RESEARCH

PLANT RESPONSE TO SALMON WASTES AND SEWAGE SLUDGE USED AS ORGANIC FERTILIZER ON TWO DEGRADED SOILS UNDER GREENHOUSE CONDITIONS

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ABSTRACT

The potential toxicity of urban sewage and farmed salmon sludge, as well as their fertilizer potential, was evaluated by a battery of tests carried out with lettuce (*Lactuca sativa* L.) and annual ryegrass (*Lolium multiflorum* Lam.) cv. Winter Star. Wastes were evaluated in a Patagonian soil (Andic cryofluvent) and a granitic soil (Ultic Palexeralf). The treatments were municipal sewage sludge (MSS), salmon ground-farming waste (PSW) and salmon lake-farming waste (LSW) at different rates: 25, 50, 75, 100 and 150 t ha^{-1}. Bioassays in lettuce were conducted for germination index (GI), radicle and hypocotyl structure length. Test in ryegrass were conducted for aboveground biomass yield. The phytotoxicological results from Patagonian soil showed significant differences ($P \leq 0.05$) among sludge, where the highest values for GI, radicle and hypocotyl length were for LSW, followed by PSW. Results from granitic soil showed no significant differences among sludge added. In both soils, MSS treatment at application rate of 150 t ha^{-1} presented the smallest radicle length, not showing development of the hypocotyl structure. Biomass data indicated that MSS, PSW and LSW sludge can be applied at 25 to 150 t ha^{-1} on Patagonian soil and only LSW sludge on granitic soil. However, its addition should be complemented with N and K inorganic fertilizer to increase pasture yield. MSS and PSW sludge applied at 150 t ha^{-1} was clearly detrimental for crop yield, especially when applied to granitic soil.

Key words: fish sludge, salmon waste, urban sludge, organic fertilizer, degraded soil.

INTRODUCTION

Use of organic wastes in agriculture seems to be a good ecological and economical alternative, since it offers a locally available fertilizer source, and their removal reduces risks of pollution and costs of disposal (Mazzarino *et al*., 1997). Sewage sludge and fish wastes contain organic matter and many nutrients and therefore could be used as fertilizer in agriculture (Shober *et al*., 2003; Teuber *et al*., 2005). On the other hand, there is an enormous preoccupation that organic wastes can constitute a risk to human health, crops, soil and water ecosystems when applied without agronomic criteria (Page and Chang, 1994). Salmon waste consists mainly of soluble metabolic products as well as solids present in the form of faeces and uneaten feed (Naylor *et al*., 1999).

In recent years, Chile has remarkably increased the production of sewage sludge, and it is expected that by the end of the present decade all residual waters from the cities will be treated. At present, Chile generates around 200 t d^{-1} of dried urban sludge, and by 2010 it could reach 300 t d^{-1} (Celis *et al*., 2006). Chilean salmon industry has evolved from a production of 24 000 t of fish in 1990 to 495 000 t in 2003; it is estimated that each ton of farmed salmon produces 1.4 tons of sludge. At present there is an enormous preoccupation that biosolids may contaminate pristine waterways, ruin livelihoods and damage Chile's reputation for quality produce. Besides nutrients and organic matter, sludge also contains pathogens, heavy metals and water, so soil application could be limited (Shober *et al*., 2003). According to Page and Chang (1994) several trace elements (As, Cd, Hg, Pb, Se, and Zn) present in organic wastes could pose risks to human health, plants (Cu, Ni, and Zn), or animals (Mo).

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In some volcanic soils its addition should be complemented with inorganic nutrients to obtain adequate mineralization (Teuber *et al*., 2005). The presence of crops can greatly induce P mineralization and, consequently, enhance N mineralization process (Ibrikci *et al*., 1994). Application of organic wastes to agricultural land must be done at rates that allow nutrient needs of the crop not to be exceeded (Sims and Pierzynski, 2000). At certain rates, sludge-amended soils reduce the possibility that runoff could contaminate water with N and P and contribute to eutrophication (Shober *et al*., 2003). According to Mazzarino *et al.* (1997), soils of the Argentinean Andean-Patagonian region show a high capacity of P retention and organic matter stabilization, which may reduce both P and N availability. There is little research published on the application of sewage sludge and salmon wastes into eroded soils in South America, and particularly on Chilean Patagonian soils. Previous studies are limited to volcanic soils (Teuber *et al*., 2005) and agricultural soils (Salazar and Saldaña, 2007) of southern Chile, and of the Argentinean Patagonian region (Mazzarino *et al*., 1998; Laos *et al*., 2000). In the Chilean Patagonian region, 80% of soils are affected by wind erosion processes, whereas 39% of the soils in the Bio-Bio Region are rain-eroded (Pérez and González, 2001). For that reason, there is a great potential to recover degraded soils that could be used for recycling of organic residues as fertilizer.

The objectives of this research were to: (i) identify the nutrients of municipal sewage sludge and salmon wastes and (ii) evaluate rates of these organic wastes amended to degraded soils in a bioassay test with lettuce and in a greenhouse trial with ryegrass as an indicator plant to determine their potential use in agriculture.

