SEÇÃO IX - POLUIÇÃO DO SOLO E QUALIDADE AMBIENTAL

SEWAGE SLUDGE APPLICATION TO AGRICULTURAL LAND AS SOIL PHYSICAL CONDITIONER[1]

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SUMMARY

Water resource quality is a concern of today's society and, as a consequence, low pollutant wastewaters and sludges are being increasingly treated, resulting in continuous production of sewage sludge. Sewage sludge (SS) can be used as soil physical conditioner of agricultural or degraded lands, due to its organic C component. The objective of this research was to evaluate the long-term SS effects on soil physical quality of properties such as bulk density, porosity, permeability and water retention of degraded soils treated with annual SS applications. The SS rates were calculated according to the crop N demand. The field experiment consisted of three treatments: mineral fertilization, 10 and 20 Mg ha^{-1} of SS (once and twice the SS quantity to meet the maize N demand, respectively), in annual applications to the surface layer of a eutroferric Red Latosol. SS reduced bulk density, increased macroporosity and decreased microporosity after the third application, but did not significantly alter the soil permeability and physical quality as measured by the S index in the surface layer.

Index terms: soil quality, bulk density, soil permeability.

RESUMO: *APLICAÇÃO DE LODO DE ESGOTO COMO CONDICIONADOR DE PROPRIEDADES FÍSICAS DE UM SOLO AGRÍCOLA*

A preocupação da sociedade civil com os recursos hídricos tem levado ao aumento do tratamento de esgotos e de águas residuais com baixa carga poluidora, resultando na produção de lodo de esgoto (LE). Por conter C orgânico em sua composição, o LE pode atuar como condicionador de propriedades físicas do solo. O objetivo do presente trabalho foi analisar o

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efeito do LE sobre atributos do solo (densidade, porosidade, permeabilidade e retenção de água), buscando avaliar se a aplicação anual de LE em um solo degradado, em longo prazo e em quantidades determinadas em função da necessidade de N pela cultura, determina modificações na qualidade física do solo. O ensaio constou da aplicação de três tratamentos: adubação mineral, 10 e 20 Mg ha^{-1} de LE (uma e duas vezes a quantidade de LE necessária para suprir o nitrogênio recomendado para a cultura de milho, respectivamente), aplicados anualmente na camada superficial de um Latossolo Vermelho eutroférrico. A aplicação de LE reduziu a densidade do solo, aumentou a macroporosidade e diminuiu a microporosidade a partir da terceira aplicação, porém não influenciou significativamente a permeabilidade e o parâmetro S de qualidade física do solo na camada superficial.

Termos de indexação: qualidade do solo, densidade do solo, permeabilidade do solo.

INTRODUCTION

Water resource preservation and quality is a major concern of today's society and has led to extensive treatment of low pollutant wastewaters and sludges. Sewage sludge (SS) is a complex output of the wastewater and sludge treatment process, containing organic matter, inorganic components, plant nutrients and potentially toxic substances. Large amounts of SS are constantly produced and the disposal routes into the environment are also a matter of great concern and an urgent challenge.

The use of SS as organic fertilizer is believed to be potentially useful for plant growth in agricultural lands due to its nutrient-rich composition, as well as being to be a cheaper way and less impacting to the environment compared to other alternatives for its disposal.

In Brazil, the use of SS in agriculture has been regulated through the directive CONAMA (2006), based on several quality criteria. This directive also prohibits SS application to forage and horticultural crops, especially green vegetables, tubers, roots, flood-irrigated crops and every crop which a food product is grown in contact with the soil.

Studies reporting on SS application as fertilizer for agricultural and forest cultivations are frequently mentioned in the literature (Melo & Marques, 2000; Galdos et al., 2004; Lemainski & Silva, 2006). The SS-organic matter, macro and micronutrient contents seem to play fundamental roles in crop production and soil fertility. The addition of organic matter also appears to improve soil physical properties.

