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Effects of the incorporation of biosolids on soil quality: temporal evolution in a degraded inceptisol (typic endoaquepts)

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Abstract

The purpose of this study was to determine the temporal evolution of soil properties following the incorporation of biosolids in a degraded Inceptisol soil (Typic Endoaquepts). The study was conducted in the Araucanía Region of Chile, where two sampling zones were established: a control zone without biosolid incorporation and a zone with biosolid incorporation. Experimental field plots were used to measure soil quality, including soil respiration (SR), infiltration (IN) and bulk density (BD), according to standard USDA methodology. Laboratory analyses of soil chemistry, including pH, electrical conductivity (EC), organic matter (OM), nitrogen (N), aluminium (Al), phosphorus (P) and sulphur (S), were performed using the analytical techniques of the Chilean Society of Soil Science's CNA. Measurements were performed 17, 170, 365 and 510 days after the biosolids were applied. The results indicated significant changes in soil quality 1.4 years after the incorporation of the activated sludge, particularly in sustained increases of phosphorus content, soil respiration and infiltration. In addition, there was a significant increase in the electrical conductivity of the soil, which ranged from normal to high.

Keywords: land degradation, activated sludge, sewage sludge, soil properties, wastewater, soil parameters

1. Introduction

In Chile, the treatment of domestic wastewater must comply with standards governing the quality of the industrial discharge into surface waters. In recent years, the number of wastewater treatment plants has increased across the nation and was projected to reach 99% treatment coverage by 2010 (SISS, 2006). These treatment plants generate 220,000 tons of biosolids per year, 31% of is generated in the Araucanía Region. The country is therefore facing a new environmental issue associated with the generation and disposal of biosolids (sludge), which represent between 1 and 2% of the total volume of treated wastewater (Sánchez-Monedero *et al.*, 2004).

Biosolids are defined as residual by-products of wastewater treatment that contain accumulations of organic sediment, semi-solids and/or liquids produced during the water purification process, high levels of microorganisms, macro- and micro-nutrients, trace elements and water (Whitehouse *et al.*, 2000; Marambio and Ortega, 2003).

One of the main problems associated with wastewater treatment is in the final destination of the biosolids generated during the treatment. Currently, biosolids are deposited in landfills, but this option has proven to be inadequate as a result of the increasing volumes of biosolids that are being generated. This has led to an urgent search for alternatives for depositing and re-using biosolids (Sanchez-Monedero *et al.*, 2004), and applying them to soil has become an accepted practice in most developed countries. The application of biosolids to soils that have been cultivated for decades could remedy nutrient deficiencies by providing nitrogen, phosphorus, micro-nutrients and organic matter to the soil (Walter *et al.*, 2006).

The nutrients contained in biosolids have several advantages over inorganic fertilisers, foremost of which is that they can be incorporated slowly by growing plants. This is because these organic forms are less soluble in water, and it is thus less likely that they will leach into groundwater or run off into surface waters (EPA, 2000). However, the use of biosolids in agriculture has been criticised due to the possible contribution of heavy metals and an excess of micro-nutrients (e.g. Zn, Cd, Cu, Pb, Cr and Ni) that could become potentially toxic at levels that are two or more orders of magnitude above natural concentrations (McBride *et al*., 1997). This potential source of pollution in agroecosystems could then be transferred to the biotic food chain (Nriagu and Pacyna, 1988).

The potential benefits of biosolids extend beyond their use as traditional fertilisers in agriculture to include soil quality enhancement. Doran *et al.* (1999) define soil quality as “the continuous capacity of the soil to perform as a living system within the limits of the ecosystem and of land use, in order to sustain biological productivity, contribute to the quality of the air and water in the environment, and help maintain the well-being of vegetation and of animal and human life”. In light of this concept, soil should be considered a non-renewable, dynamic and living resource. Thus, from the perspective of soil resource conservation, organic matter content, physical properties (e.g., texture, structure, aggregate stability, porosity) and chemical properties are indicators of soil quality (Wander *et al.*, 2002).

As has been noted in CONAMA-MINAGRI (2000), soil is one of Chile’s most damaged resources; the damage is so extensive that it is difficult to find soils that do not show signs of degradation. Seventy-eight percent of the area under study show moderate to very severe signs of erosion. Moreover, published studies report that 62% of Chile’s territory is currently subject to a process of desertification. This scenario is exacerbated by the fact that soils are the only natural resource that is not covered by legislative regulations designed to guide and ensure sustainable management.

