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RESEARCH ARTICLE

Residual and cumulative effects of soil application of sewage sludge on corn productivity

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Abstract The objective of this study was to evaluate the effect of frequent and periodic applications of sewage sludge to the soil, on corn productivity. The experiment was carried out as part of an experiment that has been underway since 1999, using two types of sludge. One came from the Barueri Sewage Treatment Station (BS, which receives both household and industrial sludge) and the other came from the Franca Sewage Treatment Station (FS, which receives only household sludge). The Barueri sludge was applied from 1999 up to the agricultural year of 2003/2004. With the exception of the agricultural years of 2004/2005 and 2005/2006, the Franca sludge was applied up to 2008/2009. All the applications were made in November, with the exception of the first one which was made in April 1999. After harvesting the corn, the soil remained fallow until the next cultivation. The experiment was set up as a completely randomized block design with three replications and the following treatments: control without chemical fertilization or sludge application, mineral fertilization, and dose 1 and dose 2 of sludge (Franca and Barueri). The sludges were applied individually. Dose 1 was calculated by considering the recommended N application for corn. Dose 2 was twice dose 1. It was evident from this work that the successive application of sludge to the soil in doses sufficient to reach the productivity desired with the use of nitrogen fertilizers could cause environmental problems due to N losses to the environment and that the residual and cumulative effects should be considered when calculating the application of sludge to soil.

Keywords Sewage sludge · Corn · Nitrogen fertilization · Residual nitrogen · N cycling

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Introduction

The increasing costs of commercial fertilizers and the large amounts of sewage sludge produced worldwide have made cropland application of this residue an attractive disposal option. Thus the application of sewage sludge to agricultural land has been considered as an environmentally acceptable management strategy. Sewage sludge is rich in organic matter and plant nutrients, such as phosphorus (P), nitrogen (N), and micronutrients, which are essential to plant growth and make sludge suitable as a soil amendment and fertilizer. The application of sewage sludge to land can improve stability aggregation (Tejada and Gonzalez 2007), soil water content (Kelly et al. 2007), and stimulate microbiological activity (Vieira 2001; Fernández et al. 2009).

Most of the N in sludge is in the organic form, which is not readily available to plants until it has become mineralized in the soil. Only part of the sludge N will become available during the growing season when sludge is applied. Appropriate management of the N from sewage sludge requires an understanding of the factors and processes that influence the extent and rate of conversion of organic N to forms that are available for plant uptake or loss to the environment (He et al. 2000). The immobilized N content should also be considered, the N fixed to clay particles, and the N contained in not completely labile compounds that are not immediately available to the crops but will be available in coming years (Yagüe and Quílez 2010). This nitrogen is denominated as residual, and its accumulation in the soil could increase with successive annual sludge applications, leading to large applications of N which could cause detrimental environmental effects on water reserves and soils. The dynamics of the N applied with the sludge is thus highly complex and demands studies in the sense of evaluating how the availability of N to a plant changes after continuous applications of sludge to the soil. However, despite its relatively low cost and potential benefits, neither the amount of sludge to be applied to the soil nor the frequency of application has yet been well established.

Although N is an extremely important nutrient for the productivity of cultures, one should not forget that these residues also contain significant amounts of phosphorus (P) and heavy metals, which could accumulate in the soil (Liang et al. 2011). Phosphorus, although being an essential nutrient for plant development, can cause eutrophication of freshwater reserves (Medeiros et al. 2005). The heavy metals cause harm to the soil–plant system and in addition might pose a serious risk to human health (Turkdogan et al. 2003). The disposal of sewage sludge on agricultural fields may also result in an increase in the concentration of pollutants in the soil which could result in health and environmental risks (Passuello et al. 2012).

Numerous studies have evaluated the impacts of short-term applications of sewage sludge on the soil (<5 years) (Cogger et al. 1999; Barbarick and Ippolito 2000; Withers et al. 2001; Sigua et al. 2005; Gibbs et al. 2006; Oladeji et al. 2007). Studies evaluating long-term, repeated sewage sludge applications are more limited and involve studying the residual and cumulative effects of N on culture yields, and the distribution of this element in the various parts of the plant (Johansson et al. 1999; Mullen et al. 2005; Sullivan et al. 2006; Barbarick and Ippolito 2007). According to Jin et al. (2011), in order to prevent water pollution by nitrates, a long-term application rate of 22 Mg per ha per year could be sustainable. However, besides the agronomic criteria, one should also consider other environmental constraints. Oleszczuk (2006) stated that the preferred method should be a 1-year system, with a sludge application of ≤75 Mg ha^{-1}, allowing for degradation of the polycyclic aromatic hydrocarbons (PAHs) contained in the sludge.

The majority of the long-term studies (>10 years) evaluated the effects of sewage sludge on soil humic acid (Fernández et al. 2008; Adani and Tambone 2005), on the diversity and density of specific bacteria (Azhari et al. 2012), on soil organic matter (Parat et al. 2005), on soil fractionation of phosphorus (Alleoni et al. 2012), on soil heavy metal concentrations (Bergkvist et al. 2003), and on the cumulative and residual effects of sewage sludge on the lead and cadmium concentrations in the soil (Karami et al. 2007). Studies relative to the residual and cumulative effects of nitrogen on the soil after the application of sewage sludge for long periods of time (>10 years) are nonexistent. Similarly, studies relating the above mentioned factors with the application of different types of sewage sludge to the soil, in different doses, are also nonexistent. Thus if we considered the damaging effects of N on the soil, such a study would be primordial.

