RECOVERY OF AN OXISOL DEGRADED BY THE CONSTRUCTION OF A HYDROELECTRIC POWER PLANT

Joseane Carina Borges de Carvalho(1), Carlos Roberto Espindola(2), Marlene Cristina Alves(3), Getulio Coutinho Figueiredo(4) and Sonia Carmela Falci Dechen(5)*

(1) Universidade Estadual de Campinas, Instituto de Geociências, Departamento de Geografia, Programa de Pós-graduação em Geografia, Campinas, São Paulo, Brasil.
(2) Universidade Estadual de Campinas, Instituto de Geociências, Departamento de Geografia, Campinas, São Paulo, Brasil.
(3) Universidade Estadual Paulista, *Campus* de Ilha Solteira, Departamento de Fitossanidade, Engenharia Rural e Solos, Ilha Solteira, São Paulo, Brasil.
(4) Instituto Agronômico, Centro de Pesquisa e Desenvolvimento de Solos e Recursos Ambientais, Programa de Pós-graduação em Solos e Recursos Ambientais, Campinas, São Paulo, Brasil.
(5) Instituto Agronômico, Centro de Pesquisa e Desenvolvimento de Solos e Recursos Ambientais, Campinas, São Paulo, Brasil.
* Corresponding author.
E-mail: dechen@iac.sp.gov.br

ABSTRACT

The removal of thick layers of soil under native scrubland (*Cerrado*) on the right bank of the Paraná River in Selvíria (State of Mato Grosso do Sul, Brazil) for construction of the Ilha Solteira Hydroelectric Power Plant caused environmental damage, affecting the revegetation process of the stripped soil. Over the years, various kinds of land use and management systems have been tried, and the aim of this study was to assess the effects of these attempts to restore the structural quality of the soil. The experiment was conducted considering five treatments and thirty replications. The following treatments were applied: stripped soil without anthropic intervention and total absence of plant cover; stripped soil treated with sewage sludge and planted to eucalyptus and grass a year ago; stripped soil developing natural secondary vegetation (*capoeira*) since 1969; pastureland since 1978, replacing the native vegetation; and soil under native vegetation (*Cerrado*). In the 0.00-0.20 m layer, the soil was chemically characterized for each experimental treatment. A 30-point sampling grid was used to assess soil porosity and bulk density, and to assess aggregate stability in terms of mean weight diameter (MWD) and geometric mean diameter (GMD). Aggregate stability was also determined using simulated rainfall. The results show that using sewage sludge incorporated with a rotary hoe improved the chemical fertility of the soil and produced more uniform soil pore size distribution. Leaving the land to develop secondary vegetation or turning it

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over to pastureland produced an intermediate level of structural soil quality, and these two treatments produced similar results. Stripped soil without anthropic intervention was of the lowest quality, with the lowest values for cation exchange capacity (CEC) and macroporosity, as well as the highest values of soil bulk density and percentage of aggregates with diameter size <0.50 mm, corroborated by its lower organic matter content. However, the percentage of larger aggregates was higher in the native vegetation treatment, which boosted MWD and GMD values. Therefore, assessment of some land use and management systems show that even decades after their implementation to mitigate the degenerative effects resulting from the installation of the Hydroelectric Plant, more efficient approaches are still required to recover the structural quality of the soil.

Keywords: aggregate stability, soil compaction, stripped soil, soil quality.

