Yield, resource use efficiency and trace metal uptake of weeping lovegrass grown on municipal sludge-amended soil

Running title: Municipal sludge for dryland pasture production: is it sustainable?

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ABSTRACT

BACKGROUND: There are concerns that fertilization using sludge in semi-arid areas, where water is limiting, will compound the effect of drought, resulting in the decline of yield from potential salt accumulation. We investigated (8 years) impacts of annual sludge application at 0, 4, 8, and 16 Mg ha^{-1} on weeping love grass hay yield, crude protein content (CP), rainfall use efficiency (RUE) and nitrogen use efficiency (NUE), and trace metal uptake.

RESULTS: Both hay yield and RUE increased by 5-53% as the sludge rate increased. Hay yield was highest (13.3 Mg ha^{-1}) during the wet season while RUE (27.1 kg mm^{-1}) during the dry season. Rainfall use efficiency was highest at sludge rates of 16 Mg ha^{-1} and NUE at 4 Mg ha^{-1}. Similarly, municipal sludge application increased CP as well as crop Cr and Zn uptake from the 16 Mg ha^{-1} treatment.

CONCLUSION: Results from this study indicated that eight consecutive years of treated municipal sludge application increased weeping lovegrass hay yield, CP content and WUE. Similarly, trace metal uptake by crop did not differ between the zero control and the 16 Mg ha^{-1} treatment, except for Zn and Cr, which showed a slight increment. Nonetheless all trace metals remained well below the domestic animals maximum tolerable dietary concentrations.

Key words: Trace metals; weeping lovegrass; Hay yield; Crude protein; Municipal sludge

Abbreviations: CP, crude protein; NUE, nitrogen use efficiency; RUE, rain use efficiency.

INTRODUCTION

Pastures are ideal for sludge application because they are often situated in the close vicinity of urban areas; they display efficient nitrogen utilization under intensive management practices, and can be harvested repeatedly during the year.[1]

The use of municipal sludge with low contaminant concentrations on agricultural lands has been successfully deployed in many countries.[2,3,4] The organic matter added through sludge improves soil structure thereby improving soil porosity, stability of aggregates, water retention, and cation exchange capacity (CEC).[5,6,7] In addition to improving soil structure, sludge is a good source of macro[8] and micro nutrients. Recycling sewage sludge to pasture-based animal production is quite productive as nutrient sources.[9]

The use of sludge for pasture production is well-documented in the Northern Hemisphere, especially U.S.[1,10] and some European countries.[8,11] However, little has been documented on forage yield, crude protein content, nitrogen and water use efficiency in Sub-Saharan African countries and other arid and semi-arid areas of the world, where both water and nitrogen, are limiting for pasture production. There are concerns that fertilization using sludge will compound the effect of drought, resulting in the decline of yield[12] as a result of the potential salt accumulation.[13] This is because both water deficit and osmotic effects are probably the major physiological mechanisms for growth reduction as both stresses lower the soil water potential.[14]

The aim of this study was to test the hypothesis that in semi-arid areas, where rainfall is erratic, continuous application of municipal sludge based on plant N requirements will not negatively affect weeping lovegrass hay yield, crude protein content, rainfall use efficiency, and nitrogen use efficiency regardless of the erratic rainfall nature of the area. Similarly, weeping lovegrass planted to soils amended with low trace metal concentration municipal sludge will not result in the accumulation of trace metals in the short to mid-term.

MATERIALS AND METHODS

Field Site Description

Field experiments were conducted at the East Rand Wastewater Care Works (ERWAT), Johannesburg, Gauteng, South Africa. The study site is situated at 26^o 01'S, 28^o 16'E, 1577 m asl. The annual rainfall ranged between 405 mm during the dry year of 2006/07 and 710 mm during the wet growing season of 2007/08, mainly during the months of October to March (Table 1). The soil is a clay loam (Hutton; Soil Classification Working Group, 1991) or a loamy, kaolinitic, mesic, Typic Eutrustox with an average soil profile depth >1 m (Table 2).

Table 1 Two-weekly mean temperature (Temp (C^{o})) and cumulative precipitation (mm) for the 2004/2005 to 2011/2012 growing seasons, ERWAT, Ekurhuleni district Pretoria, South Africa