The application of sewage sludge to the soil for years could therefore incur an excess of nutrients in the soil, which could affect the environment in different ways. In relation to the N content of the soil, constant applications of sewage sludge could possibly incur an excess of this element in the soil due to its cumulative and/or residual effect. It is also not known what frequency of sewage sludge application would make this practice sustainable. Considering these effects, the aim of this work was to verify the residual and cumulative effect of the application of sewage sludge to the soil, on the nitrogen concentrations, such that this practice could be considered an environmentally acceptable disposal option.

Material and methods

Site characteristics and experimental design

The experimental site was located in Jaguariúna, São Paulo State, Brazil, on a loamy/clayey-textured dark red dystroferric oxisol soil, where the accumulated monthly precipitations for the months from November to May ranged from 50 to 236 mm. The mean monthly temperature in the same period ranged from 18 to 25 °C (Fig. 1a, b). These data are considering the two agricultural years.

The experiment was started in the dry period (April 1999) when the soil received its first application of sewage sludge, but the data related to the present study were collected during the agricultural years of 2007/2008 and 2008/2009. Two types of sludge produced in São Paulo State were used, one from the Barueri Sewage Treatment Station (BS) and the other from the Franca Sewage Treatment Station (FS). Both types of sludge had been anaerobically digested before application. The Barueri station receives both household and industrial types of sludge, but the Franca station only receives household sludge.

The experiment was set up as a completely randomized block design with three replications and included the following treatments: neither fertilizer nor sewage sludge were applied (C), inorganic fertilization (MF), and dose 1 (1FS, 1BS) and dose 2 (2FS, 2BS) of each sewage sludge. Dose 1 was calculated by considering the recommended N application for corn (Boeira et al. 2002). Dose 2 was twice dose 1. In all, 18 nonirrigated plots were assessed.

Every year, the sludge doses were based on the prior determination under controlled conditions, of the mineralization of the organic N contained in the sludge. The potentially

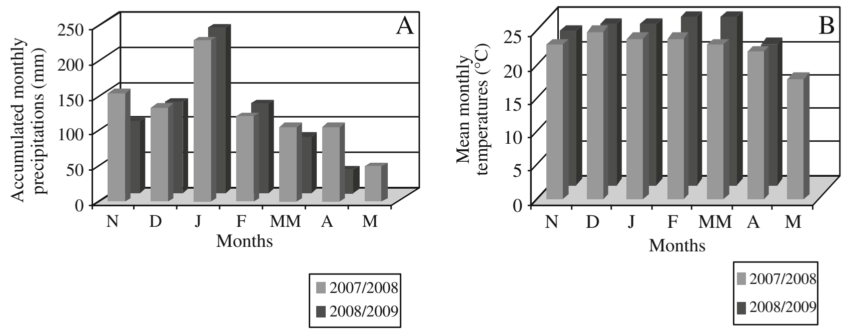

Fig. 1 Accumulated monthly precipitations (mm) and mean monthly temperatures (°C) during the experiment for the agricultural years of 2007/2008 and 2008/2009. *N* November, *D* December, *J* January, *F* February, *MM* March, *A* April, *M* May

available N (NPA) for the crop was estimated as follows (CETESB 1999): Ndisp=NPA/100 (Nt-Nam)+1/2Nam+Nnit, where Ndisp is the available N in the sludge (kg kg^{-1}), Nt is the total N content of the sewage sludge as determined by the Kjeldahl method, Nam is the NH_4^+ content of the sewage sludge, and Nnit is the NO_3^- content of the sewage sludge. The final sludge dose, on a dry weight basis, was calculated as follows: sludge dose (kg ha^{-1})=recommended N for the crops (kg ha^{-1})/Ndisp (kg kg^{-1} of sludge).

In the mineral fertilization treatment, the nutrients P and K were applied as recommended for a corn crop (Cantarella et al. 1997). With respect to N, 15.6 and 22.36 kg N ha^{-1} were applied on planting, for the agricultural years of 2007/2008 and 2008/2009, respectively. As side dressing, the N was applied at a rate of 86 and 90.56 kg N ha^{-1} in the agricultural years of 2007/2008 and 2008/2009, respectively. The N source was always urea. Fertilizers were not added to treatments 1BS and 2BS, since the objective was to evaluate the residual effect. Due to the low amount of K in the sludges, potassium chloride was added according to the organic compost-dose used.

The sewage sludges were always uniformly distributed on the soil surface and rototilled to a depth of 20 cm. Soil management was conventional with annual plowing. Table 1 shows the times each type and dose of sludge was applied. From 1999 to 2008, about 43.5, 87.9, 29.7, and 60.5 t ha^{-1} of sludge were applied in the treatments 1FS, 2FS, 1BS, and 2BS, respectively. With the exception of the first, all sludge applications were done in the month of November.

Corn (*Zea mays* L., AG 4051) was used as the test plant in all cultivations, and after each corn harvest, the soil was left fallow until the next cultivation. In April 1999, before the start of the experiment, the area had been fallow for approximately 9 years and was predominantly occupied by *Brachiaria* sp. Each experimental plot (20×10 m) included 12 rows, 10 m long and spaced 0.9 m apart, with approximately five seeds per meter. In the agricultural year of 2007/2008, the corn was seeded 10 days after soil amendment with sewage sludge (DASA), and in the agricultural year of 2008/2009, it was seeded 13 DASA. More details of the planting and direction of the experiment can be found in Vieira and Cardoso (2003) and in Vieira et al. (2005).

