CHAPTER 5

PERENNIAL DRYLAND PASTURE - WEEPING LOVEGRASS (*Eragrostis curvula* L.)

The following hypotheses are tested in this chapter.

HYPOTHESIS 1

- Sludge loading above the 8 Mg ha^{-1} yr^{-1} norm could improve weeping lovegrass hay yield, crude protein content, and water use efficiency.

HYPOTHESIS 2

- The ideal sludge loading rate to satisfy weeping lovegrass N demand is dynamic and could exceed the 8 Mg ha^{-1} yr^{-1} sludge norm.

HYPOTHESIS 3

a. Under high hay yield production conditions, N supply from double the norm can be fully utilized and are not prone to excessive nitrate leaching.

HYPOTHESIS 4

- Sludge application according to weeping lovegrass N demand results in the accumulation of total and Bray-1P in the soil profile.

5.1 Hay yield, crude protein content, and water use efficiency

5.1.1 Hay yield

Doubling of the sludge upper limit norm significantly improved weeping lovegrass annual hay yield except during 2005/06, where the difference was not statistically significant (Table 5.1). Hay yield was generally higher for the first cut compared with the second each year, except for the 2007/08 growing season, where the second cut was higher than the first (Table 5.2). It was interesting to note that weeping lovegrass annual hay yield from the 8 Mg ha^{-1} yr^{-1} sludge treatment was similar to that of the inorganic fertilizer. The only exception was during the wet 2007/08 growing season, where hay yield from the inorganic fertilizer was significantly higher than the 8 Mg ha^{-1} treatment.

Table 5.1 Annual hay yield of weeping lovegrass as affected by three sludge application rates, inorganic fertilizer, and control.

Treatments	Weeping lovegrass hay yield			
	2004/05	2005/06	2006/07	2007/08
	Mg ha^{-1}			
Control†	10.18	9.08	6.97	8.15
4 Mg ha^{-1} yr^{-1}	10.74	9.64	10.05	12.70
8 Mg ha^{-1} yr^{-1}	14.10	12.50	11.87	14.90
16 Mg ha^{-1} yr^{-1}	15.08	12.78	12.36	17.31
Inorganic fertilizer ‡	13.78	12.56	11.78	16.50
LSD (5%)	0.61	0.43	0.46	0.73
CV, %	3	3	3	3

† Zero sludge and inorganic fertilizer applied
‡ 200 kg N and 80 kg P per hectare per annum applied

In general, hay yield throughout the study period was much higher than the long term average values of 6 Mg ha^{-1} reported by Dickinson et al. (2004) from Hutton soils receiving similar annual rainfall. This is most probably due to a better nutrient status of the soil from this study compared with the soils reported by Dickinson et al. (2004).

The relatively low hay yield from the second cut compared with the first cut of each year was mainly attributed to the relatively low rainfall experienced during the second half of the season (Fig. 5.1). This is because a relatively higher rainfall experienced during the second cut of the 2007/08 growing season rendered higher forage yield than the first cut. The amount of rainfall and weeping lovegrass hay yield of a control and three sludge rate treatments are presented in a 3 D graph (Fig. 5.2). The graph vividly shows that weeping lovegrass hay yield response to sludge rate increases with increase in rainfall. This coincides with the explanation by Miles and Manson (2000) and Dickinson et al. (2004), who report that weeping lovegrass response to N increases with increase in the availability of water (rainfall).

Table 5.2 Weeping lovegrass hay yield per cut of three sludge application rates, an inorganic fertilizer, and a control during the 2004/05 to 2007/08 growing seasons.

† Zero sludge and inorganic fertilizer applied

	Weeping lovegrass hay yield per cut							
	2004/05		2005/06		2006/07		2007/08	
Treatments	First cut	Second cut	First cut	Second cut	First cut	Second cut	First cut	Second cut
	Mg ha^{-1}							
Control†	6.69	3.49	4.96	4.12	4.09	2.88	4.00	4.15
4 Mg ha^{-1} yr^{-1}	6.97	3.77	5.51	4.13	5.96	4.09	5.94	6.76
8 Mg ha^{-1} yr^{-1}	8.65	5.45	7.39	5.11	7.34	4.53	6.12	8.78
16 Mg ha^{-1} yr^{-1}	9.14	5.94	7.66	5.21	7.74	4.62	6.67	10.64
Inorganic fertilizer‡	8.49	5.29	7.44	5.12	7.16	4.62	7.16	9.34
LSD (5%)	0.41	0.25	0.26	0.26	0.26	0.31	0.38	0.64
CV, %	3	3	3	4	3	5	4	5

‡ 100 kg N and 40 kg P per hectare per annum per cut applied

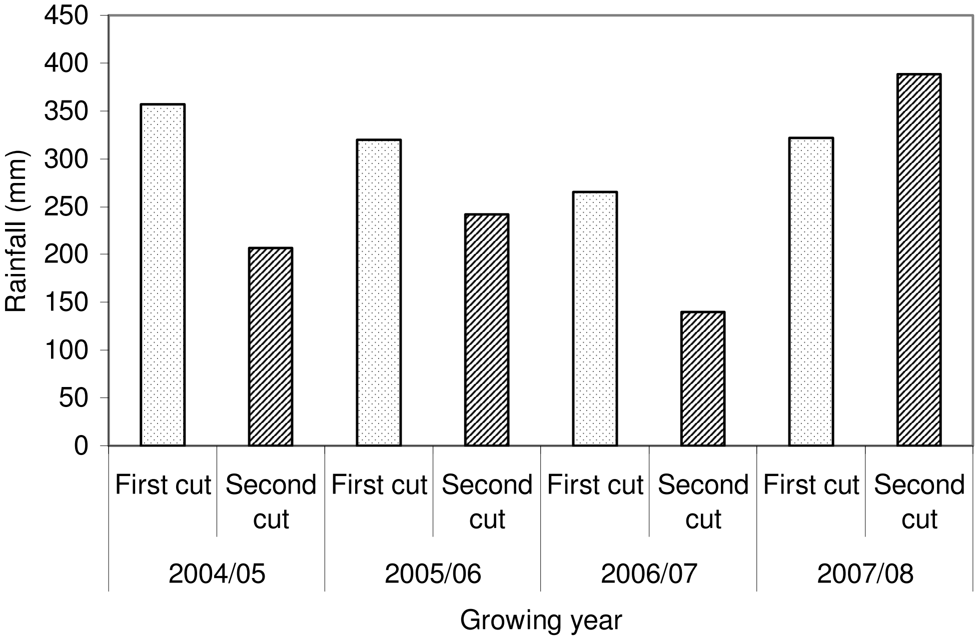

Figure 5.1 Rainfall distribution during the first and second cuts of weeping lovegrass planted during the 2004/05 to 2007/08 growing seasons, at ERWAT, Ekurhuleni district, South Africa.

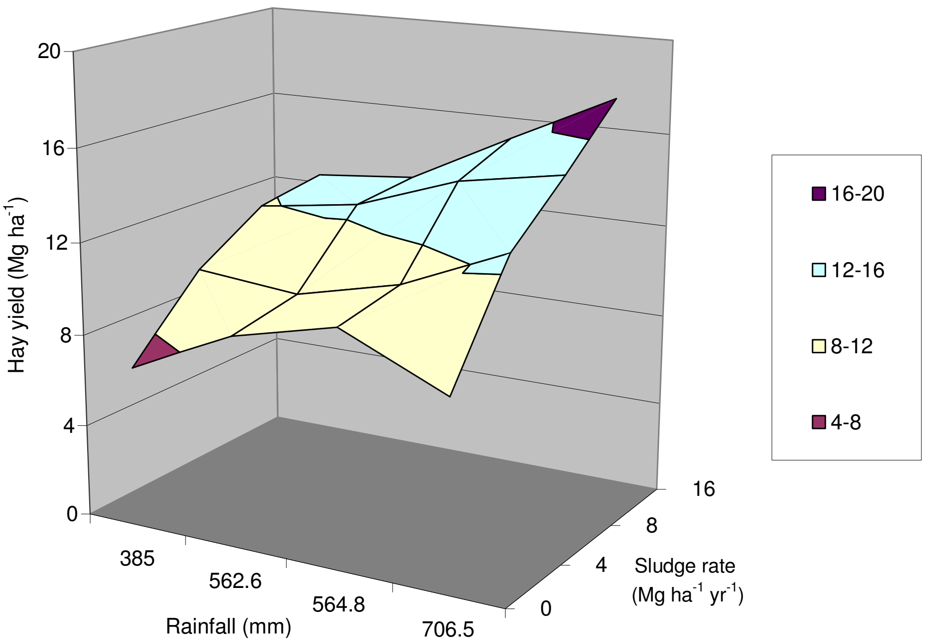

Figure 5.2 Weeping lovegrass hay yield as affected by rainfall amount and sludge application rate.

5.1.2 Crude protein content

Doubling of the annual upper sludge limit improved weeping lovegrass crude protein content, except for the second cuts of the 2006/07 and 2007/08 growing seasons (Table 5.3). It was also evident that the level of crude protein from the second cut of each year was lower than that of the first. Crude protein content is the most limiting constituent for animal performance feeding on pasture and was estimated by multiplying hay N content by a factor of 6.25 as reported by Meissner et al. (2000).

The increase in the level of crude protein with doubling of the 8 Mg ha^{-1} sludge limit was mainly attributed to the increase in the availability of N, because crude protein of weeping lovegrass increases with fertilization under nutrient limiting conditions (Masters and Britton, 1990). The low crude protein observed during the second cut of the first three years was mainly due to the low rainfall, because weeping lovegrass crude protein content decreases under drought conditions (McFarland, 1999). This is most probably due to the translocation of N from leaves to roots, which is common in warm season grasses during drought periods (Heckathron and Delucia, 1999). The low crude protein content observed during the second cut of 2008 was, however, mainly attributed to a dilution effect as a result of the high biomass production (Table 5.2, column 9).

Generally, the crude protein levels of all the treatments were within the ranges reported by Strickland (1973) for weeping lovegrass (63-175 g kg^{-1}). It was also above the minimum crude protein requirements of ruminants (70-80 g kg^{-1}) Meissner et al., (2000), except for the second cut of the control treatment during the 2007/08 growing season.

Table 5.3 Crude protein content of weeping lovegrass as affected by three sludge application rates, an inorganic fertilizer treatment, and a control.