RESUMO: *RECUPERAÇÃO DE UM LATOSSOLO DEGRADADO PELA IMPLANTAÇÃO DE UMA USINA HIDRELÉTRICA*

A retirada de espessas camadas de solo sob cerrado nativo da margem direita do rio Paraná, em Selvíria, MS, para a construção da Usina Hidrelétrica de Ilha Solteira, provocou degradação ambiental, com reflexos no processo de revegetação do solo decapitado. Esse local foi submetido às tentativas de usos e manejos diversificados ao longo dos anos, constituindo o objetivo deste trabalho avaliar o efeito das abordagens aplicadas à recuperação da qualidade estrutural do solo. O experimento foi realizado considerando cinco tratamentos e 30 repetições. Os tratamentos experimentais consistiram em: solo degradado (decapitado), sem intervenção antrópica e com ausência de cobertura vegetal; solo degradado, tratado com lodo de esgoto e cultivado com eucalipto e gramínea há um ano; solo degradado, mantido com capoeira em regeneração natural desde o ano de 1969; solo com pastagem desde 1978, em substituição à vegetação nativa; e solo sob vegetação nativa (Cerrado). A caracterização química do solo para cada tratamento experimental foi realizada na camada de 0,00-0,20 m. Uma grade de amostragem com 30 pontos foi utilizada para avaliar a porosidade e densidade do solo e os índices de estabilidade de agregados diâmetro médio ponderado (DMP) e diâmetro médio geométrico (DMG). A estabilidade de agregados foi também determinada com chuva simulada. Os resultados evidenciaram que a utilização de lodo de esgoto incorporado com enxada rotativa melhorou a fertilidade química e promoveu distribuição mais equilibrada do tamanho de poros do solo. Os tratamentos com capoeira e pastagem apresentaram nível intermediário de qualidade estrutural do solo, sendo mais similares entre si. A qualidade do solo degradado e sem intervenção antrópica foi a mais prejudicada, havendo valores menores de capacidade de troca catiônica e macroporosidade, bem como valores maiores de densidade do solo e de porcentagem de agregados com diâmetros <0,50 mm, corroborados pelo seu menor teor de matéria orgânica. Já o porcentual de agregados de tamanhos maiores foi mais expressivo no tratamento sob vegetação nativa, o que refletiu positivamente nos valores de DMP e DMG. Portanto, mesmo decorridas várias décadas da implantação de alguns dos sistemas de uso e manejo avaliados, para mitigar os efeitos deletérios advindos da instalação dessa Usina Hidrelétrica, ainda são necessárias abordagens mais eficientes para recuperar a qualidade estrutural do solo.

Palavras-chave: estabilidade de agregados, compactação, solo decapitado, qualidade do solo.

INTRODUCTION

Among the disturbances that can be imposed upon a soil body, the removal of thick soil layers leads to the most significant deterioration of natural resources and can compromise the sustainability of the environment (Doran and Parkin, 1994). Construction of embankments, creation of landfill sites, clearing of routes for highways, and mining activities all involve this procedure, which typically requires the use of heavy, high capacity earthmoving machinery. These large-scale civil engineering projects promote soil compaction, principally within the layers closest to the surface. The concomitant damage to the soil structure may hampers the growth of plant root systems, and also reduces aeration and water infiltration. Decreased infiltration contributes to surface runoff, with consequent dislodging and transport of soil particles associated with fertilizers and organic matter for example. This transport can occur in the form of aggregates and, or, as aqueous suspensions (Letey, 1985; Soane, 1990; Soane and Ouwerkerk, 1995; Streck et al., 2004).

The anthropogenic actions which frequently cause the most severe degradation to soils are inappropriate mining practices and the installation of hydroelectric plants, both of which have potentially degenerative effects on the chemical, physical, and biological properties of the soil (Duda et al., 1999; Colodro et al., 2007; Modesto et al., 2009). Mining activities can completely alter the characteristics of the remaining substrate, including the soil particle composition of the soil (Espindola et al., 2000). Since the 1960s, the increasing demand for energy within Brazil has been met by expanding the number and generating capacity of hydroelectric plants. The construction of each new plant has been accompanied by the removal of thick layers of soil in the surrounding area. The magnitude and extent of the consequent impacts on the environment extend far beyond the time and space of the construction period and area. However, when the mantle is thick, as is the case with Oxisols, it has proven possible to construct a new and fertile soil profile (Tavares Filho et al., 1999) in a relatively short period of time. This has been achieved through measures such as land leveling; control of soil acidity; fertilization; cultivation of, for example, leguminous plants (Boni et al., 1994) or eucalyptus associated with grasses after application of sewage sludge (Colodro et al., 2007).

Soil aggregates consist of assemblies and rearrangements of the primary soil particle fractions (sand, silt, and clay), and determine the soil structure (Brady, 1989). Therefore, evaluation of the soil physical quality can be performed by considering the properties of its aggregates. Aggregate development and modification are dependent on specific local circumstances, such that aggregate characteristics are sensitive indicators of the history of land use and soil management (Watts and Dexter, 1997; Tormena et al., 2008; Vezzani and Mielniczuk, 2011). In addition, chemical properties, such as organic matter content, have been positively associated with macroaggregation in soils (De Gryze et al., 2008; Anders et al., 2010) and with soil structural quality (Sá et al., 2010). Monitoring of chemical properties may assists in understanding the mechanisms through which land mitigation may be achieved, for instance in restoration of areas degraded by the installation of hydroelectric plants.

The hypothesis of this research is that environmental mitigation techniques applied to the areas surrounding the Ilha Solteira Hydroelectric Plant, SP, Brazil, provide the recovery of degraded soil. The objective of the present study was evaluation of soil chemical and physical quality in areas surrounding this hydroelectric plant. This was carried out through examination of the soil under various land use and management systems that represent different levels and periods of human intervention.