Soil sampling and chemical analysis

In the agricultural year of 2007/2008, the soil was sampled on various occasions to evaluate the mineral N contents (NH_4^++ NO_3^-, μg g^{-1} soil) of all the plots. For each plot, 10 subsamples of soil were removed and mixed to form a bulk sample. The soils were removed at a distance of 20 cm from the plant. The collections were made at depths of 0–10 and 10–20 cm, 5 days after sludge application (DASA) in Franca and then 10, 13, 18, 24, 34, and 56 DASA. The soils of the plots previously supplemented with Barueri sludge were sampled at the same points in time. The soils from all the plots were also sampled

Table 1 Application rates of sewage sludge during the experiment

Application time of sludge (agricultural years)[a]	Sewage sludge dry matter from Franca (t ha^{-1})		Sewage sludge dry matter from Barueri (t ha^{-1})	
	Dose 1	Dose 2	Dose 1	Dose 2
April 1999	3.0	6.0	8.1	16.2
November1999	3.5	7.5	4.0	8.8
November 2000	3.8	7.6	5.3	10.6
November 2001	4.4	8.8	5.3	10.6
November 2002	4.3	8.7	3.2	6.5
November 2003	5.7	11.5	3.8	7.8
November 2004	NA	NA	NA	NA
November 2005	NA	NA	NA	NA
November 2006	7.6	15.2	NA	NA
November 2007	5.7	11.4	NA	NA
November 2008	5.6	11.2	NA	NA
Total	43.5	87.9	29.7	60.5

The potentially available N (NPA) for the crop was estimated as follows Ndisp=NPA/100 (Nt-Nam)+1/2Nam+Nnit, where Ndisp is the available N in the sludge (kg kg^{-1}), Nt is the total N content of sewage sludge, Nam is the NH_4^+ content of sewage sludge, and Nnit is the NO^{3-} content of sewage sludge. The final sludge dose was calculated as follows: sludge dose (kg ha^{-1})=recommended N for the crops (kg ha^{-1})/Ndisp (kg kg^{-1} of sludge)

Dose 1 sewage sludge based on the nitrogen concentration that provides the same amount of N as in mineral fertilization, *Dose 2* about twice dose 1, *NA* not applied

[a] Periods of sludge soil amendment up to the date of soil collection

7 days before applying the sludge, in order to evaluate soil fertility (Table 2). The soils were not sampled to evaluate the mineral N contents in the agricultural year of 2008/2009. The NH_4^+ and NO_3^- contents were determined in 1 M KCL extracts by steam distillation (Keeney and Nelson 1982), using a 1:10 soil to extraction solution ratio and shaking for 30 min at 120 rpm. The mineral N concentration was determined in field-fresh soil samples, and the results expressed based on soil dry weight. For the other chemical analyses carried out on the soils before applying sewage sludge in 2007 and 2008, the soil samples were first air dried and passed through a 2 mm sieve. The pH was measured using sample to water ratio mixtures in a 1:2.5 ratio. Organic C was determined by dichromate oxidation of the sample and subsequent titration with ferrous ammonium sulfate (Nelson and Sommers 1982). The macronutrients (P, K, Ca, and Mg), micronutrients (Zn, Mn, Fe, and Cu), and cation exchange capacity (CEC) were determined by the methods described in Embrapa (1999).

Grain productivity and N parameters

Productivity was determined for the harvests in the agricultural years of 2007/2008 and 2008/2009. For these determinations, carried out at the R6 stage (Magalhães and Durães 2006), 30 ears obtained from three rows at the center of each plot were used to measure productivity (moisture content of approximately 13 %). The total N uptake per grain (TNG= productivity*N concentration of grain), total N uptake by corn (TNC=TNG*100/74), and total N uptake by the straw (TNS=TNC−TNG) were also determined. The latter two were calculated considering that about 74 % of the N absorbed by the corn plant is translocated to the grains (Coelho et al. 2006). TNG was determined using the Kjeldahl method (Keeney and Nelson 1982). The ratio of the productivity to nitrogen uptake by the corn (RYNU, kg kg^{-1}) or utilization efficiency was also calculated, defined according to the Eq. (1) (Yagüe and Quílez 2010):

$$\mathrm{RYNU}\left(\mathrm{kg\ kg^{-1}}\right) = \mathrm{Yield}\left(\mathrm{kg\ ha^{-1}}\right) / \mathrm{N_{uptake}}\left(\mathrm{kg\ ha^{-1}}\right) \quad (1)$$

Statistical analyses

An one-way analysis of variance (ANOVA) was performed to determine the significant differences in the parameters studied. A separation of means was performed using the LSD's least significant difference test.

Results

Dynamic changes in soil mineral N concentrations over time

In the agricultural year of 2007/2008, the mineral N concentrations in the soil at the two depths studied showed no significant differences between the treatments in the samples taken before application of the Franca sludge (Table 3). However, 5 days after sludge application, the mineral N contents were higher in the samples from plots treated with Franca sludge. At a depth of 0–10 cm, the mineral N contents in soil samples from the 1FS and 2FS treatments were 35 and 200 %, respectively, higher in relation to the means of the other treatments. At a depth of 10–20 cm, the N contents were also higher for the 1FS and 2FS treatments in relation to the

