CHAPTER 3

MATERIALS AND METHODS

3.1 Field site description

Field experiments were conducted at the East Rand Water Care Works (ERWAT), Johannesburg, Gauteng, South Africa. The study site is situated at an elevation of 1577 m above sea level, latitude 26^o 01' 01" S and longitude of 28^o 16' 55" E. The area has a long term annual average rainfall of 700 mm, mainly during the months of October to March. The soil of the experimental site is a clay loam (Hutton, Soil Classification Working Group, 1991) having a clay content of 36-46%, and pH (H_2O) of 5.3 to 6.1. In the beginning of the study, the cation exchange capacity of the soil (ammonium acetate extract) was 10-12 cmol kg^{-1} and the electrical conductivity ranged from 8 mS m^{-1} at 1.2 m depth to 36 mS m^{-1} in the top 0.3 m soil layer.

3.2 Sludge characteristics

The sludge used in this study was anaerobically digested and paddy-dried. According to the current South African sludge guideline (Snyman and Herselman, 2006), this sludge is classified as pollutant class "a" due to its low heavy metal content (Table 3.1). Based on the microbiological report from the ERWAT laboratory, the sludge can also be classified as microbiological class "A".

Table 3.1 Chemical characteristics of anaerobically digested, paddy dried sludge used during the 2004/05 – 2007/08 growing seasons (source Vlakplaats wastewater treatment plant)

Element	Unit	Year			
		2004/05	2005/06	2006/07	2007/08
N	%	3.032	1.884	2.219	3.094
NH_4_N	mg kg^{-1}	2018	4362	4064	7660
NO_3_N	mg kg^{-1}	183	6	40	11
P	%	1.962	1.844	2.76	2.24
P – Bray1	mg kg^{-1}	166	154	40	66
Total C	%	23	20	21	20
Water content	%	46	30	28	38
EC_e	mS m^{-1}	1814	1212	1412	3110
K	mg kg^{-1}	3804	710	689	1356
Ca	mg kg^{-1}	25116	13062	17450	10042
Mg	mg kg^{-1}	5358	591	829	1145
pH (H_2O)		6.01	6.2	6.02	6.08
Cd	mg kg^{-1}	1.63	0.07	0.15	18.91
Hg	mg kg^{-1}	1.70	0.02	0.03	1.81
Cr	mg kg^{-1}	51.93	1.50	2.92	503.8
As	mg kg^{-1}	7.08	0.18	0.23	17.94
Pb	mg kg^{-1}	54.46	9.41	1.37	102.0
Zn	mg kg^{-1}	459.9	4.33	20.85	2325
Ni	mg kg^{-1}	23.81	1.37	0.97	144.5
Cu	mg kg^{-1}	97.2	3.21	4.59	526.8

Considering the low odour and vector attraction characteristics of the sludge, it can be classified as stability class 1. The current South African sludge guideline (Snyman and Herselman, 2006) allows such quality sludges to be utilized in agriculture without restriction, as long as the N applied does not exceed crop demand, with the upper limit set at 10 Mg ha^{-1} yr^{-1}. Selected chemical characteristics of this A1a sludge are presented in Table 3.1. The total amount of N and P added from sludge to each cropping system is presented in the corresponding chapters while other macro elements and heavy metals are presented in Appendixes 1 and 2.

3.3 Field trial and treatments

Plots of 25 m^2 were arranged in a randomized complete block design comprising four replications of five treatments. The trial was laid out to accommodate widely different levels of bio-solid application to high and low productivity-cropping systems. It consisted of four farming systems namely: irrigated maize-oat rotation, dryland maize, dryland pasture and turfgrass.

3.3.1 Dryland maize and irrigated maize/oats rotation

The treatments for dryland maize and irrigated maize-oats rotation consisted of three sludge rates (4, 8, and 16 Mg ha^{-1} yr^{-1}), a control, and an inorganic fertilizer treatment. The value of 8 Mg ha^{-1} yr^{-1} represents the annual agricultural upper limit of the 1997 South African sludge guideline (Water Research Commission, 1997), which has recently been raised to 10 Mg ha^{-1} yr^{-1} (Snyman and Herselman, 2006). Sludge rates of 4 and 16 Mg ha^{-1} yr^{-1} represent half and double the former norm.

Applications to the inorganic fertilizer maize treatment were conducted according to the recommendations of the OMNIA Fertilizer Company in 2005, with some modification to the amount of K recommended (K application increased due to deficiency symptoms) since the 2005/06 growing season for all crops (Table 3.2). As municipal sludge is a poor source of K, a similar amount to that applied to the inorganic fertilizer treatments was applied to all sludge treatments. The amount of inorganic fertilizer applied to irrigated oats was based on the Fertilizer Handbook (Fertilizer Society of South Africa, 2000) for a target forage yield of 11 Mg ha^{-1} (Table 3.2). For the irrigated maize-oats rotation, the annual sludge application was split into two, with half applied to both crops at planting. For dryland maize, however, the entire amount was applied at the beginning of the season before planting.

Sludge and inorganic fertilizer were broadcast and immediately incorporated into the soil with a manually operated, diesel powered rotovator (Agria). After sludge incorporation, the soil was levelled using rakes and maize (PAN 6966) was planted in 0.9m rows at rates of 80000 seeds per hectare under irrigation and half this rate under dryland conditions. Each plot consisted of 6 rows of 5 m in length, with the outer one row on either side taken as boarder row.

After harvesting irrigated maize, sludge and inorganic fertilizer was applied accordingly and again incorporated, after which oats were planted. Oats were planted at a rate of 90 kg ha^{-1} using a hand-drawn planter with double disk openers. Each oats plot consisted of 15 rows, spaced 0.3 m apart and 5 m in length, with two border rows on either side. Maize and oats planting and harvesting dates are presented in Table 3.3. The time and amount of inorganic fertilizer applications for dryland maize and irrigated maize/oat rotation are presented in Table 3.2.

Table 3.2 Inorganic fertilizer application timing and type of fertilizer applied to dryland maize, irrigated maize, and irrigated oats during the 2004/05 to 2007/08 growing seasons at ERWAT, Ekurhuleni district, South Africa.

Time of fertilizer application	Fertilizer type	Dryland maize			Irrigated maize			Irrigated oats		
		N	P	K	N	P	K	N	P	K
		kg ha^{-1}								
At planting time	NPK 2:3:2(22%)	13	20	13	6	9	6	6	9	6
	LAN (28% N)	17								
	KCl (50% K)			7			14			
Three weeks after planting	Limestone ammonium nitrate (LAN)				90			84		
	Super phosphate (18.5% P)					31			11	
Five weeks after emergence	LAN				64			55		
	Super phosphate								10	
	KCl						40			40
Seven weeks after emergence	LAN	66			66			55		
	Super phosphate								10	
	KCl			40			40			40
Cumulative annual application		**96**	**20**	**60**	**226**	**40**	**100**	**200**	**40**	**86**

NB. During the 2005/06, 2006/07 and 2007/08 growing seasons K application was increased to 20 kg ha^{-1} at planting (both dryland and irrigated maize), to 40 kg ha^{-1} five weeks after germination (irrigated maize), and 40 kg ha^{-1} at seven weeks after germination (both dryland and irrigated maize) due to deficiency symptoms observed in leaves.

Table 3.3 Planting and harvesting dates for dryland maize, irrigated maize, and irrigated oats experiment conducted during the 2004/05-2007/08 growing seasons at ERAWAT, Ekurhuleni district, South Africa.

	Dryland maize		Irrigated maize		Irrigated oats	
Growing season	Planting date	Harvesting date	Planting date	Harvesting date	Planting date	Harvesting date
2004/05	13 Dec. 2004	03 May 2005	13 Dec. 2004	03 May 2005	27 June 2005	15 Dec. 2005
2005/06	16 Dec. 2004	†	16 Dec. 2004	†	12 Apr. 2006	28 Nov. 2006
2006/07	20 Dec. 2006	10 May 2007	20 Dec. 2006	10 May 2007	‡	‡
2007/08	18 Nov. 2007	15 Apr. 2008	18 Nov. 2007	15 Apr. 2008	02 May 2008	15 Nov. 2008

† Maize was damaged by herbicide and was harvested before maturity.

‡ Oats were not planted during this season.

3.3.2 Weeping lovegrass (*Eragrostis curvula*)

The treatments for the dryland pasture (weeping lovegrass) consisted of three sludge rates (4, 8, and 16 Mg ha^{-1} yr^{-1}), a control, and an inorganic fertilizer treatment. The annual sludge application rate for all weeping lovegrass treatments was split into two so that half was applied in the beginning of the season and the remaining half following the first cut. Nitrogen, phosphorus, and potassium were applied to the inorganic fertilizer weeping lovegrass treatments based on the Kynoch pasture Handbook (Dickinson et al., 2004) for a target annual hay yield of 10 Mg ha^{-1}.

In the beginning of the study, during the 2004/05 growing season both sludge and inorganic fertilizers were broadcast over the soil surface and immediately incorporated into the top 10cm soil layer with a manually operated, diesel powered rotovator (Agria). After sludge incorporation, the soil was levelled using rakes. A mixture of 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. During the rest of the study period, however, both sludge and inorganic fertilizer were broadcast over the soil surface of the already established weeping lovegrass plots. Unlike maize and oats, however, both sludge and inorganic fertilizers were left on the soil surface without incorporation. Sludge application and hay cutting dates are presented in Table 3.4. The amount and timing of inorganic fertilizer applications are presented in Table 3.5.

Table 3.4 Sludge applications and hay cutting dates for Weeping lovegrass during the 2004/05 to 2007/08 growing seasons at ERWAT, Ekurhuleni district, South Africa.

Growing season	Sludge application date		Hay cutting date	
	First	Second	First	Second
2004/05	14/11/2004	20/02/2005	17/02/2005	22/05/2005
2005/06	01/11/2005	20/02/2006	31/01/2006	11/05/2006
2006/07	20/10/2006	10/01/2007	09/01/2007	16/04/2007
2007/08	26/09/2007	14/01/2008	11/01/2008	16/04/2008

Table 3.5 Type of fertilizer applied and application timing for a weeping lovegrass experiment during the 2004/05 to 2007/08 growing seasons at ERWAT, Ekurhuleni district, South Africa.

Time of fertilizer application	Fertilizer type	Amount of Individual nutrient added		
		N	P	K
			kg ha^{-1}	
At planting time, or beginning of sprouting, and after every first cut in a season	NPK 2:3:2(22%)	13	20	13
	Limestone ammonium nitrate (LAN) (28% N)	87		
	KCl (50% K)			27
Four weeks after first application	LAN	100		
	Super phosphate (18.5% P)		20	
	KCl			47
Cumulative annual application		**200**	**40**	**87**

3.3.3 Turfgrass (Kikuyu, *Pennisetum clandestinum* Hochst. ex Chiov.)

The five treatments of the turfgrass experiment consisted of 0, 8, 33, 67, and 100 Mg ha^{-1} sludge per sod harvest (on oven-dry mass basis). The value of 8 Mg ha^{-1} represents the annual agricultural upper limit of the 1997 guideline (Water Research Commission, 1997). Rates of 33, 67, and 100 Mg ha^{-1} are equivalent to depths of 5, 10, and 15 mm sludge respectively, assuming a sludge bulk density of 666 kg m^{-3}.

