STRUCTURAL REMEDIATION OF AN ALFISOL BY MEANS OF SEWAGE SLUDGE AMENDMENTS IN ASSOCIATION WITH YELLOW SERRADELA (*Ornithopus compressus* L.)

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ABSTRACT

Wastewater treatment generates large amounts of sewage sludge, which when are disposed in highly degraded soils (with a complete loss of the A horizon and a great part of the B horizon), represent an interesting alternative to recover the aggregate level into soil. Within the hierarchy of soil systems, the aggregate level is the one that integrates soil properties that are directly related to soil sustainability. The aim of this study was to determine the effect of different dose of sewage sludge and an annual legume on the structural recovery of a degraded Alfisol. Sludge was added to soil at 0, 15, 30 and 60 t ha^{-1} in treatments with and without yellow serradela (*Ornithopus compressus* L.). After 6 months, the following structural indicators were identified: aggregate distribution, water aggregate stability and bulk density (Da). Results showed that the higher the sludge dose the higher the proportion of macroaggregates and their stability, whereas Da decreased. In spite of the short-term study, data showed that there was a positive effect when amendments were combined with *O. compressus* L. It demonstrated that degradation is likely to be reversed, thus giving to soil more physical support.

Keywords: Biosolids, degraded soils, soil remediation, physical properties.

INTRODUCTION

The generation of large quantities of waste from urban activities and different types of agricultural, industrial and water-related activities, is a concern to environmentalists, farmers and government agencies (Pinochet *et al*., 2004).

Wastewater treatments generate huge amounts of sewage sludge as a result of mechanical, biological and/or chemical treatments applied to these wastes, which are generically called municipal sludge (Marambio and Ortega, 2003; Aguilera *et al*., 2005). At a national level, water treatment plants generate around 220,000 tons of sludge yearly (Carrasco *et al*., 2004). Therefore, sludge disposal is a key issue that may result in a severe problem in the environment. Estimations indicate that, by the end of this decade, wastewater treatment in Chile will be in place in almost very city of the country, generating only in Santiago about 400 tons of sludge per day (Marambio and Ortega, 2003). Under these circumstances, it is clear that failure to seek disposal alternatives we will be facing a serious environmental problem.

Different alternatives for the disposal of such waste have been proposed at the international level, including the option of recycling waste in agricultural soils (Fytili and Zabaniotou, 2008; Fernández *et al*., 2007), as a way to help degraded soils restore their productivity (Esparza *et al*., 2004; Schleef *et al*., 2004; Aravena *et al*., 2007; Lakhdar et al., 2010). It is important to note that at least 46% of the Chilean agricultural area (34.5 million hectares) has certain degree of erosion of which 33% is severely affected (Esparza *et al*., 2004). The interior drylands of the Chilean Coastal Mountain, which are mainly constituted by Alfisols, are one of Chile's most eroded natural regions, with around 2 million hectares highly degraded (University of Chile, 2000). Intensive farming has accelerated this destructive process due to the use of inappropriate practices that severely reduce organic matter, resulting in a decrease of soil quality and unviable conditions for crop production (Celis *et al*., 2007; Curaqueo *et al*., 2010).

Sludge applications to degraded farmlands help improving soil productivity by increasing pH, OM and the levels of N, P and K (Aravena *et al*., 2007, Gallardo *et al*., 2007, Celis *et al.* , 2008). Increased levels of OM tend to promote physical parameters such as soil aggregation and porosity (Darwish *et al*., 1995; Sandoval *et al*., 2008; Sandoval *et al*., 2010), also improving the environment for roots and plant growth (Ellies, 2004). Studies conducted on soils with applications of up to 5% of sewage sludge increased up to 78% aggregate stability as compared to the initial condition of the soil (Guerrero *et al*., 2001). This provides evidence that sludge applications exert a protective effect against erosion (Roldán *et al*., 1996).