† Zero sludge and inorganic fertilizer applied

Treatments	Weeping lovegrass crude protein content							
	2004/05		2005/06		2006/07		2007/08	
	First cut	Second cut	First cut	Second cut	First cut	Second cut	First cut	Second cut
	g kg^{-1}							
Control†	121	94	96	79	106	85	77	62
4 Mg ha^{-1} yr^{-1}	126	98	100	86	107	89	104	77
8 Mg ha^{-1} yr^{-1}	128	102	100	89	108	85	104	77
16 Mg ha^{-1} yr^{-1}	155	112	102	99	112	85	107	77
Inorganic fertilizer‡	136	106	104	94	109	85	107	82
LSD (5%)	4	3	3	4	6	1	3	1
CV, %	2	2	2	3	2	2	2	1

‡ 200 kg N and 80 kg P per hectare per annum applied

5.1.3 Effect of sludge application rate on rainfall use efficiency

Sludge applied at double of the upper limit norm significantly improved the annual rainfall use efficiency compared with lower rates (Table 5.4). The significant improvement in annual water use efficiency was due to the significant increase in hay yield per unit water used for each cut, or for one of the two cuts in a season (Table 5.5). Rainfall use efficiency (RUE) is a factor which indicates the productivity of an ecosystem (Guevara et al., 2005). This depends on soil and vegetation condition and its dynamic status (Le Houérou, 1984).

During the 2006/07 growing season, the water use efficiency of treatments that received 8 and 16 Mg ha^{-1} sludge and an inorganic fertilizer was highest compared with similar treatments during the other three growing seasons, which experienced higher rainfall and hay yield. Nevertheless, each treatment had relatively lower hay yield compared with similar treatment due to the low rainfall experienced during the specified year. Generally, the rainfall use efficiency from this study was much higher than the ranges reported by Guevara et al. (2005) for weeping lovegrass (3.7-10 kg DM ha^{-1} year^{-1} mm^{-1}) in Argentina. This is most probably due to higher water holding capacity and nutrient status of the soil from this study among other factors.

Table 5.4 Annual rainfall use efficiency of weeping lovegrass as affected by three sludge application rates, an inorganic fertilizer, and a control.

Treatments	Annual rainfall use efficiency			
	2004/05	2005/06	2006/07	2007/08
	kg ha^{-1} mm^{-1}			
Control†	18	16	18	12
4 Mg ha^{-1} yr^{-1}	19	17	26	18
8 Mg ha^{-1} yr^{-1}	25	21	31	21
16 Mg ha^{-1} yr^{-1}	27	23	33	24
Inorganic fertilizer‡	24	22	31	23
LSD (5%)	1	1	1	1
CV, %	3	2	3	4

† Zero sludge and inorganic fertilizer applied
‡ 200 kg N and 80 kg P per hectare per annum applied

To summarize, sludge applied at double the norm improved weeping lovegrass hay yield, crude protein content, and water use efficiency compared with lower rates under the prevailing climatic conditions. Therefore, the following hypothesis was accepted:

- Sludge application above the 8 Mg ha^{-1} yr^{-1} norm could improve dryland pasture (weeping lovegrass) hay yield, crude protein content, and water use efficiency.

Table 5.5 Rainfall use efficiency of weeping lovegrass per cut as affected by three sludge application rates, an inorganic fertilizer, and a control.

† Zero sludge and inorganic fertilizer applied

Treatments	Weeping lovegrass seasonal rainfall use efficiency							
	2004/05		2005/06		2006/07		2007/08	
	First cut	Second cut	First cut	Second cut	First cut	Second cut	First cut	Second cut
	kg ha^{-1} mm^{-1}							
Control†	19	17	16	17	17	21	13	11
4 Mg ha^{-1} yr^{-1}	19	18	17	17	25	29	19	17
8 Mg ha^{-1} yr^{-1}	24	26	22	21	30	33	19	23
16 Mg ha^{-1} yr^{-1}	26	28	24	22	32	33	21	27
Inorganic fertilizer‡	24	25	23	21	30	33	22	24
LSD (5%)	1	1	1	1	1	2	1	2
CV, %	3	4	3	4	3	4	5	6

‡ 200 kg N and 80 kg P per hectare per annum applied

5.2 Hay N uptake

Weeping lovegrass annual hay N uptake increased significantly with doubling of the annual upper sludge application limit (Table 5.6). Annual hay N uptake from the control treatment tended to decrease over time. Other treatments, however, did not show a specific trend across years. Crop N uptake was higher during the first cut than the second, except in 2008, where the second cut was higher for the 8 and 16 Mg ha^{-1} yr^{-1} sludge treatments (Table 5.7).

Table 5.6 Annual weeping lovegrass N uptake from three sludge application rates, inorganic fertilizer treatment, and a control during the 2004/05 to 2007/08 growing seasons.

Treatments	Weeping lovegrass hay N uptake			
	2004/05	2005/06	2006/07	2007/08
	kg ha^{-1}			
Control†	182	129	109	91
4 Mg ha^{-1} yr^{-1}	200	145	160	182
8 Mg ha^{-1} yr^{-1}	266	192	188	210
16 Mg ha^{-1} yr^{-1}	333	208	202	245
Inorganic fertilizer‡	275	201	189	245
LSD (5%)	10	8	8	10
CV, %	3	3	3	3

† Zero sludge and inorganic fertilizer applied
‡ 200 kg N and 80 kg P per hectare per annum applied

Table 5.7 Weeping lovegrass hay N uptake per cut from three sludge application rates, inorganic fertilizer treatment, and a control

Treatment	Weeping lovegrass hay N uptake							
	2004/05		2005/06		2006/07		2007/08	
	First season	Second season	First season	Second season	First season	Second season	First season	Second season
	kg ha^{-1}							
Control†	130	52	76	53	70	40	50	41
4 Mg ha^{-1} yr^{-1}	141	60	88	57	102	58	99	84
8 Mg ha^{-1} yr^{-1}	177	89	118	73	127	62	102	108
16 Mg ha^{-1} yr^{-1}	227	106	125	83	139	63	115	131
Inorganic fertilizer‡	185	90	124	77	126	63	123	123
LSD (5%)	8	3	5	5	6	4	7	8
CV, %	3	3	3	5	4	5	5	6

† Zero sludge and inorganic fertilizer applied

‡ 200 kg N and 80 kg P per hectare per annum applied

The reported increase in N uptake for every increment in sludge rate depicts the increase in the availability of nitrogen. This is because nitrogen uptake is a more sensitive indicator of nitrogen availability from nitrogenous fertilizer sources (Kiemnec et al., 1987). This increase in plant N availability enhanced weeping lovegrass hay yield, because N is considered the key element for dry matter production (Miles and Manson, 2000) and dry matter production of weeping lovegrass increases with the availability of nitrogen (Rethman et al., 1984). In contrast, the decline in N uptake over time for the control treatment was mainly due to the decline in soil N availability.

Assuming that 50 percent of the organic N is released during the first year of sludge application (Snyman and Herselman, 2006) followed by 8, 3, 1, and 1 percent of the organic N applied during the first year being released during the second, third, fourth, and fifth years, respectively (Sullivan and Cogger, 2000). The four year mean N uptake by the 16 Mg ha^{-1} sludge treatment was equivalent to an N supply from a 15.8 Mg sludge ha^{-1} during the first year of application (Fig. 5.3). The rate decreased during the following 8 years and reached an equilibrium application rate of 13.2 Mg ha^{-1} from the 10th year on. If the sludge N content was 3.85%, the annual sludge application rate could have equilibrated at 8.8 Mg ha^{-1} from the 10th year on (Fig. 5.3). The decline in sludge application rate across years was mainly due to the N carry over effects from previous year's applications.

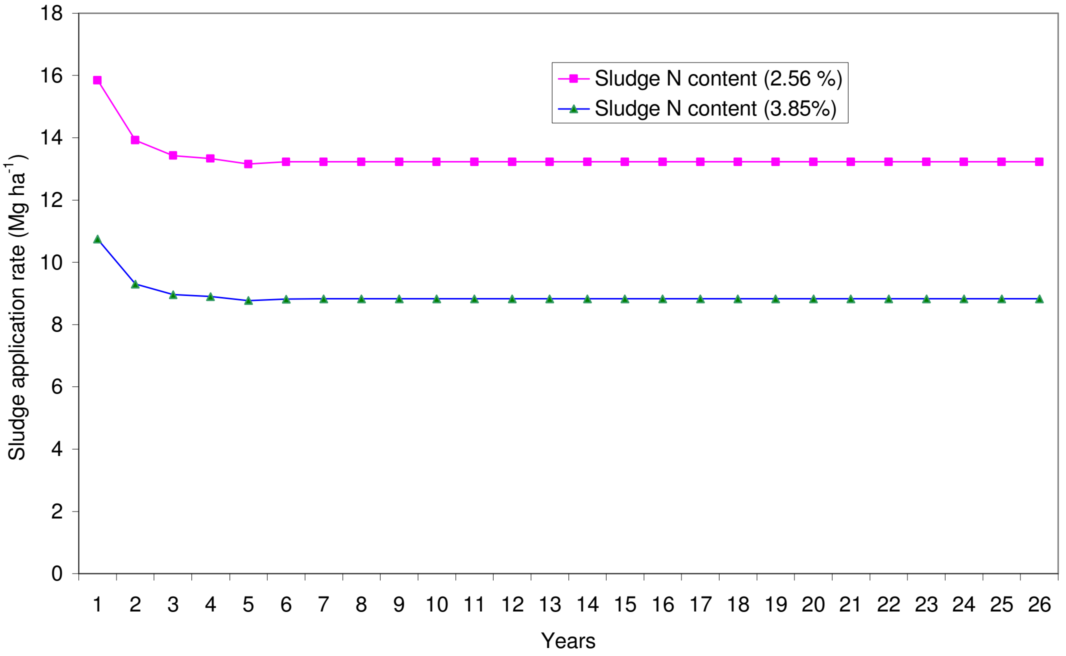

Figure 5.3 Sludge application rate to satisfy four year mean weeping lovegrass N demand (247 kg N ha^{-1}) as affected by sludge N content and N carry over effects.

The higher hay N uptake during the first cut compared with the second was mainly attributed to the availability of higher rainfall during the first cut of the year (Fig. 5.1). The event during the 2007/08 growing season, where higher rainfall during the first cut from the 8 and 16 Mg ha^{-1} sludge treatments produced higher yield than the second proved this reality. The availability of water plays a significant role in the mineralization of organic nitrogen (Jansson and Persson, 1982; Vinten and Smith, 1993), nitrification of ammonium (Breuer et al., 2002) and crop uptake (Mackay and Barber, 1985).

Therefore, the following hypothesis was accepted:

- The ideal sludge application rate to satisfy dryland pasture (Weeping lovegrass) N demand is dynamic and could exceed the 8 Mg ha^{-1} yr^{-1} sludge norm.

5.3 Soil profile total N mass balance, nitrate leaching, residual nitrate and ammonium

5.3.1 Total N mass balance

Based on the mass balance calculation of N imported with sludge less N exported with hay, total N from sludge applied according to the 8 Mg ha^{-1} limit was close to being but not quite sufficient to satisfy weeping lovegrass N demand (net negative mass balance) (Table 5.8). Negative mass balances of all but the 16 Mg ha^{-1} treatment shows that the crop utilized N from the soil reserve. Therefore, total N supply from sludge with 2.56% mean N applied according to the 8 Mg ha^{-1} norm is not sufficient for optimal weeping lovegrass hay production under the prevailing climatic and soil conditions. Doubling of the upper limit sludge norm, however, resulted in a net positive mass balance. This indicates that the total N supply surpassed hay N uptake. The excess N from double the norm was accumulated mainly in the 0-0.1 m soil layer, because the sludge was surface applied (Fig. 5.4).