MATERIALS AND METHODS

Soil and sludge samples

The experiment was performed using two different degraded soils; samples were taken from the surface (0-20 cm) of a deforested site under native pasture. In one case, soil samples of a Patagonian soil (Entisol), Andic cryofluvent, were obtained from a site located 50 km east from Coyhaique (45º30' S; 71º44' W), in the Chilean Patagonian region. Physically, this Patagonian soil is sandy loam textured, with less than 5% slope and 1 g cm^{-3} bulk density (by own determination in lab). Sampling location corresponded to a cold steppe, at the Eastern slope of the Andes Mountains, near to the borderline with Argentine. In the second case, soil samples of a granitic soil (Alfisol), Ultic Palexeralf, were obtained of a site located 10 km west from Quillón (36º40' S; 72º27' W) in the Bío-Bío Region. This granitic soil presents low water infiltration, typical of the rain-eroded coastal region of Chile, clay texture, with more than 15% slope and 1.4 g cm^{-3} bulk density (Stolpe, 2005). In this study these two degraded soils were tested based on their evolution processes: a young wind-eroded soil (Entisol), and an old rain-eroded soil (Alfisol).

Urban municipal sewage sludge (MSS) was collected from an activated sludge reactor at the wastewater treatment plant of the city of Coyhaique (45º34' S; 72º04' W). Salmon sludge was collected from the settling zones at two commercial salmon farms: i) a land-based salmon pisciculture located 10 km from Puerto Octay (40º58' S; 72º52' W), Los Lagos Region, and ii) a lake-salmon farm located in Lake Tarahuín (42º42´S; 73º45´W), Chiloé. Land-based salmon pisciculture waste (PSW) was collected with shovel from the sediment in accumulation ponds, whereas lake-salmon waste (LSW) was collected with dredges from the sediment (0-20 cm) under cages at 20 m deep.

Soil and sludge samples were air-dried to ambient temperature and then ground to pass a 2 mm sieve. Then, different sludge/soil ratios were prepared from mixing 1 kg of soil with sludge at doses of 25, 50, 75, 100 and 150 t ha^{-1} (dry-weight basis). These sludge/soil ratios were incubated in clean plastic bags by 15 days, using a growing chamber with controlled temperature (25 ± 2 ºC) and humidity (60-70%). After that, chemical analysis (dry-weight basis) was performed to each sludge/soil ratio with no duplicate.

Bioassay test

Incubated sludge/soil mixtures allowed germination tests, following the methodology described by Zucconi *et al.* (1981), here modified. Single layer of 20 lettuce seeds were placed in covered 10-cm Petri dish on filter paper Whatman Nº 3 previously moistened with 5 mL of an extract prepared at 1:10 ratio of 50 g mixture:500 mL distilled water, obtained from each sludge/soil ratio with four replicates. Following, each dish was covered and then placed in plastic bags to avoid humidity losses. Dishes were placed in germination chamber at 22 ± 2 °C by 120 h in darkness. As negative control, to assure germination, distilled water was used. As positive control, to assure total seed inhibition, a salt of Zn (II) 0.001 M was used.

Consequently, germination treatments were MSS, PSW and LSW at different sludge addition rates (25, 50, 75, 100 and 150 t ha^{-1}). A control with no sludge addition to soil, was also included (T). Radicle and hypocotyl emerged from seeds were measured after germination period. A seed was considered germinated when a radicle structure was visible. Germination index (GI) was calculated according to Tiquia (cited by Celis *et al*., 2006). Petri dishes were placed in a freezer at -3 ºC immediately after germination, and when dishes were defrosted biological material had a soft consistency, facilitating measurements on radicle and hypocotyl.

Greenhouse trial

Air-dried soils and sludge ground to pass a 2 mm sieve were employed. Pots with drainage holes were filled with 1.2 kg of soil mixed thoroughly with sludge. Annual ryegrass var. Winter Star was sown at 0.4 g pot^{-1} by 11 October 2006. Soil water content in the pots was maintained at 70-80% of field capacity throughout the experiment. Mean greenhouse temperature ranged between 18 and 24ºC. Photoperiod was 17:7 (Light: Dark). A completely randomized design with three replicates was used to compare sludge at 0 (control), 25, 50, 75, 100 and 150 t ha^{-1} (dry weight) and inorganic fertilizer (140 kg N, 200 kg P and 130 kg K ha^{-1}) applied as potassium nitrate and superphosphate. A no-fertilizer control (T), and an inorganic fertilizer (F) were included. Triplicate subsamples were used for chemical analyses in laboratory at Environmental Sciences Centre-Universidad de Concepción (EULA). The ryegrass was cut two times during the experiment period of two months (5 cm residual height). Samples were weighted fresh and oven dried at 65 ºC for 48 h to determine biomass yield (g pot^{-1}) and then transformed to dry matter (kg ha^{-1}).