Insufficient attention has been paid to the impact of the application and incorporation of biosolids on soil quality in Chile. In this study, the impact of biosolid application on the physical, chemical and biological properties of the soil and their temporal evolution in degraded soil was determined.

2. Materials and methods

2.1. Area of Study

This study was conducted in the Araucanía Region of Chile (38°03´52.96´´south, 72°51´15.03´´west, 98 meters above sea level) (Figure 1). The climate is predominately warm and rainy with a Mediterranean influence. It rains every month of the year (over 550 mm a^{-1}), although there is a concentration of precipitation in the winter months (approximately 200 mm). The average annual temperature is 12°C with an annual variation of 5°C.

The soils in this area are Los Sauces series Inceptisol, (Typic Endoaquepts) and are textually classified as a moderately fine surface texture (clay 35%, silt 34% and sand 31% within the upper 16 cm of the soil profile) with clay beneath. The soils are deep and are characterised by an alluvial terrace composed of fine, quartz-rich sediment. In general, the topography of the study site is flat or presents a moderate (1 to 3%) slope. Floods occasionally occur during the winter because of the presence of closed valleys (CIREN, 2002). At the time of this study, the land had been used for livestock grazing on natural grasslands for more than five years. The soils showed signs of degradation that manifest as very low plant cover and moderate erosion.

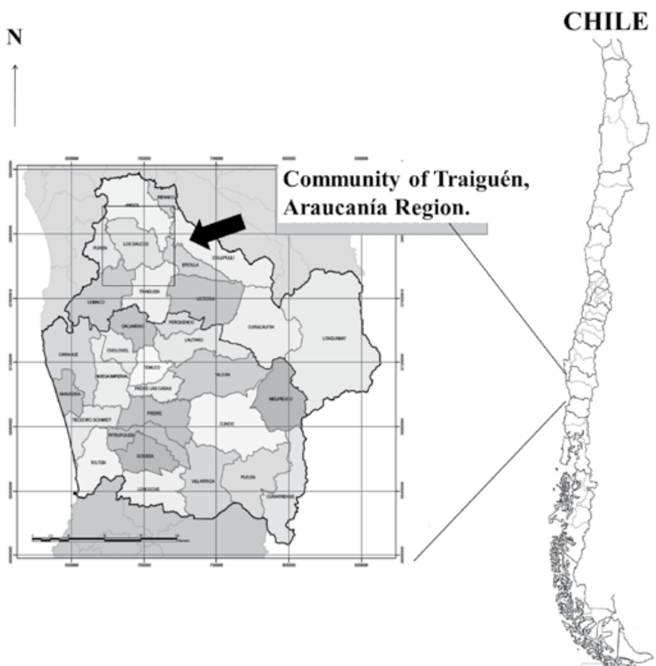

Figure 1. Study site location.

2.2. Experiment

Biosolids

The biosolids applied to the study area were from the wastewater treatment plant located in the community of Traiguén, Araucanía Region. The biosolids have basic pH and high organic matter content (Table 1) and were incorporated into the soil once at a dose of 30 t ha-[1], covering a total surface area of 40 ha. This dose corresponds to the maximum permitted application rate for degraded soils in Chile. The sludge was distributed in homogeneous layers using a dunghill hopper machine, before being incorporated into the soil by ploughing to a depth of 20 cm.

Table 1. Characteristics of the biosolid used.

Parameter	Value
pH	6.9
OM*	587
EC (dS m-1)	2.9
Moisture (%)	75.5
P*	12.0
N*	44.5

OM: organic matter, EC: electric conductivity, * mg kg^{-1}, dry matter.

2.3. Soil Sampling

Between 2008 and 2010, the soil was sampled at 17, 170, 385 and 510 days following biosolid treatment. Two sampling zones were established at the study site: Zone 1, which is the control where no biosolids were applied and Zone 2, where biosolids were applied. Samples were taken at the beginning and end of the evaluation period in Zone 1. In Zone 2, four plots of 20 m^2 each were established two meters apart from one another. The time between the incorporation of the biosolids and the sampling of the soil varied for each plot (Table 2).