Period	Month	Jan		Feb		Mar		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
	Weeks	1-2	3-4	1-2	3-4	1-2	3-4	1-2	3-4	1-2	3-4	1-2	3-4	1-2	3-4	1-2	3-4	1-2	3-4	1-2	3-4	1-2	3-4
2004	Temp (C^{o})																			22	23	22	22
	Rain (mm)																			12	29	72	64
2005	Temp (C^{o})	23	21	22	21	20	15	14	13	12	11	10	12	13	15	17	19	19	20	20	21	20	20
	Rain(mm)	111	56	17	79	27	18	1	0	0	0	0	0	0	0	0	0	0	12	55	54	35	68
2006	Temp (C^{o})	21	21	20	21	18	14	13	10	12	9	11	13	11	14	15	16	20	22	21	20	22	23
	Rain mm)	51	57	103	70	13	9	0	3	0	0	0	0	10	30	0	0	0	13	42	75	13	121
2007	Temp (C^{o})	21	21	21	23	22	15	13	10	10	9	8	11	11	13	20	18	16	16	19	20	18	19
	Rain (mm)	47	24	30	0	6	19	0	0	29	0	0	0	0	0	0	17	85	34	4	45	68	12
2008	Temp (C^{o})	20	18	19	21	19	17	16	13	12	12	10	12	14	15	17	16	19	20	20	20	21	21
	Rain (mm)	59	148	56	5	117	0	33	10	14	3	0	0	0	0	0	0	0	52	52	45	59	67
2009	Temp (C^{o})	22	21	23	21	20	19	17	15	14	13	13	11	10	13	14	14	19	20	25	20	23	23
	Rain (mm)	111	57	21	73	15	56	45	18	1	0	0	0	0	0	1	0	14	1	4	90	12	27
2010	Temp (C^{o})	23	21	23	21	19	19	17	15	14	13	12	11	10	13	14	14	18	21	24	20	23	23
	Rain (mm)	111	57	21	73	15	56	52	11	1	0	0.1	0	0	0	1	0	14	1	4	90	12	27
2011	Temp (C^{o})	19	21	20	19	21	20	17	14	15	13	11	10	8	10	12	14	18	16	17	21	20	19
	Rain (mm)	94	76	29	35	84	51	38	31	5	1	22	0	0	0	5	0	2	0	37	45	5	75
2012	Temp (C^{o})	20.7	19.8	20.4	21.1	19.7	18.5	14.9	16.0	17.4	12.8	10.2	10.9	11.7	11.6	10.1	17.7	13.4	16.1	19.1	17.0	18.3	20.0
	Rain (mm)	74	52	23	69	22	29	2	13	0	0	0	3	0	0	0	0	88	7	27	40	10	60

Sludge Characteristics

The sludge used in this study is mainly of domestic origin (96%) with the rest 4% accounting from industry. The sludge was digested anaerobically to 44% volatile suspended solid destruction in mesophilic anaerobic digesters with a retention time of 17 days (15 primary and 2 secondary). The sludge was dried on concrete beds in thick layers of 25 cm before applying to the experimental plots. According to the current South African sludge guideline,[15] as described by Tesfamariam[16], this sludge is classified as pollutant class "a" because of its low trace metal content (Table 3). The only exception was the high Zn concentration reported in 2008/09, 2009/10 and 2010/11 causing the sludge to be categorized as class "b". On the basis of the microbiological report from the ERWAT laboratory, the sludge didn't have viable pathogens and is classified as microbiological class "A". Considering the low odour and vector attraction characteristics of the sludge, it is classified as stability class 1. This sludge type (A1a) is equivalent to the EPA class D biosolid. The current South African sludge guideline allows such quality sludge to be utilized in agriculture without restriction, as long as the N applied does not exceed crop demand, with the upper limit set at 8 Mg ha^{-1} per year. Selected chemical characteristics of this A1a sludge are presented in Table 3.

Field Trial and Treatments

The study was conducted in a formerly natural grassland area. Plots of 25 m^2 were arranged in a randomized complete block design comprising four replications of four treatments. The treatments consisted of 0 (control), 4, 8, and 16 Mg ha^{-1} dry sludge per hectare per year. The 8 Mg ha^{-1} yr^{-1} treatment represents the former South African upper sludge application rate, which was still in place, when this study commenced. The 4 Mg ha^{-1} and 16 Mg ha^{-1}

treatments represent half and double of this former norm. The annual sludge application rate was split into two so that half was applied at the beginning of the season and the remaining half following the first cut.

At the beginning of the study, during the 2004/05 growing season, the sludge was broadcasted over the soil surface and immediately incorporated into the top 0.1-m soil layer with a manually operated, diesel powered rotovator (Agria). After sludge incorporation, the soil was leveled using rakes. A mixture of perennial weeping lovegrass (10 kg ha^{-1}) and teff (*Eragrostis teff)* (6 kg ha^{-1}) were planted on 15 Nov. 2004 and a hand drawn roller was used to ensure good seed-soil contact for better germination. In this experiment, teff was mainly planted as a nurse crop to suppress weed growth. It is an annual grass and after the first harvest in 2004/05 growing season, the plots were fully covered by weeping lovegrass. During the rest of the study period, however, the sludge was broadcast over the soil surface of the already established weeping lovegrass plots.

Sampling and Analyses

Above-ground samples for hay dry matter yield determination were collected 0.05 m above the soil surface at about 50% flowering from a 1 m^2 area. Generally, two rounds of sampling for hay dry matter yield determination took place per annum and the hay dry matter yield presented reflects the cumulative yield per year. The samples were dried in a forced oven at 60^{o}C until plant material reached constant weight. In addition, a hand grab of grass samples were collected at harvest from each plot for grass N content determination. Crude protein content was estimated by multiplying hay N content by a factor of 6.25. Nitrogen use efficiency (NUE) (kg DM kg^{-1} N) was estimated using Eq. 1[17] and rainfall use efficiency (RUE) using Eq. 2[18].

