CHAPTER 3

Soil Description

3.1 Introduction

As discussed in the preceding chapters the disposal of biosolids is problematic and in South Africa it is often disposed of sacrificially on land. Although sacrificial disposal includes a wide range of practices the two soils that were used for this study have undergone broadly similar ways of biosolids disposal. Soil 1 was a dystrophic pale-yellow gravelly sandy loam soil from Rooiwal, north of Pretoria, that originated on coarse-grained granite and Soil 2 was a dystrophic red sandy clay loam that originated on dolomite from Hartebeestfontein, southeast of Pretoria. The Rooiwal sludge is aerobically digested and is distributed on the land by means of a centre pivot irrigation system (Figure 3.1). The sludge from the Hartebeestfontein works is anaerobically digested and it is disposed through flood irrigation (Figure 3.2). In both cases the dried sludge is incorporated into the soil through ploughing before the following sludge addition. Both sludges vary between 1.5 and 4 % solids and the metal and nutrient contents also vary significantly over time (data not presented here).

Prolonged addition of the sludge to soil leads to a build-up of nutrients, heavy metals, acidity and organic matter (refer to analysis data discussed later in the chapter). The organic matter accumulation is especially pronounced in the Rooiwal soil, which originally very hard in the dry state, becomes spongy due to the accumulation of organic matter as well as regular ploughing (Figure 3.3). After ploughing the soils are left for weeds to grow before further additions take place (Figures 3.4 and 3.5). In some cases trials have been conducted by the local staff to investigate the possibility of growing crops on the land such as at Hartebeestfontein (Figure 3.6) and in others parts of the land is used for informal production of maize, probably without the consent or knowledge of the authorities, such as at Rooiwal (Figure 3.7).

Figure 3.1. Disposal of an aerobically digested biosolids on land by means of a centre pivot irrigation system at Rooiwal.

Figure 3.2. Flood irrigation of an anaerobically digested sludge at the Hartebeestfontein water works.

Figure 3.3. Accumulated organic matter in the Rooiwal soil with shoeprints of up to 5 cm deep due to the spongy nature of the altered soils.

Figure 3.4. Weeds growing at the Rooiwal site (with the Rooiwal power station in the background).

Figure 3.5. Weeds growing at the Hartebeestfontein site with a tractor ploughing a commercial farming land in the background.

Figure 3.6. Maize plants in a field irrigated with biosolids at Hartebeestfontein.

Figure 3.7. Informal production of maize on the edge of a centre pivot field at the Rooiwal site.

The maximum permissible or extractable heavy metal contents in soils is a subject of broad debate in South Africa and guideline levels are currently being reviewed. To illustrate the heavy metal data presented in this chapter one set of data from guidelines of the Water Research Commission (1997) and another suggested by Bruemmer and van der Merwe (1989) are listed in Table 3.1. The merits of the guidelines and guideline levels will only be alluded to briefly in this study.

3.2 Materials and Methods

Bulk topsoil samples from the two soils were collected and from each of these samples a representative sample was collected for chemical and physical analysis Samples were also collected from non-polluted soils in the vicinity of the sacrificial soils to serve as reference samples. It is important to note that biosolids composition varies widely and that those applied to Soils 1 and 2 were from different water treatment plants.

Table 3.1. Maximum metal content in soil (Water Research Commission, 1997), and suggested preliminary threshold values for NH_4-EDTA (pH 4.5) extractable heavy metals for the soils of South Africa (Bruemmer and van der Merwe, 1989)

Element	Maximum permissible metal and inorganic content in soil (mg kg^{-1} soil)	Suggested threshold values (NH_4-EDTA extractable) (mg kg^{-1} soil)
Cd	2	1
Cr	80	50
Cu	6.6	60
Ni	50	20
Pb	6.6	100
Zn	46.5	100

3.2.1 Soil pH and Organic Carbon

The pH of the soils was determined through the method described by the Non-Affiliated Soil Analysis Work Committee (1990) in water, 1 *M* KCl and 0.01 *M* $CaCl_2$, with four repetitions each. Organic carbon was determined according to the Walkley-Black method as described by The Non-Affiliated Soil Analysis Work Committee (1990), also with four repetitions.

3.2.2 Extractable Heavy Metals

An EPA 3050 digestion was done on all the soils (including a reference soil - Canadian Certified Reference Materials, Reference Soil No SO-4, Canada Centre for Mineral and Energy Technology) to determine the “total” Mn, Fe, Cu, Zn, Pb, Ni, Cd, and Cr. Each digestion was repeated four times and blank samples were included. All metals were determined through Atomic Absorption Spectrophotometry. Iron was included in all further trials due to its influence on the mobility of many of the heavy metals of interest.