Table 2. Soil sampling zones and periods of biosolid application.

Soil sampling zones	Time between the application of biosolid and soil sampling (days)
Zone 1, control	0
Zone 2, biosolid incorporation plot	17
Zone 2, biosolid incorporation plot	170
Zone 2, biosolid incorporation plot	385
Zone 2, biosolid incorporation plot	510

Soil samples were collected at random locations within in each plot, with three replicates for the physical (infiltration [IN] and bulk density [BD]) and biological parameters (soil respiration [SR] analyses, and five replicates for the chemical (organic matter [OM], pH, P, N, S, Al and electrical conductivity [EC]) analyses. More detailed information for these analyses is provided below:

a) Physical properties. IN was measured on site using a 15.2 cm diameter x 10.2 cm long aluminium cylinder, plastic wrap, a 500 ml graduated cylinder, distilled water and a stopwatch in accordance with USDA methodology (2001). BD was measured using the cylinder method with a 7.6 cm diameter x 12.7 cm long aluminium cylinder. The contents of the cylinder were weighed in the laboratory, dried in an oven at 360°C for 48 hours and weighed again.

b) Biological properties. We estimated SR by measuring CO_2 emissions from the soil using the methodology described by the USDA (2001). SR was assessed twice: first with a sample of dry soil and then at field capacity six hours after wetting.

c) Chemical properties. Five soil samples were collected from each plot at a depth of 20 cm. The samples were mixed (approximately 600 g), air-dried and sifted at 2 mm. The following parameters were analysed according Sadzawka *et al.* (2004): pH in KCl in a 1:1 ratio; OM by acid digestion with potassium dichromate and determination by potentiometric titration; available N by KCl extraction and distillation using the Kjeldahl method; P by the Olsen bicarbonate method and colorimetric determination of molybdenum blue; available S by extraction in a solution of calcium dihydrogen phosphate and turbidimetric determination; and Al by extraction with potassium chloride solution and atomic absorption spectrometry analysis. EC was determined in soil extracts.

2.4. Data Analyses

Mean physical, chemical and biological parameters were compared using analysis of variance (ANOVA). The assumptions of the normality of data were tested using the Anderson-Darling test. The Bartlett test was used to test for homoscedasticity. Multiple comparisons were made using Tukey's range test (at $p < 0.05$). The relationship between study parameters was assessed using Pearson's correlation coefficient (r) (Zar, 2010).

3. Results and discussion

The means obtained for physical, chemical and biological soil parameters are shown in Table 3, and the Pearson's correlation coefficients and p-values between the parameters are shown in Table 4.

Table 3. Mean and standard deviation of chemical, physical and biological parameters in the soil without (control) and with the incorporation of biosolids.

Parameter	Control	17 days	170 days	385 days	510 days
pH H_2O	5.75±0.14	6.79±0.11	6.67±0.05	6.40±0.03	5.83±0.02
OM (%)	6.02±1.72	10.12±1.51	5.65±1.40	7.92±0.96	7.49±1.21
Available N (mg kg^{-1})	19.5±1.64	22.33±2.88	18.67±1.52	20.24±0.63	21.72±0.76
Available P (mg kg^{-1})	17.08±2.5	38.3±0.57	35.3±1.15	30.5±1.4	48.3±0.40
Available S (mg kg^{-1})	4.13±0.86	42.81±1.20	37.32±2.19	39.72±3.05	10.79±1.07
Exchangeable Al(cmol(+) kg^{-1})	0.004±0.001	0.007±0.001	0.012±0.001	0.004±0.002	0.002±0.001
EC (dS m^{-1})	1.05±0.09	2.16±0.01	1.73±0.07	2.34±0.09	2.98±0.09
IN (cm hr^{-1})	7.57±0.59	6.06±0.12	15.58±1.20	14.71±0.57	10.08±0.18
BD (gr cm^{-3})	0.99±0.05	1.18±0.09	1.03±0.07	1.06±0.12	1.01±0.13
SR (kgC(CO_2) $ha^{-1}d^{-1}$)	15.16±0.78	8.99±1.24	65.50±5.97	52.34±1.80	39.51±2.13

OM: organic matter, EC: electric conductivity, IN: infiltration, BD: bulk density, SR: soil respiration.