Table 2 Selected physical and chemical characteristics of the soil at the study (ERWAT, Ekurhuleni district Pretoria, South Africa)

Soil layer depth (m)	Sand	Silt	Clay	TOC	TON	C/N	EC mS m^{-1}	pH (H_2O)
	g kg^{-1}							
0 – 0.3	364	256	380	16.77	1.41	11.86	30.67	5.73
0.3 – 0.7	362	225	413	8.74	0.89	9.79	21.00	5.58
0.7 – 1.2	368	205	427	3.70	0.54	6.82	10.67	5.59

$$\text{NUE} = (\text{Sludge treated plot yield (kg)} - \text{Zero sludge plot yield (kg)})/(\text{N applied (kg)}) \quad (1)$$

$$\text{RUE} = \text{Hay dry biomass yield (kg m}^{-2}\text{)/Rainfall (mm)} \quad (2)$$

Total P in sludge as well as trace metals in plant samples and sludge were determined after wet acid digestion using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) (SpectroFlame Modula; Spectro, Kleve, Germany). The wet acid digestion was conducted on a ground 0.5 g sample, which was digested with 7 ml HNO_3 (conc. nitric acid, 65%) and 3 ml $HClO_4$ (perchloric acid, 70%) at temperatures up to 180°C. This was followed by the gradual addition of 0.5 ml H_2O_2 (hydrogen peroxide, 50%) further heating for 20 minutes. The digestate was removed from the block to partially cool down for about 10 minutes. Finally a 10 ml of a 1:1 hydrochloric acid solution was added and shaken to mix before transferring to a 100 ml volumetric flask. Sludge and plant samples were ground to pass through a 150 μm screen and analyzed for total C and N using a Carlo Erba NA1500 C/N analyzer (Carlo ErbaStrumentazione, Milan, Italy). Sludge samples were extracted in 1:5 1*M* KCl and tested for ammonium and nitrate with the Lachat Autoanalyzer (Lachat Quick Chem Systems, Milwaukee, WI, U.S.). Sludge electrical conductivity was analyzed on 1:2 sludge to water ratio extract. Extracts were analyzed for electrical conductivity using a Beckman conductivity bridge and reported in units of mS/m.

T**able 3** Chemical characteristics of anaerobically digested, paddy dried sludge used during the 2004/05 – 2011/12 growing seasons

		Year							
Element	Unit	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12
N	g kg^{-1}	30.3	18.8	22.2	30.9	27.4	22.4	27.5	21.6
NH_4_N	mg kg^{-1}	2018	4362	4064	7660	3000	3542	3260	2106
NO_3_N	mg kg^{-1}	183	6	40	11	180	95	138	50
P	g kg^{-1}	19.6	18.4	27.6	22.4	34.3	31.3	42.04	30.2
P– Bray1	mg kg^{-1}	166	154	40	66	50	80	120	187
Total C	g kg^{-1}	230	200	210	200	212	166	219.6	180
Water content	g kg^{-1}	460	300	280	380	340	404	655	440
EC_e	mS m^{-1}	1814	1212	1412	3110	945	1559	1218	1423
K	mg kg^{-1}	3804	710	689	1356	1720	2530	1850	2710
Ca	mg kg^{-1}	25116	13062	17450	10042	26950	23147	28312	28600
Mg	mg kg^{-1}	5358	591	829	1145	3410	3490	3624	3860
pH	(H_2O)	6.01	6.2	6.02	6.08	8.1	5.7	5.6	4.7
Cd	mg kg^{-1}	1.63	0.07	0.15	18.91	19.0	12.2	10.75	3
Hg	mg kg^{-1}	1.70	0.02	0.03	1.81	1	1	0.4	0.4
Cr	mg kg^{-1}	51.93	1.50	2.92	503.8	419	369.7	315.8	249
As	mg kg^{-1}	7.08	0.18	0.23	17.94	6.5	5.88	5.64	5.9
Pb	mg kg^{-1}	54.46	9.41	1.37	102.0	75	88.38	66.76	46
Zn	mg kg^{-1}	459.9	4.33	20.85	2325	4920	3459	5755	2886
Ni	mg kg^{-1}	23.81	1.37	0.97	144.5	152	111.13	103.27	127
Cu	mg kg^{-1}	97.2	3.21	4.59	526.8	681	497.29	544.52	440

Statistical Analyses

Statistical analyses were performed to evaluate the effect of various sludge application rates on hay yield, crude protein contents, rainfall use efficiency, and Nitrogen use efficiency. These variables (termed as response variables) were measured from the same blocks every year for eight consecutive years and this constituted a repeated measures data. Because the year or time is a quantitative variable we model the response variables as a polynomial function of time. Furthermore, the plots for the combined annual means of the response variables (see Figures 2 and 3) indicate that higher order polynomial terms of time should be added in the model. Therefore, quadratic equations for regressions of these responses on time were introduced to the fitted models. The data were analyzed using Procedure MIXED of SAS.[19] This procedure provides specification of various types of covariance structures for repeated measurements. The covariance and correlation matrices obtained from the data sets (for brevity results not shown) suggested analyzing the data using heterogeneous variances with time. Since there were sufficient observations for hay yield, crude protein content and rainfall use efficiency, the unstructured (UN) covariance matrix model was used first but the number of observations for nitrogen use efficiency were relatively small to consider this model. Since the measurements were done at equal time intervals the heterogeneous autoregressive of order one (ARH(1)) was used.