Table 2 Soil chemical properties before application of Franca's sludge

Element	Unit	C		MF		1FS		2FS		1BS		2BS	
		07/08	08/09	07/08	08/09	07/08	08/09	07/08	08/09	07/08	08/09	07/08	08/09
pH		5.3a	5.7a	5.1a	5.9a	5.1a	5.6a	5.2a	5.8a	5.4a	5.8a	5.3a	5.9a
P	mg kg^{-1}	3.0c	5.2d	16.0b	20.0c	20.3b	37.0b	39.3a	80.7a	22.0b	20.3c	49.3a	50.0b
K	cmol (+) kg^{-1}	0. 04c	0.13a	0.11a	0.06c	0.09ab	0.10ab	0.08b	0.07bc	0.07bc	0.07bc	0.08b	0.07bc
OM	%	2.5c	3.2b	3.0ab	3.1b	2.7bc	3.5b	3.0ab	4.9a	3.0ab	3.5b	3.2a	3.4b
Ca	cmol (+) kg^{-1}	2.6c	2.7b	2.9ab	2.9b	2.8ab	3.4ab	3.3ab	4.2a	3.3ab	3.4ab	3.7a	4.2a
Mg	cmol (+) kg^{-1}	1.3a	0.1c	1.2a	1.5a	1.1a	1.3ab	1.3a	1.6a	1.5a	1.6a	1.5a	1.7a
CEC	cmol (+) kg^{-1}	6.7c	9.0cd	7.4bc	8.5d	7.1bc	9. 4bcd	7.6ab	10.6a	7.8ab	9.8abc	8.2a	10.1ab
Zn	mg kg^{-1}	0.4d	2.2c	0.9d	5.9c	2.4cd	10.1bc	4.8bc	18.1b	8.1b	16.3b	20.2a	38.7a
Mn	mg kg^{-1}	1.1d	2.1b	1.4cd	2.2b	2.2ab	2.8ab	2.5a	3.3a	1.6bcd	2.4b	2.0abc	2.6ab
Fe	mg kg^{-1}	28.0c	87.8d	28.7c	105.8cd	44.0bc	234.3b	54.7ab	328.7a	65.7ab	137.7cd	72.0a	161.0c
Cu	mg kg^{-1}	0.6e	1.5c	0.7de	1.9c	1.0d	2.8bc	1.4c	4.0b	2.4b	3.9b	5.3a	8.7a

Means followed by the same small letters, in the same line, in each year, do not differ significantly according to the LSD test, 0.05 %

C control treatment, *MF* mineral fertilizer, *1FS* dose 1 of Franca sludge, *2FS* dose 2 of Franca sludge, *1BS* dose 1 of Barueri sludge, *2BS* dose 2 of Barueri sludge, *OM* organic matter, *CEC* cation exchange capacity

Table 3 Soil mineral N concentration ($NO_3^- + NH_4^+$, μg g^{-1}) change over time in the different treatments during the 2007/2008 agricultural year

Treatments	BSA[a]	5 DASA[b]	10 DASA	13 DASA	18 DASA	34 DASA	56 DASA
0–10 cm depth							
C	31.8 a	33.8cd	73.3 c	42.0 bc	34.0 d	36.6 bc	38.1 bc
MF	30.3 a	33.1cd	69.9 c	38.7 c	34.8 d	35.9 bc	24.1 e
1FS	29.9 a	45.3 bc	127.6 b	53.6 b	56.1 b	54.7 a	42.7 ab
2FS	33.3 a	100.9 a	184.6 a	86.0 a	106.0 a	41.3 abc	50.4 a
1BS	31.0 a	33.2cd	64.3 c	44.1 bc	45.7 bcd	36.5 bc	32.0 cde
2BS	36.5 a	34.4cd	81.5 bc	36.1 c	32.9 d	38.4 abc	33.3 cde
10–20 cm depth							
C	34.3 a	31.1 d	64.1 c	39.6 bc	38.0cd	34.9 c	36.8 bc
MF	33.7 a	32.5 d	69.5 c	35.0 c	36.0cd	35.7 c	36.8 bc
1FS	32.2 a	38.4 bcd	87.9 bc	35.9 c	40.3cd	46.8 abc	38.3 bc
2FS	30.4 a	46.9 b	101.4 bc	39.5 bc	49.1 bc	48.6 ab	40.9 abc
1BS	37.36 a	29.27 d	73.6 c	44.1 bc	46.9 bcd	37.4 bc	30.0 de
2BS	35.47 a	27.66 d	83.0 bc	33.4 c	42.0 bcd	37.7 bc	40.5 abc
SE	3.1	4.3	15.9	4.9	4.9	4.3	3.8

C, control treatment; *MF*, mineral fertilizer; *1FS*, dose 1 of Franca sludge; *2FS*, dose 2 of Franca sludge; *1BS*, dose 1 of Barueri sludge; *2BS*, dose 2 of Barueri sludge.[a] *BSA*, seven days before sludge application; [b] *DASA*, days after sludge application.

Means followed by the same small letters in the same column do not differ significantly according to the LSD test 0.05 %; *SE*, standard error

other treatments but to a lesser extent. At 10 DASA, the mineral N contents increased for all the treatments at both depths studied. Again, although not always at significant levels, the mineral N contents in the treatments with Franca sludge, tended to be higher. In the same period, the mineral N contents in the 2BS treatment tended to be higher than the control and MF treatments. As expected, as from 13 DASA, a strong tendency was observed for the mineral N contents to be higher in the 1FS and 2FS treatments at a depth of 0–10 cm. However, at a depth of 10–20 cm, the mineral N contents showed little difference between the treatments and the control, with the exception of 34 DASA, where the mean values for the mineral N contents of the 1FS and 2FS treatments were about 31 % higher than the mean values for the other treatments. No residual effect could be observed for the application of Barueri sludge with respect to the N content of the soil. For all samplings, the mineral N contents of the 1BS and 2BS treatments did not differ significantly from the MF treatment or the control. Nitrate represented about 42 % of the mineral nitrogen in all the evaluations, showing an intense nitrification process of the soil (data not presented).