Table 5.8 Cumulative N supply (CUM NS)), uptake (CUM NU), and mass balance of a weeping lovegrass treated with three sludge application rates, inorganic fertilizer, and a control.

Treatment	Four years cumulative mass balance				
	CUM-NS	CUM-NU	CUM-NS less CUM-NU	Change in soil N storage	Mass balance difference
	kg ha^{-1}				
Control†	0	511	-511	-600	89
4 Mg ha^{-1} yr^{-1}	409	687	-278	-381	103
8 Mg ha^{-1} yr^{-1}	818	856	-38	-203	165
16 Mg ha^{-1} yr^{-1}	1637	988	649	330	319
Inorganic fertilizer‡	800	910	-110	-271	161

† Zero sludge and inorganic fertilizer applied
‡ 200 kg N per hectare per annum applied

Soil profile sampling to a depth of 0.8 m (change in soil storage) (Table 5.8) showed similar trends to the supply less uptake mass balance. According to this profile analyses, doubling of the annual sludge upper limit resulted in a net positive mass balance while sludge applied according to the norm had a net negative mass balance. Interestingly, however, there was a net positive difference between the two mass balances: supply less uptake (CUM_NS less CUM-NU) and change in storage between final and initial soil profile N contents (Chance in soil N storage). This difference increased with increase in sludge application rate (Mass balance difference) (Table 5.8).

The most probable cause for the mass balance difference was ammonia volatilization losses, which is not accounted for in the N import less export mass balance. This is because the sludge used in this study was anaerobically digested with about 20-25% of total N in ammonium form. In addition, the sludge was surface applied. Previous studies conducted by Adamsen and Sabey (1987) showed that 40.3% of the NH_4-N from surface applied sludge could be lost as NH_3 gas during the first two weeks of its application. This was in contrast to 0.35% loss from an incorporated sludge reported in the same study. Similarly, other studies have also shown that on average 89% of the initial ammonium could be lost in the form of ammonia gas from a surface applied anaerobically digested sludge (Henry et al., 1999). Other possible sources of the differences include sampling errors, N content variation within the sludge matrix, soil heterogeneity, and probably denitrification (which is not dominant under dryland cropping), and leaching (which could have been insignificant due to the low rainfall experienced).

Comparison of mass balance differences was conducted between dryland maize forage production, where sludge was incorporated immediately after application, (Table 4.10) and weeping lovegrass, sludge surface applied, (Table 5.8). The mass balance difference of weeping lovegrass for the 8 and 16 Mg ha^{-1} sludge treatments was more than four times higher than similar treatments under dryland maize conditions. In addition, the wetting front detectors buried at 0.3 m depth responded only four times during the four year study period, each event with nitrate concentrations of less than 14 mg L^{-1}. This implies the presence of high ammonia volatilization losses from surface application under the weeping lovegrass production, supporting the previous argument on the most probable reason for the mass balance difference.

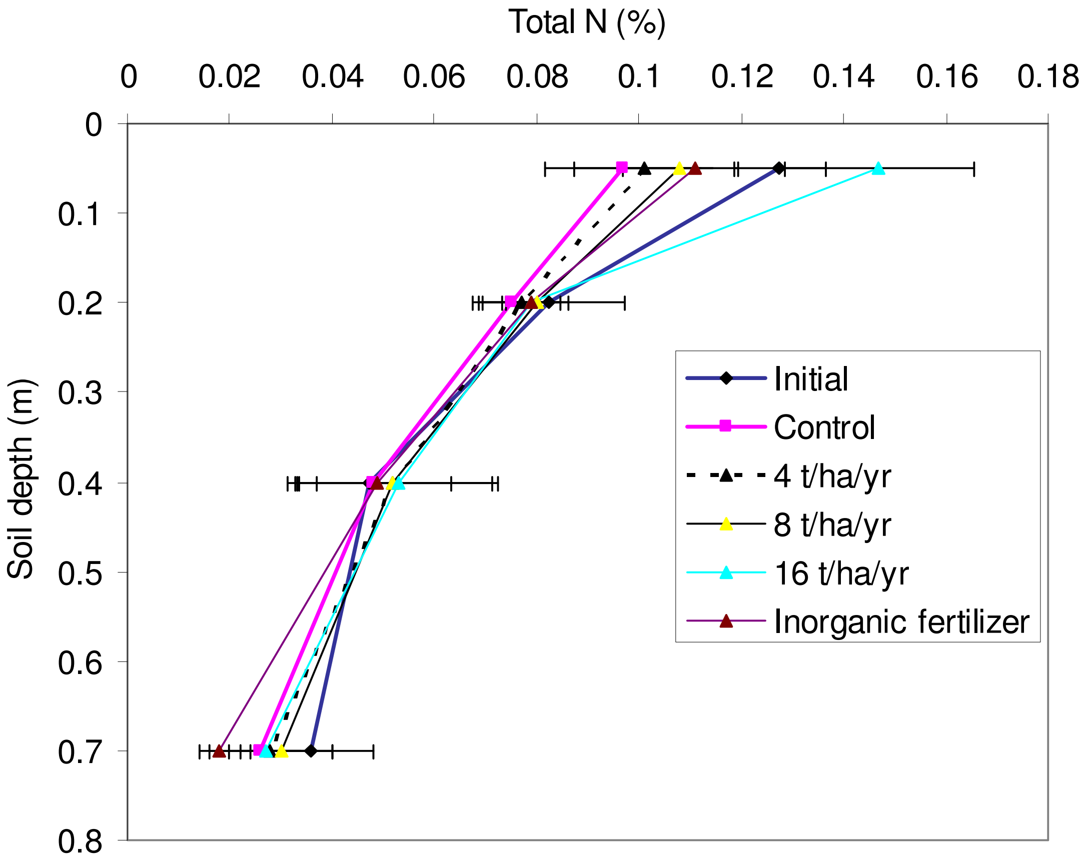

Figure 5.4 Initial soil profile total N and after four years of study with three sludge rates (4, 8, and 16 Mg ha^{-1} yr^{-1}), an inorganic fertilizer (200 kg N ha^{-1} yr^{-1}), and a control.

5.3.2 Residual nitrate and nitrate leaching

Residual nitrate in the top 0.5 m soil layer of all treatments including sludge applied at double the norm remained less than the initial amount throughout the study period (Table 5.9). The reduction in nitrate content of all treatments was evident in the 0-0.3 m soil stratum, while the content in the 0.3-0.8 m layer remained similar to initial values (Fig. 5.5). It was also evident that sludge applied at double the norm had relatively lower residual nitrate than lower sludge rates in 2005/06, but higher at the end of 2007/08 growing season growing season.

Table 5.9 Residual nitrate mass in the top 0.5 m soil stratum of weeping lovegrass plots treated with three sludge rates, an inorganic fertilizer, and a control treatment.

Treatment	Initial	After 2nd hay cut in 2005/06	After 2nd hay cut in 2007/08
		kg ha-1	
Control†	96	60	18
4 Mg ha^{-1} yr^{-1}	96	62	18
8 Mg ha^{-1} yr^{-1}	96	52	16
16 Mg ha^{-1} yr^{-1}	96	51	58
Inorganic fertilizer‡	96	33	51

† Zero sludge and inorganic fertilizer applied
‡ 200 kg N and 40 kg P per hectare per annum applied

Although residual nitrate at the end of the study was relatively higher for the 16 Mg ha^{-1} yr^{-1} sludge treatment than other treatments, it was still low and was almost half of the initial mass. The main reason for monitoring residual nitrate after harvest was that nitrate leaching under dryland conditions usually takes place in the beginning of the rainy season, especially before active root nutrient uptake in the presence of high rainfall and residual soil nitrate. Nitrate is susceptible to diffusion and transport through mass flow with soil water because there is little tendency for soil colloids to absorb nitrate, which is negatively charged, as they mostly posses a net negative charge (Cameron and Haynes, 1986).

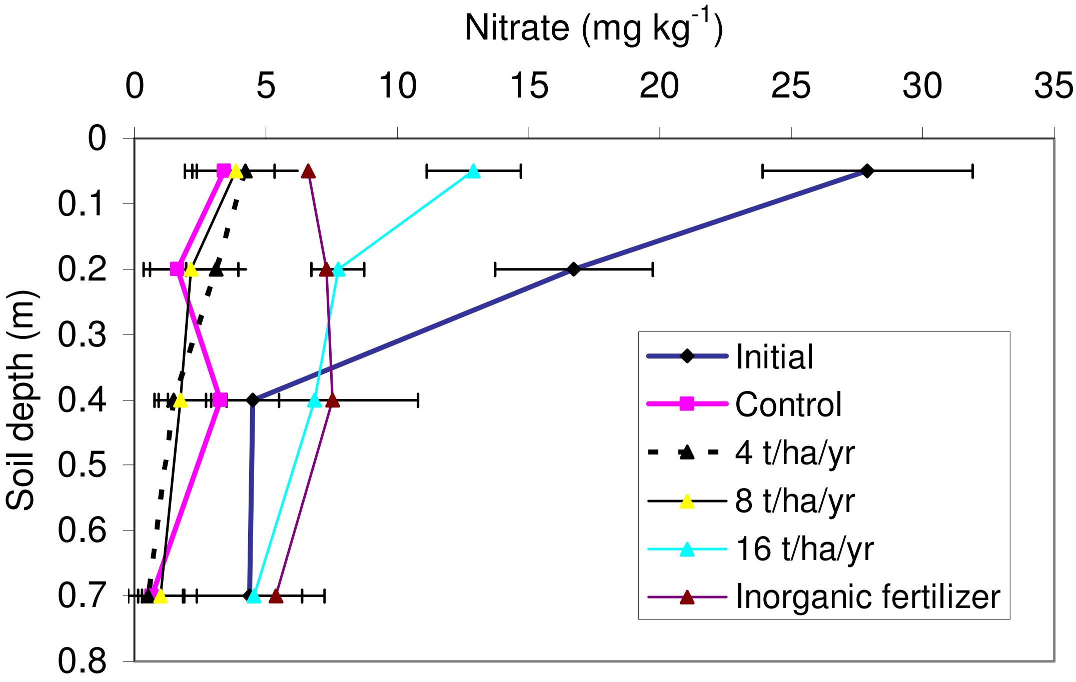

Figure 5.5 Residual nitrate before treatment application (initial) and after four consecutive years of treatment application (three sludge rates, inorganic fertilizer and control).