When treatment effects were found to be significant, LSMEANS option was used to compare the mean value of the response variable between the different treatments at 0.05 level.

RESULTS

Hay Yield

There was a highly significant (*P* <0001) year × sludge application treatment interaction for weeping lovegrass hay yield when data were combined for all years (Table 4). The dry matter yield showed great variations in response to rainfall variability as indicated in Fig. 1a.

Table 4 Type 3 tests of fixed effects for weeping love grass hay yield, crude protein content, rainfall use efficiency, and nitrogen use efficiency as affected by sludge application rate, time and quadratic time effects

Parameter	Hay yield		Crude protein		Rainfall use efficiency		Nitrogen use efficiency	
Effect	**F Value**	**Pr > F**	**F Value**	**Pr > F**	**F Value**	**Pr > F**	**F Value**	**Pr > F**
Treatment	105.58	<.0001	1158.24	<.0001	86.81	<.0001	1608.23	< 0.0001
Time	458.71	<.0001	528.59	<.0001	35.23	<.0001	3017.56	< 0.0001
Time*Treatment	24.10	<.0001	243.41	<.0001	61.72	<.0001	1623.12	< 0.0001
Time2	377.72	<.0001	585.66	<.0001	0.17	0.7043	3792.57	< 0.0001
Time2*Treatment	29.13	<.0001	545.07	<.0001	45.99	<.0001	1885.47	< 0.0001
Block	1.62	0.2522	1262.98	<0.0001	2.73	0.1057	1058.58	< 0.0001