On 3 March 2005, kikuyu (*Pennisetum clandestinum* Hochst. ex Chiov.) turfgrass was established vegetatively using sods which completely covered the soil surface. Sod was harvested on 15 June 2005, leaving 0.02-0.03 m wide ribbons of sod, 0.5 m apart, after which sludge was spread uniformly on the soil surface according to the treatments, whereafter the trial commenced. Turf then re-established itself vegetatively from these ribbons and the first trial sod harvest occurred 8 months later (14 February 2006). The same procedure was followed for the second season trial (second cutting), which started on 20 February 2006 and sods were again harvested on 29 October 2006.

3.4 Rainfall and irrigation

3.4.1 Rainfall

Weather data was collected from an automatic weather station located about 100 m from the experimental site. The automatic weather station consisted of an LI 200X pyranometer model PY 47034 (LiCor, Lincoln, Nebraska, USA) for measuring solar radiation, an electronic relative humidity and temperature sensor (Thermistor Humitter 50Y) installed in a gill screen (R.M. Young, Minnesota, USA), an electronic cup anemometer to measure wind speed (R.M. Young, Minnesota, USA), an electronic rain gauge Model TR-525M-R2 (Texas Electronic Inc., Dallas, Texas, USA), and a CR10X data-logger (Campbell Scientific Inc., Utah, USA). Monthly rainfall distribution during the study period is presented in Table 3.6.

3.4.2 Irrigation

Irrigated maize/oats rotation

The irrigated maize-oats rotation experiment was planted under drip irrigation. The lateral spacing between dripper lines was 0.5 m during summer 2005, but was reduced to 0.3 m since the 2005 winter for the rest of the study period. The distance between the drippers in a line was 0.3 m. The drip system was operated at a pressure of 100-150 kPa with an average drip rate of 1.3 l hr^{-1} per emitter (13.8 mm hr^{-1}). In the absence of rainfall, maize was irrigated 10 mm every three days for the first four weeks after planting. In 2005, this was followed by irrigation according to the FAO crop factor method in the SWB model once every five days until harvest in the absence of rainfall. In 2007 and 2008, however, maize was irrigated according to neutron probe deficit readings to fill the profile to field capacity once a week in the absence of rainfall.

During the winter seasons of each year, oats were irrigated every three days (9 mm in 2005 and 10 mm in 2006 and 2008) for the first four weeks. This was followed by irrigations according to a site calibrated neutron water meter (Model 503 DR CPN Hydroprobe, Campbell Pacific Nuclear, California, USA) deficit readings to a depth of 1.2 m for the rest of the season until harvest, mostly twice a week in 2005. In 2006 and 2008, however, the crop was irrigated weekly based on site calibrated neutron probe soil water deficit readings followed by next irrigation schedule according to SWB model recommendation.

Table 3.6 Monthly rainfall distributions during the 2004/05 to 2007/08 growing seasons at ERWAT, Ekurhuleni district, South Africa.

Months	Growing seasons				
	2004	2005	2006	2007	2008
January		168	108	70	207
February		94	145	38	60
March		70	78	31	159
April		63	18	19	21
May			4	1	
June					
July					
August					
September				18	
October		12	18	117	73
November	32	129	117	56	101
December	89	84	132	72	112

Turfgrass

Adjustable nozzle micro-sprayers (Hunter, California, USA) at the four corners of each plot were used to irrigate the turfgrass using municipal drinking water. The micro-sprayers were adjusted to a 90^{o} spray pattern and had a delivery rate of 72 mm hr^{-1}. In the absence of rainfall, 10 mm of irrigation was applied every third day for the first 30 days after sludge application. During the rest of the growing season, until sod harvest, turf was irrigated twice a week (first irrigation 15 mm, followed three days later by irrigation sufficient to cause a Wetting Front Detector (WFD, www.fullstop.com.au) buried 0.3 m below the original pre-harvest soil surface to collect a water sample). A WFD is a funnel shaped instrument that converges the downward flow of water, producing saturation when the surrounding soil reaches 2-3 kPa suction (Stirzaker, 2003; Stirzaker and Hutchinson, 2005). It is essentially a passive lysimeter, which signals the passing of a wetting front and stores a soil water sample as the front passes. The WFDs were installed in all but the 67 Mg ha^{-1} treatment.

3.5 Soil solution sampling and analyses

Nitrate and salt leaching was monitored by wetting front detectors (WFDs) installed both at 0.3 and 0.6 m depths located in the middle of a plot. The detectors were installed in all treatments of the irrigated maize/oats rotation, in the control, 8 and 16 Mg ha^{-1} yr^{-1} treatments of the dryland maize and dryland pasture. The detectors were also installed in the control, 8, 33, and 100 Mg ha^{-1} sludge treatments of the turfgrass trial.

Soil solution samples collected from the wetting front detectors were analyzed for electrical conductivity (EC) using an ECScan-High EC meter (Eutech Instruments, Malaysia) and nitrate concentration was analyzed using a C99 Multiparameter Bench Photometer (Hanna Instruments, Italy).

3.6 Plant sampling

3.6.1 Dryland and irrigated maize

In 2004/05 growing season, above-ground samples were collected approximately every two weeks for growth analyses from an area of 0.5 m^2 (typically two plants under dryland and four under irrigation). In 2006/07 and 2007/08 growing seasons, however, plant samples were taken only three times during the growing season: First sample taken at the eight leaf growth stage, second at the soft dough stage and the third at crop maturity. At the soft dough stage, plant samples were taken for forage yield determination from 2 m lengths of the three middle rows (typically 22 plants under dryland and 43 plants under irrigation).

Additional plant samples were collected at the eight leaf growth stage, at the soft dough stage, and at crop maturity from both dryland and irrigated maize for crop N and P uptake determinations. At crop maturity, plant samples were taken for grain yield determination from 2 m lengths of the three middle rows in 2004/05 and 2 m length of the middle four rows in 2006/07 and 2007/08. Two additional plant samples per plot were taken from dryland maize and four plants from irrigated maize for crop N and P uptake determinations.

3.6.2 Irrigated oats

Whole plant (above-ground) samples were collected every two weeks from all plots for growth analyses from an area of 0.45 m^2 (typically three rows of 0.5 m length). A hand grab of additional plant samples were collected randomly from all plots twice during the growing season before the soft dough stage for N and P analyses. At the soft dough stage plant samples were collected for forage yield determination from 2 m lengths of the 6 middle rows. At the same time a hand grab of additional plant samples were collected for N and P uptake determination.

The crop was harvested once the crop matured during the 2005 and 2006 growing seasons. In 2008, however, the crop was harvested at the hard dough stage to minimize damage by birds. Samples during harvesting were collected from 2 m lengths of the six middle rows. In addition, a hand grab of plant samples were collected for N and P uptake determination.

3.6.3 Weeping lovegrass

In 2004/05, four replications of whole plant (above-ground) samples were harvested 0.05 m above the soil surface approximately every two weeks for growth analyses from an area of 0.5 m^2. In the years which followed (2005/06, 2006/07, 2007/08), however, plant samples were taken approximately once a month from an area of 0.5 m^2. A 0.5m border was left around all sides of each plot during sampling. A hand grab of additional plant samples were taken randomly twice during the growing season from each plot for N and P uptake determination.

Above-ground samples for hay yield determination were collected 0.05 m above the soil surface at flowering from a 1 m^2 area. In addition, a hand grab of grass samples were collected at harvest from each plot for grass N and P uptake determination.

Growth analyses

Plant samples collected for growth analyses from dryland maize, the irrigated maize-oats rotation, and weeping lovegrass were partitioned into leaves, stems, and grain (maize and oats). One sided leaf area was measured with an LI-3100 belt driven leaf area meter (LI-COR, Lincoln, NE, USA). Leaf area index (LAI) was computed from the measured one-sided leaf area divided by the ground sampling area. The components (leaves, stems, and grain) were then dried in a forced-air oven at 60 ^oC for 48 hours to determine above-ground biomass. Above-ground biomass was calculated as the sum of leaf, stem, and seed.

3.6.4 Turfgrass

Clipping samples were collected from a 0.5 m^2 area during each mowing for dry matter determination. Additional clipping samples were taken during the season for N and P analyses. A measure of sod integrity was determined by picking up and holding each sod vertically from one of the narrow edges and reporting the percentage that remained intact. Sod samples of 0.25 m^2 were collected from each plot for dry-matter determination. Plant material was separated from the soil in the sod, oven dried, and weighed. The soil was dried separately for 24 hours at 105 ^oC and weighed. Additional sod samples were taken randomly, combined into one sample for each plot and separated into plant and soil for N and P analyses. The plant samples were washed free of soil before analysis, using deionised water. The wash solution was combined with soil, and plant components were dried in a forced-air oven at 60 ^oC. After drying, plant samples were ground in a rotary mill (Arthur H. Thomas Co., Philadelphia, PA) to pass a 2 mm screen and soil samples pulverized, whereafter samples were analyzed.

3.7 Soil sampling

Soil samples for chemical analyses from the top soil layer were collected from differing depths for the various farming systems, depending on the impact of tillage in the distribution of nutrients within the soil profile. Consequently, soil samples from the top layer were collected from a depth of 0.3m in dryland maize and irrigated maize-oats rotation because the soil was rotovated each season to a depth of 0.3m. Soil samples from dryland pasture and turfgrass, however, were collected from the top 0.1 and 0.15m layers respectively because the sludge was surface applied in both farming systems.

3.7.1 Dryland maize and irrigated maize/oats rotation

At the beginning of the study, soil samples were collected on 11 Dec. 2004 before treatment application from the dryland maize and irrigated maize/oats rotation plots using an auger. The samples were collected from the 0-0.3 m, 0.3-0.6 m, 0.6-0.9 m, and 0.9-1.2 m layers. The samples from each layer of the dryland maize and irrigated maize/oats rotation plots in a block (replication) were combined and mixed to make a single homogenous soil sample per layer.

At the end of each growing season, three soil samples were collected diagonally from each plot of a treatment using an auger for the dryland maize. The samples were collected from the 0-0.3 m, 0.3-0.6 m, 0.6-0.9 m, and 0.9-1.2 m layers. The three samples from each layer of a plot were combined and mixed to make a single homogenous soil sample per layer. Similar procedures were followed during soil sampling and sample preparation of the irrigated maize-oats rotation farming system.

3.7.2 Dryland pasture

At the beginning of the study, soil samples were collected on 09 Nov. 2004 before treatment application from the dryland pasture plots using an auger. The samples were collected from the following layers: 0-0.1m, 0.1-0.3m, 0.3-0.5m, and 0.5-0.8 m. The samples from each layer of the dryland pasture in the same block (replication) were combined and mixed to make a single homogeneous soil sample per layer.

At the end of each growing season, three soil samples were collected diagonally from each plot using an auger from the dryland pasture treatment plots. The soil samples were collected from the 0-0.1m, 0.1-0.3m, 0.3-0.5m, and 0.5-0.8m layers. The three samples from each layer of a plot were combined and mixed to make a single homogenous soil sample per layer.