In this specific study the mean annual rainfall was low (405 mm in 2007) to moderate (710 mm in 2008). The wetting front detectors buried at 0.3 m depth responded only four times during the four year study period. The dates of response and the corresponding nitrate concentrations from the 16 Mg ha^{-1} yr^{-1}

sludge treatment were: 21/02/2005 (10 mg L^{-1} NO_3), 01/03/2006 (14 mg L^{-1} NO_3), 22/01/2008 (8 mg L^{-1} NO_3), and 16/03/2008 (11 mg L^{-1} NO_3). The control and 8 Mg ha^{-1} yr^{-1} sludge treatments had similar or lower nitrate concentrations during the same time period. None of the WFDs buried at 0.6 m, however, responded. Therefore, considering the low to moderate rainfall experienced during the study period, low residual nitrate, and low nitrate concentrations collected during very few events might indicate that nitrate leaching was minimal during the study period.

5.3.3 Residual ammonium

Residual ammonium in the top 0.5 m soil stratum remained equal or less than initial values for all treatments (Table 5.10). Residual ammonium increased with increase in sludge application rate at the end of the 2007/08 growing season, though it did not have any specific trend in 2005/06.

The low residual ammonium mass reported at the end of the study, despite a net positive total N mass balance, might indicate that the ammonium added from the sludge was either nitrified or taken up by the plants. The possibility for ammonium to leach below the active root zone (0-0.6 m) in this specific soil type under the prevailing rainfall and sludge rates is unlikely, considering the following facts. Primarily the predominantly negatively charged soil clay and organic matter particles can fix ammonium through the process of cation exchange. Secondly ammonium can easily be immobilized by microbial biomass, and lastly, ammonium is unstable and is readily nitrified (Cameron and Haynes, 1986).

Table 5.10 Residual ammonium mass in the top 0.5 m soil stratum after every second weeping lovegrass hay cut during the 2004/05 to 2007/08 growing seasons.

Treatment	Initial	After 2nd hay cut in 2005/06	After 2nd hay cut in 2007/08
	kg ha^{-1}		
Control†	65	16	20
4 Mg ha^{-1} yr^{-1}	65	41	38
8 Mg ha^{-1} yr^{-1}	65	31	46
16 Mg ha^{-1} yr^{-1}	65	36	65
Inorganic fertilizer‡	65	59	47

† Zero sludge and inorganic fertilizer applied
‡ 200 kg N and 40 kg P per hectare per annum applied

Despite the net positive total N mass balance of the 16 Mg ha^{-1} yr^{-1} sludge treatment (Table 5.8), residual ammonium and nitrate remained similar or less than initial values. This indicates that a large fraction of the N in the soil is present in organic form.

In conclusion, sludge applications that produced the highest weeping lovegrass hay yield are not necessarily in total N balance. In this study, the 16 Mg ha^{-1} yr^{-1} sludge treatment significantly improved weeping lovegrass hay yield but was not in total N mass balance. The same treatment accumulated an extra 649 kg N ha^{-1}

(supply less uptake) or 330 kg N ha^{-1} (final less initial soil N storage change) following four consecutive years of sludge application and hay harvest events. Despite this net positive total N mass balance, there was neither residual nitrate nor ammonium accumulation in the soil profile above the initial values. In addition, the few soil solution samples collected from 0.3 m deep WFDs presented low nitrate concentrations. The implications are that sludge applications of up to 16 Mg ha^{-1} yr^{-1} should have minimal environmental impacts through nitrate leaching in the medium-term (four years) for weeping lovegrass hay production under the prevailing climatic and edaphic conditions of the study site.

Therefore, the following hypothesis was accepted:

- Sludge applications of up to 16 Mg ha^{-1} yr^{-1} that produced the highest hay yield under the prevailing climatic and edaphic conditions were not prone to excessive nitrate leaching in the medium-term (four years).

The following hypothesis was rejected:

- Under high hay yield production conditions, N supply from double the norm can be fully utilized.

Nevertheless, long term model simulations should be conducted because the mineralization of N from sludge could take several years before reaching steady-state conditions.

5.4 Total P mass balance and residual Bray-1P

5.4.1 Total P mass balance

Sludge applications of all rates resulted in a net positive total P mass balance (CUM-PS less CUM-PU) following four years of sludge applications and weeping lovegrass hay harvest events (Table 5.11, columns 4 and 5). Based on the mass balance calculation of total P imported with sludge less exported with weeping lovegrass hay yield, sludge applications of 4 Mg ha^{-1} yr^{-1} supplied a cumulative excess of 279 kg P ha^{-1} during the four year study.

Table 5.11 Cumulative total P supply (CUM-PS), uptake (CUM-PU), and mass balance of a weeping lovegrass treated with three sludge rates, inorganic fertilizer, and a control

	Four years cumulative total P mass balance				
Treatment	CUM-PS	CUM-PU	CUM-PS less CUM-PU	Change in soil P storage	Mass balance difference
	kg ha^{-1}				
Control†	0	59	-59	-50	-9
4 Mg ha^{-1} yr^{-1}	352	73	279	302	-23
8 Mg ha^{-1} yr^{-1}	705	93	612	660	-48
16 Mg ha^{-1} yr^{-1}	1409	102	1307	1316	-9
Inorganic fertilizer‡	160	93	67	96	-29

† Zero sludge and inorganic fertilizer
‡ 40 kg P ha^{-1} per year applied

Soil sampling to a depth of 0.8 m (Change in soil P storage) also supported after trends for the total P supply less uptake mass balance (Table 5.11). Most of the excess P added with the sludge was located in the 0-0.1 m soil layer with a slight increase in the deeper 0.1-0.3 m soil layer (Fig. 5.6). The slight total P increment in this soil layer was most probably due to the physical migration of colloidal sludge particles between cracks formed during dry periods of the year, or from preferential flow of particulate P (Jensen et al., 2000; Brock et al., 2007). The grave concern with P surface accumulation is the potential threat to surface water bodies through transport by runoff, enhancing the rate of eutrophication in fresh water bodies (Carpenter et al., 1998).

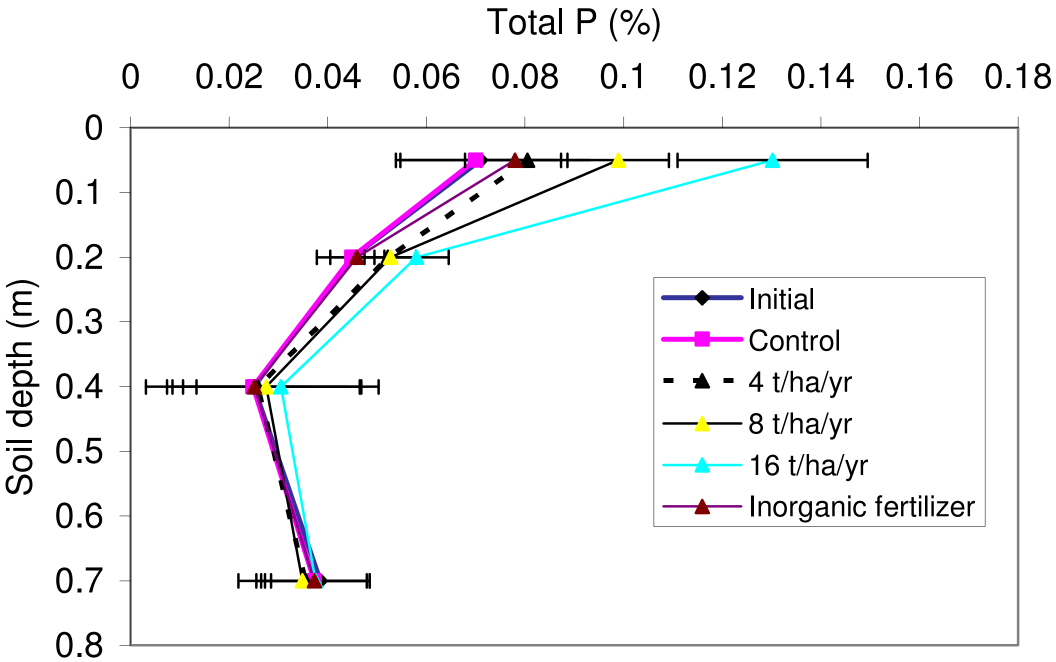

Figure 5.6 Initial soil profile total P and after four consecutive years of treatment applications in a weeping lovegrass hay production trial.

There was a mass balance difference between the supply less uptake mass balance (Table 5. 11, column 4) and the final less initial soil profile total P mass balance (Table 5. 11 column 6). The possible sources of difference are sampling errors, P content variation within the sludge matrix and soil heterogeneity.

The main reason for the accumulation of P in the soil profile was the low sludge N:P ratio of the sludge compared with that of crops. Therefore, P accumulation is inevitable if sludge is applied according to crop N demand (Shober and Sims, 2003).

5.4.2 Soil profile residual Bray-1 extractable P

Bray-1P decreased as the sludge application rate increased to 8 Mg ha^{-1} yr^{-1}, but increased at higher rates (Table 5.12). Four years of sludge application according to the limit reduced residual Bray-1P by 42%. This is in contrast to the net positive total P mass balance reported for the same treatment on Table 5.11. On the other hand, sludge applied at double the limit increased residual Bray-1P in the top 0.5 m by 33 and 58%, compared with the control and 8 Mg ha^{-1} sludge treatments, respectively.

Generally the mean background Bray-1P concentration of the soil in the 0-0.3 m soil stratum (65 mg kg^{-1}) was higher than the optimum concentration required for most crops (25-30 mg kg^{-1}). It was also higher than the concentration for an optimum soil quality (50 mg kg^{-1}) above which the risk for surface water body pollution increases as reported (Sims and Pierzynski, 2000).

The decline in Bray-1P reported for the 4 and 8 Mg ha^{-1} sludge treatments was mainly due to the $FeCl_3$ added to the sludge at the waste treatment plants, which reduced the solubility of P (Huang et al., 2007; O'Connor et al., 2004; Huang and Shenker, 2004; Elliott et al., 2002; Maguire et al., 2000). The build up of Bray-1P reported from doubling of the sludge upper limit is most probably because the P supply from the sludge exceeded the buffer capacity of the soil and sludge (Elliott and O'Connor, 2007) or a decline in the sludge's P-sorbing capacity over time (Lu and O'Connor, 2001). It is also possible that the Fe-P minerals may have released P by dissolution as reported by Huang et al. (2007). Therefore, it is apparent from this study, that although, sludge treated with $FeCl_3$ reduced P plant availability; it is likely that P availability could also increase at higher rates over time.

Despite the high background concentration and additional P added with the sludge, there were no visible phosphorus toxicity symptoms during the study period. This is most probably due to the high Zn added with the sludge, because previous studies conducted by Loneragan et al. (1979), Safaya (1976), Parker (1997), Webb and Loneragan (1988), and Silber et al. (2002), all show that plant P toxicity is enhanced under Zn deficient conditions.