Analytical methods

The samples were freeze-dried and ground to a fine powder to ensure homogeneity before analysis. Soil samples were analyzed according to Sadzawka *et al.* (2006). Municipal sludge and fish waste was analyzed for macronutrients, micronutrients and heavy metals. Samples of wastes were analyzed according to Sadzawka *et al.* (2005). Waste pH was determined in a sludge/water solution (equivalent to 1:5). Soil pH was determined in a soil/water solution (equivalent to 1:2.5). Total N in all samples was determined by semi-micro Kjeldahl. Heavy metals (As, Cd, Cr, Cu, Pb, Hg, Mo, Ni, Se and Zn) were determined by flame atomic absorption spectrometry (Perkin-Elmer spectrometer, model 1100B, Phoenix, Arizona, USA). Organic C by Walkley-Black wet digestion and extractable P in 0.5 M $NaHCO_3$ (Olsen-P) using the molybdate ascorbic acid method. Elements Ca, Mg, K and Na were determined in 1 N NH_4OAc by flame emission spectrometry and EDTA titration. Zn, Cu, Mg and Fe were determined by flame atomic absorption spectrometry and HNO_3-HCl digestion. Aluminum was extracted with a solution of KCl 1 M and by atomic absorption spectrometry.

Statistical analysis

Data (GI, radicle and hypocotyl length, biomass, and nutrient absorption) were subjected to analysis of variance (ANOVA) procedures for a randomized complete block design using the SAS Statistical Software Package. Differences among treatment means were compared by means of the Tukey´s test. Statistical comparison was made with a 5% significance level.

RESULTS AND DISCUSSION

Initial degraded soils data showed low organic matter (OM), N, P, Ca, Na and Al concentrations (Table 1). In comparison, Patagonian soil analysis indicated lower P, Al, Mn, Zn and Cu, and higher pH, OM, N, K, Ca and Na than granitic soil. Both soils presented high K concentrations. Municipal sewage sludge and salmon wastes presented high OM (values >15%) and NH_4-N (values >700 mg kg^{-1}). All three sludge showed low C/N ratios with values of <11/1. Even though it is difficult to compare these values with those from other studies because of the differences in conditions under which the wastes were produced, these values are generally similar than previously reported values for salmonid manure content (Teuber *et al*., 2005). MSS had much higher OM, N, P, K, Mg, and Na contents, and lower pH, Al, Fe, and C/N than PSW and LSW. Ca, Fe, and Mn were higher in LSW than in MSS and PSW. LSW had low N and P concentrations, in agreement with Teuber *et al.* (2005), probably because sludge came from underneath cages of lake. Higher K levels in LSW than in PSW were probably the result of lake sediment in the waste than of waste composition since soluble components from fish feces and food are leached by moving water. Calcium and Na concentrations were higher in LSW than in PSW, probably because of the decomposing lacustrine organisms. High Al, Fe and Mn concentrations could be related to silica and sand contamination (Teuber *et al*., 2005).

One of the chemical characteristics of interest when livestock manure is used as a soil fertilizer is the concentrations of toxic substances, such as heavy metals (Naylor *et al*., 1999). Sewage sludge and salmon wastes used in this study did not exceed the heavy metal levels (Table 2), a similar trend observed by Salazar and Saldaña (2007). It is precise to indicate that at present date, there is no official Chilean regulation regarding sludge land application.

Sludge application in Chilean Patagonian soil resulted in increases in N, P, Mn, Zn and Cu, as well as a decrease of K and Al in soil solution as sludge rates increased (Table 3). NH_4-N and Olsen-P increased with increasing sludge rates, ranging 37.3 to 2197.5 mg kg^{-1} and 7.3 to 38.3 mg kg^{-1}, respectively.

Sludge application in Chilean granitic soil resulted in increases in N, P, Mn, Zn and Cu, as well as a decrease of K and Al in soil solution as sludge rates increased, similarly than on Patagonian soil (Table 4). Granitic soil NH_4-N and Olsen-P increased with increasing sludge rates, ranging 28.5 to 1716.7 mg kg^{-1} and 6.3 to 41 mg kg^{-1}, respectively. In both degraded soils the treatments influenced OM, NH_4-N, and Olsen-P content of the soil, the highest values corresponding to the highest rates, in agreement with other study conducted in volcanic soil (Mazzarino *et al*., 1997). There can be advantages to the increase in bioavailable P in sludge-amended soils, such as improved plant growth as soil P deficiencies are corrected; and disadvantages, such as an increased potential for the loss of water-soluble P (Shober and Sims, 2003). All treatments resulted in

Table 1. Initial chemical characteristics (dry-weight basis) of Granitic soil, Patagonian soil, municipal sewage sludge (MSS), land-based salmon pisciculture waste (PSW) and lake-salmon sludge (LSW).