3.7.3 Turfgrass

Soil samples were collected on 16 June 2005 before treatment application from all lawn plots using an auger. The samples were collected from the following layers: 0-0.15m, 0.15-0.45 m, 0.45-0.75 m, and 0.75-1.05 m. The samples from each layer of the turfgrass plots in the same block (replication) were combined and mixed to make a single homogeneous soil sample per layer.

After two consecutive sludge applications and sod harvests, three soil samples were taken diagonally from each plot using an auger. The samples were collected from the 0-0.15 m, 0.15-0.45 m, 0.45-0.75 m, and 0.75-1.05 m layers. The three samples from each layer of a plot were combined and mixed to make a single homogenous soil sample per layer.

All soil samples from all cropping systems were dried and pulverized. The dried and ground soil samples were digested and analyzed for N, P, NO_3^-, NH_4^+, and Bray -1P.

3.8 Plant and soil chemical analyses

Total P in sludge, soil, and plant samples as well as plant heavy metal uptake were determined after wet acid digestion using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) (SpectroFlame Modula; Spectro, Kleve, Germany). Plant extractable soil P was analyzed using the Bray-1 extraction method, following standard procedures (Non-affiliated Soil Analyses Work Committee, 1990). Soil 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 Erba Strumentazione, Milan, Italy). Soil 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, USA). Soil salinity was estimated from saturation extracts (Non-affiliated Soil Analyses Work Committee, 1990). Extracts were analyzed for electrical conductivity using a Beckman conductivity bridge and reported in units of mS m^{-1}. Sludge electrical conductivity was also analyzed on a 1:2 sludge to water ratio extract following similar procedures.

3.9 Additional methods involved in turfgrass trial

3.9.1 Mowing and sod harvest

Turf was cut with a reel mower (Protea Turf, Germiston, South Africa) to a height of 0.03 m each week. Clippings were removed according to common practice in the area, which also assists in exporting additional nutrients from the field. Sods were harvested to a depth of 0.02 m from all treatments when the slowest growing treatment had reached full cover. A hand operated, light-weight, gasoline powered sod cutter (Protea Turf, Germiston, South Africa), used by commercial sod growers in the area, was used. Each sod had a width of 0.5 m and length of 1 m.

3.9.2 Soil loss through sod lifting

Three 0.5 m long iron pegs of 0.010 m diameter were inserted vertically into each plot with 0.05 m exposed above the surface, to determine soil loss during sod harvesting. Two pegs were located at adjacent corners of each plot, and the third was in the middle of the plot. Each was marked with a single groove 0.04 m above the soil surface to indicate the position at which to tie a length of string. After each sod harvest, the string was stretched between the two adjacent corner pegs across the peg in the middle of the plot, giving a “V” shaped transect. Distance to soil surface readings were then taken every 0.7 m along this transect, using a vernier-calliper. The difference in soil surface elevation before and after each sod harvest was recorded as the depth of soil exported with the sod. This assumes negligible soil disturbance, as a light-weight sod cutter was used and there was no tillage after harvest.

3.9.3 Turfgrass establishment rate

Rate of turf establishment was evaluated 34 and 65 days after sludge application as percent basal coverage, using the 10 pin bridge method. The bridge had 4 legs supporting a 0.5 m long horizontal frame with 10 pins located every 0.05 m. The bridge was placed randomly five times in each plot and the number of pins touching grass counted. Visual ratings of turf colour were conducted according to a scale of 1 to 9, where 1 was straw brown and 9 represented dark green (Linde and Hepner, 2005), with a rating of 6 considered minimally acceptable (Morris, 2007). Visual evaluations were made monthly and averaged over the growing season.

3.10 Model parameter description

The new SWB model requires specific crop parameters as well as management, weather and soil data as an input to run both the crop growth and nutrient models. The input parameters required by the model namely, specific crop parameters, soil data, crop data, and nutrient module parameters and data are listed below. Details on parameters and their determination can be obtained from

Annandale et al. (1999) for the crop growth model and Stöckle and Nelson (2000) for the nitrogen model.

3.10.1 Crop growth model

Specific crop parameters

a. Canopy extinction coefficient for solar radiation (*K*);
b. Dry matter: water ratio (*DWR*) in kPa;
c. Radiation use efficiency (E_c) in kg MJ^{-1};
d. Base temperature (T_b) in ^oC;
e. Optimum temperature (*Tlo*) in ^oC;
f. Maximum temperature ($T_{cut\text{-}off}$) in ^oC;
g. Thermal time: emergence (*EMDD*) in d ^oC;
h. Thermal time: reproductive phase (*FLDD*) in d ^oC;
i. Thermal time: maturity (*MTDD*) in d ^oC;
j. Thermal time: transition (*TransDD*) in d ^oC;
k. Thermal time: leaf senescence in (*MaxLeafAge*) in d ^oC;
l. Leaf water potential at maximum transpiration rate (*psilm*) in kPa or J kg^{-1};
m. Maximum transpiration rate (Tr_{max}) in mm d^{-1};
n. Specific leaf area (*SLA*) in m^2 kg^{-1};
o. Leaf stem partitioning factor (*PART*) in m^2 kg^{-1};
p. Total dry matter at emergence (*TDMstart*) in kg m^{-2};
q. Root fraction (f_r);
r. Stem translocation (*Transl*);
s. Root growth rate (*RGR*) in m^2 $kg^{-0.5}$;
t. Maximum canopy height (H_{Cmax}) in m, and
u. Stress index (*SI*).

Soil data*:*

a. Runoff curve number in mm;
b. Matric potential at field capacity and permanent wilting point in kPa or J kg^{-1};
c. Maximum drainage rate in mm d^{-1} and drainage factor;
d. Soil layer:
e. Thickness in m;
    - Volumetric soil water content at field capacity and permanent wilting point in m m^{-1};
    - Initial volumetric water content in m m^{-1}, and
    - Bulk density in Mg m^{-3} of each layer.

Crop data*:*

a. Model type;
b. Name of the crop;
c. Planting date;
d. Starting date of the simulation;
e. Weather ID;
f. Area of the field in ha;
g. Irrigation timing options (amount in mm, interval in days, depletion in %);
h. Irrigation system (type and design details), and
i. Management (root zone or profile).

Weather data*:*

a. Latitude (^oN or ^oS);
b. Hemisphere;
c. Wind speed in m s^{-1} and its height of measurement;
d. Maximum and minimum daily temperature in ^oC;
e. Solar radiation in MJ m^{-2} d^{-1};
f. Precipitation in mm, and

g. Maximum and minimum relative humidity in % or vapour pressure in kPa or else dry and wet bulb temperatures in ^{o}C.

3.10.2 Nitrogen model

Initial soil profile data for each layer:

a. Organic matter (%)
b. Soil pH (H_2O)
c. CEC (mmol/100g)
d. Nitrate (mg kg^{-1})
e. Ammonium (mg kg^{-1})
f. Residue mass (kg ha^{-1})

Fertilizer and tillage:

a. Fertilizer type (organic, inorganic)
b. Fertilizer form (Solid, liquid)
c. Application method (Incorporated, surface applied)
d. Amount applied (kg ha^{-1})
e. Depth of cultivation
f. Residue management after harvest (fraction of standing and surface residue left after harvest)

Organic fertilizers (biosolids, manure) parameters:

a. Carbon fraction

b. Ammonium fraction

c. Nitrate fraction

d. Water content

e. Fast cycling fraction, half life, and C:N ratio

f. Slow cycling fraction, half life, and C:N ratio

g. Lignified fraction, half life, and C:N ratio

3.11 Statistical analyses

Statistical analyses were performed to evaluate the impact of various sludge application rates on the following measured traits: Forage, grain yield and crude protein contents of dryland maize, irrigated maize, and oats; hay yield and crude protein contents of weeping lovegrass; turfgrass establishment rate, colour, sod strength, thickness of soil and sod mass exported, sod N and P, and plant N and P exported with the sod. The statistical analyses were conducted using Analysis of Variance (ANOVA) and General Linear Model (GLM) procedures of Windows SAS version 9.0 (SAS Institute, 2002), to determine significant treatment effects on measured response variables. When treatment effects were found to be significant, Fisher's protected LSD at the 0.05 level was used to separate means.

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CHAPTER 4

AGRONOMIC CROPS

The following hypotheses are tested in this chapter.

HYPOTHESIS 1

Sludge application above the 8 Mg ha^{-1} yr^{-1} limit will increase:

a. Dryland maize and irrigated maize-oat rotation grain yield.

b. Dryland maize and irrigated maize-oat rotation forage yield.

HYPOTHESIS 2

a. More N can be exported in either grain or forage under irrigated rotation than dryland cropping.

b. Under both dryland and irrigated conditions, more N can be exported in forage than grain.

HYPOTHESIS 3

a. High yielding irrigated and dryland cropping systems can fully utilize N supply from double the norm and are not susceptible to excessive nitrate leaching.

HYPOTHESIS 4

Sludge application according to crop N demand results in the accumulation of total and plant available P in the soil profile.

4.1 Grain and forage yield

4.1.1 Grain yield

a. Dryland maize (*Zea mays* L.)

Dryland maize grain yield was significantly increased by doubling the recommended annual sludge limit of 8 Mg ha^{-1} yr^{-1} for the first two crops, but not the third. Inorganic fertiliser gave higher yields than the 8 Mg ha^{-1} yr^{-1} limit in two of the three years (Table 4.1).

Table 4.1 Dryland maize grain yield response to three sludge application rates, a control, and an inorganic fertilizer treatment during the 2004/05 to 2007/08 growing season.

Treatment	Dryland maize grain yield		
	2004/05	2006/07	2007/08
		Mg ha^{-1}	
Control†	4.98	1.33	4.92
4 Mg ha^{-1} yr^{-1}	5.86	1.52	6.47
8 Mg ha^{-1} yr^{-1}	6.17	1.74	8.00
16 Mg ha^{-1} yr^{-1}	6.87	2.04	8.29
Inorganic fertilizer	6.35	2.17	8.56
LSD (5%)	0.32	0.09	0.37
CV, %	3	3	3

† zero sludge and inorganic fertilizer applied

The rainfall was 564, 405, and 710 mm for the three seasons respectively, and the low yield for the 2006/07 growing season was a consequence of drought. Water stress during the silking, tasseling and pollination stages results in severe yield losses by inhibiting pollination, reducing silk elongation as well as delaying silk formation (Rhoads and Bennett, 1990). Even though crop response to nutrient supply is influenced by the availability of water (Tisdale et al., 1985), there was a clear response to increasing nutrition in dry (2006/07) as well as wet years (2007/08).

b. Irrigated maize-oat (*Avena sativa* L.) rotation

Irrigated maize grain yield was significantly improved by doubling of the 8 Mg ha^{-1} yr^{-1} sludge limit in all three seasons (Table 4.2). Yields under irrigation were much higher than dryland, ranging from 65% greater in a wet year to 7 fold greater in a dry year. The 16 Mg ha^{-1} yr^{-1} sludge application always gave a significantly higher yield than inorganic fertiliser. Irrigated oats grain yield also benefited from double the recommended sludge in all three seasons. There was no clear difference between the highest sludge application and the inorganic fertiliser treatments on oat grain yield.