However, despite the reported positive effects of SS on the soil physical properties, significant results evidencing such effects have only been observed for a few physical properties after heavy SS applications or for a specific soil type or management. Jorge et al. (1991) applied two annual SS rates (40.0 and 80.0 Mg ha^{-1}) to a clayey Red Latosol for four years and observed differences related to soil micro and macropores, whereas no changes were noted in bulk density, total soil porosity and soil water infiltration. Similar results were obtained by Melo et al. (2004) when studying two soil types: a dystrophic Red Latosol and a clayey eutroferric Red Latosol. Also, Barbosa et al. (2004) found no significant effect of SS application on the soil hydraulic conductivity. In a long-term experiment, Macedo et al. (2006) applied four SS rates, (ranging from 3.0 to 60.0 Mg ha^{-1}) to an Latosol and used SS from two sewage treatment plants (Franca and Barueri, State of São Paulo, Brazil). These authors evaluated soil physical properties such as bulk density, total porosity, micro and macroporosity, and initial and final infiltration rates. After three years, they concluded that the soil physical properties evaluated had not been improved by SS applications, and ascribed the results to the mechanical procedure used of incorporating SS into the soil with a hoe. On the other hand, Boeira & Souza (2007) and Trannin et al. (2008) observed lower bulk density in a SS-treated surface layer than in a plot without SS addition.

The SS application rate for agricultural soils is calculated based on at least three criteria: (a) SS-N release or crop N demand; (b) limit of pH increase at 7.0; and (c) limit of total accumulated heavy metal content, as established by CONAMA (2006). Usually, the calculated SS quantity originated from domestic waste is restricted by the SS-N release or crop demand, and the rates applied to the soil are normally lower than the rates causing changes in the soil physical properties reported in the literature cited.

Nevertheless, De Maria et al. (2007) carried out an experiment to evaluate the effects of annual SS soil applications on the runoff water quality of a clayey ferric Red Latosol and observed increased soil particle aggregation after two years, suggesting soil physical improvement as a consequence of the applied SS-organic matter. This experiment with annual SS applications was continued for another four years and is the subject of the present paper.

Therefore, the objective of this work was to evaluate the effects of six consecutive years of SS applications to a degraded soil on the physical attributes (bulk density, porosity, permeability and water retention), in the same long-term experiment. The S index (Dexter, 2004) was also determined to evaluate the SS effect on the physical soil quality, since this parameter has been considered an indicative of changes caused by different agricultural soil managements.

MATERIAL AND METHODS

The experiment was carried out at the experimental station of Instituto Agronômico, in Campinas, state of São Paulo, Brazil (22 º 9 ' South latitude; 41 º 1 ' West longitude). The regional climate is humid tropical (Köppen), and is characterized by two distinct seasons: rainy summer and dry winter, with annual average temperatures of 20.5 °C and rainfall of 1,400 mm. The rainy season occurs between October and March (warmer period) when 76 % of total annual rainfall occurs.

The soil used was classified as a clayey eutroferric Red Latosol, according to the Brazilian System of Soil Classification (Embrapa, 2006). The average values of some physical and chemical properties in the 0–20 cm layer, before the experiment, are presented in table 1.

The experiment consisted of three treatments: MF (mineral fertilization) = without SS application, using NPK fertilizer at maize sowing and sidedressing according to the crop demand (Raij et al., 1996); L1 = SS dose to supply the maize crop demand, determined based on the SS chemical analysis and maize requirements, plus complementary KCl to supply the same K quantity given by the mineral fertilization treatment; L2 = the double SS rate of L1, plus complementary KCl fertilization. The experiment was arranged in a completely randomized design with three treatments, three positions in the plot (upper, medium and lower) and four replications. The declivity of each 4 x 25 m plot was 10 %. The MF treatment corresponded to annual applications of mineral fertilizers: N = 4.8 kg ha^{-1}; P_2O_5 = 48 kg ha^{-1}; and K_2O = 17 kg ha^{-1} at maize sowing; plus 165 kg ha^{-1} of N sidedressing as urea.

From 2001 onwards, SS was applied every year before maize sowing. After each grain harvest, the dry crop residues were left on the field plots and SS rates were manually applied and incorporated into the top soil layer by hoeing. The surface of the plots without SS application layers was treated similarly.

The first SS rates applied (in 2001) corresponded to 10.8 (L1) and 21.6 Mg ha^{-1} (L2) of SS dry mass, calculated considering 30 % of N mineralization rate. In the second year, L1 and L2 rates were 10.2 and 20.5 Mg ha^{-1} of SS dry mass, respectively. In the following years (2003 to 2006), SS rates were standardized at 10.0 (L1) and 20.0 Mg ha^{-1} (L2) of SS dry mass.

Dolomitic limestone was applied twice (October, 2001 and November, 2004) at a rate of 4 Mg ha^{-1} to reach pH 6.5 and 50 % base saturation, according to the procedure recommended by CETESB (1999) in the manual for sewage sludge application in agriculture, which preceded the regulatory directive CONAMA (2006).