Characteristic	Granitic soil	Patagonian soil	MSS	PSW	LSW
pH (water)	5.6	6.8	6.4	7.0	6.7
Organic matter, %	2.5	2.9	49.90	20.7	18.3
Total N, %	0.15	0.12	5.89	1.10	1.35
NH_4-N, mg kg^{-1}	3.3	3.8	4905.0	1687.5	730.0
Olsen-P, mg kg^{-1}	5.4	3.2	1407.8	480.0	19.9
K available, mg kg^{-1}	129.8	414.3	3604.2	30.0	120.8
Ca, cmol kg^{-1}	3.73	6.09	6.66	0.76	17.9
Mg, cmol kg^{-1}	1.37	1.69	7.81	0.74	0.43
Na, cmol kg^{-1}	0.03	0.08	0.92	0.14	0.57
Al, cmol kg^{-1}	0.02	0.01	0.02	0.03	0.03
Fe, mg kg^{-1}	8.3	9.1	4.4	6.2	11.0
Mn, mg kg^{-1}	7.6	0.3	1.2	0.6	2.5
Ratio C/N	9.3	13.4	4.9	10.5	7.5

Table 2. Heavy metals concentrations (mg kg^{-1}) presented in municipal sewage sludge (MSS), land-based salmon pisciculture waste (PSW) and lake-salmon sludge (LSW).

Parameter	Sludge[1]			EU[2]
	MSS	PSW	LSW	
Arsenic (As)	1.33	0.73	0.94	40
Cadmium (Cd)	0.74	0.69	1.77	40
Chromium (Cr)	11.74	8.68	9.7	1500[3]
Copper (Cu)	239.6	29.0	24.3	1200
Lead (Pb)	0.89	2.05	29.98	400
Mercury (Hg)	0.63	0.024	0.15	20
Molybdenum (Mo)	< 0.15	< 0.15	< 0.15	-
Nickel (Ni)	12.7	24.5	7.4	420
Selenium (Se)	0.054	0.81	1.16	100
Zinc (Zn)	684.6	390.4	364.8	2800

[1] Values at dry-weight basis; [2] Ceiling concentration limits for all sludge applied to land at European Union; [3] As applied at Spain. Source: Castro *et al.* (2007).

Table 3. Soil chemical analyses (dry-weight basis) per treatment at the end of incubation period of municipal sewage sludge (MSS), land-based salmon pisciculture waste (PSW) and lake-salmon sludge (LSW). Based on the addition of sludge at different rates in a degraded Chilean Patagonian soil.

Treatment	pH	OM	Total N	NH_4-N	P	K	Ca	Mg	Na	Al	Fe	Mn	Zn	Cu	C/N
		%		mg kg^{-1}			cmol kg^{-1}				mg kg^{-1}				
T[1]	6.8	2.6	0.12	25.4	4.7	97.8	5.7	1.87	0.09	0.06	80.2	0.7	0.8	0.1	12.4
MSS[2]															
25	6.6	2.6	0.14	274.0	8.4	86.9	5.28	1.83	0.10	0.01	74.2	1.7	4.4	1.8	10.5
50	6.6	2.8	0.17	1227.0	13.0	90.0	5.38	1.71	0.10	0.01	61	3.8	10.4	3.1	9.7
75	6.7	3.1	0.18	1415.6	15.4	87.9	5.30	1.66	0.10	0.01	70.6	5.4	14.8	4.1	10.1
100	6.7	2.9	0.18	1321.2	20.4	81.9	5.18	1.62	0.10	0.01	82.4	7.8	18.8	5.3	9.4
150	7.1	3.2	0.19	2197.5	28.1	76.9	5.07	1.54	0.10	0.01	69.4	8.8	25.4	6.8	9.7
PSW[2]															
25	6.5	2.7	0.14	37.8	7.3	90.9	5.32	1.83	0.09	0.02	75.0	1.3	1.8	1.1	11.4
50	6.5	2.6	0.16	87.7	10.0	87.9	5.25	1.66	0.09	0.03	73.4	2.0	3.2	1.1	9.3
75	6.6	2.7	0.16	182.0	18.1	83.9	5.57	1.79	0.09	0.04	74.0	2.6	5.2	1.2	9.8
100	6.8	3.23	0.16	176.4	21.3	81.9	5.57	1.75	0.10	0.03	76.4	2.4	5.0	1.1	11.6
150	7.2	2.6	0.18	213.4	29.0	83.9	5.70	1.62	0.10	0.04	74.6	3.0	8.2	1.3	8.5
LSW[2]															
25	6.4	2.6	0.17	37.3	10.3	97.8	6.20	1.95	0.10	0.05	89.8	2.6	2.2	1.0	8.7
50	6.3	2.8	0.19	67.4	15.7	92.9	5.88	1.79	0.10	0.05	108.4	4.0	2.6	1.0	8.9
75	6.3	2.9	0.16	86.5	21.9	87.9	5.93	1.83	0.10	0.05	119.8	5.4	3.6	1.1	10.3
100	6.2	3.3	0.16	105.6	27.1	84.9	5.8	1.75	0.10	0.05	196.0	10.2	5.0	1.1	11.6
150	6.2	3.6	0.19	160.6	38.3	77.9	6.43	1.66	0.11	0.06	192.0	10.6	6.8	1.1	10.9

[1]Control (no addition); [2]Treatments at different rates (25, 50, 75, 100 and 150 t ha^{-1}).