Corn productivity and N contents in different plant parts

Figures 2 and 3 show the corn productivity parameters for all treatments in the two agricultural years. In 2007/2008, the corn yields were much higher in the plots supplemented with Franca sludge. On average, the corn yield was 29 % higher in these plots in relation to the MF, 1BS, and 2BS treatments, and the lowest productivity was obtained for the control treatment. The N contents of the corn grains were about 49 % higher in the treatments with Franca sludge in relation to all the other treatments, with the exception of the control treatment, where the difference was much higher. For the two sludge treatments, the productivities and the N contents exported to the grains did not differ between the two sludge doses applied.

The total N uptake by corn (TNC) was about 48 % higher in the treatments with Franca sludge in relation to the mean values obtained for the MF, 1BS, and 2BS treatments. The lowest TNC value was obtained for the control treatment. The total N uptake by the straw (TNS) was about 38, 19, and 10 kg N ha^{-1} for the means of the FS treatments, the means of the MF, 1BS, and 2BS treatments, and for the control, respectively. The ratio of the yield to nitrogen uptake (RYNU) was lower for the two doses of Franca sludge, followed by the MF treatments, and the control. The highest RYNU values tended to be obtained for the treatments with Barueri sludge. There was no significant difference in this index in relation to the doses of sludge.

In the agricultural year of 2008/2009, the greatest corn productivities were also obtained with the treatments supplemented with Franca sludge, with no significant difference between the doses. In relation to the MF and 2BS treatments, the percent increase in productivity was close to that obtained the previous year. To the contrary of that occurring in the agricultural year of 2007/2008, the productivity for the 1BS treatment was about 57 % smaller than the mean for the MF and 2BS treatments but was 97 % higher than the productivity of the control treatment. All the other parameters, that is, TNG, TNC, and TNS, were about 57 % higher for the treatments with Franca sludge in relation to the mean values obtained for the MF and 2BS treatments. This increase leads to a greater decrease in the values for RYNU in the treatments with Franca sludge, the decrease being 46 % in relation to the mean values obtained for the 1BS and 2BS treatments, and 39 % in relation to the C and MF treatments. The quantities of