MATERIAL AND METHODS

The study was carried out on the Teaching and Research Farm of Universidade Estadual Paulista, Ilha Solteira, SP, Brazil, and is located within the municipality of Selvíria, MS, on the right bank of the Paraná River (51º 22’ W, 20º 22’ S) at an altitude of 355 m. The local climate type (Köppen classification scheme) is Aw, with average annual precipitation of 1,300 mm. The relative humidity is from 60 to 80 % during the rainy months (October to March), and from 50 to 60 % in the driest months. The average annual temperature for the region is 23.7 °C, with an average of 25.7 °C for the hottest months (January and February), falling to 20.6 °C in the coldest months (June and July) (Setzer, 1966).

The local topography is gently undulating to flat, with the soil covered by native vegetation typical of the Cerrado. The original soil is an Oxisol (Soil Survey Staff, 2010), corresponding to a *Latossolo Vermelho* by the Brazilian classification system (Embrapa, 2006), of medium texture, and very deep and rich in Fe and Al oxyhydroxides (Demattê, 1980). In the early 1960s, part of the soil (from an area of 700 ha) was excavated to a depth of 6.0 m and taken to the embankment and foundations of the Ilha Solteira Hydroelectric Power Plant, SP. The stripped soil exhibits part of the B horizon, and this has remained exposed since 1969. An inspection in 1992 found high levels of soil surface compaction (Bonini and Alves, 2011). However, in some areas, natural regeneration in the form of rarefied and low-growing vegetation has started and has been allowed to remain in this condition until the present study was conducted.

In 2003, the soil condition (stripped and hence degraded, or undisturbed during the power plant construction) and vegetation (natural, pasture, natural regeneration, or bare) of the land available for the study around the Ilha Solteira Hydroelectric Plant were surveyed. Soil samples for analysis were collected, in which there were 30 sampling points (repetitions) within a 12 × 10 m plot per treatment. Areas corresponding to four treatments were delineated: SD, degraded stripped soil with an absence of spontaneous plants and without human interventions for land regeneration; SDCap, stripped soil upon which secondary scrub vegetation (*capoeira*) has developed since 1969 as a result of natural regeneration; SNat, soil beneath the native vegetation of the *Cerrado*; and SPas, where the native vegetation has been replaced by pasture. For treatment SD, the B horizon has remained exposed since 1969. A regeneration treatment, consisting of the application of sewage sludge, followed by the cultivation of eucalyptus and grasses, was applied to randomly selected plots within the SD area, establishing the fifth treatment: SDle.

The conversion of part of the SD area to SDle was through the following operations. A sequence of two subsoilings to a depth of 0.40 m was performed in January and February of 2003. In July 2003, the sewage sludge was applied in a single broadcast operation (rate: 60 Mg ha^{-1}, dry weight basis). The sludge was first manually distributed over the surface, and then incorporated to a depth of 0.10 m using a rotary hoe. The sewage application rate was defined after considering the rates adopted in various investigations of soil regeneration, such as those by Kitamura et al. (2008) and Colodro and Espindola (2006), which had previously been conducted in the same geographical region of Brazil as the present study. The sewage sludge, which was predominantly of domestic origin and had been produced by the extended aeration process, was obtained from the Sewage Treatment Plant operated by Sanear (Araçatuba Sanitation Company S.A.) in Araçatuba, SP, Brazil. Chemical characterization of the sludge was performed by Colodro and Espindola (2006), who determined that the concentrations of heavy metals in the sewage sludge met the limits established by the principal national and international environmental monitoring agencies (Table 1). Microbiological characterization of the sludge, performed by Modesto et al. (2009), indicated 0.04 eggs g^{-1} of total solids, for both protozoa and helminths, satisfying the maximum limit established by Cetesb (1999) and identifying the sludge type as Class B. Correction of soil acidity was performed with limestone, incorporated by light harrowing, so that base saturation was raised to 60 %. In August 2003, the experimental plot was planted to eucalyptus (*Eucalyptus citriodora*) in a 2.0 m between rows and 1.5 m between plants in 0.40 m deep furrows. Seeds of the grass *Brachiaria decumbens* were broadcast over the entire surface of the plot, with two objectives: to absorb the excess nitrate generated by the addition of the sewage sludge and to increase the organic matter content of the soil. The grass was not cut.

For treatment SPas, the substitution of native vegetation for pasture (*Brachiaria decumbens*) was effected in 1978. Soil preparation consisted of heavy harrowing (large disc harrow) and light harrowing (leveling harrow). Liming to raise the base saturation to 60 % and fertilization were performed as part of the conversion to pasture and during subsequent renovations of the pasture. The animal stocking rate was 2.5 animal units ha^{-1} yr^{-1}.