Table 4. Chemical treatments analyses (dry-weight basis) at the end of incubation period of municipal sewage sludge (MSS), land-based salmon pisciculture waste (PSW) and lake-salmon sludge (LSW). Based on the addition of sludge at different rates in a degraded Chilean granitic soil.

Treatment	pH	OM	Total N	NH_4-N	P	K	Ca	Mg	Na	Al	Fe	Mn	Zn	Cu	C/N
		%		mg kg^{-1}			cmol kg^{-1}				mg kg^{-1}				
T[1]	5.5	2.0	0.11	43.7	1.6	31.0	3.40	1.38	0.03	0.08	39.4	27.0	1.1	2.0	10.7
MSS[2]															
25	5.8	2.2	0.13	294.4	6.3	30.0	3.33	1.34	0.03	0.01	40.2	30.8	5.4	3.1	9.7
50	6.1	2.4	0.13	921.3	10.1	29.0	3.28	1.29	0.03	0.01	42.2	37.8	9.0	4.1	10.9
75	6.3	2.3	0.12	1307.8	13.8	31.0	3.63	1.34	0.03	0.01	36.6	47.2	13.2	4.9	11.2
100	6.6	2.4	0.17	1469.5	18.5	31.9	3.95	1.34	0.04	0.01	37.0	56.4	16.8	5.8	8.2
150	6.9	2.5	0.23	1716.7	25.7	33.9	3.72	1.25	0.03	0.02	39.4	110.0	23.6	8.2	6.2
PSW[2]															
25	5.7	2.2	0.10	46.2	8.0	30.0	3.20	1.25	0.03	0.04	37.6	26.2	3.2	3.2	12.3
50	5.9	2.3	0.12	61.8	11.8	28.0	3.22	1.25	0.03	0.04	39.4	25.0	4.6	7.1	10.9
75	6.1	2.5	0.12	73.1	16.3	30.0	3.60	1.29	0.03	0.04	37.2	21.0	4.8	5.1	11.7
100	6.5	2.7	0.16	102.2	17.7	28.0	3.55	1.21	0.03	0.04	39.6	26.4	5.6	5.2	9.8
150	6.5	2.5	0.16	180.9	22.7	26.0	3.65	1.17	0.03	0.05	43.6	40.0	7.6	2.4	9.1
LSW[2]															
25	5.4	2.1	0.10	28.5	10.8	31.0	3.20	1.25	0.03	0.07	53.6	26.0	2.8	4.4	11.6
50	5.5	2.1	0.12	60.7	19.1	31.0	3.22	1.25	0.03	0.06	76.6	26.4	3.4	2.3	10.0
75	5.6	2.7	0.12	111.2	24.0	30.0	3.60	1.29	0.03	0.07	84.0	26.0	4.0	2.0	13.0
100	5.6	3.0	0.13	112.3	33.1	30.0	3.55	1.21	0.03	0.07	94.4	27.8	5.2	2.1	13.3
150	5.6	3.1	0.15	155.0	41.0	29.0	3.65	1.17	0.03	0.07	162.0	32.0	7.0	2.2	11.7

[1]Control (no addition); [2]Treatments at different rates (25, 50, 75, 100 and 150 t ha^{-1}).

a depletion of available K, the lowest concentration corresponding to the highest rates, a similar trend observed by Mazzarino *et al.* (1997).

Germination assay performed on Patagonian soil showed that there were significant differences ($P \leq 0.05$) among biosolids, where the highest values for GI were for LSW, followed by PWS (Figure 1). Data from granitic soil showed no significant differences among organic wastes ($P \geq 0.05$). In general, GI values were higher for Patagonian than granitic soil. All treatments showed GI values higher to 80%, with the exception of treatment MSS at 150 t ha^{-1}. At this dose, urban sewage sludge showed the smallest GI values, being lower than 50%, inferior limit considered