Table 5.12 Residual Bray-1P in the top 0.5 m soil stratum after the second hay cut of dryland pasture (weeping lovegrass) during the 2004/05 to 2007/08 growing seasons.

Treatment	Initial	After 2nd hay cut in 2005/06	After 2nd hay cut in 2007/08
		kg ha^{-1}	
Control†	274	282	254
4 Mg ha^{-1} yr^{-1}	274	253	230
8 Mg ha^{-1} yr^{-1}	274	150	159
16 Mg ha^{-1} yr^{-1}	274	367	378
Inorganic fertilizer‡	274	276	295

† Zero sludge and inorganic fertilizer applied
‡ 200 kg N and 40 kg P per hectare per annum applied

In summary, doubling of the annual sludge upper limit to satisfy crop N demand enhanced the build up of total P. Furthermore, this study showed that plant availability of P (Bray-1P) from dryland pasture soils fertilized with surface applied sludge, treated with $Fe\text{-}Cl_3$, is affected by the rate of sludge application. Consequently, Bray-1P decreased as the sludge application rate increased to 8 Mg ha^{-1}, but increased at higher rates over time.

Therefore, the following hypotheses were accepted:

- Sludge application according to weeping lovegrass N demand results in the accumulation of total and Bray-1P in the soil profile.

5.5 Conclusions

Weeping lovegrass hay yield, crude protein content, and rainfall use efficiency increased with doubling of the annual upper limit sludge application norm for sludge with 2.56% mean N. Highest yield was harvested from years which experienced high rainfall compared with similar treatments experiencing low rainfall for all sludge treatments. Weeping lovegrass annual N uptake increased significantly as the sludge application rate was doubled. Sludge applied according to the norm of 8 Mg ha^{-1} yr^{-1} was not sufficient to satisfy weeping lovegrass N demand. Doubling the upper sludge limit norm did not cause the accumulation of nitrate and ammonium in the profile. Sludge applied at double the norm, however, increased both total and Bray-1P with time.

Therefore, the following hypotheses were accepted under the prevailing climatic conditions:

1. Sludge application above the 8 Mg ha^{-1} yr^{-1} norm could significantly increase dryland pasture (weeping lovegrass) hay yield, crude protein content, and water use efficiency.
2. The ideal sludge application rate to satisfy dryland pasture (Weeping lovegrass) N demand is dynamic and could exceed the 8 Mg ha^{-1} yr^{-1} sludge norm.
3. Sludge applications of up to 16 Mg ha^{-1} yr^{-1} that produced the highest hay yield under the prevailing climatic and edaphic conditions are not prone to excessive nitrate leaching in the medium term (four years).
4. Sludge application according to weeping lovegrass N demand results in the accumulation of total P.

5. Sludge application according to weeping lovegrass N demand could result in the accumulation of Bray-1P at higher rates.

The following hypothesis was rejected under the prevailing low rainfall conditions of the study site:

- Under high hay yield production conditions, N supply from double the norm can be fully utilized.

Nevertheless, long-term model simulations should be conducted under varying rainfall, sludge N concentration, sludge type, and soil types in order to get a site specific real-time ideal sludge loading rate because N mineralization from sludge could take several years before reaching steady-state conditions.

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CHAPTER 6

TURFGRASS

The following hypotheses are tested in this chapter.

High sludge surface loading rates well above recommendations based on crop removal:

1. Are possible without reducing turf growth and quality.
2. Do not cause an accumulation of N and P below the active root zone.
3. Can minimize soil loss through sod harvesting, and
4. Do not cause unacceptably high nitrate and salt leaching.

6.1 Turfgrass growth and quality

6.1.1 Establishment rate

Establishment rate was estimated from mean percent basal cover. Sludge application rates above the 1997 South African upper limit norm (8 Mg ha^{-1}) significantly improved turf establishment rates (Table 6.1). The rapid rate of establishment in the high sludge application treatments can be attributed to the increase in the availability of essential nutrients, especially N and P and/or the low bulk density of the growing medium. Sludge application rates above agronomic limits, therefore, could have the advantage of increasing the number of sod harvests per season by speeding up the rate of turfgrass growth. This opens up an opportunity to export even more sludge.

6.1.2 Turfgrass colour

Turfgrass colour rating significantly improved with increase in sludge application rate (Table 6.1). Turfgrass which received sludge rates higher than the former South African upper limit norm exceeded the ‘acceptable’ colour ratings (7 - 9). The highest colour rating was scored by the 67 and 100 Mg ha^{-1} treatments and the lowest by the zero sludge treatment. The increase in colour rating observed with increase in sludge application rate was most likely as a result of the increase in plant available N, as reported by Bilgili and Acikgoz (2005). Nitrate concentration data from the WFDs installed at 0.3 m (Fig. 6.1) also clearly illustrated that there was an increase in the availability of N with increase in sludge

Table 6.1 Kikuyu (*Pennisetum clandestinum* Hochst. ex Chiov.) turfgrass sod quality (establishment rates (% mean vegetative cover), visual colour ratings, and sod integrity) as affected by five sludge application rates during the 2005 and 2006 growing seasons at East Rand Water Care Works, Johannesburg, South Africa.

	Days after sludge application				Seasonal mean visual colour rating†		Sod integrity (percent harvestable sod per unit area)	
	2005		2006					
Sludge application rate	34	65	34	65	2005	2006	2005	2006
	Mean vegetative cover, %				Colour ratings		%	
Control	34	58	36	68	4.0	3.8	72	71
8 Mg ha^{-1} per cut	41	74	43	75	4.8	5.3	72	73
33 Mg ha^{-1} per cut	56	88	59	87	7.0	7.3	93	96
67 Mg ha^{-1} per cut	63	95	68	95	8.5	8.5	90	88
100 Mg ha^{-1} per cut	71	98	71	98	8.5	9.0	58	62
LSD (5%)	6	5	6	6	0.7	0.7	7	7
CV‡, %	7	4	7	5	6	7	6	6

† Visually rated on a scale from 1 to 9 (1 = straw brown; 9 = dark green).
‡ Coefficient of variation

application rate during most of the growing season.

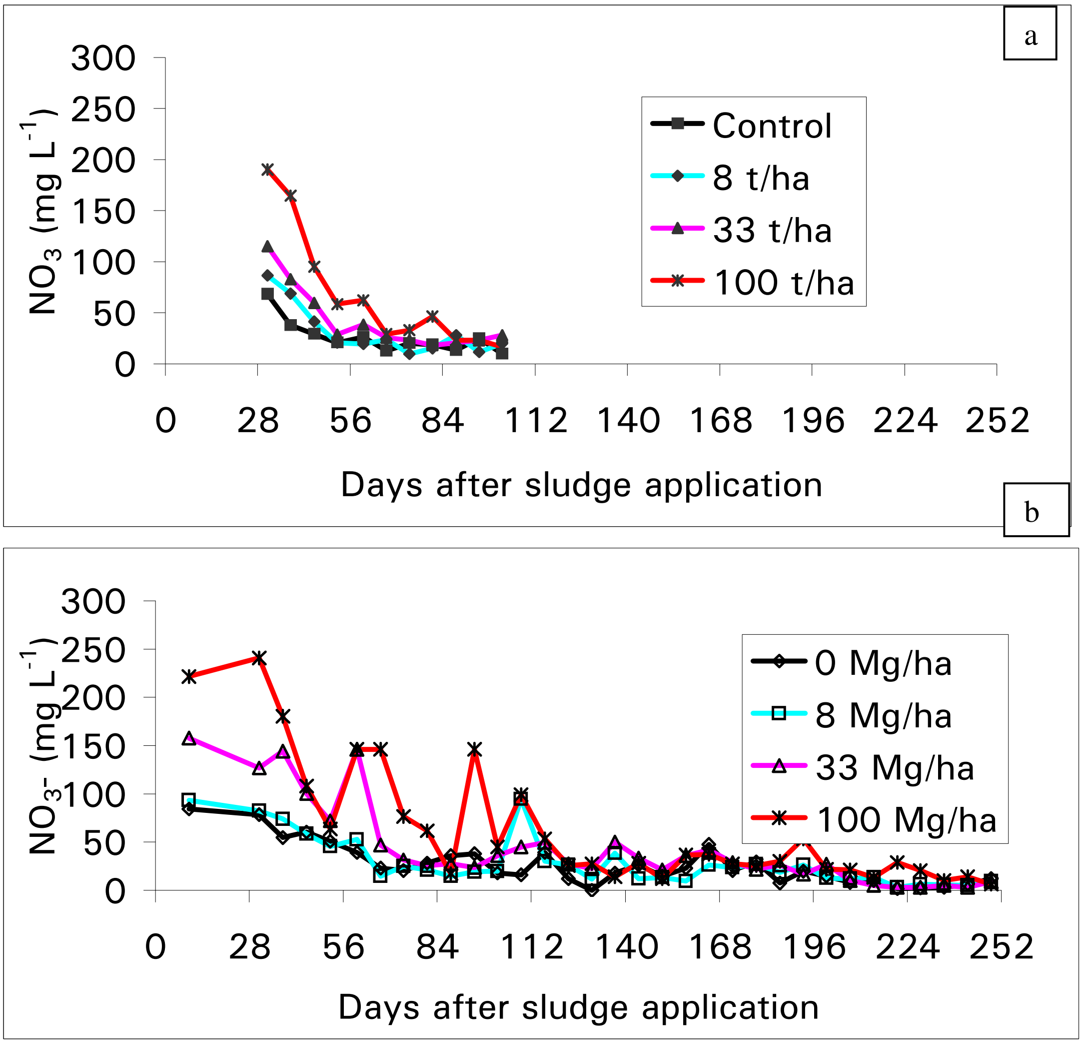

Figure 6.1 Concentration of nitrate in soil solution samples collected from wetting front detectors installed at 0.30 m of a turfgrass sod (*Pennisetum clandestinum*) trial for four sludge application rates (0 Mg ha^{-1}, 8 Mg ha^{-1}, 33 Mg ha^{-1}, and 100 Mg ha^{-1}) during (a) year 2005 and (b) 2006.

6.1.3 Sod integrity

The percentage of sods that did not break during handling increased as the sludge application rate increased to 33 Mg ha^{-1}, but decreased at higher rates (Table 6.1). The 0 Mg ha^{-1} sludge treatment produced heavy sods up to 54 Mg ha^{-1} heavier than the treatment receiving 100 Mg ha^{-1}. An increase in the sludge application rate to 33 Mg ha^{-1} reduced sod mass and the more vigorous turf was able to bind the soil/sludge mix effectively. However, as the sludge application rate increased to 67 and 100 Mg ha^{-1}, the sod became weaker and a greater proportion fell apart during handling and loading. Nevertheless, sod integrity was still good at 67 Mg ha^{-1}, and was not significantly different from the 33 Mg ha^{-1} treatment in 2005 (93 vs. 90%). Although significant in 2006 (96 vs. 88%), the difference was only 8%. Highest percentages of strong intact sods were harvested from the 33 Mg ha^{-1} treatment, and the lowest from the 100 Mg ha^{-1} treatment for both seasons.