Table 4. Pearson's correlation coefficients (A) and p-values between parameters analysed (B).

(A)

Parameter	Pearson									
	pH	P	Al	EC	OM	N	S	SR	BD	IN
pH	**1**									
P	0.201	**1**								
Al	0.780	0.073	**1**							
EC	0.238	**0.966**	0.122	**1**						
OM	0.497	0.505	0.081	0.557	**1**					
N	0.155	0.696	0.346	0.676	**0.887**	**1**				
S	**0.941**	0.308	0.663	0.406	0.460	0.124	**1**			
SR	0.281	0.323	0.418	0.408	0.303	0.379	0.508	**1**		
BD	0.787	0.328	0.309	0.343	**0.872**	0.649	0.681	0.241	**1**	
IN	0.327	0.167	0.449	0.285	0.317	0.471	0.555	0.980	0.221	**1**

(B)

Parameter	p-values									
	pH	P	Al	EC	OM	N	S	SR	BD	IN
pH	**0**									
P	0.702	**0**								
Al	0.067	0.890	**0**							
EC	0.650	**0.002**	0.818	**0**						
OM	0.315	0.307	0.879	0.251	**0**					
N	0.770	0.125	0.502	0.140	**0.018**	**0**				
S	**0.005**	0.552	0.151	0.425	0.359	0.815	**0**			
SR	0.590	0.532	0.410	0.422	0.560	0.459	0.303	**0**		
BD	0.063	0.526	0.552	0.506	**0.024**	0.163	0.137	0.646	**0**	
IN	0.527	0.751	0.372	0.584	0.541	0.346	0.253	**0.001**	0.674	**0**

The bold values are different from 0 with a significance level of alpha = 0.05.
OM: organic matter, EC: electric conductivity, IN: infiltration, BD: bulk density, SR: soil respiration.

The pH of the control soil and the pH of the soil to which the biosolids were applied, which was measured 510 days after the application of the biosolids, were similar ($p > 0.05$). However, these values are less than those described by CIREN (2002), where pH ranged from 6.0-6.7 depending on soil depth in contrast with the 5.8 value obtained from the present study. At 17 days after the biosolids were incorporated into the soil, the pH values were significantly different than the control ($p < 0.05$). These results are consistent with those obtained by Tang and Yu (1999), who observed that pH rises sharply after the incorporation of biosolids and then gradually decreases. The drop in pH to the same levels as the control soil after 510 days was likely because the biosolids were treated with lime prior to their use, observed no progressive acidification processes. Aravena *et al.* (2007) suggested that when biosolids with high levels of organic material are incorporated into the soil, there is a reactivation of the bacteria present in both the biosolids and the soil, increasing the metabolism and decreasing soil pH values. It is particularly important to consider the pH of the soil with respect to the abundance of trace metals in some biosolids (Singh and Agrawal, 2008).

pH was significant correlated with available S ($p < 0.05$, r = 0.94), with 89% joint variability (Table 4). This likely resulted because available S is subject to microbial oxidation, which transforms S into sulphate under aerobic conditions and leads to a decrease in soil pH. The type of soil to which the biosolid is applied also influences this process (Deng *et al.*, 1990). Similarly, Celis (2007) observed a highly significant positive correlation between the content of biosolid and bacterial growth, and suggested that the OM content of sludge and the resulting metabolic activity of bacteria produced organic acids that caused acidification.

When biosolids were added to the soil, the P concentration increased significantly relative to the control soil (Table 3). This is consistent with the observation by Heathwaite *et al.* (2006), who noted that the increase in available P due to the incorporation of biosolids had a cumulative effect over time. Significant increases in available P in plots with biosolids incorporated suggest the occurrence of solubilisation processes. This is consistent with the results of Afif *et al.* (1995), who evaluated the effect of manure application on soils, finding that OM through manure application increased P availability because the humic radicals compete for phosphorus adsorption sites.