The most likely explanation for the significant response to sludge was N supply, since the plant available background soil P of 29 mg kg^{-1} remained within or higher than the optimum range required for most crops, (25-30 mg kg^{-1}), as defined by Sims and Pierzynski (2000). The role of N in the development of kernels in maize is to establish and maintain the crop's photosynthetic ability (Below, 1995 and 1997), as well as facilitating the development of reproductive sinks (Below et al., 2000). Thus N is generally the limiting factor in irrigated maize production through its effect on kernel number and mass (Rhoads and Bennett, 1990; Lemcoff and Loomies, 1986; Jacobs and Pearson, 1992).

Table 4.2 Irrigated maize-oat rotation grain yield response to three sludge application rates, a control, and an inorganic fertilizer treatment during the 2004/05 to 2007/08 growing seasons.

	Irrigated maize-oat rotation grain yield					
	Maize			Oats		
Treatment	2004/05	2006/07	2007/08	2005	2006	2008
	Mg ha^{-1}					
Control†	13.61	5.00	4.82	2.75	2.69	2.32
4 Mg ha^{-1} yr^{-1}	14.80	7.47	7.06	3.32	3.78	3.08
8 Mg ha^{-1} yr^{-1}	16.10	10.40	10.31	3.89	4.34	3.60
16 Mg ha^{-1} yr^{-1}	19.94	15.21	14.10	4.09	4.93	4.04
Inorganic fertilizer	15.06	11.18	11.05	4.01	4.51	4.30
LSD	1.11	0.72	0.38	0.18	0.13	0.22
CV, %	5	5	3	3	2	4

† zero fertilizer and inorganic fertilizer applied
NB: During the 2005/06 growing season maize was damaged by herbicide at early stage and oats was not planted during the winter season of 2006/07 due to technical problems.

Similarly, nitrogen influences the grain yield of oats by affecting the various yield components, such as panicle density, kernel number, dry matter production and harvest index. N deficiency results in the decline of yield by causing abortion of kernels located at the end of the ear, or by interrupting dry matter accumulation prematurely (Pearson and Jacobs, 1987).

In summary, doubling the annual upper limit of sludge from 8 to 16 Mg ha^{-1} improved dryland maize yield in two out of three seasons. The yield of irrigated maize and oats was increased each year. Consequently, Hypotheses 1a was accepted for irrigation conditions, and in the majority case for dryland conditions.

4.1.2 Forage yield

a. Dryland maize

Sludge applied at double the annual 8 Mg ha^{-1} limit significantly improved dryland maize forage yield, except during the third growing season (Table 4.3). As was the case for grain, forage yield was reduced in the drier than average 2006/07 season. Dryland maize forage yield from the 8 Mg ha^{-1} yr^{-1} sludge treatment was similar to the inorganic fertilizer, apart from the dry 2006/07 growing season.

The increase in forage yield with higher sludge applications is most likely a consequence of the increasing N supply. However, it is not clear why there was still a significant response to increasing sludge in the dry as well as wet seasons, since the demand for N in season two would only have been about one third of that for season three.

Table 4.3 Dryland maize forage yield response to three sludge application rates, a control, and an inorganic fertilizer treatment during the 2004/05 to 2007/08 growing seasons.

Treatment	Dryland maize forage yield		
	2004/05	2006/07	2007/08
		$Mg\ ha^{-1}$	
Control†	11.67	4.50	11.69
4 $Mg\ ha^{-1}\ yr^{-1}$	13.73	4.79	15.15
8 $Mg\ ha^{-1}\ yr^{-1}$	14.89	5.44	18.65
16 $Mg\ ha^{-1}\ yr^{-1}$	15.78	6.18	18.70
Inorganic fertilizer	14.44	6.42	19.29
LSD (5%)	0.57	0.27	1.69
CV, %	3	3	7

† Zero sludge and inorganic fertilizer applied.

b. Irrigated maize-oat rotation

Doubling of the recommended annual upper sludge limit significantly improved irrigated maize as oat forage yield in all three seasons (Table 4.4). There was a noticeable decline in irrigated maize forage yield over time, especially in the control and low sludge treatments. The highest sludge application of 16 $Mg\ ha^{-1}$ produced greater yields than inorganic fertiliser for maize forage in all seasons, and for oats in two of the three seasons.

The forage yield response to sludge is again attributed to N supply (Christie et al., 2001; Moser et al., 2005) and is consistent with previous studies conducted in other countries (Collins et al., 1990; Wang et al., 2000; Bozkurt et al., 2006). The inorganic fertiliser and 16 Mg ha^{-1} sludge treatments received similar N applications of 1278 kg and 1309 kg respectively over the three seasons. Nevertheless the irrigated maize forage yield was greater under the 16 Mg ha^{-1} of sludge, suggesting that the beneficial effects of sludge were more than just N supply.

Table 4.4 Irrigated maize-oat rotation forage yield response to three sludge application rates, a control, and an inorganic fertilizer treatment during the 2004/05 to 2007/08 growing seasons.

Treatments	Irrigated maize-oat rotation forage yield					
	Maize			Oats		
	2004/05	2006/07	2007/08	2004/05	2005/06	2007/08
	Mg ha^{-1}					
Control†	31.56	14.66	14.31	8.24	8.05	8.04
4 Mg ha^{-1} yr^{-1}	32.45	19.53	19.37	10.32	11.83	11.18
8 Mg ha^{-1} yr^{-1}	34.30	25.18	25.01	11.35	12.86	12.78
16 Mg ha^{-1} yr^{-1}	41.88	33.45	31.22	13.64	16.44	15.82
Inorganic fertilizer	32.81	25.00	24.95	12.96	14.57	14.27
LSD	1.89	1.27	2.20	0.62	0.42	1.5
CV, %	4	4	6	4	2	8

† Zero sludge and inorganic fertilizer applied

The yield of oats was higher with 16 Mg ha^{-1} sludge than fertiliser in two of the three seasons, although both received similar levels of N. However, oats forage yield was higher from the inorganic fertiliser than the 8 Mg ha^{-1} yr^{-1} sludge treatment, due most likely to the lower total N applied in the sludge and the slower mineralisation rate during the winter period.

Hypotheses 1 b was accepted for irrigated conditions, namely that sludge application above the 8 Mg ha^{-1} yr^{-1} limit will increase the forage yields of maize and oats in rotation. Hypothesis 1b was accepted in the majority cases for dryland maize forage yield.

4.2 Crop N uptake

4.2.1 Grain N uptake

a. Dryland maize

Dryland maize grain N uptake increased significantly with increase in sludge application rate (Table 4.5) for sludge rates ranging between 0 and 16 Mg ha^{-1} yr^{-1}. Grain N uptake was lower during the 2006/07 growing season and higher during 2007/08 in response to rainfall patterns. Grain N uptake was highest from the inorganic fertilizer treatment. This occurred despite higher total N supply from the 16 Mg ha^{-1} sludge treatment (485, 355, and 495 kg N ha^{-1} as opposed to 96 kg N ha^{-1} of inorganic fertilizer each year during 2004/05, 2006/07, and 2007/08 respectively).

Table 4.5 Dryland maize grain N uptake from a clay loam soil treated with three sludge application rates, an inorganic fertilizer, and a control during the 2004/05 to 2007/08 growing seasons.

Treatments	Dryland maize grain N uptake		
	2004/05	2006/07	2007/08
		kg ha^{-1}	
Control†	72	22	61
4 Mg ha^{-1} yr^{-1}	88	24	92
8 Mg ha^{-1} yr^{-1}	102	28	117
16 Mg ha^{-1} yr^{-1}	117	33	131
Inorganic fertilizer	123	40	138
LSD (5%)	3	1	3
CV, %	2	2	2

† Zero sludge and inorganic fertilizer applied
NB. In 2005/06 maize was harvested at early stage due to damage by herbicide.

b. Irrigated maize

Irrigated maize grain N uptake increased significantly as the sludge application rate increased, with highest uptake recorded from the 16 Mg ha^{-1} sludge treatment (Table 4.6). Similarly, oats grain N uptake increased as sludge application rate increased to the maximum rate, except in 2004/05. Irrigated maize grain N uptake decreased over time, and the effect was greatest at lower application rates of sludge.

Table 4.6 Irrigated maize-oat rotation grain N uptake from a clay loam soil treated with three sludge application rates, an inorganic fertilizer, and a control during the 2004 to 2007/08 growing seasons.

Treatments	Irrigated maize-oat rotation grain N uptake					
	Maize			Oats		
	2004/05	2006/07	2007/08	2004/05	2005/06	2007/08
	kg ha^{-1}					
Control†	195	74	60	50	29	42
4 Mg ha^{-1} yr^{-1}	219	103	93	62	54	45
8 Mg ha^{-1} yr^{-1}	282	143	132	76	57	63
16 Mg ha^{-1} yr^{-1}	391	204	220	76	73	70
Inorganic fertilizer	292	160	161	86	76	83
LSD	8	7	12	1	2	4
CV, %	2	3	6	1	2	4

† Zero sludge and inorganic fertilizer application
NB. In 2005/06 maize was harvested at early stage due to damage by herbicide.

In general, grain N uptake was higher under irrigated maize compared with similar treatments under dryland conditions, except the control which was slightly lower during the 2007/08 growing season. In addition, the overall annual grain N uptake by irrigated maize-oat rotation was at least three times higher than similar treatments under dryland conditions during the 2004/05 growing season and twice higher in 2007/08. This indicates that nitrogen demand of grain production under intensive cropping systems was much higher than dryland conditions and sludge application rates should be adjusted accordingly.

4.2.2 Forage N uptake

a. Dryland maize

Dryland maize forage N uptake increased with increase in sludge application rate throughout the study period except in 2005/06 where maize was damaged by herbicide (Table 4.7). Similar to grain N uptake, dryland maize forage N uptake was lower in 2006/07 but higher in 2007/08. Dryland maize forage N uptake was highest from the inorganic fertilizer treatment except in 2004/05.

Table 4.7 Dryland maize forage N uptake from a clay loam soil treated with three sludge application rates, an inorganic fertilizer, and a control during the 2004/05 to 2007/08 growing seasons.

Treatments	Dryland maize forage N uptake			
	2004/05	2005/06	2006/07	2007/08
	kg ha^{-1}			
Control†	123	20	66	126
4 Mg ha^{-1} yr^{-1}	148	25	69	162
8 Mg ha^{-1} yr^{-1}	188	24	79	238
16 Mg ha^{-1} yr^{-1}	201	20	92	244
Inorganic fertilizer	197	64	103	254
LSD (5%)	8	8	2	14
CV, %	3	2	2	5

† Zero sludge and inorganic fertilizer applied

NB. In 2005/06 maize was harvested at early stage due to damage by herbicide, thus forage N uptake was very low.