For each treatment, soil particle distribution analysis was conducted on a composite sample from the 0.00-0.20 m layer collected from a 30-point grid. The maximum differences identified between treatments (≤48 g kg^{-1}) for clay and total sand content were considered to be of low physical significance (Table 2).

Soil sampling was performed in 2004. Chemical characterization was conducted on samples collected from the 0.00-0.20 m layer, with the aim of assisting understanding of the evolution of the experimental treatments since their inception, and focused on parameters likely to affect the stability of aggregates. The methodology made available in Raij et al. (2001) was employed, with soil coming from 10 sampling points per treatment.

Determinations of soil bulk density (Blake and Hartge, 1986), and porosity (Camargo et al., 2009), consisting of total, macro-, and microporosity (water content retained under a tension of 6 kPa) were performed with undisturbed samples. These samples were taken from the 0.00-0.05 m layer in the designated plot for each experimental treatment using 100 cm^3 volumetric rings. For each plot, the 30 sampling points were on a square grid, with a distance of 2 m between adjacent points.

Analysis of the stability of the soil aggregates in water was performed according to methods outlined by Kemper and Chepil (1965). Sampling points were located on the previously established 30-point grid, and undisturbed soil samples were obtained from the 0.00-0.20 m layer. In duplicate, 25 g of the air-dried soil sample for each sampling point were passed through a set of sieves with mesh openings of 9.52, 7.93, 6.35, 4.00, 2.00, 1.00, and 0.50 mm. From the soil masses retained in the sieves, the distribution of the soil aggregates by size class was determined, from which mean weight diameter (MWD) and geometric mean diameter (GMD) of the aggregates were computed.

Additional stability testing was performed using a rain simulator, operated under hydraulic loading conditions sufficient to maintain a constant rate of raindrop formation (Boyle-Mariotte principle), as described by Roth et al. (1985). In duplicate, 3 g of the air-dried soil sample for each sampling point, as previously mentioned, were kept under an average precipitation rate of 60 mm h^{-1} for a period of 20 min; sieves were utilized to retain aggregates of three size classes: 9.52-6.35, 9.52-4.00, and 9.52-2.00 mm. The retained size-selected aggregates were subsequently transferred to aluminum crucibles with the aid of a wash bottle, and dried in an oven (105 °C) to constant weight. From the dry weights determined, the percentages of aggregates which resisted the simulated rainfall were obtained.

The experimental data were subjected to analysis of normality (SAS, 2002) and were transformed whenever necessary to achieve an approximately normal distribution. Mean values of soil properties between treatments were compared using the confidence intervals (95 %), according to Payton et al. (2000).

RESULTS AND DISCUSSION

Chemical properties of the soil demonstrate that for all the experimental treatments the pH remained in the acid range, with values <5.0 (Table 3). The highest concentration of organic matter (OM) was found in the soil under native vegetation, that is, Cerrado with no history of human interventions. The average OM content did not differ significantly between the soil under native vegetation and the soil now under pasture, showing the positive effect of grasses on the accumulation of organic C in the soil.

Table 1. Chemical and physical characterization of the sewage sludge, with maximum permitted limits

Attribute(1)	Observed value	Maximum permitted limit	
		Cetesb(3)	Usepa(4)
pH (*in natura*)	7.1		
Moisture (m^3 m^{-3})	65.7		
Volatile solids (dag kg^{-1})	71.5		
Organic carbon (g kg^{-1})	406.0		
Ammoniacal-N (g kg^{-1})	8.9		
Nitrate-nitrite-N (g kg^{-1})	105.7		
Total N (g kg^{-1})	57.1		
P (g kg^{-1})	27.7		
K (g kg^{-1})	8.4		
Ca (g kg^{-1})	3.9		
Mg (g kg^{-1})	3.3		
S (g kg^{-1})	3.0		
B (mg kg^{-1})	10.7		
Cu (mg kg^{-1})	159.8	4,300.0	1,500.0
Fe (mg kg^{-1})	7,385.0		
Mn (mg kg^{-1})	77.8		
Zn (mg kg^{-1})	474.4	7,500.0	2,800.0
Mo (mg kg^{-1})	ND(4)	75.0	18.0
Al (mg kg^{-1})	4,968.0		
As (mg kg^{-1})	ND	75.0	41.0
Cd (mg kg^{-1})	1.6	85.0	39.0
Pb (mg kg^{-1})	28.7	840.0	300.0
Total Cr (mg kg^{-1})	20.4	-	1,200.0
Hg (mg kg^{-1})	ND	57.0	17.0
Ni (mg kg^{-1})	18.1	420.0	420.0
Se (mg kg^{-1})	ND	100.0	36.0
Na (mg kg^{-1})	1,255.0		

(1) Metals determined by ICPAES according to method SW3051 of the Usepa (Usepa, 1993). (2) Concentration values on dry weight basis. (3) Cetesb: Companhia de Saneamento do Estado de São Paulo (Cetesb, 1999). (4) Usepa: Regulation 40 CFR Part 503 (Usepa, 1993), limits are for sludge of exceptional quality. ND: not detected.

