5 degrees of freedom (df) for treatments and 4 df for error; averages followed by same letters within crop cycles on columns do not differ to Tukey HSD test at $P = 0.05$.

Besides being effective, the application of 20 $t\,ha^{-1}$ sludge (dry basis) as source of N resulted in foliar N concentrations not statistically different ($P > 0.05$) to that with 400 $kg\,ha^{-1}$ N from fertilizer (Figure 3(a)).

Under Brazilian soil and climate conditions different plant species already have shown that the biosolid was efficient to sustain the crop yield at similar levels than the observed with purely mineral fertilizer treated plots [1, 7, 27, 31, 33–36]. The application of biosolid to sugarcane cropped soils as source of N and P supplied 100% of N and 35% of the P requirements on these nutrients [1]. Ryegrass cultivated on soils treated with different types of SS also recovered approximately 36–75% of the N and 4–7% of the P supplied [7]. This suggests that biosolid is an effective source of N to *Musa* spp. plants.

3.3. Leaf Endurance Index. There was no statistical significant difference on leaf endurance index, plant height, and stem diameter within treatments for the third growing season (Table 3).

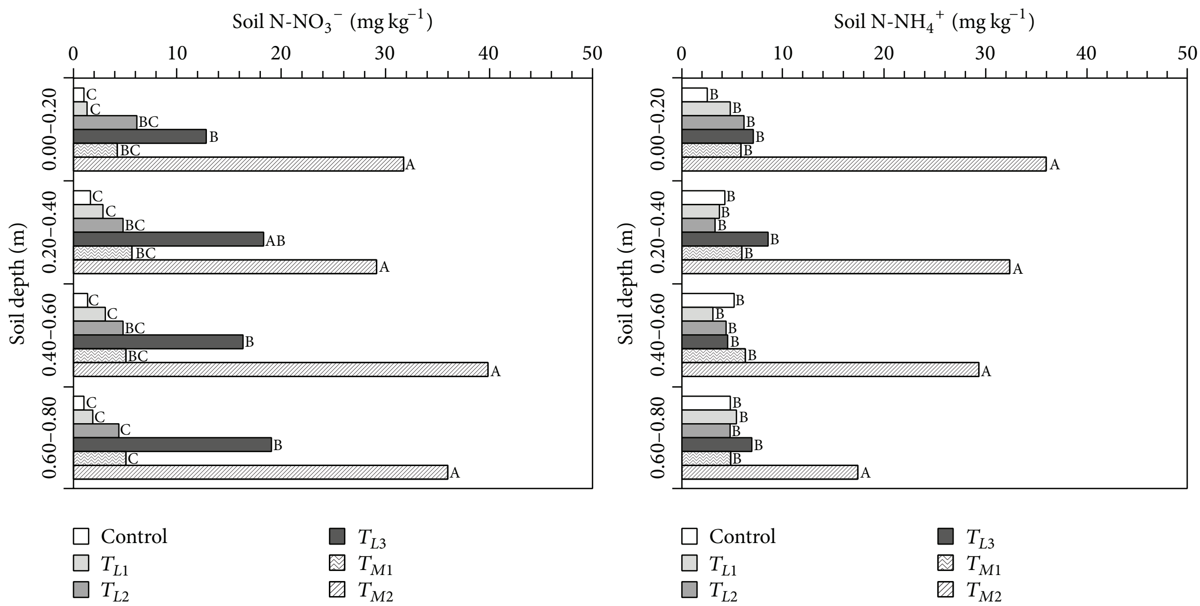

FIGURE 4: Soil nitrate (N-NO$_3^-$) and ammonium (N-NH$_4^+$) as effect of biosolid (T_{L1}, 100; T_{L2}, 200; and T_{L3}, 400 kg ha^{-1} N) and mineral fertilizer (T_{M1}, 200 and T_{M2}, 400 kg ha^{-1} N). Means followed by same letters, within depths, do not differ statistically by Tukey's test ($P > 0.05$).

Leaf endurance index (LEI) showed to be more sensitive to detect differences between biosolid and mineral fertilizer then height and diameter. For the same N rate addition, biosolid resulted in a LEI decrease of 6% (T_{L2} versus T_{M1}) and 4% (T_{L3} versus T_{M2}) in the first season. The same comparison, made with second season data, showed biosolid depressive effects on LEI of 5% (T_{L2} versus T_{M1}) and 10% (T_{L3} versus T_{M2}) (Table 3). Although blamed to be an important index to banana cropping management, LEI did not present relationship to fruit yield as the differences between T_{L2} versus T_{M1} and T_{L3} versus T_{M2} were favorable to biosolid addition in the first growing season (Figure 2). Biological relevance of differences of these magnitudes should be better investigated in future.