One may expect that the strategy of harvesting sods once the slowest growing treatments had reached full cover may also have contributed to differences in sod integrity among the treatments as a result of differences in maturity. However, it is interesting to note that the slowest growing treatments (0 and 8 Mg ha^{-1}) did not have the weakest sods, as the high fraction of soil in the sod matrix, increased their integrity relative to the 100 Mg ha^{-1} treatment, which had a very high fraction of sludge in the sod.

The growth study showed that establishment and colour continued to improve up to an application of 67 to 100 Mg ha^{-1}, well above the maximum recommended limit, but that sod integrity decreased after 33 Mg ha^{-1}.

6.2 Accumulation of N and P in soil below active root zone

6.2.1 Nitrogen

The mass of N exported with the sod increased significantly with increase in sludge application rate (Table 6.2), with 86 to 91% in the substrate fraction of the sod. The amount of N in the plant component of the sod also increased significantly with increase in application rate, although plant N contributed only 10-15% of the total sod N. Similarly, Vietor et al. (2002) reported the export of a large N fraction in the soil component of the sod. Excess N exported with the sod can provide nutrition for turfgrass at the new site of establishment, where the original topsoil has often been removed due to construction. It was also evident that a significant amount of N was removed with clippings.

The total N content within the top meter of soil declined over the two year period in all treatments receiving less than 100 Mg ha^{-1} sludge (Table 6.3). Based on soil sampling over this depth (change in soil storage), sludge applications of around 67 Mg ha^{-1} were approximately in balance for nitrogen (Table 6.3). Generally a mass balance difference was observed in the top 1 m soil layer for all treatments. This could be attributed to leaching (Sierra et al., 2001; Samaras et al., 2008), volatilization (Beauchamp et al., 1978; Robinson and Polglase, 2000), and denitrification losses (Monnett et al., 1995). Considering the high leaching fraction experienced in this study, the largest loss was most likely through leaching. Sampling errors, N content variation within the sludge matrix, and soil heterogeneity may also have contributed to the differences.

Total soil N content decreased with depth for all treatments (Fig. 6.2a). After two years, the total N content of the top 0.15 m layer was less than the initial total N content of the same layer for all treatments. This could be due to grass uptake, leaching to lower layers, and the removal of a thin surface layer of soil during sod harvesting, which is rich in organic matter. Significant accumulation of N was evident in the 0.15-0.75 m layers of the 100 Mg ha^{-1} and the 0.45-0.75 m layers of the 67 Mg ha^{-1} treatments (Fig. 6.2a), despite the decline in the top 0.15 m layer. This indicates that N was leached to the lower layers because of the high leaching fraction experienced during the study period.

Soil nitrate concentration is a highly dynamic property, reflecting the size of the labile N pool and the antecedent conditions favouring mineralization and leaching. Sludge application rates lower than 33 Mg ha^{-1} showed a marked depletion in nitrate levels by the end of the study (Fig. 6.2b). Rates of 33 Mg ha^{-1} and above, maintained the nitrate concentration of the soil profile close to initial values, which as a benchmark, were within the ranges reported for golf courses from a lysimeter study (Wong et al., 1998).

Table 6.2. Total N imported with sludge, vs. exported with sods and clippings during the 2004/05 and 2005/06 growing seasons at East Rand Water Care Works, Johannesburg, South Africa.

	N imported with sludge vs. exported with sod and clippings									
	Imported		Exported							
			2005				2006			
Sludge application rate			Sod		Clippings	Total	Sod		Clippings	Total
	2005	2006	Soil	Plant			Soil	Plant		
Mg ha^{-1}	kg ha^{-1}									
0	0	0	400	66	174	640	297	37	154	488
8	243	151	466	77	268	811	358	47	255	660
33	1001	622	773	96	487	1356	655	68	419	1142
67	2031	1262	1050	141	620	1811	798	100	582	1480
100	3032	1884	1104	143	797	2044	1094	143	712	1949
LSD (5%)			70	10	30	78	56	4	30	61
CV‡, %			6	7	6	5	6	3	5	5

† Means in the same column followed by the same letter are not significantly different at $P < 0.05$ level.
‡ Coefficient of variation

Table 6.3 Total nitrogen and total phosphorus mass balances after two years of sludge application and sod harvest events for five sludge application rates during the 2005 and 2006 growing seasons

Sludge application rate	Nitrogen				Phosphorus			
	Imports	Exports	Change in soil storage†	Mass balance difference‡	Imports	Exports	Change in soil storage†	Mass balance difference‡
Mg ha^{-1}	kg ha^{-1}							
0	0	1128	-1295	-167	0	459	-465	-6
8	394	1471	-1318	-241	305	713	-452	-44
33	1623	2498	-1116	-241	1257	1389	-165	-33
67	3293	3291	-254	-256	2551	2349	175	-27
100	4916	3993	740	-183	3806	3479	291	-36

† Estimated by subtracting the initial soil profile N or P content before treatment application from the soil profile N or P content at the end of the two year study period (2006).

‡ Estimated by subtracting the change in soil storage from the (Imports – Exports).

The concentration of ammonium was elevated at applications greater than 33 Mg ha^{-1} (Fig. 6.2c). This was probably due to adsorption to CEC sites, as the soil had a high and fairly uniform clay content (34%-40%) to a depth of 1.2 m.

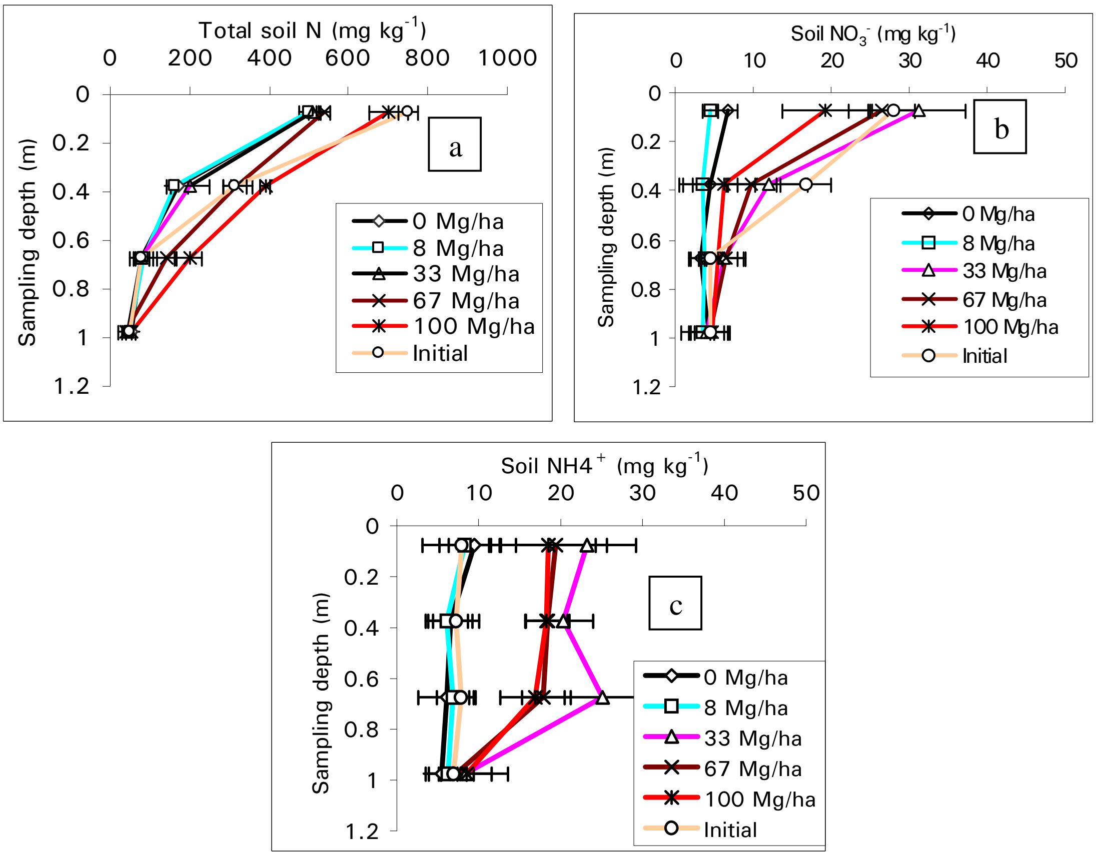

Figure 6.2 Soil profile (a) total N (b) nitrate (c) ammonium (d) total P (e) Bray-1 extractable P, and (f) electrical conductivity (ECe) as affected by two consecutive years of sludge application at five rates (0, 8, 33, 67, and 100 Mg ha^{-1}) in a turfgrass sod (*Pennisetum clandestinum*) field trial, sampled before treatment application in 2005 (initial) and after two sod harvests in 2006.

6.2.2 Phosphorus

The mass of P exported with the sod increased significantly as the sludge application rate increased (Table 6.4), with 93% to 99% in the substrate fraction of the sod. Phosphorus stored in the soil profile declined over the two year period in all treatments receiving less than 67 Mg ha^{-1} of sludge, based on soil sampling over the 1.0 m depth (Table 6.3). Based on this sampling depth (change in soil storage), sludge application rates of 33 to 67 Mg ha^{-1} were approximately in balance for phosphorus. However, the 67 Mg ha^{-1} treatment was associated with a net positive P accumulation (175 kg ha^{-1}) within two years. A mass balance difference was evident for all treatments and could most probably be from sampling errors, P content variation within the sludge matrix, and soil heterogeneity.

Soil profile total P (mg kg^{-1}) and Bray-1 extractable P (mg kg^{-1}) decreased with depth for all treatments (Figs. 6.3a and 6.3b). Sludge application rates higher than 33 Mg ha^{-1} resulted in the build up of total P in the top 0.15 m soil layer. However, the concentrations of Bray-1 extractable P for all treatments were less than the initial soil profile concentration (before treatment application) (Fig. 6.3b). The build up of total P in the top 0.15 m soil layer of the 67 and 100 Mg ha^{-1} rates may be from some sludge remaining after sod lifting or from preferential flow of particulate P (Jensen et al., 2000; Brock et al., 2007).

Table 6.4 Total phosphorus imported with sludge, vs. exported with sods and clippings during the 2005 and 2006 growing seasons at East Rand Water Care Works, Johannesburg, South Africa.