Degraded soil resulting from stripping which had experienced no human interventions directed toward regeneration (treatment SD) was highly compacted (soil bulk density (Bd) = 1.92 Mg m^{-3}) and displayed the lowest content of organic matter, approximately 12 % of the maximum observed value (soil under native vegetation, SNat; Table 3). Soil from stripped areas where scrub vegetation (*capoeira*) appeared as a result of natural regeneration reached an organic matter content approximately half that of the soil under natural vegetation (SNat) and under pasture (SPas). The determination of OM content for the degraded soil to which sewage sludge was applied (SDle) showed that this treatment was effective in improving the condition of the degraded soil. Regeneration of the soil occurred, the organic matter content of the soil increased, and this made the cultivation of eucalyptus possible. The effectiveness of sewage sludge in the regeneration of degraded soils has been verified in other investigations, such as Colodro and Espindola (2006).

Cation exchange capacity (CEC) values for the soils of the different treatments followed, in general, the same trend as observed for the organic matter content (Table 3). However, although the organic matter content of the soil treated with sewage sludge (SDle) was approximately 40 % lower than for the SNat and SPas soils, the SDle soil displayed the highest mean CEC. An explanation for this observation can be found in the presence of organic matter in an amorphous state within the SDle soil; this colloidal material has a significantly greater surface area than for organic materials in a less

Table 2. Soil particle size distribution, determined in 2004, for soil from the 0.00-0.20 m layer around the Ilha Solteira Hydroelectric Plant, SP, Brazil

Treatment(1)	Clay	Silt	CS	FS	TS
	g kg^{-1}				
SD	221	28	405	346	751
SDle	225	39	360	376	736
SDCap	216	43	338	403	741
SPas	221	34	458	286	744
SNat	177	39	408	376	784

(1) SD: degraded soil, no human intervention; SDle: degraded soil, treated with sewage sludge and planted to eucalyptus and grasses; SDCap: degraded soil displaying natural regeneration (*capoeira*); SPas: soil under pasture, where grass has substituted native vegetation; SNat: soil under native vegetation (*Cerrado*). Clay: <0.002 mm (pipette method); Silt: 0.053-0.002 mm; CS: coarse sand, 2.000-0.210 mm; FS: fine sand, 0.210-0.053 mm; TS: total sand, 2.000-0.053 mm (Camargo et al., 2009).

advanced state of decomposition (such as plant remains), which contributed to the increase in the negative charge carried by soil (Lopes and Guidolin, 1989). With regard to the chemical fertility of the soils, the SDle treatment led to large increases in the levels of nutrients, especially P, Ca, and Mg, with associated improvements in the sum of bases (SB) and the base saturation (V). The treatment also offered control of Al toxicity to plants and of the acidity of the soil. Taken together, these observations serve to emphasize the importance of the type and the quality of the OM applied in recovery programs for degraded soils. These results are in agreement with other investigations carried out in the same geographical region as the present study, which evaluated soils treated with biosolids and cultivated with corn and beans (Nascimento et al., 2004), and with tree species (Modesto et al., 2009).

For the soil under the native vegetation of the Cerrado, soil Bd = 1.19 Mg m^{-3} was consistent with its soil particle properties (Reichert et al., 2009) and the absence of any agricultural use and management (Tables 2 and 3). The soil under *capoeira*, which was regenerating naturally (SDCap), displayed a Bd = 1.65 Mg m^{-3} very close to that observed for the soil under pasture (SPas, Bd = 1.68 Mg m^{-3}). This similarity in Bd and hence compaction reflects, in part, the history of the stresses applied to the soils of these treatments. There was regular traffic of heavy machinery over the SDCap soil during the construction period of the hydroelectric plant, while the SPas soil was burdened by grazing livestock. Excluding the soil under native vegetation, the soil from the SDle treatment exhibited the lowest Bd (1.61 Mg m^{-3}), an observation which may be attributed principally to the alleviation of compaction provided during the incorporation of the broadcast sewage sludge. The most intense degradation was observed where the soil had been stripped and there had been no subsequent regeneration (treatment SD); this was evidenced by the high value for Bd of 1.92 Mg m^{-3}, which is a recognized consequence of the occurrence of high accumulated strains on a soil.