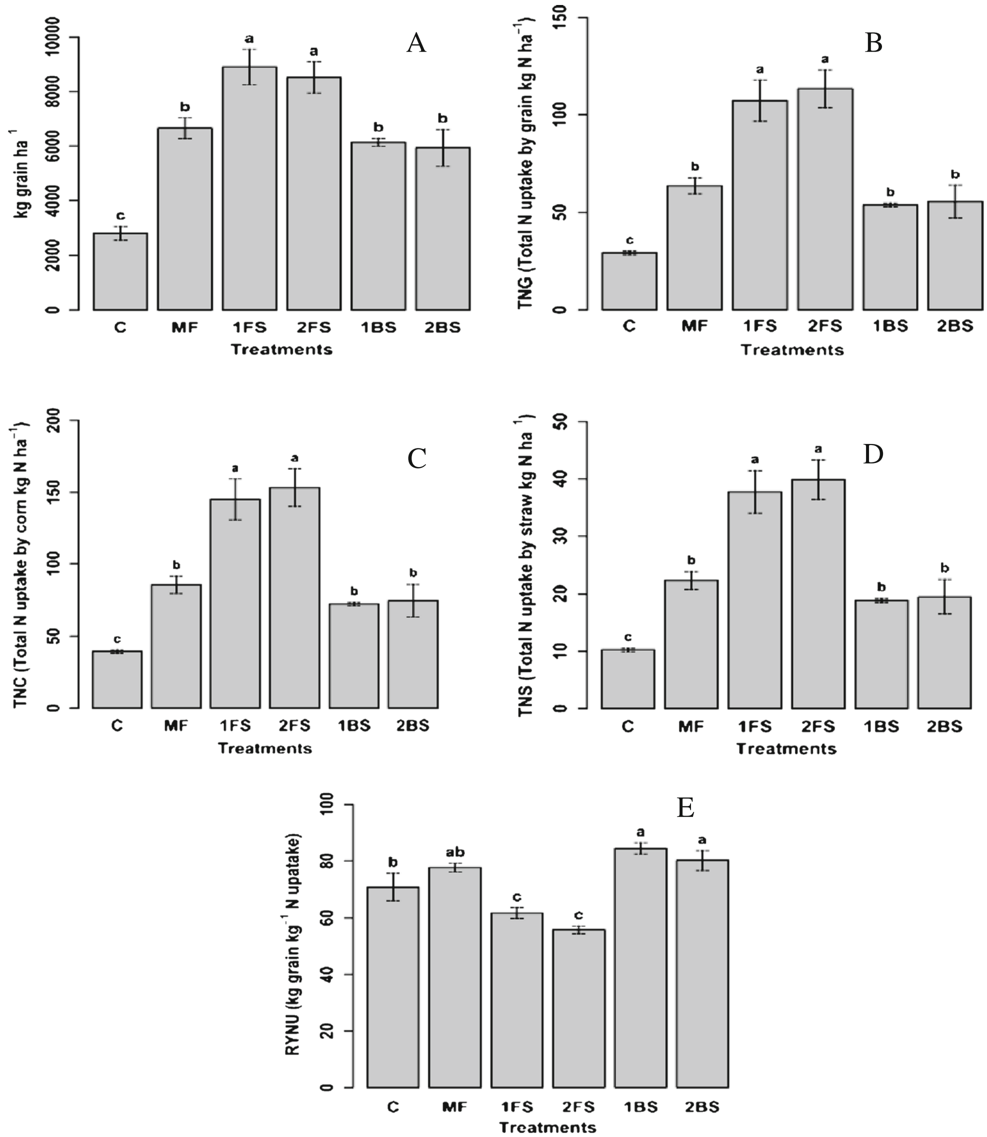

Fig. 2 Yield (**a**), total N uptake by grain (**b**), total N uptake by corn (**c**), total N uptake by straw (**d**), and the ratio of yield to total N uptake by corn (**e**) in the agricultural year of 2007/2008. *C* control treatment, *MF* mineral fertilizer, *1FS* dose 1 of Franca sludge, *2FS* dose 2 of Franca sludge, *1BS* dose 1 of Barueri sludge, *2BS* dose 2 of Barueri sludge. Means followed by the *same letters* in each graph do not differ significantly according to the LSD test, 0.05 %. *Errors bars* represent standard deviation

N that returned to the soil with the straw were about 47.82, 21.30, 17.85, 10.79, and 6.16 kg N ha^{-1}, respectively, for the treatments FS (mean of dose 1+dose 2), MF, 2BS, 1BS, and control.

Discussion

The residual effect of the Barueri sludge in relation to the N content of the soil was not evident in this study, due to the high content of this element in the soil. On the other hand, the similarity in corn productivity between the treatments with Barueri sludge and the MF treatment showed the residual effect with regard to the other nutrients. This was evident when compared with the control treatment, where the productivity was much lower than for all the other treatments, despite the high N contents in the soil. Similarly, it was difficult to attribute the higher productivities obtained with the treatments with Franca sludge to a cumulative effect of N in the soil. As can be seen in the initial soil analysis, the N contents of the soil were the same for all treatments before applying the sludge. The higher N contents found in the 1FS and 2FS treatments could have been due to the previous applications to the soil. It is interesting to note that in the 1FS treatment, the P contents in the soil were 82 % higher in the 2008/2009 agricultural year than in the 2007/2008 agricultural year, which could suggest a cumulative effect of this element in the soil due to the application of Franca sludge the previous year. It should be pointed out that if the application is done sequentially, that is, every year, the content of this element in the soil could reach environmentally unacceptable levels.

The field application of sewage sludge, especially in agricultural areas, is widely practiced (Wang 1997). Despite the economic benefits that the soil amendment with sludge can