	P imported with sludge vs. exported with sod and clippings									
	Imported		Exported							
			2005				2006			
			Sod				Sod			
Sludge application rate	2005	2006	Soil	Plant	Clippings	Total	Soil	Plant	Clippings	Total
Mg ha^{-1}	kg ha^{-1}									
0	0	0	229	16	13	258	170	19	12	201
8	157	148	358	18	21	397	275	21	20	316
33	648	609	661	18	48	727	598	22	42	662
67	1315	1236	1148	18	53	1219	1056	25	49	1130
100	1962	1844	1782	21	112	1915	1440	26	98	1564
LSD (5%)			108	1	3	108	59	1	3	59
CV†, %			6	5	4	4	6	5	6	5

† Coefficient of variation

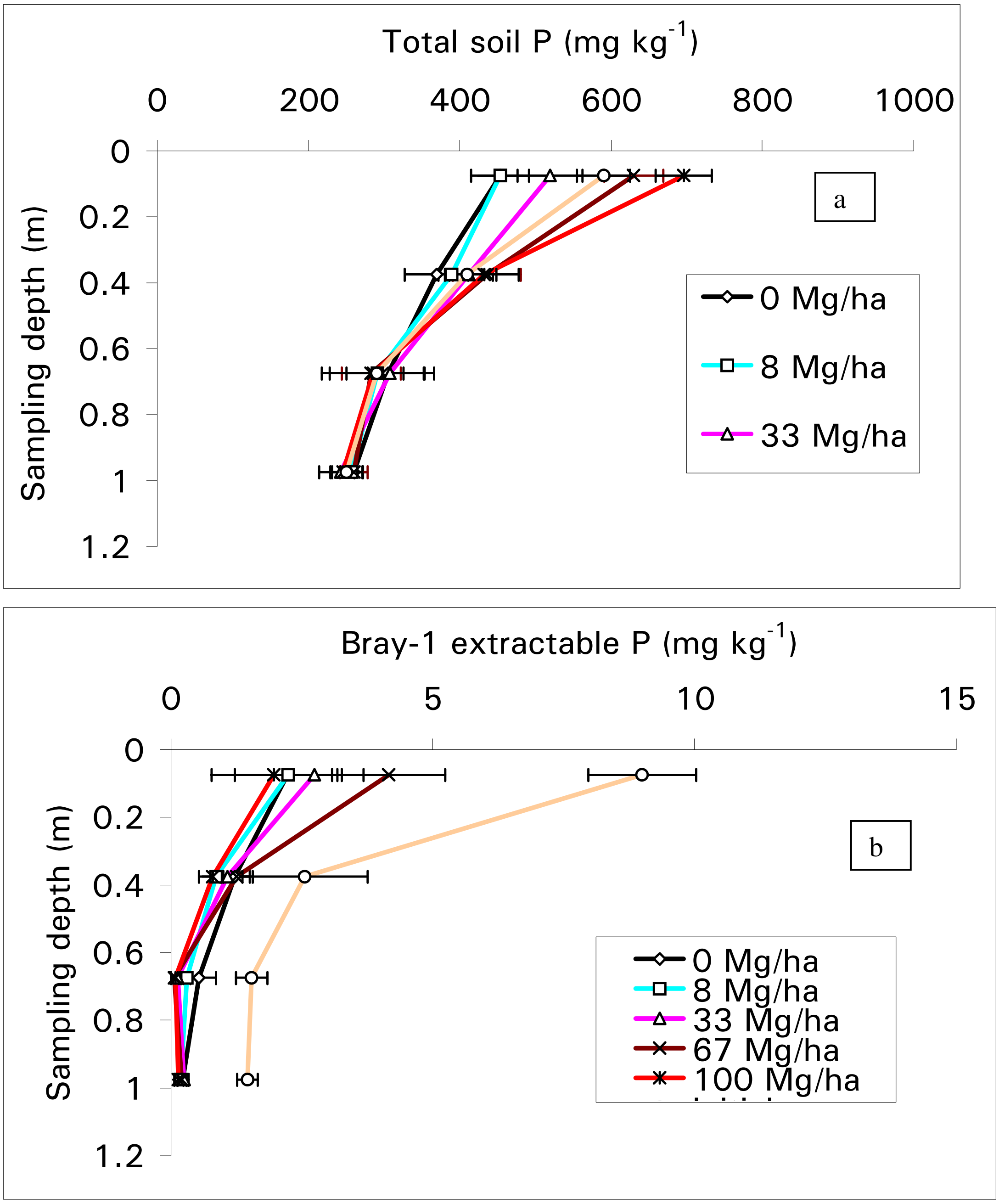

Figure 6.3 Soil profile (a) total P (b) Bray-1 extractable P as affected by two consecutive years of sludge application at five rates (0, 8, 33, 67, and 100 Mg ha^{-1}) in a turfgrass sod (*Pennisetum clandestinum*) field trial, sampled before treatment application in 2005 (initial) and after two sod harvests in 2006.

The Bray-1 extractable P concentrations of all treatments were below the optimum concentration of 25 to 30 mg kg^{-1} required for most crops (Sims and Pierzynski, 2000) and below the ‘low sufficiency’ range of 6-12 mg kg^{-1} for the common soil Bray-1P test reported by Havlin et al. (2005). The decline in Bray-1 extractable P from all sludge loadings of less than 67 Mg ha^{-1} could most probably be due to plant uptake. For treatments receiving sludge rates higher than 67 Mg ha^{-1}, however, it might also be caused by the Fe added with the sludge. This is because the sludge used in this study has gone through tertiary treatment, and is rich in insoluble Fe-P compounds. Chemicals used in tertiary treatments such as Al or Fe salts, decrease the labile P fraction (Elliott et al., 2002; Häni, et al., 1981; Kyle and McClintock, 1995).

In summary, total N within the top meter of soil decreased over the duration of the trial for rates not exceeding 67 Mg ha^{-1}. Total P content within the same depth also declined for rates not exceeding 33 Mg ha^{-1}. Bray-1 extractable P, however, decreased for all treatments. Based on soil sampling over a depth of 1.0 m, sludge applications of around 67 Mg ha^{-1} approximately preserved N mass balance, but was associated with significant N leaching to the lower 0.45-0.75 m soil layer. The P mass balance was, however, preserved at loading rates of 33 Mg ha^{-1}. Total P accumulation was evident mainly in the top 0.15 m of treatments which received sludge loading rates higher than 33 Mg ha^{-1} under the prevailing management practices and climate.

6.3 Soil loss through sod harvesting

Soil loss from the site was estimated from the soil depth exported with the sod. Results from this study show that severe soil loss takes place in turfgrass sod production areas where little or no amendment is applied (Table 6.5). The depth of soil exported from the site decreased significantly with increasing sludge application rates above 8 Mg ha^{-1}. The application of 33, 67, and 100 Mg ha^{-1} saved 120, 217, and 290 Mg ha^{-1} soil respectively from being exported from the site within two years (assuming a soil bulk density of 1380 kg m^{-3}). Considering the very slow average global rate of soil formation, 700 kg ha^{-1} yr^{-1}, (Wakatsuki and Rasyidin, 1992) the 33, 67, and 100 Mg ha^{-1} treatments saved soil from being exported which could have taken 86, 155, and 207 years to form, respectively.

Sod mass decreased for every increment in sludge application rate because of the low bulk density of sludge (666 kg m^{-3}) compared with soil (Table 6.5). This also has a direct financial implication for sod transportation. Thus sludge applied above agronomic limits, will also reduce sod transportation costs.

In summary, the application of sludge did help to reduce the rate of soil loss through sod harvesting and should reduce transportation cost through lowering sod mass. Rates as high as 100 Mg ha^{-1} were required to completely avoid soil loss. However, such high loading rates deleteriously affected sod integrity.

Table 6.5. Sod mass and cumulative soil thickness exported with turfgrass sods as affected by five sludge application rates after two consecutive sludge application and sod harvest events at East Rand Water Care Works, Johannesburg, South Africa.

Sludge application rate	Sod mass		Cumulative Soil thickness exported (2005-2006)
	2005	2006	
	$Mg\ ha^{-1}$		mm
0	149	156	22.0
8	147	155	21.5
33	141	148	13.3
67	112	128	6.3
100	99	102	1.0
LSD (5%)	9	10	1.6
CV†, %	4	5	8

† Coefficient of variation

6.4 Nitrate and salt leaching

Soil solution nitrate and EC measurements were made on samples collected by the 0.3 m deep WFDs during the first three months after sludge application in 2005, and throughout the 2006 study period. Because the 67 Mg ha^{-1} treatment did not have WFDs, this treatment is excluded from the discussion that follows.

6.4.1 Nitrate leaching

In the beginning of the season, soil solution nitrate concentration increased with sludge application rate (Fig. 6.1). This is to be expected as nutrient supply far exceeds demand directly after sod harvest, as explained in detail by Geron et al. (1993). Later during the season, the concentration of nitrate remained at low levels (Fig. 6.1), presumably because the greater demand from the turf matched the mineralization rate from the sludge. Similar results and trends were recorded both during the 2004/05 (Fig. 6.1a) and 2005/06 (Fig. 6.1b) growing seasons.

Generally, the concentrations of nitrate in the soil solution from all treatments were within the ranges reported by Biró et al. (2005) for leachate from organic and conventionally managed horticultural lands (0-255 mg L^{-1} NO_3^-). It was also less than the maximum nitrate concentration in leachate from a simulated golf green (376 mg L^{-1} NO_3^-) reported by Shuman (2001).

The concentration of nitrate leachate from all treatments remained higher than South African drinking water standards (44 mg NO_3^- L^{-1}) (Korentajer, 1991) for the first two to three months in the 100 Mg ha^{-1} sludge treatment (Fig. 6.1). The wetting front detectors installed at 0.6 m depth, however, did not collect soil solution samples from any of the treatments. Therefore, it was not clear whether the nitrate that passed the WFD at 0.3 m, had leached below the WFD at 0.6 m, perhaps in a weak front below the detection level of the WFD, or was stored between the two depths.

The seasonal average nitrate leachate concentrations for the 0, 8, and 33 Mg ha^{-1} sludge treatments (26, 29, and 43 mg NO_3^- L^{-1} respectively) were less than the South African drinking water standard (44 mg L^{-1}) (Korentajer, 1991) and the EU nitrate concentration limit for groundwater (50 mg NO_3^- L^{-1}) (Vlassak and Agenbag, 1999). The seasonal average nitrate concentration for the 100 Mg ha^{-1} treatment (63 mg NO_3^- L^{-1}), however, exceeded both limits. Compared with the zero sludge treatment, the addition of 8, 33, and 100 Mg ha^{-1} sludge increased the average seasonal nitrate concentration of the leachate by 3, 17 and 36 mg NO_3^- L^{-1} respectively.