Recent research has been done with forage species possible to be adapted to drylands, thus reducing soil degradation problems in the same area under study. Among studied species, it is worth mentioning the annual legume *Ornithopus compressus* L. This legume presents good prospects to be integrated in the interior drylands (Ovalle *et al*., 2005), since these terrestrial environments require species and crops able to survive and reach adequate levels of production under acid conditions and low levels of organic matter. Existing data (Ovalle *et al*., 2006; Del Pozo and Ovalle, 2009) provide evidence that this legume shows better adaptation than native clover usually used on the area. Covering soil with crops have been described as a sustainable alternative for soil management because it allows increasing OM and nutrients in soil profile due to degradation of aboveground and root biomass, as well as improving porosity, soil structure and stability of aggregates (Ovalle *et al*., 2007). This is also supported by Bronick and Lal (2005) who suggest that well managed crops increase C inputs, so reducing erosion. Therefore, the aims of this study was to determine the effect of different application rates of sewage sludge and yellow serradela´s roots on the structural remediation of a degraded Alfisol.

MATERIALS AND METHODS

Soil and sludge sampling

Soil samples were taken from the interior drylands of the Bío-Bío Region (36 ° 37 '18.6 "S, 72 ° 19' 42.2" W) at 0-20 cm deep. Soil taxonomic classification corresponded to a fine, kaolinitic, thermic Ultic Palexeralfs, clayed soil, slopes higher than 15%, having a bulk density of 1.6 g cm^{-3} (Stolpe *et al.*, 2008). These Alfisols are severely degraded by aggressive agricultural practices, with a complete loss of horizont A and almost all of horizont B.

Sewage sludge samples were taken at the wastewater plant of the city of Chillán (36° 36 'S, 72° 07' W). Sludge was produced from mechanically aerated biological reactors, having a capacity of 500 to 600 t of fresh sludge (80% humidity) monthly.

Soil and sludge characterization

Prior to the preparation of mixtures, soil and sludge samples were dried at room temperature in laboratory, and then sieved (2 mm) to allow homogenization of the material. After that, a representative sample for each sludge and soil was taken for chemical characterization (Table 1).

Table 1. Initial chemical characterization of the Alfisol and sewage sludge.

	Units	Soil	Sewage sludge
pH (H_2O)		5.60	5.94
MO	%	2.53	41.95
NO_3-N	mg kg^{-1}	6.50	17.1
NH_4-N	mg kg^{-1}	3.30	424.0
Olsen-P	mg kg^{-1}	5.40	853.2
K available	mg kg^{-1}	29.80	5,591.0
Sum of bases	cmol kg^{-1}	5.47	42.67
Al exchangeable	cmol kg^{-1}	0.02	0.01
CICE	cmol (+) kg^{-1}	5.49	42.7
S available	mg kg^{-1}	1.70	24.6
Fe available	mg kg^{-1}	8.30	836.0
Mn available	mg kg^{-1}	7.60	204.0
Zn available	mg kg^{-1}	1.00	216.0
Cu available	mg kg^{-1}	2.00	4.8
B available	mg kg^{-1}	0.10	10.6
Total N	%	0.15	5.47
C/N		9.3	4.5

Methodology for soil chemical characterization was in accordance with Sadzawka *et al*. (2006) by using composed samples. Additionally, methods recommended by Sadzawka *et al*. (2005) were used for the sludge chemical characterization.

Assay establishment

The assay was conducted in a glass greenhouse located at the experimental field of the Faculty of Agronomy of the University of Concepción, Campus Chillán. The treatments were as follows: CS = non amended soil, no legume; CS-P = non amended soil, cropped with legume; LU15 = soil amended with 15 t ha^{-1} sludge; LU15-P = soil amended with 15 t ha^{-1} sludge and cropped with legume; LU30 = soil amended with 30 t ha^{-1} sludge; LU30-P = soil amended with 30 t ha^{-1} sludge and cropped with legume; LU60 = soil amended with 60 t ha^{-1} sludge; LU60-P = soil amended with 60 t ha^{-1} sludge and cropped with legume.

Treatments with legume were established on the basis of 9 pots per treatment, 3 of which were used to determine soil aggregation, 3 for bulk density determination, and 3 for root biomass. Treatments without legume were established in 6 pots per treatment, 3 of which were used to determine soil aggregation, whereas 3 for bulk density and total porosity.