The SS chemical characteristics are presented in table 2, with the average composition of SS applied in the experimental period between 2001 and 2006. The average SS-pH value was 6.9 and the determined SS-heavy metal concentrations were below the concentration limit established by the directive P4230 (CETESB, 1999).

The soil physical properties were characterized before the experiment, in 2001. The bulk density, soil porosity and water retention were evaluated in the years 2002 (1st year), 2004 (3rd year), and 2007 (sixth year) according to Camargo et al. (1986), as well as the S index (Dexter, 2004). Soil permeability was determined in the years 2002 (1st year), 2003 (2nd year), 2005 (4th year) and 2007 (sixth year).

All determinations were performed in non-deformed soil samples collected from the same surface soil layer where SS was incorporated. Samples were collected using a 100 cm^3 volumetric ring with sharp border, pressed into the soil until the ring center reached 10 cm depth. Samples were saturated in water, and then transferred to Richards' chambers under pressures of 0; 0.5; 2; 6; 10; 30; 100; 300 and 1,500 kPa. The samples analyzed in 2002 were only submitted to tensions of 0; 6; 10; 30 and 1,500 kPa. Total porosity (TP) was estimated based on the water content determined in saturated soil samples. Microporosity (Mi) was considered as the water content of the soil samples submitted to 6 kPa tension. And macroporosity (Ma) was calculated by the difference between total porosity and microporosity. The field capacity (FC) and permanent wilting point (PWP)

Table 1. Physical and chemical properties in the surface layer of a eutroferric Red Latosol, before the experiment

Sand	Silt	Clay	Ds	T	SB	Ca	OM	P	Fe	pH $CaCl_2$
g kg^{-1}			Mg m^{-3}	mmol$_c$ dm^{-3}			g dm^{-3}	mg dm^{-3}		
287	132	581	1.21	61.3	16.4	10	18	20	21.2	4.6

Ds: bulk density; T: cation exchange capacity; SB: sum of bases; Ca: exchangeable calcium; OM: organic matter; P: exchangeable phosphorus; Fe: exchangeable iron.

Table 2. Average composition of annual sewage sludge (SS) applied to the soil between 2001 and 2006

Composition	Value [1]
pH	6.9
Humidity (%)	68.2
Volatile solids (%)	56.9
C organic (g kg^{-1})	270.2
Nitrogen (total - Kjeldahl) (g kg^{-1}) [2]	29.1
Nitrogen (ammonium) (mg kg^{-1}) [2]	1,638
Nitrogen (nitrate-nitrite) (mg kg^{-1}) [2]	52.9
Aluminum (g kg^{-1})	19.9
Arsenium (mg kg^{-1})	< 0.01 [3]
Boron (mg kg^{-1})	23.8
Cadmium (mg kg^{-1})	8.3
Calcium (g kg^{-1})	11.2
Lead (mg kg^{-1})	170.5
Copper (mg kg^{-1})	566.8
Chrome (total) (mg kg^{-1})	164.2
Sulfur (g kg^{-1})	21.4
Iron (g kg^{-1})	22.2
Phosphorus (g kg^{-1})	8.6
Magnesium (g kg^{-1})	1.7
Manganese (mg kg^{-1})	587
Mercury (mg kg^{-1})	< 0.01 [3]
Molibdenum (mg kg^{-1})	< 0.01 [3]
Nickel (mg kg^{-1})	38.6
Selenium (mg kg^{-1})	< 0.01 [3]
Zinc (mg kg^{-1})	1,378
Potassium (mg kg^{-1})	3,146
Sodium (mg kg^{-1})	2,585
Barium (mg kg^{-1})	235

[1] Concentration values expressed on a dry matter basis. [2] Ammonium-N and nitrate- N values were determined in the original SS-samples using the Kjeldahl method (vapor distillation); and the organic-C was determined by titrimetry after dichromate digestion in digester block, according to Raij et al. (2001). Metals were analyzed according to the recommendations of US-EPA (SW-846) method no.3051: Na and K by flame-photometry and other metals by ICP-AES. Humidity and volatile solids were determined by mass loss between 60 and 500 °C; and SS sample pH was determined in water extract (1:5). [3] Not detected.

were estimated by the moisture content of soil samples under tensions of 10 and 1,500 kPa, respectively, and the available water as the difference between FC and PWP.