6.4.2. Salt leaching

In the beginning of the season soil solution EC increased with sludge application rate (Fig. 6.4). The EC of soil solution samples from the 100 Mg ha^{-1} treatment collected 10 days after sludge application were only slightly higher than the threshold value with 10% yield reduction of 300 mS m^{-1} for kikuyu (Yiasoumi et al., 2005). Nevertheless, highest mean percent vegetative cover was recorded for this treatment (Table 6.1). Treatments receiving less than 100 Mg ha^{-1} sludge, however, had lower soil solution EC values than this threshold (Figs. 6.4a and b). For soil solution samples from the 33 and 100 Mg ha^{-1} treatments, the EC dropped very fast at the beginning of the season. This indicates that most of the salts added through the sludge were leached below the active root zone during the first 60 to 84 days after application. This was mainly because of the high leaching fraction (0.27 in 2004/05 and 0.3 in 2005/06) experienced during those periods from irrigation and rainfall.

An increase in soil salinity following sludge application is inevitable and was also observed in the studies conducted by Navas et al. (1998) and Stamatiadis et al. (1999). Nonetheless, the soil salinity levels of all the treatments at the end of the trial (Fig. 6.5) were much lower than the threshold value of 300 mS m^{-1} for kikuyu production (Yiasoumi et al., 2005). At the end of the trial, application rates higher than 33 Mg ha^{-1} significantly increased soil salinity, but the levels were still acceptably low (Fig 6.5).

In summary, the requirement to leach salts is the most difficult aspect of managing large volume sludge applications. Nitrate leaching cannot be quantified in this study, but based on the solutions collected at 0.3 m depth and the change in soil N over the two seasons (Table 6.2), it would have been significant. Based on the EC of soil water and the growth studies, the leaching fraction could have been reduced. It may also be necessary to apply the sludge in two applications, and delay the second application until low nitrate was measured in the wetting front detectors. This high leaching fraction, however, could simulate worst case scenarios.

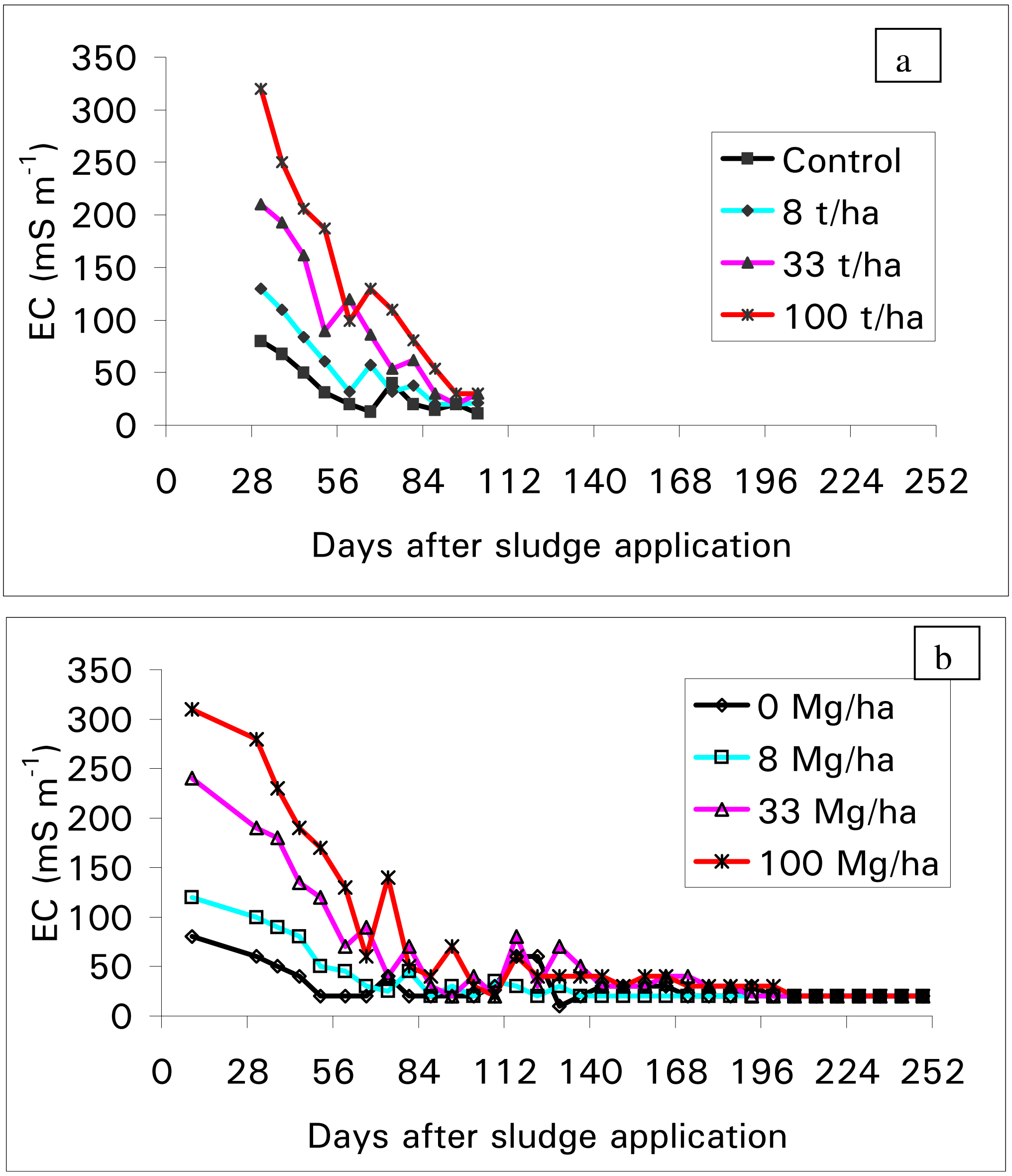

Figure 6.4 Electrical conductivity of soil solution samples collected from wetting front detectors installed at 0.30 m of a turfgrass sod (*Pennisetum clandestinum*) trial for four sludge application rates (0 Mg ha^{-1}, 8 Mg ha^{-1}, 33 Mg ha^{-1}, and 100 Mg ha^{-1}) during (a) year 2004/05 and (b) 2005/06 growing seasons.

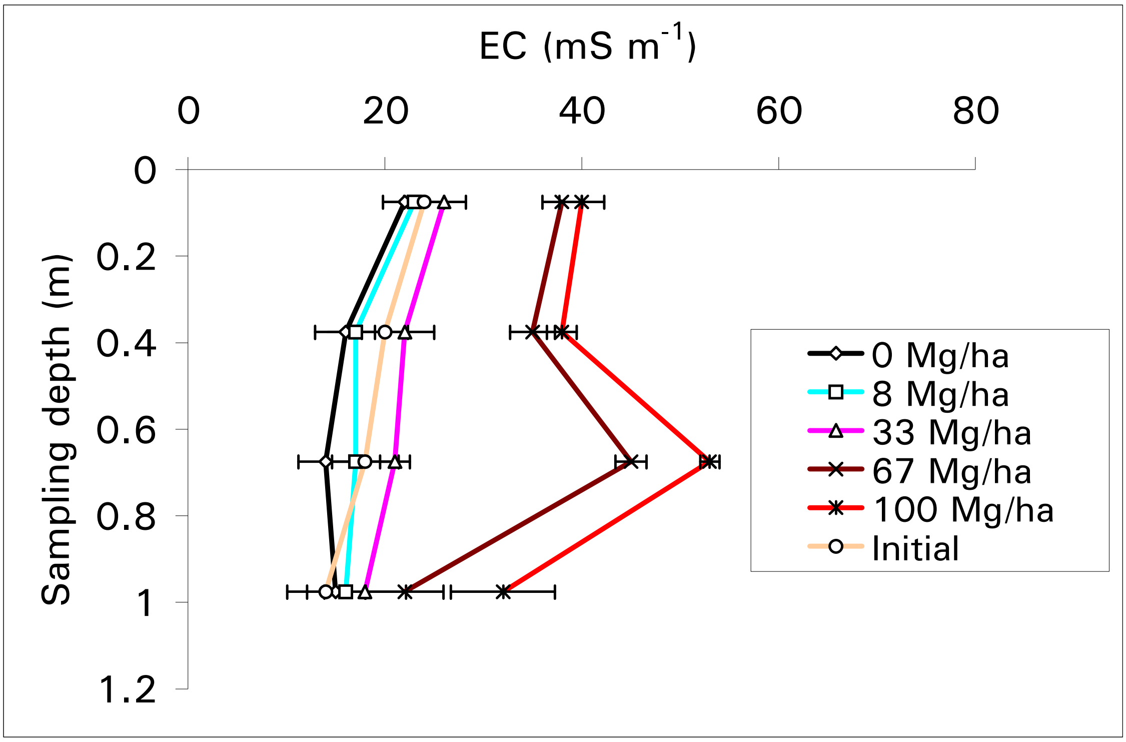

Figure 6.5 Soil profile electrical conductivity as affected by two consecutive years of sludge application at five rates (0, 8, 33, 67, and 100 Mg ha^{-1}) in a turfgrass sod (*Pennisetum clandestinum*) field trial, sampled before treatment application in 2004/05 (initial) and after two sod harvests in 2005/06.

6.5 Conclusions

The study demonstrated several advantages to large volume sludge loading of turf for sod production. Establishment rate and turf colour improved up to 67 Mg ha^{-1}. Very high loadings of 100 Mg ha^{-1} had no deleterious effect on the turf growth, despite the salt content of the sludge. High loadings also produced lighter sods, which could reduce transport costs, and minimize the loss of soil from the site. However, very high rates also drastically reduced sod integrity.

Soil sampling before and after the two year trial showed that N and P did not accumulate below a depth of 0.45 m until more than 33 Mg ha^{-1} sludge was applied. At the end of the study the available N and P were relatively low, and would not constitute a threat to groundwater in this specific soil type.

The disadvantages of excess sludge loading are apparent when comparing the N and P mass balance with the actual change as measured by soil sampling. Clearly there are large losses of N and P which are hard to manage. In particular, the requirement to leach salt makes it difficult to control the leaching of nitrate, although in this study a lower leaching fraction would have been possible. Application rates higher than 67 Mg ha^{-1} would be unacceptable on environmental grounds, but they were also unacceptable for reasons of turf quality, as the sods tended to break apart during handling.

An application rate of 33 Mg ha^{-1}, four times higher than the 1997 South African upper recommended limit or more than three times the new guideline, would be an acceptable compromise. This rate improved growth and sod quality over the zero and 8 Mg ha^{-1} application treatments. Great care would be required to minimize nitrate leaching during the first two months. Leaching could be managed by allowing the EC of leachate captured by the wetting front detectors not to exceed the threshold value of 300 mS m^{-1}. In other words, the crop coefficient could be reduced, and only increased when high salt levels were recorded. Applications greater than 33 Mg ha^{-1} could be possible if the sludge applications were split by delaying the second application until low nitrate was measured in the wetting front detectors, as long as turf quality was not negatively affected.

Therefore, all hypotheses were accepted for application rates not exceeding 33 Mg ha^{-1}, on the proviso that some soil loss was acceptable and that the leaching fraction was carefully managed during the first two months after sludge application. Further research is needed for other soil types and possible runoff losses from fields with some gradient.

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