EC (Table 3) showed a similar pattern to that of available P, increasing 17 days after the biosolids were incorporated, and then decreasing at 170 days. After 510 days, EC increased significantly. Cuevas *et al.* (2006) suggested that increases in electrical conductivity are indicative of high levels of salts and/or water-soluble compounds in soils. Matus *et al.* (2002) found that mineralised OM released soluble N, increasing electrical conductivity. In this way, the transformation of organic N into ammonia produces an increase in salt concentration and a decrease in soil pH; that is, mineralising OM in the conversion of organic N into mineral N (Gabrielle *et al.* 2005).

The results (Table 4) also showed a strong positive correlation between the values of available P and the EC ($p < 0.05$, r = 0.97 and a determination coefficient of 93%). Omonode and Vyn (2006) suggested that the apparent electrical conductivity can be an indirect indicator of soil nutrient concentrations, and that strong relationships between EC and nutrients may help delineate fertility management zones.

Heathwaite *et al.* (2006) reported significant increases in OM, N and P when biosolids were added to soil. Magdoff and Amadon (1980) suggested that the rapid decomposition of OM in the biosolids that results from low C/N ratios causes the elements N, P and S to become readily available. Likewise, Tian *et al.* (2008) noted that OM produced bioactivity over time, promoting reactions associated with nutrient availability and the entire active process between the soil components. In the current study, a high positive correlation between OM and N ($p < 0.05$, r = 0.9) was obtained with an 81% change in the values of organic matter associated with changes in concentrations of N (Table 4).

Table 3 shows that the concentration of exchangeable Al increased at 17 and 170 days and then decreased at 385 and 510 days after the incorporation of biosolids into the soil. Studies by Sauerbeck (1991), Evans *et al.* (1995) and Walter *et al.* (2006) indicate that the nature of the soil plays a fundamental role in the availability of trace metals, which suggests a difference in Al-speciation between the soils (Pypers *et al.*, 2005). Al concentration is generally higher at lower pH values. However, the current study did not find a negative correlation between pH and exchangeable Al. Pypers *et al.*(2005) propose that the ability of organic residues to decrease extractable Al-concentrations in the soil also depends on their quality; to remove the Al from the exchange complex, residues must provide substituting cations to neutralise the excess negative charge. It may therefore be suggested that basing availability of trace elements on the level of pH alone is not sufficient.

Lopez *et al.* (2006) observed that the Al content in soil decreased significantly with P application. The decrease in Al occurs because it precipitates when in contact with a strong base such as phosphates, which were added to the soil through the incorporation of biosolids. Mokolobate and Haynes (2002) found decreases in Al content after applying different types of organic waste. They attribute the decrease in Al to the process of decarboxylation during the decomposition of organic matter where there is consumption of protons. They also suggest that the $CaCO_3$ content of the organic fertilisers used could contribute to this response. No negative correlation between P and Al was observed in the current study, but available P concentrations increased significantly when biosolids were added to the soil.

We observed that the rate of water IN into the soil (Table 3) decreased when biosolids were incorporated. This is likely due to the loss of surface structure caused by mechanical fracturing of the soil that results from the incorporation of the biosolid (dunghill hopper machine) and saturation with available organic material-sludge. In turn, incorporating biosolids into the soil produces a temporary change in the silt-clay-sand percentages since biosolids contain concentrations of micro-and macro-nutrients as well as considerable amounts of sediments. Miller and Donahue (1990) found that infiltration decreased when the size or number of porous spaces were limited by conditions such as the destruction of soil structure, sealing of pores by particles or slower movement of deeper waters when they reach denser subsoils.

The IN rate increased significantly over time in soils to which biosolids were added compared with the control soil. This finding can most likely be attributed to changes in the surface layer of the soil profile that result from greater particle aggregation with OM, increasing macroporosity. Similar observations were made by Bouanani *et al.* (2002). Alternatively, Mora (1993) found that increased IN produced an increase in the leaching of bases and consequently a decrease in soil pH, which was observed at 510 days after the incorporation of the sludge into the soil in the present study. We anticipate that the addition of biosolids will cause an increase in porosity and the soil's total water retention capacity over time, thus increasing the amount of water that is available to plants.