This study showed that the amount of nitrogen exported with forage (Table 4.7) was higher than the amount exported with the grain (Table 4.5). According to the three year mean data, N exported with forage under dryland condition was twice higher than the amount exported with the grain. This indicates that N exported during forage production is much higher than grain production.

b. Irrigated maize

Irrigated maize and oats forage N uptake significantly increased with increase in sludge application rate (Table 4.8). Irrigated maize forage N uptake decreased across time for all treatments (excluding the 2005/06, where maize was harvested at early stage due to damage by herbicide). Oat forage N uptake, however, did not have similar trend of decreasing across years. Irrigated maize forage N uptake by the 8 Mg ha^{-1} yr^{-1} treatment was similar to the uptake by the inorganic fertilizer during the 2004/05 and 2006/07 growing seasons.

Forage N uptake was higher under irrigated systems compared with similar treatments under dryland conditions. According to the three year mean results from this study, forage N uptake was at least twice higher under irrigation compared with similar treatments under dryland conditions. In addition, the overall forage N uptake by the irrigated maize-oat rotation was at least three times higher than similar treatments under dryland conditions. On the other hand, the three year mean irrigated maize-oat rotation forage N uptake was twice higher than grain uptake for all treatments. This was also similar under the dryland maize production system.

Table 4.8 Irrigated maize-oat rotation forage N uptake from a clay loam soil treated with three sludge application rates, an inorganic fertilizer, and a control during the 2004/05 to 2007/08 growing seasons.

Treatment	Irrigated maize-oat rotation forage N uptake						
	Maize				Oats		
	2004/05	2005/06	2006/07	2007/08	2005	2006	2008
	kg ha^{-1}						
Control†	318	32	158	141	103	56	101
4 Mg ha^{-1}	343	43	210	179	111	109	136
8 Mg ha^{-1}	390	85	299	268	144	122	157
16 Mg ha^{-1}	545	92	401	397	187	171	217
Inorganic fertilizer	397	84	310	304	272	158	198
LSD	9	6	22	19	7	4	18
CV, %	2	4	5	5	3	2	7

† Zero sludge and inorganic fertilizer applied

NB. In 2005/06 maize was harvested at early stage due to damage by herbicide, thus forage N uptake was very low.

Forage N uptake was higher under irrigated systems compared with similar treatments under dryland conditions. According to the three year mean results from this study, forage N uptake was at least twice higher under irrigation compared with similar treatments under dryland conditions. In addition, the overall forage N uptake by the irrigated maize-oat rotation was at least three times higher than similar treatments under dryland conditions. On the other hand, the three year mean irrigated maize-oat rotation forage N uptake was twice higher than grain uptake for all treatments. This was also similar under the dryland maize production system.

According to the three year mean data for the irrigated maize-oat rotation given 16 Mg ha^{-1} yr^{-1} sludge, grain N export and forage N export was equivalent to the total N contained in 25 and 13.5 Mg ha^{-1} yr^{-1} sludge, respectively. This assumes an average sludge N content during the study period (2.56%). Under dryland maize production, however, the N uptake was equivalent to a total N supply from 7 Mg ha^{-1} yr^{1} sludge for forage production and a 3.7 Mg ha^{-1} yr ^{1} for grain production (herbicide damaged maize data of 2005/06 excluded). If the N content of the sludge was 3.85%, the amount of sludge needed to satisfy the N demand of irrigated maize-oat rotation would be 16.6 Mg ha^{-1} yr^{-1} for forage production and 9 Mg ha^{-1} y^{-1} for grain production. Therefore, this indicates that the upper limit sludge norm is dynamic and is influenced by farming intensity (intensive irrigated vs. dryland), management practices (forage vs. grain production), and N content of sludge. This is clearly presented in Fig. 4.1).

To summarize, under an annual sludge regime of 8 Mg ha^{-1} on maize, 247 kg, 505 kg, 557 kg and 957 kg of N ha^{-1} was exported from dryland grain, dryland forage, irrigated grain and irrigated forage respectively (Table 4.9). When the sludge limit was doubled, dryland grain N export increased by 14% and forage export by just 6%. The increase was much larger under irrigated conditions. Grain N export was increased by 46% and forage export by 40% when the 8 Mg ha^{-1} sludge limit was doubled.

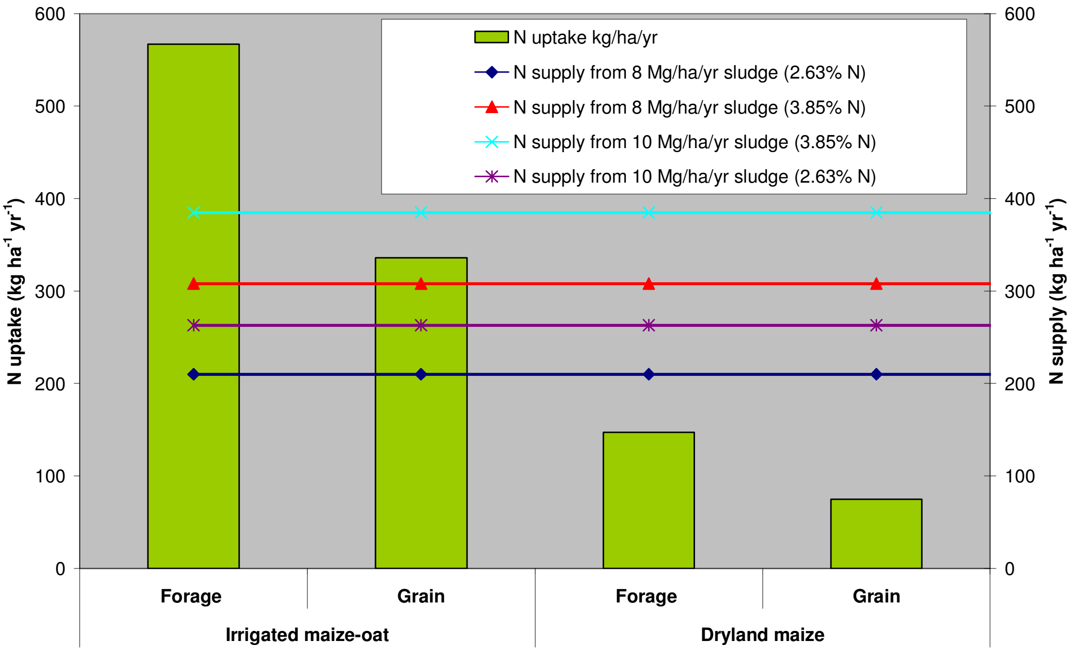


Figure 4.5 Three year cumulative mean N uptake by the 16 Mg ha^{-1} yr^{-1} sludge treated irrigated maize-oat rotation and dryland maize (bars) versus total N supply from sludge 8 Mg ha^{-1} yr^{-1}) (former norm) and 10 Mg ha^{-1} yr^{-1} (current norm) with variable N contents (2.56% mean value in his study vs. 3.85% South African sludge mean value (Snyman and Herselman, 2006)).

Clearly, N uptake is higher under irrigated rotation than dryland cropping and under both dryland and irrigated conditions, more N can be exported in forage than grain, so hypothesis 2 was accepted. The ability to add a second crop to the irrigated system allows for more N export, viz. 27-40% for N export as grain or 42-62% more as forage.

Table 4.9 Cumulative grain and forage N uptake by dryland maize and irrigated maize oat rotation during the 2004-2008 study period.

Cropping system	Treatment	N removed in maize		N removed in oats	
		Grain	Forage	Grain	Forage
		kg ha^{-1}			
Dryland maize	Control†	155	315		
	4 Mg ha^{-1}	204	379		
	8 Mg ha^{-1}	247	505		
	16 Mg ha^{-1}	281	537		
	Inorganic fertilizer	301	554		
	LSD (5%)	5	17		
	CV, %	1	2		
Irrigated maize-oats rotation	Control†	329	617	121	260
	4 Mg ha^{-1}	415	732	161	356
	8 Mg ha^{-1}	557	957	195	423
	16 Mg ha^{-1}	815	1343	219	575
	Inorganic fertilizer	613	1011	245	628
	LSD (5%)	14	29	4	19
	CV, %	2	2	3	3

† Zero sludge and inorganic fertilizer applied

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

4.3.1 Total N mass balance

Mass balance was calculated by subtracting the N exported over the 2004-2008 period from the total applied in fertiliser or sludge. Under dryland conditions, the fertiliser application of 96 kg N ha^{-1} was close to that exported in the grain, but insufficient to satisfy N export in forage. The appropriate level of sludge would be about 3 Mg ha^{-1} for dryland grain and just over 5 Mg ha^{-1} for dryland forage, substantially less than the 8 Mg ha^{-1} norm (assuming N supply from the 8 Mg ha^{-1} non-limiting). Grain N uptake in the maize-oat rotation was close to the supply from more than 8 Mg ha^{-1} sludge, but even double this quantity was insufficient to satisfy N removal in forage (Table 4.10).

Nitrogen mass balance based on sludge input – crop output is not the full story because there are other sources and sinks for N, in particular losses due to leaching, denitrification and volatilisation. Thus it is necessary to measure the change in N store in the soil profile. Under dryland conditions, the changes in total N are small, although accumulation is observable in the 8 and 16 Mg ha^{-1} sludge treatments (Fig. 4.2). This build up of N should be expected, because crop response to nutrient supply depends on the soil water status (Tisdale et al., 1985). Under water limited conditions crop N recovery is low (Ma et al., 1995), which results in the build up of residual N in the soil profile (Rimski-korsakov et al., 2009).

Table 4.10 Cumulative N mass balances (N supply less uptake) of dryland maize and irrigated maize-oat rotation for the 2004/05 to 2007/08 growing seasons.

Treatment	Cumulative crop N mass balance					
	Dryland maize			Irrigated maize-oat		
	N applied	Grain only	Forage	N applied	Grain only	Forage
	kg ha^{-1}					
Control†	0	-155	-315	0	-450	-877
4 Mg ha^{-1} yr^{-1}	334	130	-45	327	-249	-761
8 Mg ha^{-1} yr^{-1}	669	422	164	655	-98	-725
16 Mg ha^{-1} yr^{-1}	1336	1055	799	1309	275	-609
Inorganic fertilizer	288	-13	-266	1278	420	-361

† Zero sludge and inorganic fertilizer application

NB

- Nitrogen supply and uptake by maize during the summer of 2005/06 growing season was excluded from the mass balance because crop was harvested at early stage due to damage by herbicide.
- Nitrogen applied and uptake by oats during the 2005/06 is included in the mass balance of irrigated maize-oat rotation.
- Oats was not planted during the winter season of 2006/07 growing season, therefore, the N mass balance of irrigated maize-oat rotation for the same year is only for irrigated maize.
- Negative mass balance indicates that the total N supply was lower than the crop demand.

Under irrigated conditions, all treatments show a drop in total N compared to the initial values in the top 0.6m. There is little change below this depth, although the inorganic fertiliser treatment show an increase in total N. The decline in soil profile N suggests that the supply was insufficient to satisfy the demand of the crop under non-limiting water supply and is likely to be the cause behind maize grain and forage yield reduction across time. (Tables 4.2 and 4.4).