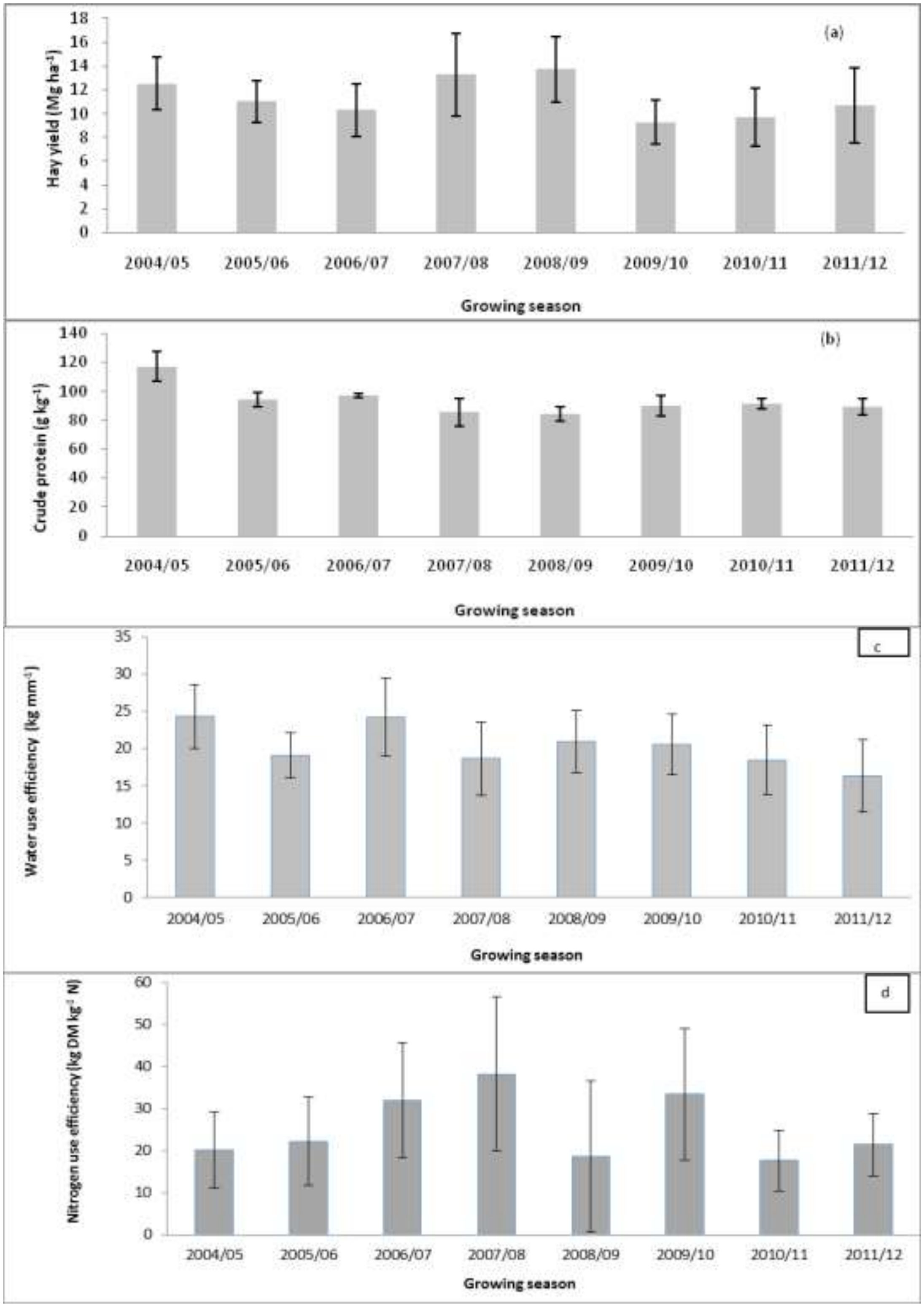

Figure 1 Mean hay yield (a), crude protein content (b), Rainfall Use Efficiency (RUE) (c), Nitrogen Use Efficiency (NUE) of weeping lovegrass combined for all treatments during the 2004/05 to 2011/12 growing seasons

The hay dry matter yield increased as the sludge application rate increased for all years (Fig. 2).

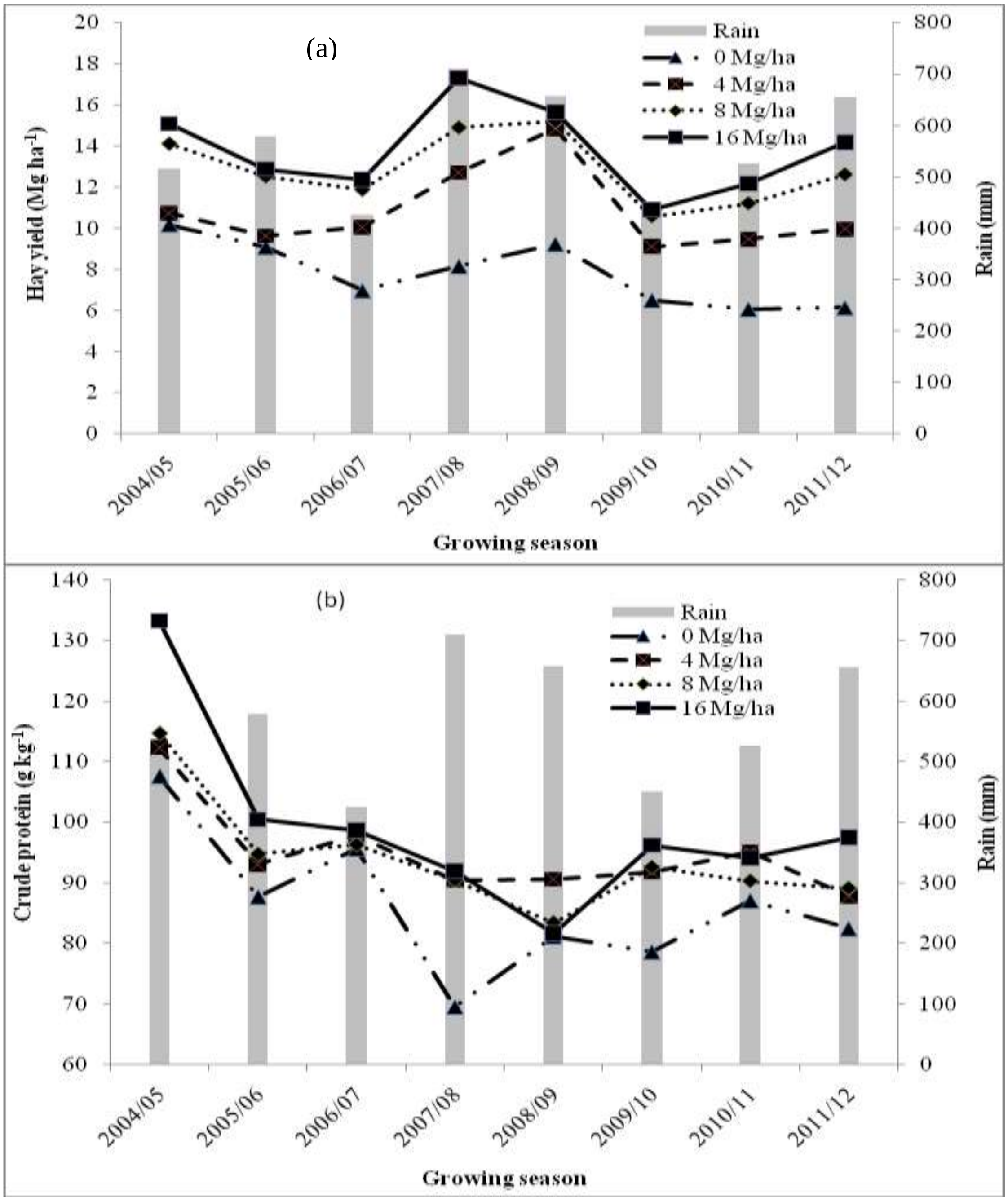

Figure 2 Combined annual mean hay yield (a) and crude protein content (b) of weeping lovegrass as affected by different rates of sludge application and amount of of rain(mm) during the 2004/05 to 2011/12 growing seasons

The pattern of yield response to sludge application rate remained similar regardless of the rainfall variation. The highest hay yield (17.31 Mg ha^{-1}) was harvested during the relatively wet season of 2007/08 (707 mm rain) from the 16 Mg ha^{-1}. In contrast, hay yield was generally low during the dry 2006/07 and 2009/10 growing periods (426 mm rain) for all treatments (Fig 2).