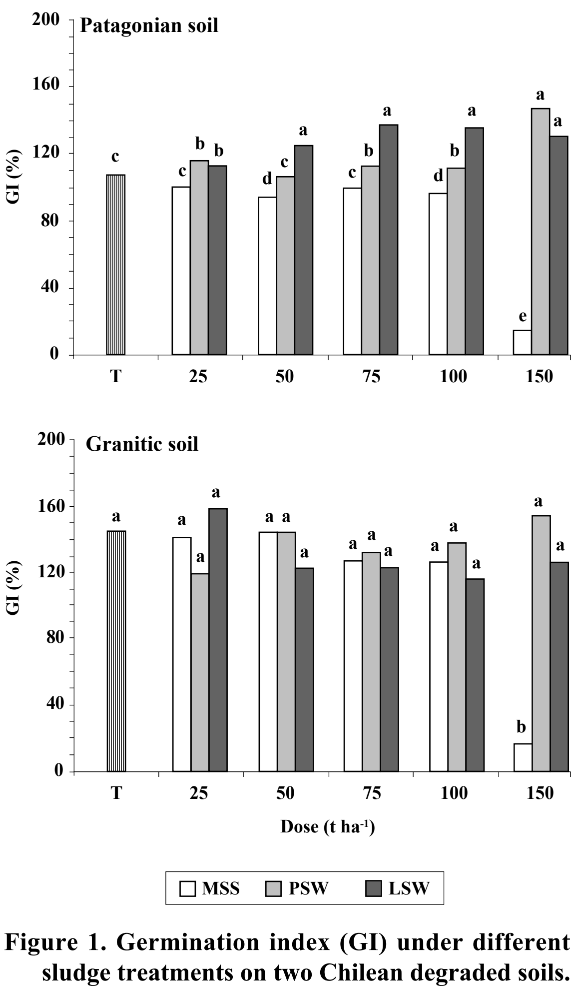

Figure 1. Germination index (GI) under different sludge treatments on two Chilean degraded soils. Municipal sewage sludge (MSS), land-based salmon pisciculture waste (PSW), lake-salmon sludge (LSW), control (T).

Different letters indicate statistical differences, according to Tukey ($P \leq 0.05$).

being toxic for plants. Patagonian soil data showed that there were no significant differences among treatments LSW in the range of 50 to 150 t ha^{-1}, so increasing sludge/soil ratio had no negative effect on the GI. However, incorporating municipal sewage sludge into a degraded either Patagonian or granitic soil at 150 t ha^{-1} rate greatly reduces germination index and seedling growth. Similar results have been reported for *Raphanus sativus* and *Cucumis sativus*, in which germination indexes are lower than 50% due to high concentrations of organic wastes (Rojas *et al.*, 2005). This can be explained for high Zn (25.4 mg kg^{-1}) and Cu (6.8 mg kg^{-1}) concentrations measured into sewage sludge-amended soil, both elements considered to be toxic for seeds (Page and Chang, 1994). Additionally, treatment MSS at 150 t ha^{-1} presented a high NH_4-N concentration (2197.5 mg kg^{-1}), which is considered very toxic for plants at this level (Olsthoorn *et al.,* 1991).

Municipal sewage sludge (MSS) added to both degraded soils presented an adverse effect on the growth of radicle and hypocotyl structure as a consequence of increasing sludge doses (Figure 2). On the contrary, there was a higher growth when salmon land-based salmon waste rate increased. Similarly than GI data, MSS treatment at 150 t ha^{-1} was detrimental for these biological structures.

Dry matter yields of annual ryegrass are shown in Table 5. On Patagonian soil, all treatments were similar to the inorganic fertilizer treatment, and biomass yield did not differ statistically between municipal sewage sludge and salmon wastes treatment. Dry matter yield, especially in the control, was small probably because of the lack of N. There were no significant differences between any other treatments, probably because of the small N inputs, as previously noted by Teuber *et al.*(2005) when using sea salmon sludge on volcanic soil. On the other hand, on a granitic soil, MSS and PSW treatments produced a significantly lower biomass yields than the control; treatments MSS and PSW at higher rates caused lower biomass yields ($P \leq 0.05$). There was no significant LSW treatment effect on biomass yield compared to control and inorganic fertilizer, even though LSW treatments produced higher yield than MSS and PSW treatments. Yield results suggest that the application in the range of 25 to 150 t ha^{-1} of municipal sewage sludge or salmon wastes was equivalent to the inorganic fertilizer treatment, but supplementary application of N and K would be needed to increase pasture yield.