Compaction of the soil under the different treatments compared to the soil under native vegetation, revealed by the changes in Bd, compromised the total porosity (TP) of the soil, and was further reflected in decreases in the macroporosity of the soil (Table 3). The TP of the SNat soil was greater than the upper value of 0.50 m^3 m^{-3} indicated as desirable for plant growth (Kiehl, 1979). The distribution of the TP between micro- and macroporosity was most balanced for the soil into which sewage sludge had been incorporated,

Table 3. Soil chemical and physical properties around the Ilha Solteira Hydroelectric Plant, SP, Brazil. Determinations were performed in 2004 for soils corresponding to different levels of anthropogenic intervention

Property	SD	SDle	SDCap	SPas	SNat
			0.00-0.20 m		
pH($CaCl_2$)	4.45 b	4.88 a	4.44 b	4.76 a	4.17 c
Organic matter (mg dm^{-3})	2.50 c	10.40 b	11.80 b	20.00 a	20.50 a
CEC ($mmol_c$ dm^{-3})	22.18 c	56.77 a	32.94 b	44.85 a	51.73 a
P (mg dm^{-3})	1.20 c	287.60 a	1.20 c	4.10 b	5.80 b
K^+ ($mmol_c$ dm^{-3})	0.38 b	1.07 ab	0.84 ab	1.25 a	1.23 a
Ca^{2+} ($mmol_c$ dm^{-3})	4.90 c	17.00 a	4.90 c	9.10 b	3.70 c
Mg^{2+} ($mmol_c$ dm^{-3})	1.67 c	12.80 a	3.40 bc	8.00 b	4.90 bc
H+Al ($mmol_c$ dm^{-3})	15.60 c	25.90 b	23.80 b	26.50 b	41.90 a
Al^{3+} ($mmol_c$ dm^{-3})	3.40 bc	1.60 d	5.00 b	2.00 cd	9.70 a
SB ($mmol_c$ dm^{-3})	6.95 b	30.87 a	9.14 b	18.35 ab	9.83 b
V (%)	29.00 bc	53.70 a	27.30 bcd	39.90 bc	18.90 d
			0.00-0.05 m		
Bulk density (Mg m^{-3})	1.92 a	1.61 c	1.65 bc	1.68 b	1.19 d
Total porosity (m^3 m^{-3})	0.36 d	0.48 b	0.44 c	0.44 c	0.52 a
Macroporosity (m^3 m^{-3})	0.12 d	0.23 b	0.17 c	0.19 c	0.35 a
Microporosity (m^3 m^{-3})	0.24 b	0.25 b	0.27 a	0.25 b	0.18 c

(1) SD: degraded soil, no human intervention; SDle: degraded soil, treated with sewage sludge and planted to eucalyptus and grasses; SDCap: degraded soil displaying natural regeneration (*capoeira*); SPas: soil under pasture, where grass has substituted native vegetation; SNat: soil under native vegetation (*Cerrado*). CEC: cation exchange capacity; SB: sum of bases; V: base saturation. Means within a line followed by the same letter do not differ significantly at the 95 % confidence level, according to Payton et al. (2000).

with the macroporosity of this SDle soil coming closest to that for the soil under native vegetation. Various authors have proposed minimum values of soil macroporosity as necessary for gas diffusion and for avoidance of physiological damage to plant roots, for example, ≥ 0.10 m^3 m^{-3} (Grable and Siemer, 1968) and ≥ 0.14 m^3 m^{-3} (Carter, 1988; Mueller et al., 2008; Reynolds et al., 2009). For most of the evaluated treatments, the macroporosity exceeded these minimum suggested values.

Indications of the structural stability of the soils from the different treatments were obtained by comparing the size distributions of the aggregates (percentages by dry weight within different size classes) that were stable in water. The soils under the SD and SDle treatments proved to be the least structurally stable from the significantly ($p<0.05$) greater proportions of aggregates smaller than 0.50 mm for these soils in comparison to the other treatments (Table 4). A higher proportion of small aggregates is attributed to more facile fragmentation of larger aggregates; in the context of the present study, this may be explained by the history of the SD and SDle soils and especially the impact of extensive use of heavy earthmoving machinery (Oliveira et al., 2004) in the area surrounding the hydroelectric plant.