Soil permeability was determined using a permeameter (infiltrometer of pressure), model IAC, developed by Vieira (1995-1998). Uniform holes (diameter 5 cm, depth 0.1 cm) were made in the soil with an auger (handheld device). Thereafter, permeability was measured under 5 cm hydraulic charges at regular intervals of 1 min until constant measures, that is, until readings were equal for at least five consecutive times. The saturated hydraulic conductivity values were calculated according to Reynolds et al. (1992).

The soil water retention curve data were fitted to the equation proposed by van Genuchten (1980), by means of the Soil Water Retention Curve-SWRC program (Dourado Neto et al., 1990). The S index was calculated based on the soil water retention curve, according to Streck et al. (2008). The S index values were interpreted according to Dexter (2004): $S > 0.035$ - good soil structure quality; S between 0.020 and 0.035 - low soil structure quality and $S > 0.020$ - very low soil structure quality.

The data was submitted to analysis of variance by the F test and treatment means were compared by the Tukey test ($p < 0.05$).

RESULTS AND DISCUSSION

A higher SS effect was expected to be found in the lower plot positions, because SS was applied to the surface layers of plots with 10 % declivity, which would let SS flow off downhill. However, the F test results indicated no significant differences for the SS effect in terms of relief position and soil physical properties (Table 3).

There were significant effects after the third consecutive year of SS application: bulk density decreased as SS rates increased, mainly at the L2 rate (20 Mg ha^{-1} $year^{-1}$); total porosity was not affected ($p > 0.05$), whereas macroporosity increased and

Table 3. Bulk density (Ds), total porosity (TP), macro (Ma) and micropores (Mi) in plots treated with mineral fertilization (MF) and two sewage sludge (SS) rates (L1 and L2) applied in the experiment (0 year) and after 1, 3 and 6 successive annual SS applications

Year	MF	L1	L2
		Ds (Mg m^{-3})	
0	1.20a	1.22a	1.23a
1st	1.19a	1.23ab	1.26b
3rd	1.20a	1.16a	1.07b
6th	1.14a	1.16a	1.02b
		Ma (m^3 m^{-3})	
0	0.255a	0.258a	0.260a
1st	0.282a	0.273a	0.283a
3rd	0.228b	0.242ab	0.274a
6th	0.257b	0.240b	0.280a
		TP (m^3 m^{-3})	
0	0.600a	0.600a	0.599a
1st	0.601a	0.598a	0.604a
3rd	0.571a	0.582a	0.589a
6th	0.615a	0.607a	0.613a
		Mi (m^3 m^{-3})	
0	0.345a	0.343a	0.339a
1st	0.319a	0.325a	0.321a
3rd	0.343a	0.340a	0.315ba
6th	0.355a	0.367a	0.334b

Means followed by the same small letters in the line did not differ by the Tukey test ($p < 0.05$). MF: Mineral fertilization; L1: SS rate 1; L2: twice L1.

microporosity decreased in the plots treated with 20 Mg ha^{-1} year^{-1}, following the same trend as observed for bulk density. Similar results were reported by Melo et al. (2004), Boeira & Souza (2007) and Trannin et al. (2008), indicating that even low annual SS rates, lower than 10 Mg ha^{-1} year^{-1}, may cause changes in those soil physical properties. Campos & Alves (2007) considered bulk density and macroporosity good indicators of degraded soil recovery by SS sludge application.

Similarly to the SS effect observed on soil bulk density and macroporosity, lower soil water retention at 10 kPa for the SS- L2 rate was observed (Table 4). There was also lower soil water retention at 1500kPa at the highest SS rate after the sixth year of application. The soil water retention curves fitted the van Genuchten (1980) equation for all treatments (Figure 1). With successive SS applications (treatment L2), soil water retention tended to decrease at all tensions. These results are different from those obtained by Melo et al. (2004), who observed no changes in water retention, as well as porosity and bulk density of soils treated with SS rates of 5–10 Mg ha^{-1} year^{-1}. Besides the soil type and SS quantity applied, other factors such as SS production process, soil and crop management, crop type and climate might also influence the results. Despite the differences observed in soil water retention, the calculated maximum available water values were similar among studied treatments, with statistically insignificant differences.