In general, the adequate supply of N tends to maximize banana growth [37]. There are some indications that the maintenance of the foliar N/K relationship around 1.5 is need to banana plants keep an adequate number of photosynthetic active leaves. In 2004 foliar N/K relationship for T_{L3} and T_{M2} were the highest (Table 3). Since K was supplied in a constant rate to all treatments, biosolid should supply N in order to keep the N/K relationship favorable to plants. This is supported in part, by the higher AgrEff 3 (Figure 2(b)).

3.4. Soil Nitrogen, Organic Carbon, and Available Phosphorus. Soil inorganic N was evaluated only in 2004, three years after the initial application of biosolid and mineral fertilizer. Effects on soil N content were observed in all soil layers (Figure 4). Only the highest rate of biosolid (T_{L3}) and all mineral fertilizer levels increased N-nitrate concentration in comparison to the control (Figure 4).

For the same amount of N, mineral fertilizer (T_{M2}) always resulted in higher concentrations of nitrate and ammonium than the biosolid (T_{L3}) at the same depth. This is a very common observation as a high percentage of the N applied in the sludge is bounded in organic matter and has to be mineralized while mineral fertilizers rapidly became available forms.

There was no statistically significant difference between T_{L2} and T_{M1} for nitrate and ammonium at all depths. These were the treatments representing the reference values of N application for banana in Brazil.

These results were in agreement to the related to fruit productivity. Part of the yield variations can be coupled to soil N because it is one of the most important elements of banana plant nutrition [2, 28, 29, 31, 33, 38, 39]. Thus, the more available the N is, the more the plant grows and produces biomass and fruits. In a different perspective, the application of 400 kg ha^{-1} N as fertilizer (T_{M2}) is more potentially dangerous than the same amount as biosolid (T_{L3}) in a single growing season due to the increase of soil N-NO$_3$ and N-NH$_4$ concentration. The most interesting fact is that the application of half of the N rate as biosolid (T_{L1}) had practically no effect on soil inorganic N accumulation but resulted in the more agronomic effective practice (Figure 2(b)).

The soil organic carbon showed a distinct pattern (Figure 5). In the first year, there was an increment on soil C content with biosolid application at 0–20 cm layer (Figure 5).

For the same treatments, in the second year the content of SOC diminished only to rise again in the third growing season. In 2003, even the treatments with mineral fertilizer or the control showed an increase in SOC until the depth of 60 cm (Figure 5). This was the result of plant growth, mainly root system, and the recycle of biomass from the stems cut after the fruit production.

It was hypothesized that the addition of N by biosolid stimulated the microorganism to degrade the organic matter

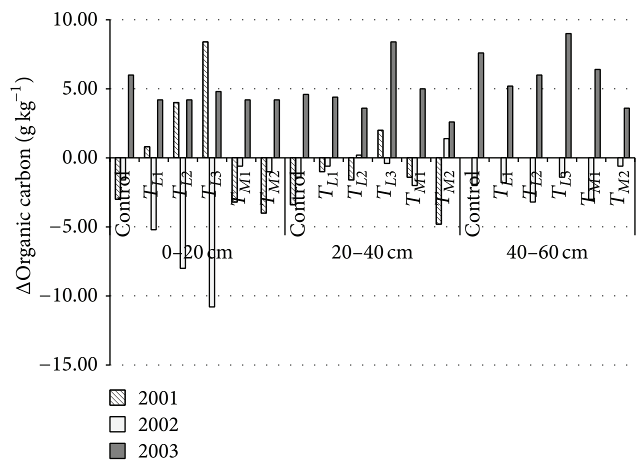

Figure 5: Soil organic carbon as effect of biosolid (T_L treatments) and mineral fertilizer (T_M treatments) rates at different depths and years.