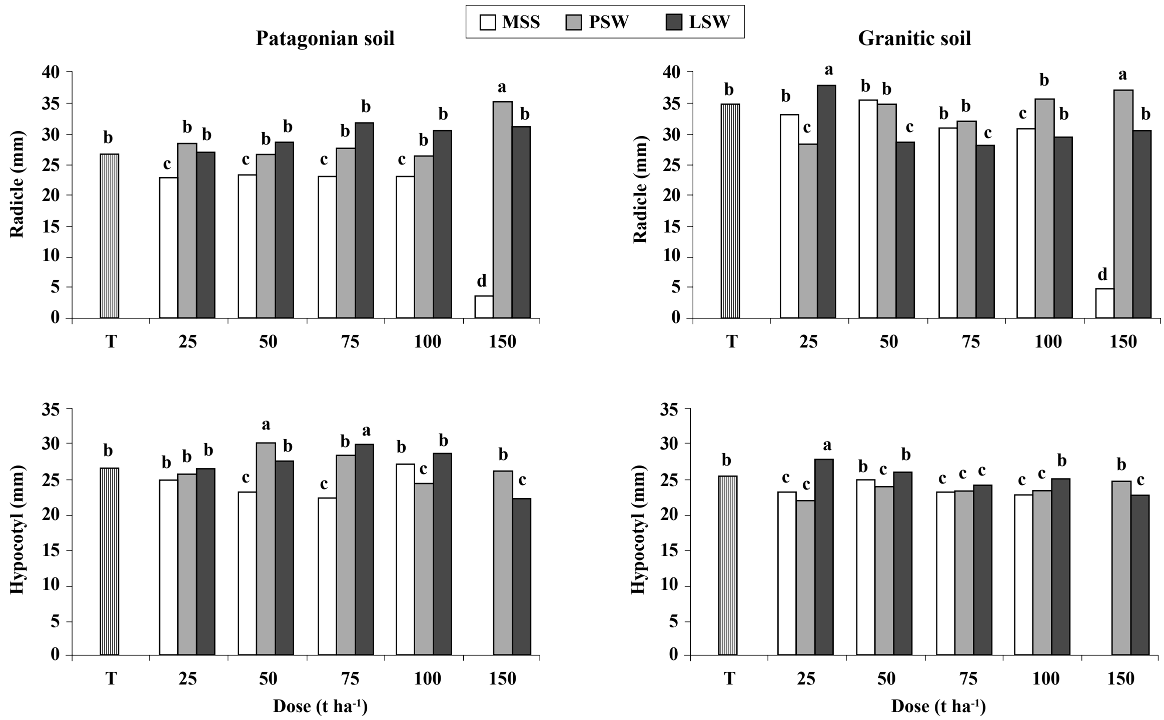

Figure 2. Phytotoxicological effects on lettuce seeds under different sludge treatments applied on two Chilean degraded soils, quantified as radicle and hypocotyl length. Municipal sewage sludge (MSS), land-based salmon pisciculture waste (PSW), lake-salmon sludge (LSW), control (T).

Different letters indicate statistical differences according to Tukey ($P \leq 0.05$).

No significant differences in N plant absorption were found among control, inorganic fertilizer, and organic wastes at 75 t ha^{-1} (Table 6). When organic wastes were amended to both soils the higher sludge rate caused greater P uptake in annual ryegrass plants ($P \leq 0.05$). This high P retention was likely due to high Ca content in organic wastes, a similar correlation previously founded by Mazzarino *et al.* (1997). Higher K and Na uptake was observed for inorganic fertilizer treatment due to high potassium and sodium content found in Chilean nitrates as used in this study. Lower plant K uptake was observed for LSW probably because fish wastes collected under cages served as poor K fertilizers due to the loss of soluble compounds in water, as stated by Mazzarino *et al.* (1997). Higher Na concentration was observed for inorganic fertilizer treatment probably due to Na content found in commercial potassium nitrate used.

Ryegrass biomass yields resulting from amending wastes showed that urban sewage sludge and salmon wastes can be applied successfully on Patagonian soil (Entisol). In comparison, data on granitic soil (Alfisol) showed that only lake-salmon waste (LSW) produced aboveground biomass similar to the control. Yield results suggest that the application of lake-salmon wastes at any rates (25, 50, 75, 100 or 150 t ha^{-1}) was equivalent to the inorganic fertilizer treatment, but supplementary application of N and K would be needed to increase pasture yield as was similarly found by Teuber *et al.* (2005) on volcanic soil.

Table 5. Dry matter yields of annual ryegrass cv. Winter Star expressed as aboveground biomass in different treatments applied in two Chilean degraded soils.

Treatment	Sludge rate						F	CV
	0	25	50	75	100	150		
	t ha^{-1}							%
Patagonian soil								
MSS	3.27a	4.60a	5.30a	3.96a	4.26a	4.10a	5.20a	16.5
PSW	3.27a	5.37a	4.76ab	4.60ab	5.10a	5.10a	5.20a	11.6
LSW	3.27a	4.80a	5.33a	3.77a	4.40a	5.37a	5.20a	17.3
Granitic soil								
MSS	3.59a	1.58bc	1.91ab	0.59bc	0.29bc	0.05c	3.45a	38.5
PSW	3.59a	1.98b	1.47b	0.22c	0.11c	0.07c	3.45a	19.6
LSW	3.59a	3.37a	3.59a	3.48a	3.57a	3.04a	3.45a	8.2

F: Inorganic fertilizer (140 kg N, 200 kg P and 130 kg K ha^{-1}); CV: coefficient of variation; MSS: municipal sewage sludge; PSW: land-based salmon farm waste; LSW: lake-salmon waste.
Different letters in same row indicate statistical differences according to Tukey ($P \leq 0.05$).

Table 6. Nutrient absorption in *Lolium multiflorum* L. cv. Winter Star at different treatments.