Sludge/soil mixtures were prepared on the basis of 1 kg of soil plus the corresponding sludge dose applied to each pot. Then they were mixed, homogenized and moistened with distilled water to reach 60% field capacity (soil moisture H-20 mA transmitter, Dragon Device). Each pot was then covered with polyethylene bags to prevent moisture loss and so kept for a month in order to standardize OM mineralization. Treatments were sown on August 20, 2009, with disinfected seeds of yellow serradela (1.5 g pot^{-1}). The assay lasted 6 months, through which soil moisture was maintained between 60-70% field capacity. Humidity was controlled by means of sensors (soil moisture H-20 mA transmitter, Dragon Device) and watered with distilled water. The average temperature ranged between 7 and 10 º C.

Determination of structural characteristics

At the end of the experiment, all pots were air-dried for 10 days. Samples from each treatments were taken from the 3 pots selected to measure bulk density, which was determined by using metal cylinders (3.5 x 5 cm). These samples were then oven-dried (105°C) until reaching constant weight (Blake and Hartge, 1986.)

Root biomass was determined in the other 3 pots for each treatment cropped with legume. Each pot was gently washed with water over a 0.5 mm sieve to collect biomass. Collected roots were air-dried just to eliminate excess of water and then placed into holed-paper bags, so being oven dried (60°C, 48 h). Root biomass was calculated by gravimetry

Both aggregates and their stability were determined from the remaining 3 pots per each treatments. It was done by gently breaking up the soil and passing it through a 4.5-mm sieve (Le Bissonnais, 1996). Then, a 100-g sample per each replicate was selected and transferred to a set of sieves of different diameters (2, 1, 0.5, 0.25 and 0.05 mm). The sieves with the soil sample were immersed in water for 5 min and then agitated for 15 min at 25 cycles min^{-1} (Yoder, 1936).

Due to the presence of a large amount of gravel in these soils, the sand fraction was removed from all samples analyzed, according to the procedure described by Sandoval *et al.* (2010). To achieve it, once the dry mass was determined, the resulting aggregate content of each sieve was immersed for 24 h in a solution of 0.5 N NaOH (50 mL). After that, the sample was agitated about 2 minutes at 15,000 cycles min^{-1}, and then particles were separated by a constant flow of water. Once sand fraction was separated, the sample was dried (105°C, 24 h), thus mass was deducted from the initial weight of the aggregates contained in each sieve. The aggregate percentage was calculated using the following expression:

$$[1] \qquad AG_i = \frac{(MA_i - Ma_i)}{W}$$

where: AG_i is the percentage of aggregate of the sieve i (sand fraction deducted), MA_i is the mass of aggregates and sand retained by the sieve i, MA_i is the mass of sand of the sieve i, W is the total mass of soil evaluated. Mean weight diameter (MWD) was determined by using the procedure described by Kemper and Rosenau (1986).

Experimental design

The experimental design was a completely randomized design with a factorial arrangement of 2 x 4 (legume x rates of sludge application). The results for the physical parameters were analyzed using the analysis of variance ANOVA ($p \leq 0.05$). When finding significant differences between treatments, means were separated according to Tukey's test (SAS, 1999).

RESULTS AND DISCUSION

Bulk density and porosity

The result of analysis of variance (Table 2) for bulk density and porosity indicates that the interaction between both factors, legume and sludge dose, was not significant.

When analyzing the treatments (Table 3), differences were found between the highest application rate (60 t ha^{-1}) and control (CS) for both Da and Pt in cropped treatments. No cropped treatments showed only significant differences ($p \leq 0.05$) for Da when comparing LU30 with CS.