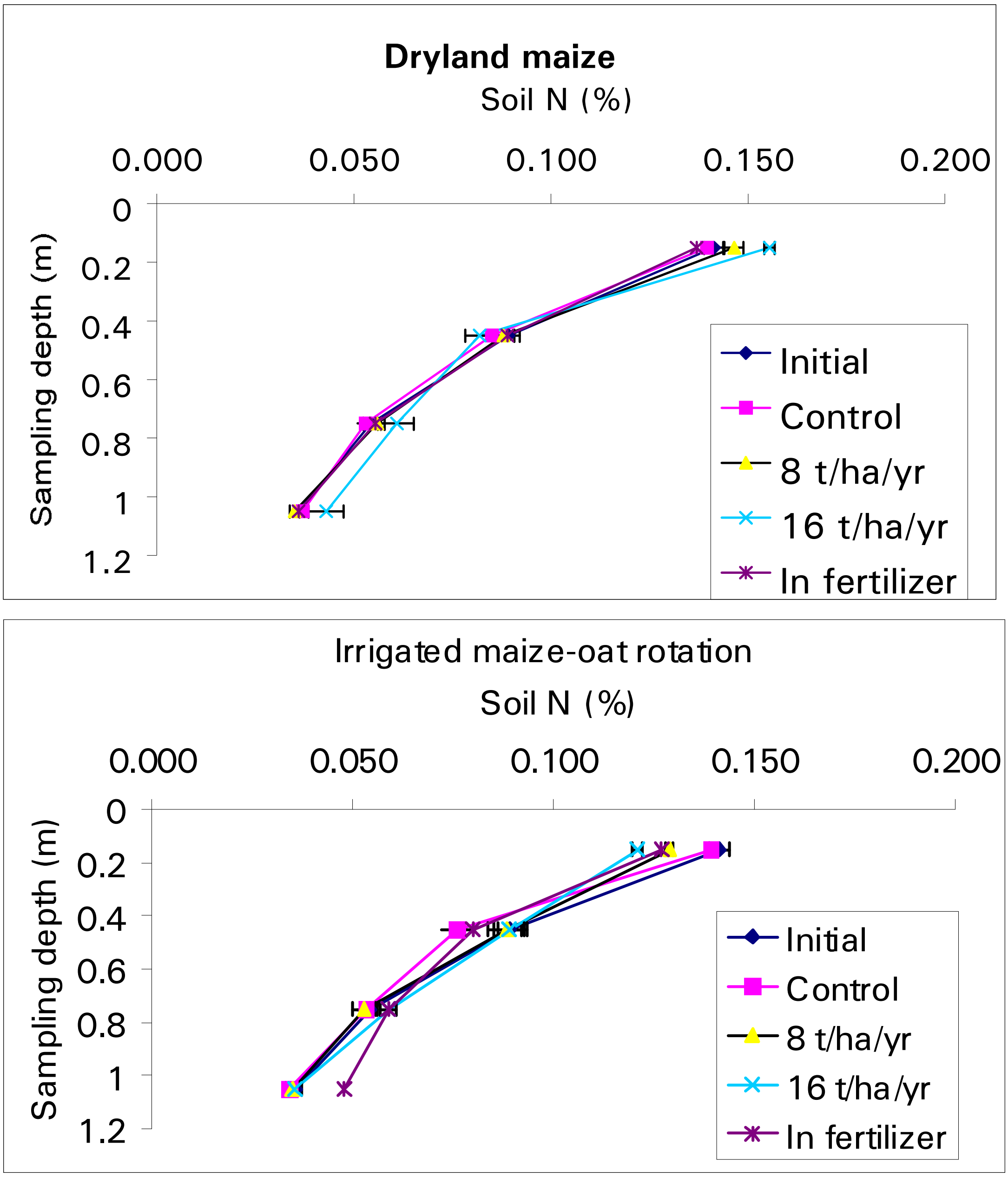


Figure 4.6 Soil profile total N content at the beginning of the study before treatment application (initial) and at the end of three years of study (2006/07).

Although the change in total N in Figure 4.2 look small, they have a major impact on the N mass balance calculation shown in Table 4.11. Total N fell over the study period in most treatments and especially under irrigated conditions. It was only under dryland conditions receiving sludge according to the norm and above which resulted in a net positive N accumulation over the study period.

Table 4.11 Cumulative N applied less forage N uptake, soil profile N change in storage and mass balance difference between the supply less forage uptake and change in storage for the 2004/05 to 2006/07 growing seasons.

† N applied from sludge and removed with the herbicide damaged maize during the 2005/06 are included in the computation.

Treatment	Cumulative N applied less forage N uptake†		Soil profile N change in storage (final less initial)		Mass balance difference ((Applied less forage uptake) less (change in storage))	
	Dryland maize	Irrigated maize-oat	Dryland maize	Irrigated maize-oat	Dryland maize	Irrigated maize-oat
			kg ha^{-1}			
Control‡	-209	-666	-244	-772	35	106
8 Mg ha^{-1} yr^{-1}	280	-558	234	-637	46	79
16 Mg ha^{-1} yr^{-1}	828	-431	869	-660	-41	229
Inorganic fertilizer	-76	-143	-137	-267	61	124

‡ Zero sludge and inorganic fertilizer applied

NB

The soil profile N change in storage and mass balance difference are computed for the years 2004/05 to 2006/07 only, because soil profile samples were not taken in 2007/08.

If there were no losses from the system, the sum of N supply in sludge less forage export and change in N storage should sum to zero. The fact that 7 of the 8 treatments show a net positive N mass balance means that there must be unaccounted losses. These losses could be attributed largely to volatilization (Robinson and Polglase, 2000) with leaching (Samaras et al., 2008; Moreno et al., 1996), and denitrification (Monnett et al., 1978) contributing under the irrigated maize-oat rotation.

Denitrification losses could account as high as 15% of the available inorganic N under irrigated systems (Henry et al., 1999). Similarly, few high rainfall events which followed an irrigation event are likely to have caused leaching losses below the depth of measurement. Sampling errors, N content variation within the sludge matrix, and soil heterogeneity may also have contributed to the observed differences.

4.3.2. Residual nitrate

Table 4.12 shows the nitrate in the soil after the oat harvest and before the sludge or fertiliser was applied to the following maize crop. This residual nitrate from the previous crop is present in the soil prior to the onset of the rainy season, a time when the N demand by the maize crop will be low. Doubling of the upper sludge limit under dryland maize production gives an almost four-fold residual nitrate in the top 0.6 m of soil, making the system more susceptible to leaching. Residual nitrate concentrations were substantially lower under irrigated maize-oat production, due to the greater demand for N combined with potential leaching losses (Table 4.12).

Van Biljon et al. (2008) suggest a lower threshold value for NO_{-3}-N for maize production of 70 kg ha^{-1} and an optimum value of 280 kg NO_3-N ha^{-1}. Thus the 16

Mg ha^{-1} sludge and the inorganic fertiliser treatments would have sufficient N in the soil for dryland production after two years of the corresponding treatment applications.

Table 4.12 Residual nitrate mass after crop harvest in the top 0.6 m soil stratum of dryland maize and irrigated maize-oat rotation during the 2004/05 to 2006/07 growing seasons

Cropping system	Treatment	Initial	After 2nd crop harvest in 2004/05	After 2nd crop harvest in 2005/06	After maize harvest in 2006/07
		kg ha^{-1}			
Dryland maize	Control†	183	95	172	99
	8 Mg ha^{-1}	183	69	114	95
	16 Mg ha^{-1}	183	188	424	355
	Inorganic fertilizer	183	140	289	282
Irrigated maize-oat rotation	Control†	183	81	31	38
	8 Mg ha^{-1}	183	66	52	51
	16 Mg ha^{-1}	183	106	22	72
	Inorganic fertilizer	183	150	59	56

† Zero sludge and inorganic fertilizer applied

4.3.3 Residual ammonium

Soil profile ammonium concentration remained similar or less than the initial values even with doubling of the upper limit sludge norm. The only exception was that of the 16 Mg ha^{-1} yr^{-1} sludge treatment at the end of the 2004/05 growing season for both dryland and irrigated maize-oat rotation (Table 4.13). Generally, the concentration of ammonium remained more or less similar throughout the soil profile monitored (data not shown). This was mainly due to the adsorption to CEC sites, as the soil had high and fairly uniform clay content (34-40%) to a depth of 1.2 m (Tesfamariam et al., 2009).

Table 4.13 Residual ammonium mass after crop harvest in the top 0.6 m soil profile of dryland maize and irrigated maize-oat rotation during the 2004/05 to 2006/07 growing seasons

Cropping system	Treatment	Initial	After 2nd crop harvest in 2004/05	After 2nd crop harvest in 2005/06	After maize harvest in 2006/07
		kg ha^{-1}			
Dryland maize	Control†	62	28	52	43
	8 Mg ha^{-1}	62	56	52	52
	16 Mg ha^{-1}	62	112	61	61
	Inorganic fertilizer	62	58	54	61
Irrigated maize-oat rotation	Control†	62	58	54	61
	8 Mg ha^{-1}	62	44	54	61
	16 Mg ha^{-1}	62	114	34	56
	Inorganic fertilizer	62	62	54	47

† Zero sludge and inorganic fertilizer applied.

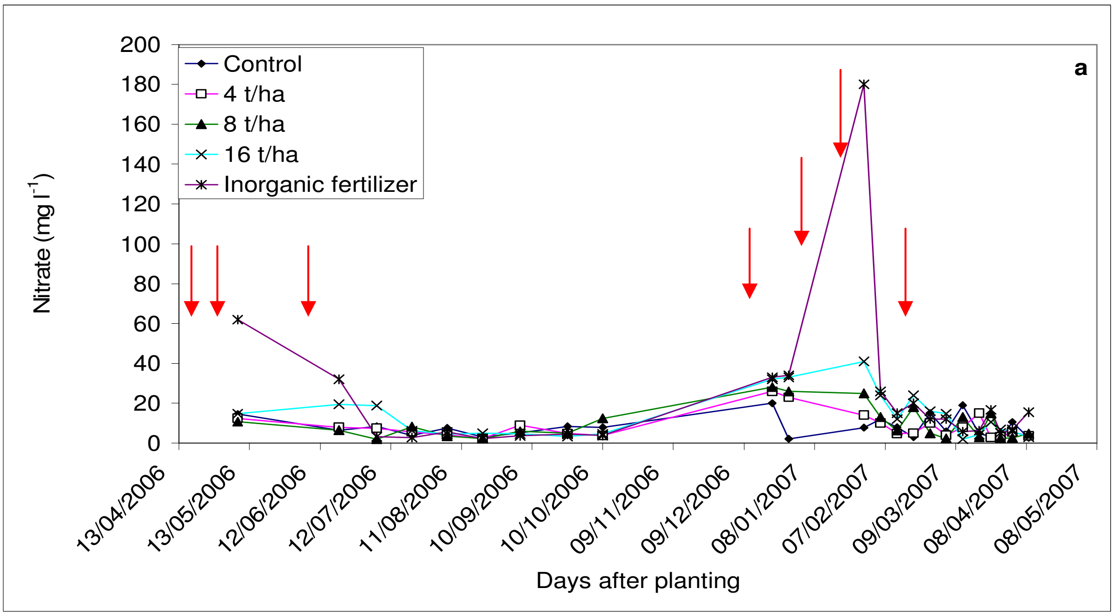
4.3.4 Nitrate leaching

Sludge applied at double the annual upper sludge limit slightly increased nitrate concentration in soil solution collected from 0.3 m deep WFDs during the first two months after sludge application (Fig. 4.3a). However the nitrate concentration from the 16 Mg ha^{-1} yr^{-1} treatment was substantially lower than the concentration collected from the inorganic fertilizer treatment. Nitrate concentration in soil solution collected from the 0.6 m deep WFDs installed in all sludge treatments

(Fig. 4.3b) were also less than the South African drinking water standards of 44 mg NO_3 L^{-1} (Korentajer, 1991).