Treatment	N		P		K		Na	
	GS	PS	GS	PS	GS	PS	GS	PS
	%							
Control	4.61b	5.06a	0.28f	0.34d	6.15b	7.06a	0.12b	0.07e
MSS[1]								
25	4.49b	4.67a	0.35e	0.33d	5.77c	6.75b	0.15b	0.10c
50	4.76b	3.92b	0.41c	0.38c	5.78c	7.42a	0.12b	0.08d
75	4.72b	4.61a	0.48b	0.43b	6.72a	6.86b	0.12b	0.09d
100	5.12a	4.45a	0.47b	0.53a	6.55a	5.66c	0.14b	0.10c
150	5.43a	4.82a	0.55a	0.52a	6.49a	5.65c	0.14b	0.08d
PSW[1]								
25	4.51b	4.30b	0.35e	0.34d	5.55c	6.04c	0.14b	0.06e
50	4.47b	3.75c	0.44c	0.38c	5.71c	6.30b	0.13b	0.10c
75	4.61b	4.97a	0.50b	0.44b	6.69a	5.87c	0.14b	0.10c
100	5.24a	4.44a	0.47b	0.44b	6.57a	5.72c	0.14b	0.10c
150	4.56b	4.71a	0.52b	0.51a	6.78a	5.67c	0.13b	0.10c
LSW[1]								
25	4.54b	4.52a	0.38d	0.30d	5.38c	6.62b	0.14b	0.09d
50	4.09c	4.96a	0.48b	0.41b	5.06d	6.73b	0.15b	0.12b
75	4.49b	4.57a	0.51b	0.45b	4.95d	6.34b	0.14b	0.10c
100	4.08c	3.97b	0.58a	0.47a	5.42c	6.22b	0.14b	0.10c
150	4.37c	4.35b	0.56a	0.47a	5.45c	5.78c	0.12b	0.09d
F	4.81b	4.60a	0.36e	0.37c	6.22b	7.45a	0.28a	0.28a

GS: granitic soil; PS: Patagonian soil.
[1] Treatments at different rates (25, 50, 75,100 and 150 t ha^{-1}). MSS: municipal sewage sludge; PSW: land-based salmon farm waste; LSW: lake-salmon waste; F: Inorganic fertilizer (140 kg N, 200 kg P and 130 kg K ha^{-1}).
Different letters in same column indicate statistical differences according to Tukey ($P \leq 0.05$).

CONCLUSIONS

Sewage sludge and salmon wastes had high organic matter contents (>45% and 15%, respectively). In general, the concentration of macro and micronutrients was high, especially for sewage sludge. Greater GI values corresponded to salmon wastes than municipal sewage sludge added to degraded Patagonian soil at any rates. Germination data indicated that municipal sewage sludge added at 150 t ha^{-1} rate had a significantly poor germination and seedling growth, indicating that this sludge resulted toxic for lettuce due to their high Zn, Cu and ammonium concentrations. Annual ryegrass yield indicated that either sewage sludge, or salmon ground-farming waste or lake-salmon waste can be applied successfully on Patagonian soil (Entisol) at 25, 50, 75, 100 or 150 t ha^{-1} rates. Only lake-salmon sludge on granitic soil (Alfisol) can be applied successfully at 25, 50, 75, 100 or 150 t ha^{-1} rates. Application of urban sewage sludge on degraded granitic soil had limited effects on germination and plant yield due to the greatly eroded horizon B/C of this clayey soil. High rates of sewage sludge and salmon ground-farming waste had a detrimental effect on annual ryegrass yield when amended to this soil.

R E S U M E N

Respuesta de plantas a la fertilización orgánica con residuos de salmonicultura y lodos municipales en dos suelos degradados bajo condiciones de invernadero. José Celis[1], Marco Sandoval[2], y Ricardo Barra[3]. En este estudio se evaluó el potencial tóxico y fertilizante de lodos urbanos y biosólidos residuales de salmonicultura, usando para ello lechuga (*Lactuca sativa* L.) y ballica anual (*Lolium multiflorum* Lam.) cv. Winter Star. Estos biosólidos fueron adicionados en mezclas a un suelo patagónico (Andic cryofluvent) y a un suelo granítico (Ultic Palexeralf). Los tratamientos fueron lodo municipal (MSS), biosólido de salmonicultura en tierra (PSW) y biosólido de salmonicultura lacustre (LSW) a diferentes tasas: 25, 50, 75, 100 y 150 t ha^{-1}. Los bioensayos con lechuga permitieron medir el índice de germinación (GI), el largo de la radícula y del hipocotilo. Se midió producción de biomasa aérea en los ensayos con ballica. Los datos de fitotoxicidad en suelo patagónico mostraron diferencias significativas ($P \leq 0,05$) entre los biosólidos, donde los mayores valores de GI, largo de radícula e hipocotilo correspondieron a LSW, seguido por PSW. Los resultados en suelo granítico no mostraron diferencias estadísticas entre los distintos biosólidos adicionados. En ambos suelos, el tratamiento MSS a una tasa de aplicación igual a 150 t ha^{-1} presentó las menores longitudes de la radícula, y ningún desarrollo del hipocotilo. Los resultados de biomasa indicaron que MSS, PSW y LSW pueden ser aplicados exitosamente entre 25 a 150 t ha^{-1} en suelo patagónico y solamente LSW en suelo granítico. No obstante, la adición de estos biosólidos debe complementarse con fertilización inorgánica de N y K para incrementar la producción de pradera. Los biosólidos MSS y PSW adicionados a razón de 150 t ha^{-1} fueron detrimentales para la pradera, especialmente en el caso del suelo granítico.

Palabras clave: lodo de peces, biosólidos, lodo urbano, fertilizante orgánico, suelo degradado.

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