SR significantly increased when biosolids were added to the soil. Respiratory activity decreased during the first measurement period (17 days) and had the greatest activity at 170 days. SR tended to stabilise thereafter, maintaining values higher than the control soil (Table 3). The decrease in SR 17 days after the incorporation of biosolids was mainly due to the reduction of the porous space because organisms in both biosolids and soil need adequate ventilation to increase their metabolism and produce CO_2. This is confirmed by the high positive correlation between SR and IN ($p < 0.05$, r = 0.98, with a joint variability of 96%; Table 4). Prochette *et al.* (1991) suggest that low respiration is obtained when there is less porosity (compaction) in the soil.

The amount of carbon dioxide produced with SR depends on the number and types of organisms present both in the soil and in the incorporated biosolids (Garland *et al.*, 2010). Varnero (1994) suggested that the measurement of evolved CO_2 is a reflection of the overall biological activity of the soil and can be considered a reflection of the energy level of the medium. Quemada and Menacho (1999) suggest that the application of biosolids to soil has a dual effect on respiration; it increases the availability of organic C and nutrients, but may decrease respiration if the sludge contains high levels of toxic heavy metals. The latter was not observed in the present study because the biosolids applied did not have significant concentrations of heavy metals.

Comparing these SR results with the classes of SR and soil conditions derived by the Woods End Research Laboratory (1997), the control soil in this study had moderately low biological activity (15.6 kg $C(CO_2)$ ha^{-1} d^{-1}). Alternatively, the soil with biosolids added had lower biological activity (8.6 kg $C(CO_2)$ ha^{-1} d^{-1}) at 17 days after application which then increased to ideal values at 170, 385 and 510 days after application (62 kg $C(CO_2)$ ha^{-1} d^{-1}, 52.3 kg $C(CO_2)$ ha^{-1} d^{-1} and 39.5 kg $C(CO_2)$ ha^{-1} d^{-1}, respectively) with adequate loads of organic matter and active microbial populations. Gabrielle *et al.* (2005) suggested that the application of biosolids to clay loam soil provides optimal OM and pH conditions, among other factors, to ensure the proper functioning of the soil's microbial action.

The BD was affected by the addition of biosolids to the soil, significantly increasing 17 days after the incorporation of biosolids. However, at 170 and 385 days, BD values decreased significantly relative to the first stage of the study. These results are consistent with those obtained by Ramirez *et al.* (2007), who found a decrease in the BD when biosolids were applied to the soil. This in turn caused a change in soil porosity because there is an inverse relationship between these two properties: as BD decreased, porosity increased. This ultimately determines the aeration capacity and behaviour of water in the soil. The decrease in soil porosity in the first evaluation period can be attributed to the soil characteristics (i.e. young and stable clay loam soils). In this respect, Matus *et al.* (2002) noted that the BD was affected by soil properties. As time passed following the incorporation of biosolid into the soil, the BD decreased to values close to those observed in the control soil. In other words, there was an increase in macroporosity due to the space that was generated within the soil matrix by the degradation of OM present in biosolids. This is confirmed by the high positive correlation obtained between BD and MO ($p < 0.05$, r = 0.87), along with a joint variability percentage of 76% (Table 4). These results are consistent with those reported by previous authors, who note that applications of OM to soils cause a decrease in BD due to an increase in macroporosity (Matus *et al.*, 2002; Cuevas *et al.*, 2006).

In general, there is a close relationship between the type and quality of biosolids incorporated into the soil and the current state of the soil that receives them. In the current study, a rapid and sustained increase in soil quality with the addition of biosolids to degraded soils was found. The rise in OM increased water infiltration and cation exchange capacity, improving soil structure and preventing erosion.

4. Conclusions

The results from this study showed significant changes in soil quality up to 1.4 years after the application of biosolids. In particular, there were sustained increases in the concentration of available P, SR and IN. After the incorporation of biosolids into the soil, OM was assimilated by the system, increasing its macroporosity. In addition, there was a significant increase in the EC of the soil analysed, which went from normal to high. The above observations allow us to present two general conclusions:

- Degraded soils respond positively to the incorporation of biosolids and their quality is improved. This represents a major step forward in the control and reduction of erosion and sedimentation of soils.
- The maximum amounts of biosolids that can be applied to the soil depend on the state of the resource as well as the characteristics of each type of soil.

Long-term studies on the effects of biosolids incorporation on the leaching of N and P from the main soil types present in the south-central Chile (Ultisols, Andisols, and Entisols) are necessary for a better understanding of the overall benefits of biosolids incorporation into soils.

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