Table 4. Water retention at 10kPa and 1,500 kPa tensions, available water (AW) and S index of plots treated with mineral fertilization (MF) and two sewage sludge (SS) rates (L1 and L2) applied in the experiment (0 year) and after 1, 3 and 6 successive annual SS applications

Year	MF	L1	L2
		10 kPa (m^3 m^{-3})	
0	0.313a	0.315a	0.313a
1st	0.279a	0.285a	0.301a
3rd	0.318a	0.314a	0.295b
6th	0.298a	0.314a	0.279b
		1,500 kPa (m^3 m^{-3})	
0	0.178a	0.176a	0.174a
1st	0.224a	0.220a	0.240a
3rd	0.229a	0.233a	0.219a
6th	0.243a	0.250a	0.218b
		AW (m^3 m^{-3})	
0	0.136a	0.139a	0.140a
1st	0.055a	0.065a	0.061a
3rd	0.089a	0.081b	0.076b
6th	0.055a	0.064a	0.060a
		S índex	
0	0.118a	0.125a	0.109a
1st	0.130a	0.163a	0.082a
3rd	0.105a	0.117a	0.118a
6th	0.145ab	0.129a	0.156b

For each soil physical attribute: Means followed by the same small letters in the line did not differ by the Tukey test ($p < 0.05$). MF: mineral fertilization; L1: SS rate 1; L2: twice L1.

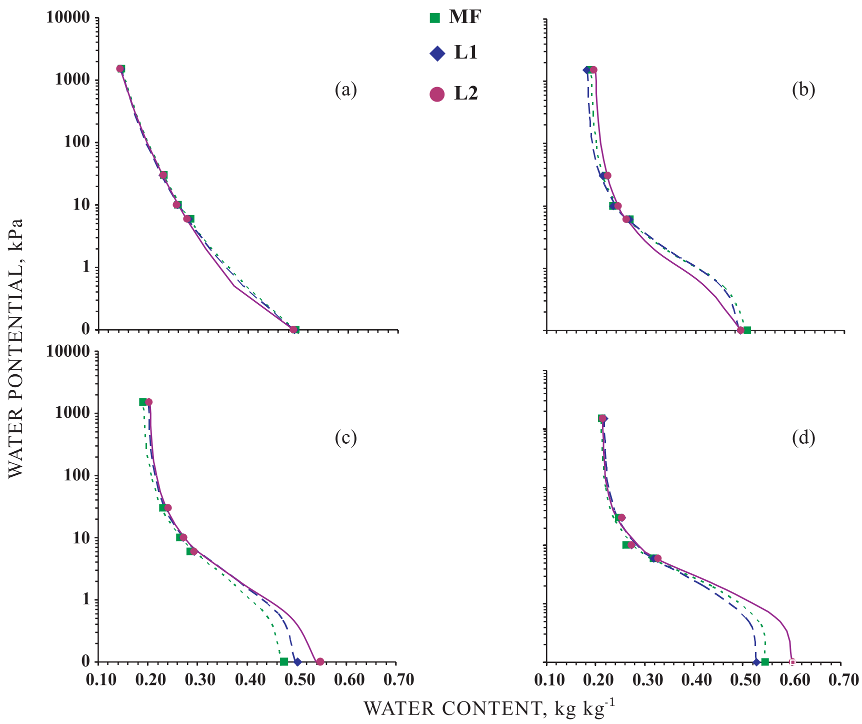

Figure 1. Water retention curves, fitted to the Genuchten equation, in function of SS rates (L1 and L2) and mineral fertilization (MF) before the experiment (initial condition) (a) and after 1 (b), 3 (c) and 6 (d) consecutive annual SS applications.

From the beginning of the experiment until the sixth SS application, changes in the curve shape of soil water retention were observed, that is, the curve tended to the characteristic S shape, which, according to Dexter (2004), would indicate soil physical quality improvement. The soil studied had been degraded by continuous erosão laminar / runoff or sheet erosion for about 10 years. Actually, the S index increased over time in all treatments (Table 4, Figure 2), evidencing that this property was sensitive to the changes in the soil, but no significant effect of SS application was observed. Interestingly, the data obtained in 2002 should be carefully analyzed, once the number of tensions applied to the soil to measure water retention was very low and did not allow adequate data fitting to the equations. However, the soil structure quality was considered adequate in all treatments, according to the classification proposed by Dexter (2004).

The average values obtained for soil permeability and saturated hydraulic conductivity (Ko) were not significantly affected by the SS rates (Table 5). In selective measurements of soil permeability under field conditions the coefficient of variation is commonly high. And the manual SS applications to the soil was not always uniform and might also have contributed to the lack of significant differences among treatments. The higher soil macroporosity value observed in the 20 Mg ha^{-1} treatment suggested that the Ko values might also be higher, since it is known that water moves mainly through macropores. Martens & Frankenberger (1992) found increased water infiltration in SS-treated soil compared to the control, after three SS applications of 25 Mg ha^{-1} which was directly related to the decreased bulk density. Alves et al. (2008) observed increased water infiltration also related to reduced bulk density in a recovering degraded SS-treated soil.