Comparatively, soil amended with sewage sludge and cropped with *Ornithopus compressus* L. had significantly lower values for Da and significantly higher Pt as compared with no cropped amended treatments. It is interesting to note that there was a remarkable effect when adding OM in presence of legume, as found by LU60-P (Table 3). Similarly, a study conducted in a Andisol located in the same region showed that Da decreased and Pt increased when plant residues were added to soil (Sandoval *et al.*, 2008). The Da values obtained in this study are slightly lower than those reported by Stolpe *et al.* (2008) for the same area, which could be explained by the favorable effect of adding to soil sewage sludge in association with legumes. García-Orenes *et al.* (2005) stated the positive effects resulting from the application of sewage sludge, indicating that these residues improve soil structure by decreasing bulk density. Moreover, crops can increase OM and nutrients in soil´s matrix due to

Table 2. F values for bulk density (Da), total porosity (Pt), mean weight diameter (DPM) and sum of macroaggregates ($\sum \geq 0.25$mm).

Source of variation	**Da ($g\ cm^{-3}$)**	**Pt (%)**	**DPM (mm)**	**$\sum \geq 0.25$ mm (%)**
Legume (A)	17.24*	20.33*	74.01*	52.15*
Sewage sludge dose (B)	10.18*	10.28*	7.55*	8.89*
A x B	0.60^{ns}	0.50^{ns}	1.37^{ns}	1.16^{ns}

*Significant ($p \leq 0.05$); ns: not significant.

Table 3. Bulk density (Da), total porosity (Pt) and organic matter (OM) for an Alfisol with different application rates of urban sludge with and without legume.

Treatments	**Da ($g\ cm^{-3}$)**	**Pt (%)**	**OM (%)**
a) With legume			
CS-P	1.53 a	43 b	2.2 b
LU15-P	1.39 ab	48 ab	2.4 b
LU30-P	1.36 ab	49 ab	2.4 b
LU60-P	1.30 b	51 a	3.6 a
b) Without legume			
CS	1.61 a	39 b	1.6 a
LU15	1.53 a	42 ab	2.0 a
LU30	1.44 a	46 a	1.7 a
LU60	1.45 a	45 ab	2.2 a

CS = control (not amended); CS-P = soil + legume; LU15 = soil + 15 t ha^{-1} sludge; LU15-P = soil + 15 t ha^{-1} sludge + legume; LU30 = soil + 30 t ha^{-1} sludge; LU30-P = soil + 30 t ha^{-1} sludge + legume; LU60 = soil + 60 t ha^{-1} sludge; LU60-P = soil + 60 t ha^{-1} sludge + legume. Different letters in same column indicate significant differences for treatments with legume and without legume separately ($p \leq 0.05$).

degradation of biomass, improving the soil physical properties such as porosity, structure and aggregate stability (Frye and Blevins, 1989), thus avoiding erosion and minimizing the dispersion of sludge to nearby areas.

Stability and distribution of water-stable aggregates

Distribution of water-stable aggregates (Table 4) showed a predominance of macroaggregates ($\sum \geq 0.25$ mm). It was observed that amended and cropped treatments showed significant differences ($p \leq 0.05$) for macroaggregates and it corresponding stability (DPM). No cropped amended treatments showed significant differences ($p \leq 0.05$) only at 30 and 60 t ha^{-1} of sludge with respect to control (CS). These results showed that the presence of roots had a fundamental role in macroaggregate stability and in soil formation, which was more notorious when soil was amended with sewage sludge.

Table 4. Distribution of macroaggregates and mean weight diameter (DPM) for the Alfisol studied.

Treatments	**Strainer size (mm)**					**$\sum \geq$ 0.25 mm %**	**DPM (mm)**
	4 - 2	**2 - 1**	**1 – 0.5**	**0.5-0.25**	**< 0.25**		
a) With legume							
CS-T	1.18	9.49	11.40	13.12	14.90	35.18 **a**	0.44 **a**
LU15-T	4.47	8.39	13.22	10.09	10.48	36.17 **a**	0.59 **a**
LU30-T	6.47	10.70	12.87	13.19	11.66	43.24 **a**	0.63 **a**
LU60-T	4.22	14.95	14.00	8.88	13.95	42.06 **a**	0.60 **a**
Cv (%)						10.14	14.76
b) Without legume							
CS	0.34	2.30	6.10	9.91	22.77	18.65 **b**	0.25 **c**
LU15	0.59	7.37	7.98	12.01	3.42	27.95 **ab**	0.40 **a**
LU30	0.77	4.37	10.83	16.86	23.07	32.82 **a**	0.32 **bc**
LU60	0.50	7.37	9.71	12.26	5.25	29.84 **a**	0.39 **ab**
Cv (%)						14.88	9.62