Comparing the proportions of aggregates stable in water among the different experimental treatments, the values for the size classes 9.52-7.93, 7.93-6.35, and 6.35-4.00 mm were largest for the soil under native vegetation (Table 4). For the treatments that underwent some degree of human intervention, clear differences among the treatments were only detected in the proportions of stable aggregates with sizes <6.35 mm. Considering the two smallest size classes, 1.00-0.50 mm and <0.50 mm, the percentages in these classes were smallest for SNat. For the 2.00-1.00 mm class, the proportion for SNat was substantially smaller than for SDCap and SPas and not significantly different from the values for SD and SDle. The predominance of larger, water-stable aggregates in the soil under native vegetation in comparison to the other treatments was attributed to the positive effect of organic C on the stability of larger aggregates (Demarchi et al., 2011; Costa Júnior et al., 2012). These results are in accord with Bonini and Alves (2011), who conducted evaluations of the physical quality of a previously exposed soil (B horizon remaining) in an experimental area similar to that of the present study. In their study, the B horizon had been exposed by deep stripping, and the soil subsequently was under 17 years of agricultural management with green manure, limestone, gypsum, and forage grasses (*Brachiaria*).

Among the managed systems, the stability of aggregates with sizes larger than 6.35 mm from soil under pasture appeared to be no better than for aggregates from the SDCap and SDle treatments (Table 4). This was despite the higher level of organic matter in the SPas soil, which was similar to the level in the soil under native vegetation (Table 3). This indicates that the soil compaction produced by trampling of the ground by cattle masked the combined contributions to the aggregation afforded by the growth of roots of pasture grasses and the activity of soil microorganisms and fauna (Haynes and Beare, 1997). The net result found for the SPas treatment was a decrease in the percentage of the macroaggregates found to be stable in water (Longo et al., 1999) compared to SNat. This decrease in macroaggregate stability in a managed system is in accordance with findings from Horn et al. (1995), who affirmed that compaction is one

Table 4. Mean values for the percentages by weight for different size classes of aggregates stable in water, and for the mean weight diameter (MWD) and geometric mean diameter (GMD) of the water-stable aggregates. Determinations were performed in 2004, for soil samples from the 0.00-0.20 m depth range, collected from five treatments in areas located around the Ilha Solteira Hydroelectric Plant, SP, Brazil

Treat[(1)]	Aggregate size class (mm)							MWD	GMD
	9.52-7.93	**7.93-6.35**	**6.35-4.00**	**4.00-2.00**	**2.00-1.00**	**1.00-0.50**	**<0.50**		
	% by dry weight							mm	
SD	0.64 c	1.86 c	3.88 d	3.49 c	4.42 b	8.40 b	77.31 a	0.82 d	0.42 d
SDle	1.84 bc	2.56 bc	5.19 d	4.64 c	4.51 b	8.00 b	73.26 a	1.06 d	0.47 d
SDCap	0.86 bc	2.98 bc	8.94 c	12.16 b	12.75 a	12.53 a	49.78 b	1.52 c	0.76 c
SPas	2.13 b	4.49 b	12.88 b	14.61 a	12.26 a	13.96 a	39.68 c	2.00 b	1.02 b
SNat	16.56 a	18.63 a	26.80 a	14.49 ab	4.41 b	5.83 c	13.28 d	4.74 a	3.61 a

(1) Treat: treatment; SD: degraded soil, no human intervention; SDle: degraded soil, treated with sewage sludge and planted to eucalyptus and grasses; SDCap: degraded soil displaying natural regeneration (*capoeira*); SPas: soil under pasture, where grass has substituted native vegetation; SNat: soil under native vegetation (*Cerrado*). Mean values within a column followed by the same letter do not differ significantly at the 95 % confidence level, according to Payton et al. (2000). Data transformation applied: $(x + 0.5)^{0.5}$ (Bonini and Alves, 2011).

of the factors responsible for the generation of denser aggregates of low structural resistance.

In regard to aggregates in the SDle soil, this treatment did not improve soil structural condition in relation to the most degraded soil (SD). For each size class, there was no difference in the percentage by weight of water-stable aggregates between the SDle and SD soils (Table 4). These contrasts with the SDCap and SPas treatments, for which the proportions of aggregates in the smallest size class (<0.5 mm) were much less than for the SD and SDle soils, with associated increases for the intermediate size classes. This apparent lack of improvement under the SDle treatment may have been a consequence of the relatively short time (one year) between the incorporation of the sewage sludge into the soil and the collection and evaluation of the soil samples. In comparison, the other treatments had been under their respective systems of management for decades. It is recognized that the duration under which a system of use and management is operated has a profound effect on the structural quality of the soil. A recognized phenomenon, which can be invoked to explain changes in aggregate stability, is *age hardening*, in which an increase in the internal resistance of the aggregates develops over time to the extent that the connections between the solid particles of an aggregate are preserved during the period following the initial tillage of the soil (Utomo and Dexter, 1981).