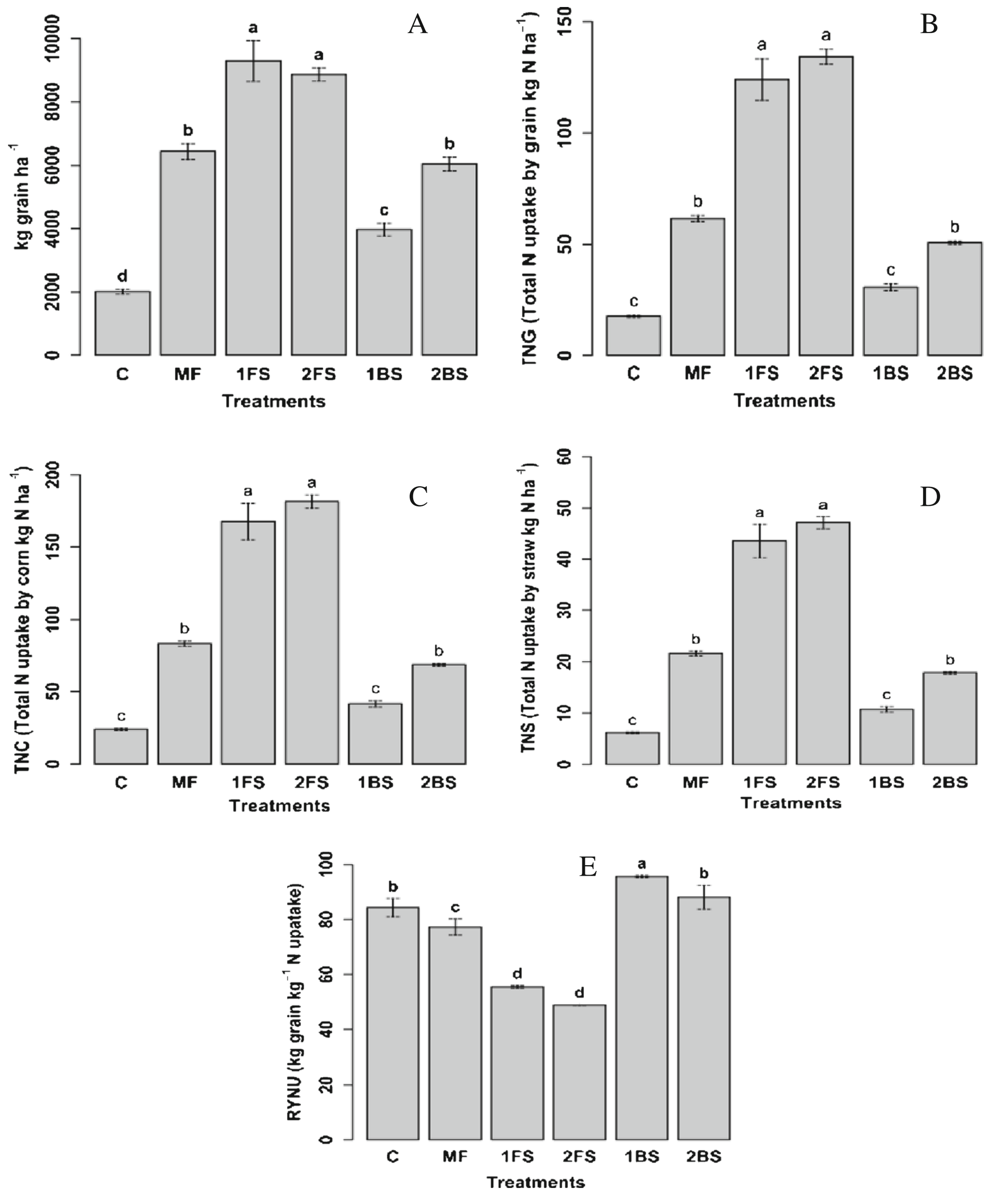

Fig. 3 Yield (**a**), total N uptake by grain (**b**), total N uptake by corn (**c**), total N uptake by straw (**d**), and the ratio of yield to total N uptake by corn (**e**) in the agricultural year of 2008/09. *C* control treatment, *MF* mineral fertilizer, *1FS* dose 1 of Franca sludge, *2FS* dose 2 of Franca sludge, *1BS* dose 1 of Barueri sludge, *2BS* dose 2 of Barueri sludge. Means followed by the *same letters* in each graph do not differ significantly according to the LSD test, 0.05 %. *Errors bars* represent standard deviation

reduce, the use of commercial fertilizers, the application frequency, and an evaluation of the effects of any residues resulting from its use as a fertilizer have not been well studied. The lack of evaluation of its residual effect can result in excessive amounts of nitrogen being added to the soil, since part of the organic N added the year before could be mineralized in the next cultivation.

Effect of sludge application on soil N dynamics

As the Barueri sludge was not applied since 2003/2004, the similarity between the mineral N contents in the 0–10 and 10–20 layers with the contents found in the MF and control treatments could possibly indicate that the N from the plots with Barueri sludge came from mineralization of the organic C of the actual soil, and hence with respect to the N contents in the soil, no residual effect was visible. This implies that soil with a high capacity to provide N to the plants was being studied, demanding even more attention in the use of sewage sludge. When sewage sludge is added to the soil, it contains large amounts of easily decomposable organic material, which, on mineralization, releases inorganic N for use by the developing plants (Akdeniz et al. 2006). However, in addition to nitrogen, the sludge also contains other nutrients which can stimulate plant growth (Pote et al. 2003). As can be seen in Table 2, the soil supplemented with Barueri sludge presented other chemical attributes capable of promoting plant growth. Thus, in this case, instead of basing the calculations of the amount of sludge to be applied on the N content of the sludge, it would be better to base it on its potential to provide other elements to the plant, such as P, for example. Consequently, tracking the labile P levels is crucial in any program for the beneficial use of sewage sludge, as already observed by other authors (Barbarick and Ippolito 2007; Schroder et al. 2008). Depending on its origin, sewage sludge can show higher or lower heavy metal contents. In the present study, the highest levels of these elements were obtained with the Barueri sludge, which received industrial residues. These elements cause harm to the soil–plant system and in addition might pose a serious risk to human health (Turkdogan et al. 2003). Although the heavy metal contents found in the treatments with Barueri sludge were higher than in the other treatments, they were still far below the maximum acceptable level considered inadequate (CETESB 1999). Logically, the heavy metal contents in the soil and groundwater should be regularly monitored in order to guarantee that the application of sewage sludge to the soil is a truly environmentally acceptable practice.

In the agricultural year of 2007/2008, it can be seen that up to 10 DASA, the amounts of nitrogen in the soils from the plots with Franca sludge were much higher than those in the other experimental plots. Considering that the corn was only seeded 10 days after applying the sludge, there was a good possibility that part of this element was lost to the environment by leaching or denitrification. Even had the corn been seeded earlier, the demand for this nutrient by the plant in this initial period is still low. It is interesting to note that soon after applying the sludge, there was an explosion of mineralization of the organic N from the sludge, as occurs with other applications of organic C to the soil. This is attributed to the addition of highly labile organic compounds, which are therefore easily mineralized by the soil microorganisms. This fact should also be taken into consideration when applying sludge to the soil, so as to avoid losses of N to the environment during the initial period of the vegetative cycle of the cultures. As can be seen in Table 3, as from 34 DASA, there was no longer any significant difference between the mineral N contents for the treatments with the larger and smaller doses of Franca sludge, indicating that the soil had a limit with respect to the dose of sludge that would result in a response by the plant. Logically, one cannot ignore the hypothesis that under conditions of frequent rain and high temperatures, the soil previously supplemented with Barueri sludge and the soil supplemented with Franca sludge could still provide large amounts of mineral N as compared to the nonamended plots. Evidently, as the years went by, the organic material added with the sludge becomes more recalcitrant, but with greater plant productivity and a greater return of straw to the soil, the organic C levels would tend to remain high, with the presence of organic compounds with variable degrees of lability.

Effect of sludge application on corn productivity and N uptake

The absorption of N by the plants in the treatments with the two doses of Franca sludge was, on average, 42 % greater than the absorption of N by the plants in the MF treatment. Despite this, the yield in the MF treatment was only 24 % smaller than the mean of the yields in the treatments with Franca sludge. This shows that there was a luxury N uptake by the plants in the FS treatments. This was also shown when the RYNU data were examined. Lower RYNU values suggest a possible decrease in sludge application, since it reflects the lower efficiency with which the absorbed N is used to produce grain. These increase in N in the plants in the FS treatments are logically a reflection of the amount of N from the sludge that was mineralized, showing that its frequent application based on the recommendation for N aimed at the plant achieving a certain level of productivity is resulting in excess N in the environment. It can be seen that this occurred even without the application of FS in the agricultural years of 2004/2005 and 2005/2006. With the data obtained for the N contents that returned to the soil with the straw (SNR), it can be seen that the greater part came from the plants treated with FS. This could be considered as a positive factor, but it does not allow one to determine the amount of N that could not be absorbed by the plants.