Crude Protein Content

There was a statistically highly significant (p<0.0001) year x sludge treatment interaction (Table 4). Generally the application of sludge improved (*P*<0001) the crude protein content relative to the zero control, in six of the 8 growing seasons (Fig. 2b). Highest CP content was recorded for the 2004/05 growing season (Fig 1b), where *Eragrostis teff* was planted as a nurse crop. Crude protein showed a generally decreasing pattern after the 2006/07 growing season. Overall doubling of the annual upper sludge limit improved weeping lovegrass crude protein content but was statistically significant only in four (2004/05, 2005/06, 2010/11, 2011/12) of the eight growing seasons (Fig. 2b). The overall CP contents ranged between 70-135 g kg^{-1} on dry matter basis.

Rainfall and Nitrogen Use Efficiency

There was a significant (*P*<0.0001) year x sludge application treatment interaction for weeping lovegrass RUE and NUE when data were combined for all years (Table 4). Generally RUE was improved with the application of sludge and it increased as the sludge application rate increased (Fig. 3a). Rainfall use efficiency indicated a declining pattern as the years progressed.

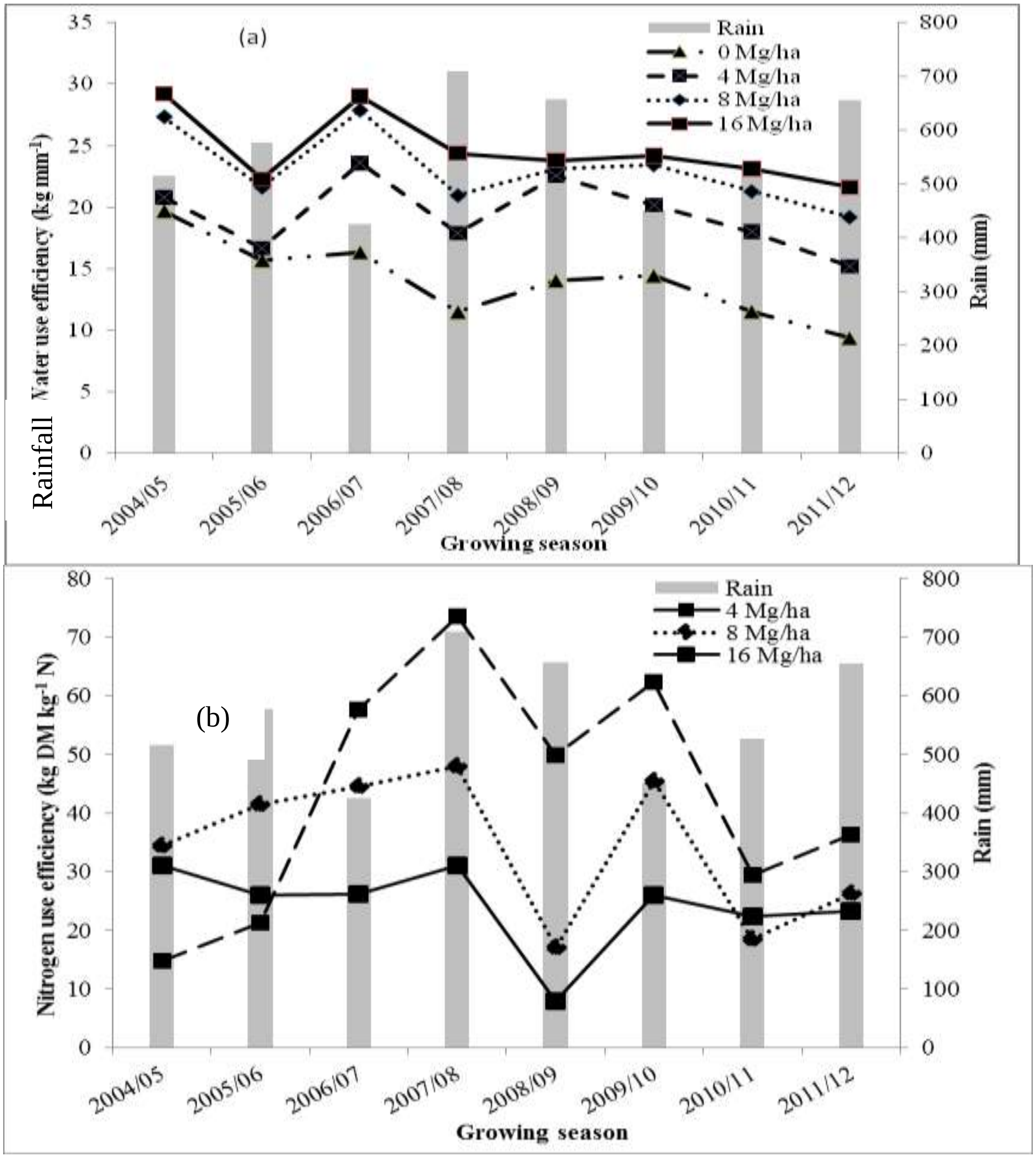

Figure 3 Weeping lovegrass mean Rain (RUE) (a) and nitrogen use efficiency (NUE) (b) as affected by sludge application rate during the 2004/05 to 2011/12 growing seasons

Nitrogen use efficiency of weeping lovegrass increased significantly ($P< 0.0001$) across years during the first four years for both the 4 and 8 Mg ha^{-1} sludge treatments (Fig. 3b). After the fourth year, all treatments showed a harmonic decline for the last four years with the 4 Mg ha^{-1} treatment showing the highest reduction (37.28 kg DM kg^{-1} N) and the 16 Mg ha^{-1} treatment the least (7.83 kg DM kg^{-1} N).