An NH_4-EDTA and NH_4NO_3 extraction were done separately to determine potentially plant-available and exchangeable metals respectively. The volumes were adapted from the original 45 cm^3 0.02 *M* NH_4-EDTA and 15 g soil stipulated by the Non-Affiliated Soil Analysis Work Committee (1990) to 50 cm^3 0.02 *M* NH_4-EDTA and 5 g soil to ensure adequate EDTA in the presence of high metal levels. The NH_4NO_3 extraction was as follows: 5 g of oven dry soil was shaken with 50 cm^3 0.2 *M* NH_4NO_3 in a stoppered bottle on a horizontal shaker for 1 hour and then filtered. In both cases Mn, Fe, Cu, Zn, Pb, Ni, Cd, and Cr were determined through Atomic Absorption Spectrophotometry.

3.2.3 Effective Cation Exchange Capacity (ECEC) and Extractable Cations

The Effective Cation Exchange Capacity (ECEC) and extractable cations of the soil, at current pH levels, were determined through a $BaCl_2$ extraction (Hendershot and Duquette, 1986). The method was adapted as follows: 5 g of soil was shaken with 50 ml 0.1 M $BaCl_2$ in a glass bottle on a horizontal shaker for 1 hour and filtered afterwards. The metals Ca, Mg, K, Na, Al, Mn, Fe, Cu, Zn, Pb, and Cd were determined through Atomic Absorption Spectrophotometry and Ni and V through ICP-MS. Due to Cl interference in the determination of Cr by ICP-MS a 0.2 M NH_4NO_3 solution was used, with the same procedure and quantities as stated for the $BaCl_2$ extraction, to determine the exchangeable Cr levels in the soils.

The water-soluble metals were determined through a saturated paste extract according to the method described by The Non-affiliated Soil Analysis Work Committee (1990). Again the metals Ca, Mg, K, Na, Al, Mn, Fe, Cu, Zn, Pb, and Cd were determined through Atomic Absorption Spectrophotometry and Ni, Cr and V through ICP-MS. Extractable acidity and Al were determined through a 1 N KCl extraction and organic carbon according to the Walkley-Black method as described by the Non-affiliated Soil Analysis Work Committee (1990).

3.3 Results and Discussion

3.3.1 Organic Carbon and pH

The organic carbon and pH values for the two sacrificial soils and two reference soils are listed in Table 3.2. From the data it is clear that both soils experienced a highly significant increase in organic material. As a consequence of the biosolids addition, the pH values of these two soils are significantly lower than the reference soils. The pH of Soil 1 is lower and the organic carbon content higher than Soil 2. This could be attributed to several factors namely: the higher pH buffer capacity of high clay content soils (Soil 2) on dolomite compared to that of sandy soils (Soil 1) on granite; a longer period of application; or greater total application on Soil 1 than Soil 2.

Table 3.2. Organic carbon and pH values for the two soils (standard deviation indicated in brackets)

		Org C	pH		
Soil	Type	%	H_2O	$CaCl_2$	KCl
1	Reference	0.59 (0.03)	7.02 (0.12)	6.52 (0.08)	4.88 (0.05)
	Sacrificial	3.70 (0.04)	4.16 (0.01)	3.76 (0.01)	3.25 (0.00)
2	Reference	0.97 (0.04)	6.34 (0.11)	5.86 (0.02)	5.07 (0.03)
	Sacrificial	2.91 (0.11)	4.00 (0.01)	3.66 (0.01)	3.50 (0.01)

3.3.2 Extractable Heavy Metals

The EPA 3050 extractable metal levels for the two soils are presented in Table 3.3 with the values in bold denoting those exceeding the values listed in Table 3.1 (Column 2). Most of the metal levels in the two sacrificial soils exceeded those in Table 3.1. In the case of Cd, Cr, Cu, Ni (except Soil 2), Pb (except Soil 2), and Zn there was a significant increase in metal content due to biosolids application. Some of the values listed in Table 3.1 (Column 2) could be excessively conservative, especially since the reference values for Cu (Soil 2), Ni (Soil 2), and Pb (Soils 1 and 2) exceed the Table 3.1 values. Possible reasons for this could include the fact that the values in Table 3.1 (Column 2) do not indicate an extraction method and the fact that many South African soils have high background metal levels, as discussed by Herselman and Steyn (2001).

Table 3.3. EPA 3050 extractable metal levels (mg kg^{-1}) for Soils 1 and 2 (values in brackets indicate the standard deviation – n = 4)[†]

	Soil 1		Soil 2	
Metal	Reference	Sacrificial	Reference	Sacrificial
Cd	[¶]0.00 (0.00)	**2.05 (1.18)**	[¶]0.00 (0.00)	**2.75 (0.71)**
Cr	10.9 (1.63)	**145 (16)**	44.7 (1.7)	**361 (26)**
Cu	4.97 (0.39)	**141 (21)**	**39.0 (3.5)**	**291 (10)**
Fe	>5000	>5000	>5000	>5000
Mn	122 (2)	60.4 (7.2)	1407 (80)	534 (61)
Ni	2.89 (2.30)	25.8 (3.8)	**58.9 (7.3)**	**68.7 (2.9)**
Pb	**9.29 (4.88)**	**188 (56)**	**24.2 (10.1)**	**46.8 (13.3)**
Zn	25.9 (2.8)	**338 (37)**	44.7 (2.3)	**97.4 (2.2)**