Abd-Alla et al. (1999) found that the application of low rates of sewage sludge (20 and 30 % (w/w)) significantly improved the growth of faba beans (*Vicia faba* I.), soybeans (*Glycine max* L.), and lupins (*Lupinus albus* L.) in desert soils but decreased the growth at higher application rates (40 and 50 %). In the present study, the application of dose 2 of both sludge types did not decrease corn productivity, but it remained the same as that obtained with dose 1. It is possible that higher doses or the successive application of sludge year after year could start a process of decreasing productivity, as already observed in other studies, when higher doses of sludge were applied (Vieira et al. 2005).

The data obtained in the case of the Barueri sludge were truly surprising since, despite the fact that the last application to the soil occurred in the agricultural year of 2003/2004, the values reached for productivity and RNYU were similar to those of the MF treatments. This could have occurred due to the presence in the soil of high residual contents of other elements necessary for high corn yields, since, as previously mentioned, the soil used had a high capacity to provide N to the plants.

Biosolids N is made available to the plant throughout the entire growing season, different from mineral fertilizer, which is only applied during the period of greater demand by the plant. The absorption of N by corn is intense in the period from 40 days after seeding (elongation, V6-leaf stage) up to male flowering (pendant emission), when the plant absorbs more than 70 % of its total needs (Ritchie et al. 2003). Seventy to seventy-seven percent of the N absorbed by the corn plant is translocated to the grains. However, some studies have shown that the timing of N application is an important factor, possibly even more so than the total amount of N applied (Yagüe and

Quílez 2010). The present experiment was not irrigated, but it can be seen from Fig. 1a that the rainfalls occurred with greater intensity early in the cultivation of the corn, causing a sharp increase in the mineral N contents in the soil, especially from 5 to 10 days after sludge application. This is not a high N-demand phase in corn development, and hence, this suggests that organic N fertilizer applied before sowing is not used efficiently by the crop. Nitrification rapidly transforms the N applied to the soil into nitrate, which will be leached out into the root zone of the crop by precipitation.

The management of sewage sludge is a problem because it can lead to serious environmental pollution. Frequent applications can lead to N losses both due to leaching and to losses in the form of gas. In addition, they can lead to an increase in the P content of the soil, which, although it could be considered beneficial, can result in an excess which is available for runoff and leaching. It should be highlighted that the levels of P can increase with successive applications of sewage sludge, and therefore, the concentrations of this element in the soil should be continuously monitored, even if the sludge is applied based on the N requirements of the cultures. It can be seen that the P contents in the treatments with Barueri sludge were similar to those of the treatments MF and 1FS, even though the last application to the soil was in the agricultural year of 2003/2004, demonstrating the residual effect of this sludge in relation to the P content in the soil.

Considering the data obtained in this experiment, it is evident that the presowing application of sludge based on the N needs of the plant is not an adequate technique for sludge application in the long term, if one considers all the possible harmful effects on the environment. It was also evident that the residual effects of the sludge can benefit the plants for a long time. In the present experiment, many conclusions could not be obtained concerning the residual nitrogen, since the nitrogen available for the corn in the control treatment was similar to that available in the BS treatments at least 56 days after plant emergence. Since mineralization of the organic nitrogen from the sludge could not be controlled, resulting in the availability of large amounts of N in the soil in periods when the demands of the plant were low, one should consider the possibility of applying the sludge at points in time when the demands of the plant for this nutrient are greater. Thus only small amounts of sludge would be applied at presowing, sufficient to supply the N needs of the crop at this initial stage. The results of Roig et al. (2012) showed that, for the same amount of sewage sludge used, the distribution of small doses with time is better than a single application, because it increases soil fertility, minimizing negative environmental impacts such as ecotoxicity and soluble nitrate losses. Since mineralization of the organic N in the soil varies with the soil conditions and the climate, the conclusions of a determined study should be viewed with caution. The forms of application should be different for irrigated and nonirrigated cultures and for management practices that consider both winter and summer cultures, which was not the case in the present study.

Conclusions

Similar corn yields can be obtained with the use of sewage sludge to those obtained with the practice of mineral fertilization. However, doses calculated based on the N content required for the culture to reach a certain productivity level can cause losses of N to the environment, especially if the soil has a high potential for providing N to the cultures. Due to the high mineralization rate of the sludge in the period immediately after its application, one should also consider the possibility of applying the sludge at the time of maximum demand for N by the plant. With this objective, sludge handling techniques that allow for the adoption of such a practice should be developed. Logically, depending on the soil, an initial application of nitrogenated fertilizer could be made. The residual and cumulative effects of the application of sewage sludge to the soil should be considered not only in relation to N but also in relation to the other nutrients, in order to establish the sludge application frequencies. The amount of nitrogen redeposited in the soil with the straw after harvesting the corn should also be considered when determining the dose of sewage to be applied. These factors associated with the residual and cumulative effects of other nutrients could result in a considerable decrease in the rate of sludge application, such that its nutrients could be more efficiently absorbed by the plant without any marked environmental constraints.

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