According to Marciano et al. (2001), the soil physical properties of well-structured soils might not present improvement with addition of high SS quantities, mainly if the spatial variability is high, as in soils with water movement. Barbosa et al. (2004) observed increased hydraulic conductivity in soils with low matrix potentials -0 and -1 kPa – treated with 12 Mg ha^{-1} of SS for two years, compared to the control and the treatment with 6 Mg ha^{-1} in a similar soil as in this study, suggesting that SS application may increase soil permeability. However, the authors found reduced soil conductivity in treatments with SS rates > 12 Mg ha^{-1} and no significant differences to the control. Besides, they found water repellence at the

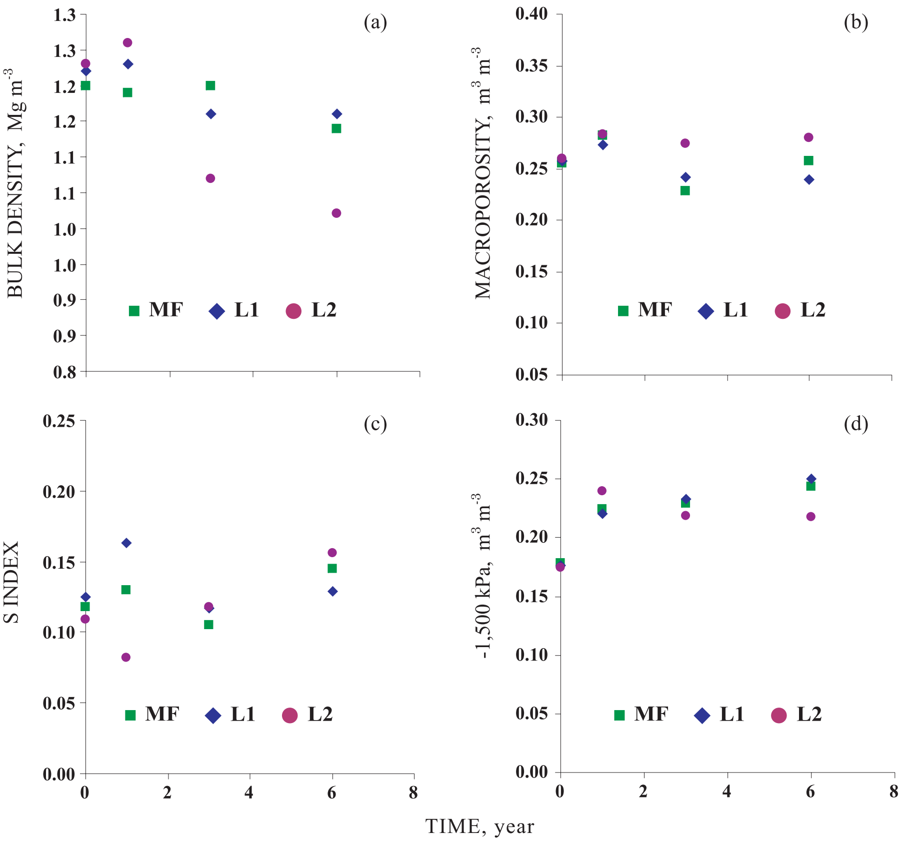

Figure 2. Soil bulk density, macroporosity, S index and water content at 1,500 kPa water potential before the experiment (initial condition) (a) and after 1 (b), 3 (c) and 6 (d) consecutive annual SS applications, in function of SS rates (L1 and L2) and mineral fertilization (MF).

Table 5. Soil permeability (P) and saturated hydraulic conductivity (Ko) at 0.10 m depth in plots treated with mineral fertilization (MF) and two sewage sludge (SS) rates (L1 and L2) applied in the experiment (0 year) and after 1, 2, 4 and 6 successive annual SS applications

Year	MF	L1	L2
		P (mm h^{-1})	
0	357.2	273.5	351.3a
1st	245.3	295.5	321.3a
2nd	460.5	428.1	493.9a
4th	435.5	324.3	388.0a
6th	921.5	816.4	795.3a
		Ko (m d^{-1})	
0	3.02	2.32	2.97
1st	2.08	2.51	2.72
2nd	2.25	2.33	2.67
4th	2.48	1.85	2.21
6th	5.24	4.65	4.54

soil surface making water infiltration more difficult. This result had also been observed by Constantini et al. (1995) and Marciano et al. (2001).