CS = control (not amended); CS-P = soil + legume; LU15 = soil + 15 t ha^{-1} sludge; LU15-P = soil + 15 t ha^{-1} sludge + legume; LU30 = soil + 30 t ha^{-1} sludge; LU30-P = soil + 30 t ha^{-1} sludge + legume; LU60 = soil + 60 t ha^{-1} sludge; LU60-P = soil + 60 t ha^{-1} sludge + legume; DPM = mean weight diameter; Cv: variation coefficient. Different letters in same column indicate significant differences for treatments with legume and without legume separately ($p \leq 0.05$).

Additionally, DPM values from amended and cropped treatments ranged from 0.44 to 0.60 mm, so that no significant differences ($p > 0.05$) were found among treatments. In contrast, no cropped amended treatments showed significant differences ($p \leq 0.05$) at 15 and 60 t ha^{-1} with respect to control (CS). In general, values were lower than cropped amended treatments, especially CS that showed a value of 0.25 mm, a very unstable structural state (Le Bissonnais, 1996).

This greater positive effect due to the contribution of OM in the presence of yellow serradela is clearly evidenced when analyzing the root biomass data (Table 5). The higher the dose amended to soil the higher the root development, being particularly different ($p \leq 0.05$) from the control (CS-P).

Table 5. Root biomass for treatments amended with sewage sludge and cropped with yellow serradela (*Ornithopus compressus* L.).

Treatments	Root biomass (g)
CS-P	4.3 **b**
LU15-P	6.5 **a**
LU30-P	7.6 **a**
LU60-P	7.9 **a**
Cv (%)	11.0

CS-P = not amended (only cropped); LU15-P = soil amended with 15 t ha^{-1} sludge and cropped with legume; LU30-P = soil amended with 30 t ha^{-1} sludge and cropped with legume; LU60-P = soil amended with 60 t ha^{-1} sludge and cropped with legume. Cv = variation coefficient. Different letters indicate significant differences ($p \leq 0.05$).

According to Bronick and Lal (2005), both plant roots and rhizosphere have positive effects on soil aggregation because glue soil particles as their release exudates, which result in physical, chemical and biological changes that positively influence aggregation. Sandoval *et al.* (2007) found a positive response in the aggregation and stability of soil aggregates when legumes (pink clover, alfalfa and white clover) were incorporated to soil in a crop rotation that included wheat, oats and corn. In addition, they also reported that these legume species favored C content into the soil. Additionally, several authors have noted the importance of fungi in soils, as their hyphae are considered to be primary soil aggregators, showing positive correlations with stability of aggregates in natural systems (Borie *et al* ., 2008; Curaqueo *et al*., 2010).

Also, data showed the importance of adding sewage sludge to soil as it increased root biomass, which also improves soil structure, where organic C acts as a nucleus in the aggregate formation (Bronica and Lal, 2005). Sandoval-Estrada *et al.* (2008) indicated that the stability of macroaggregates varies with changes in OM content and management practices, due to the fact that macroaggregates are stabilized by agents such as roots, hyphae and polysaccharides. Furthermore, Oades and Waters (1991) refer to OM as one of the major factors in soil aggregation of Alfisols.

Haynes and Francis (1990) stated the importance of legume crop rotations on soil aggregation. This has been confirmed by several studies that indicate that legume roots increase soil microbial biomass, which generates an increase in water-stable aggregates (Chan and Heenan, 1996; Haynes and Beare, 1997).

CONCLUSIONS

Sewage sludge amendments improved soil structural properties of the degraded Alfisol studied. These improvements were the result of the contribution of soil organic matter, which resulted in a decrease of bulk density, and an increase of total porosity, macroaggregates and soil stability. This was directly related to the increase of amendment application rates. The establishment of *Ornithopus compressus* L. significantly enhanced these parameters due to increased root biomass. This demonstrated that it is possible to recover certain physical properties in highly degraded soils, under the conditions in which this research study was carried out.

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