[†] Bold values denote those exceeding the values stipulated in Table 3.1 (Column 2)

[¶] Reference soil values for Cd were below detection limits during determination due to the dilution factor in the EPA 3050 procedure

The Fe levels were in excess of 5 000 mg kg^{-1} in both soils. The Mn levels decreased in both soils after biosolids addition with a significant decrease in Soil 2. From the values it is also clear that some soils derived from dolomite in the Gauteng area have high Mn levels. The decrease in Mn levels is attributed to the lowered pH and altered redox conditions in the soils after biosolids application as well as possible low levels in the sludge. Manganese is highly mobile under low pH and reduced conditions, especially in the presence of ligands (organic material), and therefore readily leaches out of the profile during the application of large volumes of water and reducing agents (organic material and N compounds that can readily undergo oxidization).

Table 3.4 indicates the NH_4-EDTA extractable metals for the two soils. Cadmium, Cr, Cu, Ni, Pb, and Zn exhibited a significant increase in extractability and this is attributed to the high levels applied. Only the sacrificial soil values for Cu (Soil 2) and Zn (Soil 1) exceeded the values suggested by Bruemmer and van der Merwe (1989) even though Cu (Soils 1 and 2 sacrificial, and 2 reference), Pb (Soils 1 and 2 sacrificial and 2 reference) and Zn (Soil 1 sacrificial) exceeded the values given in Column 2 of Table 3.1. Zinc also exceeded the Table 3.1 (Column 2) values in the NH_4NO_3 extraction (Table 3.5). Most of the metals (except Mn in both soils and Zn in Soil 1) were sparingly extractable with NH_4NO_3 but exhibited a significant increase in the sacrificial soils.

Considering that high levels have accumulated in the soils (Table 3.3) and are extractable with EDTA (Table 3.4), the values suggested by Bruemmer and van der Merwe (1989) seem high and not conservative enough, whereas the values in Column 2 (Table 3.1) seem overly conservative.

Table 3.4. NH_4-EDTA extractable metal levels (mg kg^{-1}) for Soils 1 and 2 (values in brackets indicate the standard deviation – n = 4)[†]

	Soil 1		Soil 2	
Metal	Reference	Sacrificial	Reference	Sacrificial
Cd	0.09 (0.05)	0.45 (0.04)	0.08 (0.07)	0.71 (0.05)
Cr	0.17 (0.21)	0.58 (0.25)	0.08 (0.10)	0.71 (0.10)
Cu	1.02 (0.22)	41.6 (1.42)	7.72 (0.77)	**69.2 (1.46)**
Fe	55.5 (4.65)	454 (22)	160 (13)	293 (13)
Mn	72.6 (4.1)	17.1 (0.4)	1026 (30)	45.7 (3.3)
Ni	0 (0)	4.45 (1.10)	0.31 (0.40)	2.95 (0.53)
Pb	2.69 (0.82)	10.2 (0.5)	7.25 (1.46)	9.10 (1.11)
Zn	2.64 (0.57)	**101 (6)**	10.9 (0.6)	30.9 (2.5)

[†] Bold values denote those exceeding the values stipulated in Table 3.1 (Column 3)

Table 3.5. NH_4NO_3 extractable metal levels (mg kg^{-1}) for Soils 1 and 2 (values in brackets indicate the standard deviation – n = 4)[†]

	Soil 1		Soil 2	
Metal	Reference	Sacrificial	Reference	Sacrificial
Cd	0.01 (0.01)	0.13 (0.01)	0.01 (0.01)	0.44 (0.04)
Cr	0.01 (0.02)	0.02 (0.02)	0.01 (0.01)	0.09 (0.01)
Cu	0.04 (0.02)	1.70 (0.06)	0.06 (0.06)	10.1 (0.3)
Fe	0.10 (0.20)	6.80 (0.49)	0.65 (0.54)	8.62 (0.38)
Mn	12.7 (1.9)	16.2 (0.2)	3.29 (1.48)	40.6 (1.2)
Ni	0.00 (0.03)	4.71 (0.16)	0.30 (0.03)	3.78 (0.08)
Pb	0.06 (0.02)	0.03 (0.01)	0.02 (0.01)	0.13 (0.01)
Zn	0.00 (0.00)	**65.6 (4.1)**	0.00 (0.00)	17.0 (0.9)

[†] Bold values denote those exceeding the values stipulated in Table 3.1 (Column 2)

3.4 Conclusions and Recommendations

The long-term application of biosolids to the two soils resulted in a significant accumulation of organic carbon and heavy metals, as well as a significant decrease in pH. The extractable metal levels varied considerably between the different extracting procedures, as expected. The guideline or suggested levels in soil mentioned in this paper are not realistic and should be further investigated. When maximum permissible soil metal contents are stipulated in guidelines, a clear distinction should be made with regards to total versus bio-available metal concentrations.

The fact that monitoring of loading rates and the variation in metal content of the biosolids over the application period was not done, although complicating research, should serve as a motivation for the further study into, and monitoring and rehabilitation of sacrificial lands.