In this study, higher Ko values were observed for the L1 and L2 SS-treatments after the first year, but decreased Ko values in the subsequent years, compared to the MF-treatments. These results suggested that continuous SS applications with consequent organic matter accumulation may create hydrophobic sites in the soil aggregates, as reported by Filizola et al. (2006).

Figure 2 shows the data mean variation of the studied properties over the experimental period. It is noteworthy that the bulk density decreased in plots treated with the 20 Mg ha^{-1} of SS. Nevertheless, this bulk density reduction might be due to the presence of portions of non-degraded SS organic material and not by changes in the soil structure caused by soil aggregate rearrangements in consequence of the dynamics of the applied organic matter. The lower soil water retention observed at - 1,500 kPa followed the same trend (Figure 2). Portions of non-degraded SS material remained on the soil surfaces for the entire experimental period, allowing a clear visual identification of SS treated plots. This material may also have caused the phenomenon of hydrophobia reported by other authors.

CONCLUSIONS

1. In the long term, sewage sludge applications to agricultural land at the recommended rates changed soil physical properties.

2. Sewage sludge applications decreased bulk density, increased macroporosity and decreased microporosity, but did not significantly affect soil permeability and the S index - the soil physical quality property - after six consecutive annual applications.

3. The S index was susceptible to soil alterations in comparison with the original soil, indicating soil quality recovery of plots treated with sewage sludge, compared to those treated with mineral fertilizers.

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LITERATURE CITED

ALVES, M.C.; SUZUKI, L.G.A.S. & SUZUKI, L.E.A.S. Densidade do solo e infiltração de água como indicadores da qualidade física de um Latossolo Vermelho distrófico em recuperação. R. Bras. Ci. Solo, 31:617-625, 2007.

BARBOSA, G.M.C.; TAVARES FILHO, J. & FONSECA, I.C.B. Condutividade hidráulica saturada e não saturada de Latossolo Vermelho eutroférrico tratado com lodo de esgoto. R. Bras. Ci. Solo, 28:403-407, 2004.

BOEIRA, R.C. & SOUZA, M.D. Estoques de carbono orgânico e de nitrogênio, pH e densidade de um Latossolo após três aplicações de lodos de esgoto. R. Bras. Ci. Solo, 31:581-590, 2007.

CAMARGO, O.A.; MONIZ, A.C.; JORGE, J.A. & VALADARES, J.M.A.S. Métodos de análise química, mineralógica e física de solos do Instituto Agronômico de Campinas. Campinas, Instituto Agronômico de Campinas, 1986. 94p. (Boletim Técnico, 106)

CAMPOS, F.S. & ALVES, M.C. Uso de lodo de esgoto na reestruturação de solo degradado. R. Bras. Ci. Solo, 32:1389-1397, 2008.

COMPANHIA DE TECNOLOGIA DE SANEAMENTO AMBIENTAL - CETESB. Aplicação de biossólidos de sistemas de tratamento biológico em áreas agrícolas - Critérios para projeto e operação. São Paulo, CETESB, 1999. 33p. (Manual Técnico)

CONSELHO NACIONAL DO MEIO AMBIENTE – CONAMA. Resolução nº 375, de 29 de agosto de 2006. Define critérios e procedimentos, para o uso agrícola de lodo de esgoto gerados em estação de tratamento de esgoto sanitário e seus produtos derivados, e dá outras providências. Diário Oficial da Republica Federativa do Brasil, Poder Executivo, Brasília, DF, 30 ago. 2006. p. 141-146.

CONSTANTINI, A.; LOCH, R.J.; GLANVILLE, S.F. & ORANGE, D.N. Evaluation of the potential to dispose of sewage sludge. I. Soil hydraulic and overland flow properties of *Pinus* plantations in Queensland. Austr. J. Soil Res., 33:1041-1052, 1995.

DE MARIA, I.C.; KOCSSI, M.A. & DECHEN S.C.F. Agregação do solo em área que recebeu lodo de esgoto. Bragantia, 66:291-298, 2007.

DEXTER, A.R. Soil physical quality: Part I. Theory, effects of soil texture, density and organic matter and effects on root growth. Geoderma, 120:201-214, 2004.