Trace Metal Uptake

The mean ($\pm$s.e.m) concentration of Ar, Cd, Cr, Co, Mo, Ni, Pb, V, Se, and Zn in weeping lovegrass is presented in Table 5. Continuous sludge application at rates of 16 Mg ha^{-1} significantly increased ($P<0.05$) Cr and Zn uptake by weeping lovegrass compared with the zero control both in 2007/08 and 2010/11 growing seasons. Although there was an increase in crop uptake of Ni, V, and Se with the application of sludge, the difference was not statistically significant. Elements such as As and Cd, however, did not show consistent pattern across years. Nonetheless, the concentrations of all elements remained far lower than the maximum tolerable dietary concentrations for domestic animals (Table 5).

Table 5 Mean trace metal uptake by weeping lovegrass planted to a clay loam soil that received 0 and 16 Mg ha^{-1} yr^{-1} municipal sludge for eight years (2004/05 – 2011/12)

	Grass trace metal uptake				
	2007/08		2011/12		
Element	0 Mg ha^{-1} yr^{-1}	16 Mg ha^{-1} yr^{-1}	0 Mg ha^{-1} yr^{-1}	16 Mg ha^{-1} yr^{-1}	Domestic animals maximum tolerable dietary concentration (NRC, 2005)
	mg kg^{-1}				
As	0.02±0.008	0.03±0.008	0.03±0.013	0.03±0.021	30 (horse, cattle, sheep, swine, and poultry)
Cd	0.183±0.004	0.163±0.003	0.085±0.019	0.085±0.003	10 (horse, cattle, sheep, swine, and poultry)
Cr	1.27±0.07	1.49±0.01	1.32±0.009	1.44±0.015	3000 (oxide) 100 (soluble chromium Cr^{+++}) (horse, cattle and sheep)
Co	0.272±0.004	0.252±0.006	0.228±0.010	0.213±0.007	25 (poultry, horse, cattle and sheep)
Mo	0.24±0.004	0.19±0.01	0.32±0.043	0.28±0.011	5 (horses, cattle and sheep)
Ni	3.7±0.19	3.9±0.08	1.981±0.019	2.17±0.016	100 (cattle and sheep); 50 (horses); 250 (poultry and swine)
Pb	0.85±0.03	0.96±0.07	0.934±0.053	0.784±0.005	100 (cattle and sheep); 10 (poultry, swine and horses)
V	0.79±0.01	0.85±0.07	0.81±0.013	0.82±0.01	50 (cattle and sheep); 10 (swine and horses)
Se	0.44±0.02	0.52±0.02	0.45±0.091	0.53±0.012	5 (horses, cattle and sheep); 3 (poultry); 4 (swine)
Zn	27±4.18	49±6.83	25.3±3.872	50.3±5.20	500 (cattle and horse); 300 (sheep)

DISCUSSIONS

Hay Yield

The year × sludge application treatment interaction for hay yield was primarily caused by hay yield magnitude differences among the years. Within the same growing season, hay yield increased with doubling of sludge application rate both during dry (2006/07) and wet seasons (2007/08) mainly because of an increase in nutrient availability especially N. This concurs with previous studies which reported an increase in weeping lovegrass dry matter production as the rate of nutrient application increased.[9,20,21,22]

The year x sludge interaction for the combined analyses across years is mainly attributed to the variation in the rainfall (Fig. 2a) as well as the sludge N content across years (Table 3). For instance, the N content of sludge in 2006/07 (2.22%) was higher than 2005/06 (1.88%). However, hay yield was higher in 2005/06 than similar treatments in 2006/07 because of the relatively higher rainfall received in 2005/06.

In general, hay yield throughout the study period was much higher than the local long term average values of 6 Mg ha^{-1} but was still within the local ranges.[21] Similarly, hay yield from this study was within the ranges reported from U.S.[23], despite the differences in soil and climate. The nutrient mass balance of the current study have shown that sludge applied at double the recommended rate (16 Mg ha^{-1}) did not lead to the accumulation of nitrate and ammonium in the soil profile but led to the accumulation of total and Bray1 extractable P.[16] Thus, there is a strong evidence to accept the alternative hypothesis stated that municipal sludge application based on crop N requirements had less general negative effect in the short term on weeping lovegrass hay yield planted to deep red clay loam soils that received rainfall of 405 to 710 mm.