Significantly higher ($p<0.05$) percentages of stable aggregates in the size classes from 9.52-7.93 to 6.35-4.00 mm for the soil under native vegetation were reflected in the mean weight diameter (MWD) of the SNat aggregates, 4.74 mm, which was the highest value among the treatments (Table 4). Considering the remaining treatments, the sequence of MWD values was SPas > SDCap > SDle = SD; this demonstrates the importance of plant cover in the recovery of degraded areas (Demarchi et al., 2011). The behavior of the values for geometric mean diameter (GMD) was similar. The GMD gives an estimate of the most frequently occurring size class in a soil. With the exception of the SNat soil, the estimates were ≤1.02 mm; while for the soil under native vegetation, the estimate was 3.5 times greater.

For soils displaying a high degree of compaction or where plant cover has only recently been established (Table 3), the aggregates are generally less resistant to the action of external forces (Horn et al., 1995), such as the impact of water drops from a mechanical rain simulator. These expectations were confirmed by the tests of aggregate stability under simulated rain for the treatments of the present study. Thus, the SD and SDle treatments exhibited lower percentages of weight retained for the three classes of aggregate size evaluated than did the other three treatments (Table 5).

The results for the SPas, SDCap, and SNat treatments reflected the positive effects of plant cover on soil structure. These three treatments behaved as a single group, with no significant differences among them for any of the aggregate size classes (Table 5). The tests of aggregate stability under rain for the size classes 9.52-6.35 and 9.52-4.00 mm divided the treatments into two groups: (SDle = SD) < (SDCap = SPas = SNat). However, for the size class 9.52-2.00 mm there was differentiation between the SDle and SD treatments, with division into three groups: SDle < SD < (SDCap = SPas = SNat). The placement of the SDle treatment with the degraded soil SD on the basis of the relative stability under simulated rain of different aggregate size classes was in accord with the aggregate size distribution results obtained by wet-sieving (Table 4). The soil of the SDle treatment had passed through tillage only a year before the collection and testing of the soil samples, so that the SDle aggregates were the least age-hardened (Utomo and Dexter, 1981). Thus, the rapid entrance of water into the soil pores during the testing of the dry aggregates in the rain simulator may have led to their rupture (Caron et al., 1996), thereby compromising the soil structural stability.

Table 5. Mean values for the percentages by weight of aggregates stable under simulated rain for three size classes. Determinations were performed in 2004, for soil samples from the 0.00-0.20 m layer, collected from five treatments in areas located around the Ilha Solteira Hydroelectric Plant, SP, Brazil

Treat[(1)]	Aggregate size class (mm)		
	9.52-6.35	9.52-4.00	9.52-2.00
	Mean retained (% by dry weight)		
SD	45.84 b	59.66 b	61.19 b
SDle	40.64 b	55.62 b	44.15 c
SDCap	73.70 a	84.75 a	86.80 a
SPas	75.27 a	83.97 a	82.57 a
SNat	64.11 a	81.31 a	85.75 a

(1) Treat: treatment; SD: degraded soil, no human intervention; SDle: degraded soil, treated with sewage sludge and planted to eucalyptus and grasses; SDCap: degraded soil displaying natural regeneration (*capoeira*); SPas: soil under pasture, where grass has substituted native vegetation; SNat: soil under native vegetation (*Cerrado*). Mean values within a column followed by the same letter do not differ significantly at the 95 % confidence level, according to Payton et al. (2000). Data transformation applied: $(x + 0.5)^{0.5}$ (Bonini and Alves, 2011).

CONCLUSIONS

The hypothesis of this research was partially accepted, since there was only a significant improvement in soil quality treated with sewage sludge and planted with eucalyptus and grasses. The physical quality of the stripped soil without any amelioration procedure was the most impaired. The incorporation of sewage sludge improved the chemical fertility and total porosity of the soil; in addition, soil macroporosity was increased and the distribution between macro- and microporosity became more similar to each other. The natural regeneration treatment with development of scrub vegetation (*capoeira*) and the soil under pasture presented intermediate levels of structural quality and a high degree of similarity in soil physical properties.

Alterations in land use and management caused effects on soil structure. These effects were reflected with considerable sensitivity in the stability of soil aggregates, especially when evaluated through size distributions following agitation in water.

Size distributions of the water stable aggregates were increasingly shifted towards smaller aggregates with increased environmental degradation. Key factors for improvement in the quality of aggregation are the input and residence time of organic matter in the soil.

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