DOURADO NETO, D.; JONG van LIER, Q.; BOTREL, T.A. & LIBARDI, P.L. Programa para confecção da curva de retenção de água no solo utilizando o modelo de Genuchten. Eng. Rural, 1:92-102, 1990.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA - EMBRAPA. Sistema brasileiro de classificação de solos. 2.ed. Rio de Janeiro, Embrapa Solos, 2006. 306p.

FILIZOLA, H.F.; SOUZA, M.D.; GOMES, M.A.F. & BOEIRA, R.C. Aspectos físicos de um solo tratado com lodo de esgoto: Estabilidade de agregados e argila dispersa em água. In: BETTIOL, W. & CAMARGO, O.A. Lodo de esgoto-impacto ambiental do uso agrícola. Jaguariúna, Embrapa Meio Ambiente, 2006. p.137-147.

GALDOS, M.V.; DE MARIA, I.C. & CAMARGO, O.A. Atributos químicos e produção de milho em um Latossolo Vermelho eutroférrico tratado com lodo de esgoto. R. Bras. Ci. Solo, 28:569-577, 2004.

JORGE, J.A.; CAMARGO, O.A. & VALADARES, J.M.A.S. Condições físicas de um Latossolo Vermelho-Escuro quatro anos após aplicação de lodo de esgoto e calcário. R. Bras. Ci. Solo, 15:237-240, 1991.

LEMAINSKI, J & SILVA, J.E. Utilização do biossólido da CAESB na produção de milho no Distrito Federal. R. Bras. Ci. Solo, 30:741-750, 2006.

MACEDO, J.R.; SOUZA, M.D.; REICHARDT, K. & BACCHI, O.S. Atributos físicos e hídricos em solo tratado com lodo de esgoto. In: BETTIOL, W. & CAMARGO, O.A. Lodo de esgoto-impacto ambiental do uso agrícola. Jaguariúna, Embrapa Meio Ambiente, 2006. p.193-205.

MARCIANO, C.R.; MORAES, S.O.; OLIVEIRA, F.C. & MATTIAZZO, M.E. Efeito do lodo de esgoto e do composto de lixo urbano sobre a condutividade hidráulica de um Latossolo Amarelo saturado e não saturado. R. Bras. Ci. Solo, 25:1-9, 2001.

MARTENS, D.A. & FRANKENBERGER Jr, W.T. Modification of infiltration rates in an organic-amended irrigated soil. Agron. J., 84:707-717, 1992.

MELO, V.P.; BEUTLER, A.N.; SOUZA, Z.M.; CENTURION, J.F. & MELO, W.J. Atributos físicos de Latossolos adubados durante cinco anos com biossólido. Pesq. Agropec. Bras., 39:67-72, 2004.

MELO, W.J. & MARQUES, M.O. Potencial do lodo de esgoto como fonte de nutrientes para as plantas. In: BETTIOL, W. & CAMARGO, O.A., eds. Impacto ambiental do uso agrícola do lodo de esgoto. Jaguariúna, Embrapa Meio Ambiente, 2000. p.109-141.

RAIJ, B.van; CANTARELLA, H.; QUAGGIO, A.J. & FURLANI, A.M.C. Recomendações de adubação e calagem para o Estado de São Paulo. 2.ed. Campinas, Instituto Agronômico & Fundação IAC, 1996. 285p.

RAIJ, B.van; ANDRADE, J.C.; CANTARELLA, H. & QUAGGIO, J.A., eds. Análise química para avaliação da fertilidade de solos tropicais. Campinas, Instituto Agronômico, Campinas, 2001. 285p.

REYNOLDS, W.D.; VIEIRA, S.R. & TOPP, G.C. An assessment of the single-head analysis for the constant head well permeameter. Can. J. Soil Sci., 72:439-501, 1992.

STRECK, C.A.; REINERT, D.J.; REICHERT, J.M. & HORN, R. Relações do parâmetro S para algumas propriedades físicas de solos do sul do Brasil. R. Bras. Ci. Solo, 32:2603-2612, 2008.

TRANNIN, I.C.B.; SIQUEIRA, J.O. & MOREIRA, F.M.S. Atributos químicos e físicos de um solo tratado com biossólido industrial e cultivado com milho. R. Bras. Eng. Agríc. Amb., 12:223-230, 2008.

van GENUCHTEN, M.T. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J., 44:892-898, 1980.

VIEIRA, S.R. Permeâmetro: Novo aliado na avaliação de manejo do solo. Agronômico, 47/50:32-33, 1995/1998.