Crude Protein Content

Protein is the most important constituent and costly component of feed nutrients limiting animal performance feeding on pasture.[24] Higher protein content (80-160 g kg^{-1}) in a given feed is usually desirable for maintenance, growth, production and normal feed intake and functioning of rumen microflora. Generally, the CP content for all the treatments from this study were within the ranges reported for weeping lovegrass (63-175 g kg^{-1}).[25,26] It was also above the minimum crude protein requirements of ruminants (70-80 g kg^{-1}).[24]

The year × sludge application treatment interaction for crude protein means the interaction was primarily caused by crude protein magnitude differences among the years. Within the same growing season, CP increased with doubling of sludge application rate in four of eight growing seasons mainly because of an increase in nutrient availability especially N. The year x sludge interaction for the combined analyses across years is mainly attributed to the variation in the rainfall (Fig. 2b), the variation in sludge N content across years (Table 3) as well as N carry over effects from previous seasons.

The CP content of weeping lovegrass for all treatments from the first growing season (2004/05) was generally higher than similar treatments during the other seven years (Fig 2). This is mainly attributed to the higher crude content of *Eragrostis teff*, [27] which was planted as a nurse crop, during the establishment year in 2004/05.

The increase in the CP content with the application of sewage sludge was due, in large measure to the increase in the availability of N. This is because CP content of weeping lovegrass increases with fertilization under nutrient limiting conditions.[28,29,30]

Rainfall and Nitrogen Use Efficiency

Rainfall use efficiency is a factor that indicates the productivity of an ecosystem.[18] This depends on soil and vegetation condition and its dynamic status.[31] The year x sludge treatment interaction for the combined analyses across years is mainly because of the variation in the rainfall (Table 1) as well as the sludge N content across years (Table 3). Nevertheless, annual rainfall use efficiency within a season increased as the sludge application rates doubled (Fig. 3). The significant improvement in annual rainfall use efficiency was because of the significant increase in hay yield per unit water used.

Generally, the RUE from this study was much higher than the ranges reported for weeping lovegrass (3.7-10 kg DM ha^{-1} yr^{-1} mm^{-1}) in Argentina.[18] This is most probably because of higher water holding capacity and nutrient status of the soil from this study among other factors.

In contrast to the RUE, the NUE decreased significantly with doubling of the sludge application rate for rates exceeding 8 Mg ha^{-1} during the 2004/05 and 2005/06 growing seasons and 4 Mg ha^{-1} in five of the eight years. This reduction is most probably attributed to the nutrient carryover effects from the previous years that resulted in higher total N availability for crop uptake in the years that followed. This could be clearly observed from the trends of NUE increment across years. Our results agree with Sigua[9] who showed that increasing doses of sewage sludge did not proportionally improve soil nitrogen use efficiency. The low N use efficiency of the 16 Mg ha^{-1} sludge treatment indicate that a large fraction of the N added from sludge is stored in the soil profile or lost from the system through leaching and volatilization.[16] In this study, however, a large portion of the N is stored in the soil profile because previous results from the same study site has already shown a significant build up N in the top 10 cm layer of the 16 Mg ha^{-1} sludge application rate compared with all other rates.[16]

Studies conducted by Gargano on the NUE of weeping lovegrass using inorganic commercial fertilizer as source of N, showed that NUE was highest at lowest productivity levels.[20] This is in contrast to our findings where NUE seemed to be influenced by N carry over effects at low application rates when using sludge as source of N. Therefore, although there was a clear decline in NUE with the doubling of sludge application rate, it was not because of the effect of salts but rather because of N carry over effects.

Trace Metal Uptake

The uptake and/or bioavailability of trace metals, depends on several factors, the most important of which is pH.[32] Trace metal uptake by plants is a function of the metal, sludge/soil physiochemical properties and plant species.[33] Sludge-borne trace elements are usually organically bound and less mobile compared with impurities in commercial inorganic fertilizers. Use of sewage sludge facilitates the bio-fortification of selenium through recycling of organic matter.[32] This study revealed that the application of municipal sludge significantly increased the aboveground biomass concentration of certain metals such as Cr and Zn. This is in contrast to the previous findings, which reported insignificant differences in trace metal uptake by Bermuda grass planted to a soil that received sludge for 10 years.[34] This difference may be attributed to the relatively higher concentration of Cr (239 mg kg^{-1}) and Zn (2479 mg kg^{-1}) in the sludge used for our study compared to their (Cr = 115 mg kg^{-1}; Zn = 500 mg kg^{-1}). The insignificant Ni, V, and Se uptake differences between treatments is in par with previous findings from USA.[34] Other elements such as As and Cd, however, did not show consistent trends across years. Generally the concentration of those trace metals under investigation was far lower than the reported domestic animals maximum tolerable dietary concentration as reported in NRC (2005).[35]

CONCLUSION

Results from the current study indicated that sludge application rates based on crop N requirements improved hay yield, CP content, NUE and WUE. In addition, application of municipal sludge, with low trace metal content, for weeping lovegrass hay production does not seem to cause significant uptake of trace elements to trigger animal health risk in the short to medium term. The pathological threat of products, obtained from animals feeding on pastures produced using sewage sludge, may require further investigations.

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