Generally, nitrate concentration in soil solution collected from both 0.3 and 0.6 m WFDs in the first 40 to 70 days was higher from plots which received inorganic N fertilizer. The sudden rise of nitrate concentration in soil solution collected from both 0.3 and 0.6 m deep WFDs under the inorganic fertilizer treatment were linked to fertilizer application events. The first soil solution samples from the 0.6 m deep WFDs were collected once the irrigation was applied according to neutron probe deficit readings to a depth of 1.2 m, 41 days after planting for maize and 80 days for oats. None of the WFDs installed in the dryland maize treatments, however, collected soil solution.

The higher nitrate concentration in soil solution from the inorganic fertilizer treatment compared with sludge treatment should be expected because 50% of the N in the inorganic fertilizer was in nitrate form and remaining 50% as ammonium. In contrast, 75% of the total N in the sludge was in the organic form. The potential for nitrate leaching during the first two months after sludge and inorganic fertilizer application must be minimized by proper irrigation management practices.



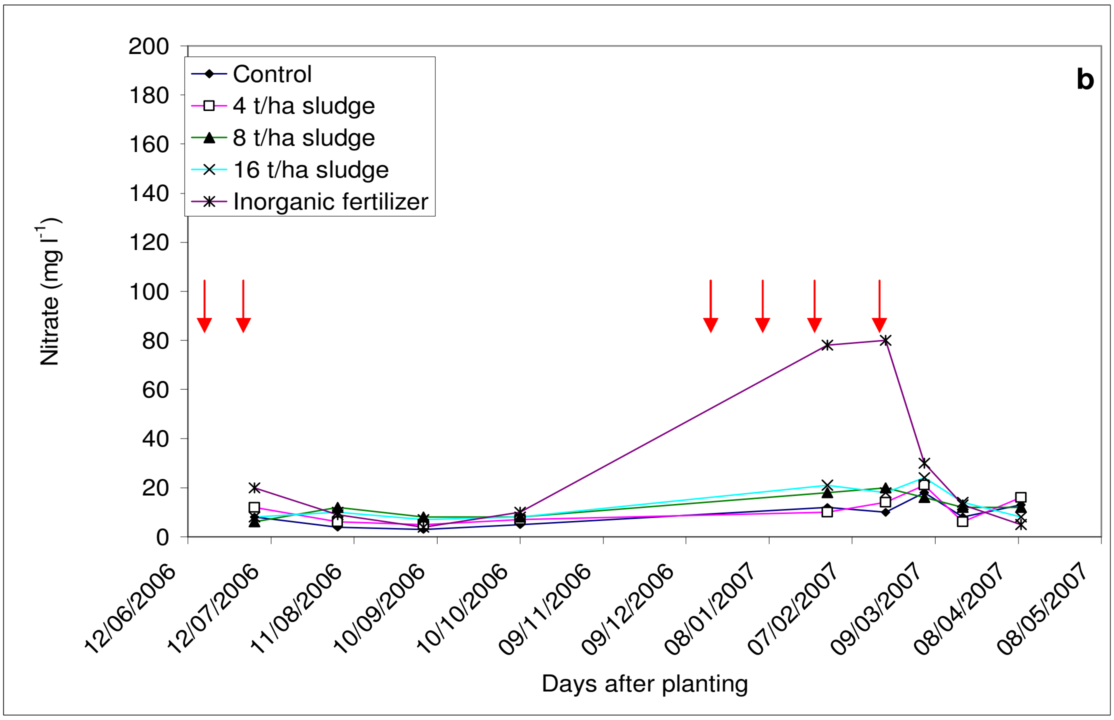


Figure 4.7 Nitrate concentration of leachate collected from 0.3 m (a) and 0.6 m (b) depth wetting front detectors in an irrigated maize-oat rotation during the 2006/07 growing season (arrows indicate inorganic fertilizer application events).

The following hypothesis was accepted:

- High yielding intensive irrigated cropping systems can fully utilize N supply from double the norm and does not seem susceptible to excessive nitrate leaching in the medium term.

The following hypothesis was rejected for dryland maize cropping system during dry years:

- High yielding dryland maize cropping system can fully utilize N supply from double the norm and is not susceptible to excessive nitrate leaching

4.4 Total P mass balance and residual Bray-1P

4.4.1 Total P mass balance

Based on the mass balance calculation of sludge imported less forage exported, total P supply from sludge rates of about 4 Mg ha^{-1} yr^{-1} were approximately similar to the uptake by the irrigated maize-oat rotation (Table 4.14). The 16 Mg ha^{-1} treatment, which was unable to satisfy the N demand of irrigated maize-oat rotation forage production, supplied 655 kg ha^{-1} extra P during the four year study period. This clearly shows that sustainable crop production using sludge must consider both N and P.

Table 4.14 Cumulative P mass balances (supply less forage uptake) of dryland maize and irrigated maize-oat rotation during the 2004/05 to 2007/08 growing seasons.

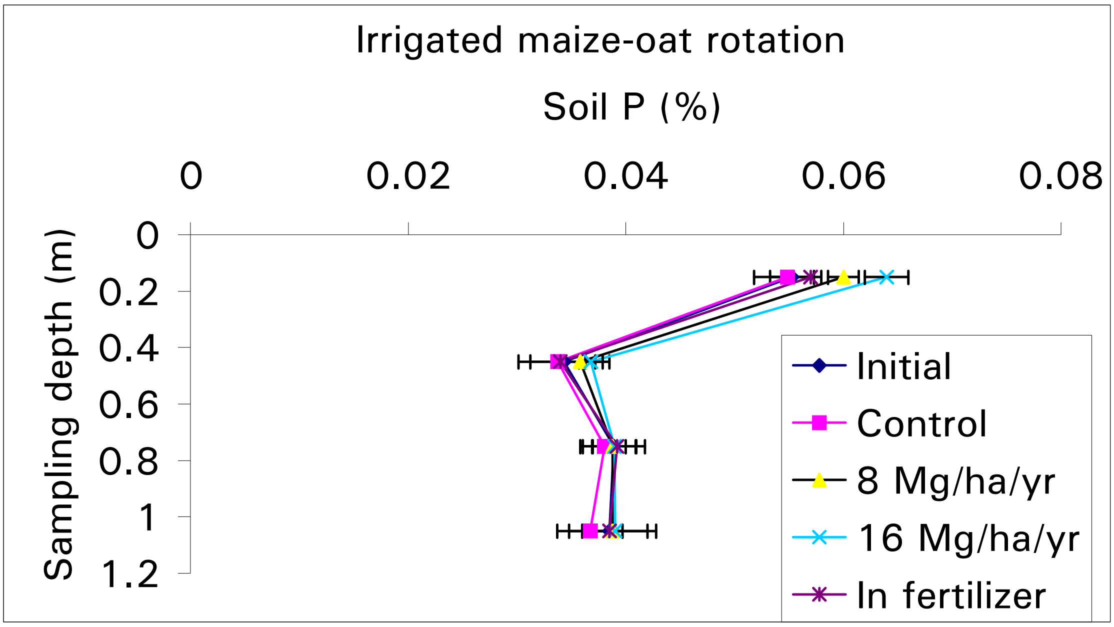
	Cumulative crop P balance			
	Dryland maize		Irrigated maize-oat	
Treatment	Grain only	Forage	Grain only	Forage
	kg ha^{-1}			
Control†	-32	-42	-86	-166
4 Mg ha^{-1} yr^{-1}	233	230	152	45
8 Mg ha^{-1} yr^{-1}	500	488	379	222
16 Mg ha^{-1} yr^{-1}	1058	1049	850	655
Inorganic fertilizer	-2	-5	99	-16

† Zero sludge and inorganic fertilizer applied

NB

- Phosphorus supply and forage P uptake by maize during the 2005/06 growing season was excluded from the mass balance because crop was harvested at early stage due to damage by herbicide.
- Phosphorus supply and uptake by oats during the 2005/06 is included in the mass balance of irrigated maize-oat rotation.
- Oats was not planted during the winter season of 2006/07 growing season; therefore, the P mass balance for the same year was only for irrigated maize.
- Negative mass balance indicates that the total P supply was lower than the crop demand.

Based on soil sampling to a depth of 1.2 m, the total P increased across time during the three year study period for all treatments except the control (Table 4.15). Total soil P significantly increased in the top 0.3 m layer of the 8 and 16 Mg ha^{-1} sludge treatments for both dryland maize and irrigated maize-oat rotation. There was slight increase of P in the 0.3-0.6 m layers of the 8 and 16 Mg ha^{-1} treatments under the irrigated maize-oat rotation. However, the difference was not significant (Fig. 4.4).



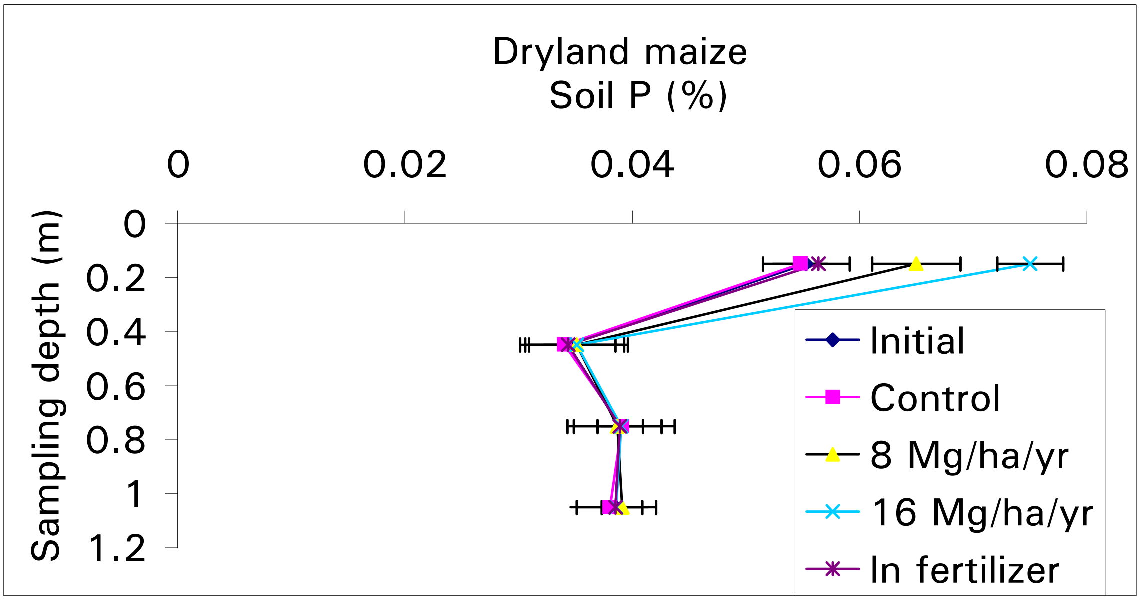


Figure 4.8 Soil profile initial total P content in contrast to P content change following three years of study with three sludge application rates, inorganic fertilizer treatment, and a control (zero sludge and inorganic fertilizer applied).