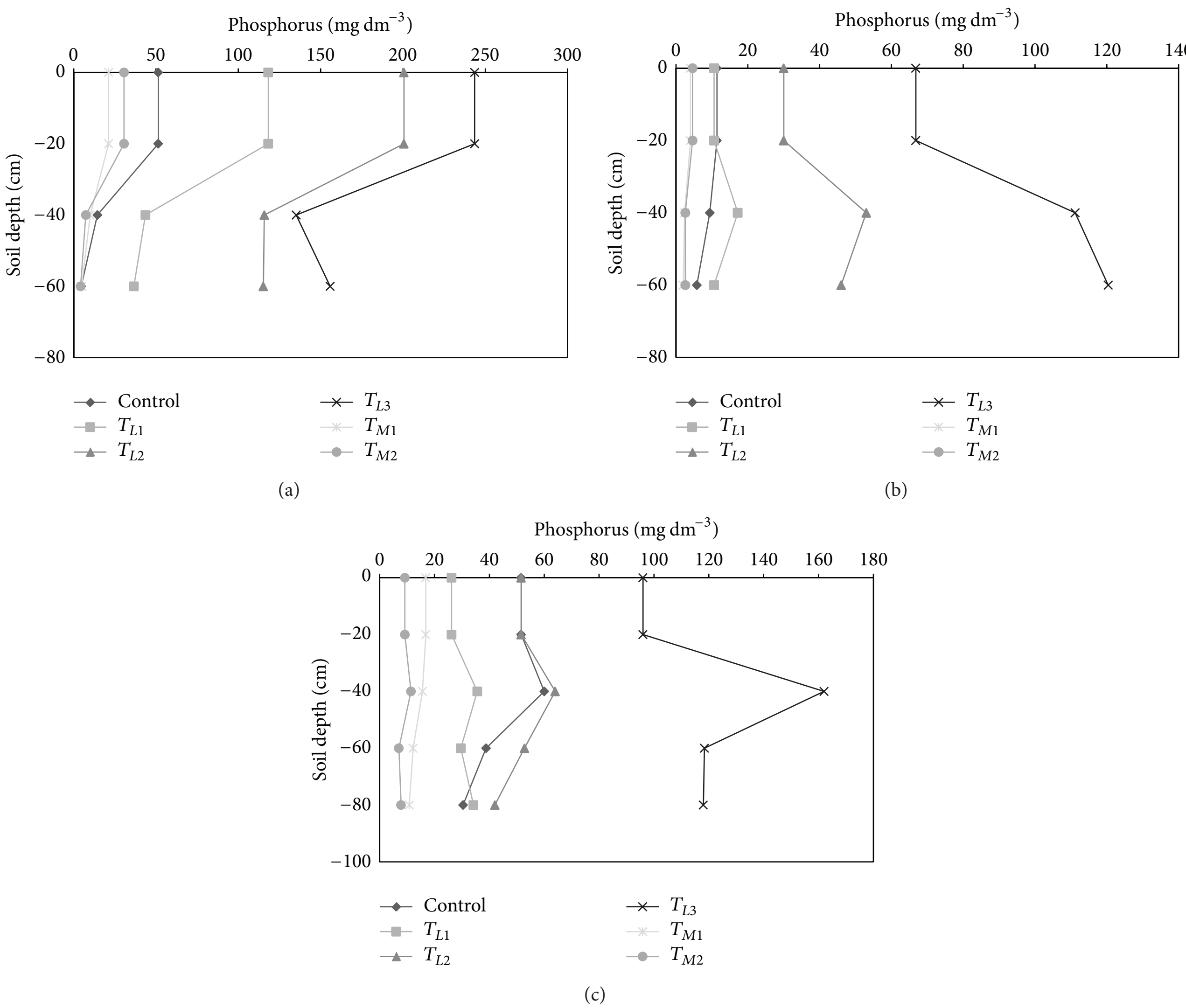

Figure 6: Available phosphorus in different growing seasons and depths as due to the application of biosolid and mineral fertilizer rates in soil cropped with banana. (a) Growing season 2001/2002; (b) growing season 2002/2003; (c) growing season 2003/2004.

preexisting into the soil in the second growing season. After this a new equilibrium was stablished resulting in the accumulation of new forms of carbon.

The two higher rates of biosolid (T_{L2} and T_{L3}) resulted in the higher concentrations of available phosphorus (Figure 6). For different species, others have reported that the biosolid can supply P [7, 40]. Chiba et al. [40] reported that for sugarcane, biosolid addition based on N release can supply approximately 35% of the P plant requirement in one growing season.

The soil profile distribution of available P needs to be more investigated. As can be seen, at T_{L2} and T_{L3} more P were available at deeper layers (Figure 5). Brazilian soils are normally rich in iron and aluminum oxides, which result in a high P retention capacity. In growing seasons 2 and 3, biosolid was spread in the soil surface and the mechanism that leads to the increase of P content at 60 to 80 cm is still unclear.

4. Conclusions

Biosolid is an affordable source of N and P for banana plants; biosolid as source of N to banana plants does not cause depressive effects on biomass production compared to mineral fertilization; the agronomic efficiency index is a reliable tool to describe the response of banana to biosolid application.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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