A mass balance difference was evident between the two mass balance methods (import less export versus final less initial soil profile total P mass) for all treatments (Table 4.15). Possible sources contributing to the difference include sampling errors, P content variation within the sludge matrix and soil heterogeneity.

Table 4.15 Cumulative soil profile P change in storage and mass balance difference between the supply less forage uptake mass balance and change in storage.

Treatment	Soil profile P change in storage (final less initial)		Mass balance difference ((Supply less uptake) less (change in storage))	
	Dryland maize	Irrigated maize-oat	Dryland maize	Irrigated maize-oat
	kg ha^{-1}			
Control†	-51	-159	16	37
8 Mg ha^{-1} yr^{-1}	451	266	23	-50
16 Mg ha^{-1} yr^{-1}	916	491	70	63
Inorganic fertilizer	29	67	-24	-62

† Zero sludge and inorganic fertilizer application

NB

- The soil profile N change in storage and mass balance difference are computed for the years 2004/05 to 2006/07 only because soil profile samples were not taken in 2007/08.
- N applied from sludge and removed with the herbicide damaged maize during the 2005/06 are included in the computation.

Therefore, it is clear from this study and previous studies conducted in other countries (Kelling et al., 1977; Peterson et al., 1994; Maguire et al., 2000) that sludge application to agricultural lands according to crop N demand will result in excess total P accumulation in the soil profile.

4.4.2 Soil profile residual Bray-1 extractable P

Under the irrigated maize-oat rotation, Bray-1P remained similar or less than the initial amount in the top 0.6 m soil stratum of the 8 Mg ha^{-1} sludge treatment. In contrast, Bray-1P mass in the 0.6 m soil stratum of the same treatment under dryland maize production increased across years (Table 4.16). At the end of the 2006/07 growing season, the amount of Bray-1P in the top 0.6 m soil stratum of the 16 Mg ha^{-1} yr^{-1} sludge treatment was 2.2 and 2.4 times higher than the initial mass for irrigated maize-oat rotation and dryland maize, respectively. It was interesting to note that the amount of Bray-1P at the end of the 2006/07 growing season for the irrigated maize-oat rotation and dryland maize control treatments was 1.17 and 1.99 times higher than the initial mass, respectively. This shows that there was also release of Bray-1P from the soil organic matter due to mineralization and/or desorption from the soil particles.

Generally, the background concentration of Bray-1 P in the top 0.3 m soil depth of the study site (29 mg kg^{-1}) was within the optimum range required for most crops, (25-30 mg kg^{-1}), as defined by Sims and Pierzynski (2000). It was, however, higher than the concentration required for optimal maize production under South African soils for similar soil types as described by Schmidt et al. (2007) (20.1 mg kg^{-1}). At the end of the three year study period, the concentration of Bray-1P in all dryland maize treatments (> 61 mg kg^{-1}) and the 16 Mg ha^{-1} yr^{-1} sludge treated irrigated maize (75 mg kg^{-1}) was above the optimum concentration as described by Sims and Pierzynski (2000) (50 mg kg^{-1}). Concentrations exceeding the optimum have negative environmental impacts due to an increase in soluble P concentration in runoff losses. According to Andraski and Bundy (2003), the concentration of dissolved P in runoff has a linear relationship with top-soil test P. A Bray-1P concentration of 250 mg kg^{-1} could yield 1 mg P L^{-1} in soil solution, which is often used as a bench mark for water pollution (Sims and Pierzynski, 2000).

Table 4.16 Residual Bray-1P mass after crop harvest in the top 0.6 m soil profile of dryland maize and irrigated maize-oat rotation during the 2004/05 to 2006/07 growing seasons

Cropping system	Treatment	Initial	After 2nd crop harvest in 2004/05	After 2nd crop harvest in 2005/06	After maize harvest in 2006/07
		kg ha^{-1}			
Dryland maize	Control†	147	186	209	272
	8 Mg ha^{-1}	147	178	240	292
	16 Mg ha^{-1}	147	167	383	357
	Inorganic fertilizer	147	136	264	332
Irrigated maize-oat rotation	Control†	147	222	144	172
	8 Mg ha^{-1}	147	146	137	143
	16 Mg ha^{-1}	147	104	172	324
	Inorganic fertilizer	147	142	117	87

† Zero sludge and inorganic fertilizer applied

The amount of Bray-1P under the 8 Mg ha^{-1} yr^{-1} sludge treated irrigated maize-oat rotation remained similar or less than the initial amount throughout the study period. This is in contrast to the net positive total P mass balance of the 8 Mg ha^{-1} treatment (Table 4.14). The same treatment under dryland maize, however, had twice higher Bray-1P in the 0-0.6 m soil stratum at the end of the three year study period. It was interesting to note that the difference in three year cumulative crop P uptake between these two treatments (148 kg ha^{-1}) was close to the difference in residual Bray-1P mass in the top 0.6 m soil stratum (149 kg ha^{-1}). Similarly, the difference in three year cumulative crop P uptake between irrigated maize-oat rotation and dryland maize control treatment (87 kg ha^{-1}) was close the difference in residual Bray-1P mass in the top 0.6 m soil stratus (100 kg ha^{-1}). This shows that the total mass of plant available P from the control and 8 Mg ha^{-1} yr^{-1} treated irrigated maize-oat rotation was similar to that of the dryland maize during the study period.

The 16 Mg ha^{-1} yr^{-1} sludge treated irrigated maize-oat rotation, however, had 1.4 times higher plant available P (plant uptake plus residual Bray-1P) than the same treatment under dryland maize production. This indicates that at higher sludge application rates plant available P could be affected by the availability of water.

The percentage of plant available P (Bray-1P) as opposed to the total P applied during the 2004/05 to 2006/07 growing seasons (Table 4.17, column 6) was higher under irrigated sludge treatments compared with similar treatments under dryland maize production. Bray-1P accounted only 7 and 12% of the total P from the 8 Mg ha^{-1} yr^{-1} sludge treatments under the dryland maize and irrigated maize oat rotation, respectively. Similarly, Bray-1P was 11 and 37% of the total P from the 16 Mg ha^{-1} yr^{-1} sludge treatments under dryland maize and irrigated maize-oat rotation, respectively. The remaining fraction is either in organic form or precipitated in the form of Fe-P because the sludge used in this study was treated with $FeCl_3$ at the wastewater treatment plant. The addition of $FeCl_3$ is responsible for the direct interaction and precipitation of a Fe-P mineral phase and adsorption onto a newly formed Fe hydroxide surface reducing 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).

Table 4.17 Cumulative P applied, total plant available P, normalized plant available P, and the percentage of Bray-1P in contrast to the total P applied during the 2004/05 to 2006/07 growing seasons.

Cropping system	Treatment	Total P applied†	Total plant available P‡	Normalized plant available P§	Bray-1P % of total P applied¶
		kg ha^{-1}			
Dryland maize	Control	0	307		
	8 Mg ha^{-1} yr^{-1}	526	343	36	7
	16 Mg ha^{-1} yr^{-1}	1051	422	115	11
	Inorganic fertilizer	60	387	80	133
Irrigated maize-oat rotation	Control	0	294		
	8 Mg ha^{-1} yr^{-1}	415	342	48	12
	16 Mg ha^{-1} yr^{-1}	830	600	306	37
	Inorganic fertilizer	200	282	-12	-6

† Total P applied is the sum of all P applied to the various treatments during the 2004/05 to 2006/07 growing seasons.
‡ Total plant available P is computed as the sum of crop P uptake during the 2004/05 to 2006/07 growing seasons and residual Bray-1P at the end of 2006/07 growing season.
§ Normalized plant available P is computed by subtracting the total plant available P of the control treatment from the total plant available P of each treatment.
¶ Bray-1P % is the percentage of Bray-1P in contrast to the total P applied to the various treatments.

In summary, soil response to various sludge rates during the three year field study show that continuous sludge applications at high rates to satisfy crop N demand resulted in the accumulation of total P and Bray-1P. Farina and Channon (1987) recommend P fertilization to build up the soil P status regardless of seasonal variation in crop yield, while Venter (1984) is in support of fertilizing crops according to the expected target yield In both cases some standardized monitoring needs to be implemented in order to evaluate the soil test P status so that it would not exceed the environmental loss threshold value.

Therefore, the following hypothesis was accepted:

- Sludge application according to crop N demand results in the accumulation of total and plant available P in the soil profile across time.

4.5 Conclusions

Doubling of the annual 8 Mg ha^{-1} sludge limit significantly increased grain and forage yield of both dryland maize and the irrigated maize-oat rotation. The increase in yield was small in the case of dryland crops, and only a small percentage of the extra N applied in the sludge was exported. Grain N export was increased by 46% and forage export by 40% when the 8 Mg ha^{-1} sludge limit was doubled.

Grain and forage yield of the irrigated maize-oat rotation displayed a decreasing trend during the study period. This may have been due to lack of N. In all sludge treatments the amount of N exported was greater than that applied, except for grain export at 16 Mg ha^{-1} sludge. This resulted in crop nutrient consumption from soil reserve, causing a decline of total N. In contrast, despite the increase in maize forage and grain yield reported with increase in sludge rate under dryland maize production, a net positive total N accumulation was evident for sludge applications of 8 Mg ha^{-1} yr^{-1} and higher.

Export of N in forage was approximately double that exported in the grain. Nitrogen exported in the forage from the irrigated rotation was at least three times higher than similar treatments under dryland maize production. Mass balance calculations involving the N applied, N exported in product and change in N storage revealed substantial losses from the system, particularly under irrigated conditions. These losses were large even in the control and fertiliser treatments, but highest in the 16 Mg ha^{-1} sludge treatment.

Soil solution samples collected from 0.3 and 0.6 m deep wetting front detectors under the irrigated maize-oat rotation indicated higher risk of ground water pollution through nitrate leaching from the inorganic fertiliser treatment compared sludge treatments. The residual nitrate left in the soil after the maize crops was higher under dryland than irrigated conditions, especially for the 16 Mg ha^{-1} application rate. The potential for nitrate leaching was clear, although the drainage volumes under dryland conditions were unknown.

Sludge applied according to crop N demand would result in total and Bray-1P accumulation in the soil profile and could cause a threat to surface water body pollution through time. Ideally the upper sludge limit to satisfy crop N demand should be dynamic because it depends on the sludge N content, the intensity of cropping, and the availability of water. But ultimately the maximum amount of sludge applied to an area will depend on the accumulation of P and the risk this poses for pollution as long as the threat from other contaminants is minimal.

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