

Modelling maize grain yield and nitrate leaching from sludge-amended soils across agro-ecological zones: A case study from South Africa

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ABSTRACT

When applying municipal sludge according to crop N requirements, the primary aim should be optimizing sludge application rates in order to maximize crop yield and minimize environmental impacts through nitrate leaching. Nitrate leaching and subsequent groundwater contamination is potentially one of the most important factors limiting the long-term viability of sludge application to agricultural soils. This study assessed maize grain yield and potential nitrate leaching from sludge-amended soils, using the SWB-Sci model, based on crop nitrogen requirements and inorganic fertilizer. The following hypotheses were tested using the SWB-Sci model and 20 years of measured weather data for 4 of the 6 South African agro-ecological zones. Under dryland maize cropping, grain yield and nitrate leaching from sludge-amended soils compared to inorganic fertilizer: (1) will remain the same across agro-ecological zones and sites, (2) will not vary across seasons at a specific site, and (3) will not vary across soil textures. Model simulations showed that annual maize grain yield and nitrate leaching varied significantly ($P > 0.05$) across the four agro-ecological zones, both for sludge-amended and inorganic fertilizer amended soils. The annual maize grain yield and nitrate leaching from sludge-amended soils were 12.6 t·ha⁻¹ and 32.7 kgNO₃-N·ha⁻¹ compared to 10.2 t·ha⁻¹ and 43.2 kgNO₃-N·ha⁻¹ for inorganic fertilizer in the super-humid zone. Similarly, maize grain yield and nitrate leaching varied significantly across seasons and soil textures for both sludge and inorganic fertilizer amended soils. However, nitrate losses were lower from sludge-amended soils (2.3–8.2%) compared to inorganic fertilizer (11.1–26.7%) across all zones in South Africa. Therefore, sludge applied according to crop N requirements has a lower environmental impact from nitrate leaching than commercial inorganic fertilizer. Further validation of these findings is recommended, using field studies, and monitoring potential P accumulation for soils that received sludge according to crop N requirements.

Keywords: sewage sludge, inorganic fertilizer, nitrate leaching, maize yield, agro-ecological zones, SWB-Sci

INTRODUCTION

Generally, biosolids are applied to agricultural lands based on the N requirement of crops (USEPA, 2012; Alvarez-Campos, 2019). This is a common practice, especially on soils with high P-fixing abilities. When applying sludge according to crop N requirements, the primary aim should be optimizing sludge application rates in order to maximize crop yield and minimize environmental impacts through nitrate leaching. Unlike inorganic fertilizer, a large fraction of the N from sludge is in organic form and is gradually released to plant in available forms of N (NH₄⁺ and NO₃⁻). Consequently, nitrate leaching from sludge-amended agricultural lands is expected to be minimal compared to soils which receive similar amounts of inorganic fertilizer (Tesfamariam et al., 2015).

Previous studies by Tesfamariam (2009) and Kayikcioglu and Delibacak (2018) have shown that there is a linear relationship between sludge application rate and maize, oat, and weeping lovegrass yield, until a point of diminishing return, which is often linked to the availability of water. This direct relationship was mainly due to an increase in plant-available N from sludge, which is considered the key element for dry matter production (Miles and Manson, 2000). An increase in sludge application rate may, however, lead to excessive nitrate leaching, especially when the rate of N release exceeds crop uptake (Tesfamariam et al., 2015; Paramashivam et al., 2017).

According to Ogbazghi et al. (2016), NO₃-N leaching and subsequent groundwater contamination is a potential

concern with the long-term sustainability of uncontrolled biosolid application to agricultural lands. Nitrate leaching is controlled by soil water dynamics and is a function of the nitrate concentration in soil solution (Ogbazghi et al., 2016; Zhao et al., 2019). Soil water dynamics is influenced by soil properties such as texture and structure, as well as by the availability of water through irrigation and/or rainfall. Nitrate leaching from agricultural lands is a result of a complex interaction between N transformation processes, soil water dynamics, and soil characteristics. Henceforth, the need for decision support tools is becoming quite important due to the ever-increasing concerns over environmental pollution associated with the use of organic and inorganic fertilizers (Tesfamariam et al., 2015). Several N computer models, as decision support tools, have been developed with varying levels of complexity depending on their purpose (Banger et al., 2017).

The SWB-Sci model is a mechanistic soil-water balance (Annandale et al., 2000), crop growth/irrigation scheduling (Annandale et al., 2000, 2003), N (Tesfamariam, 2009; Ogbazghi et al., 2016) and phosphorus (P) (Van der Laan et al., 2010) model. It has been successfully calibrated and validated for N dynamics in sludge-amended soils planted to maize, oats and weeping love grass, both under dryland and irrigated conditions (Tesfamariam et al., 2015).

The objective of this study was to assess maize grain yield and potential nitrate leaching using the SWB-Sci model from soils amended with sludge, based on crop N requirements adjusted for several South African agro-ecological zones. To achieve this, the following hypotheses were tested using the SWB-Sci model and 20 years of measured weather data for 4 of the 6 South African

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agro-ecological zones. Under dryland maize cropping, maize grain yield and nitrate leaching from sludge-amended soils compared with inorganic fertilizer: (i) will remain the same across agro-ecological zones and sites; (ii) will not vary across seasons at a specific site; and (iii) will not vary across soil textures.

MATERIALS AND METHODS

Model description

The SWB-Sci model is a mechanistic crop growth, irrigation scheduling, salt, N and P balance model. It is a generic one-dimensional, daily time-step model that uses soil, weather and crop units to mechanistically carry out crop growth, soil-water and salt balances, as well as nitrogen cycle simulations. A detailed description of the crop growth, irrigation scheduling, salt, and water balance modules of the SWB-Sci model is not presented in this paper, and can be found in Annandale et al. (2000).

The Nitrogen module of the SWB-Sci model follows a similar approach to that of the Cropping Systems Simulation Model (CropSyst) (Stöckle et al., 2003). The nitrogen balance in the SWB-Sci module includes nitrogen transformations (mineralisation, nitrification, denitrification and ammonia volatilisation), ammonium sorption, nitrogen transport and crop nitrogen uptake. The model simulates ammonium sorption using the approach presented by Stöckle and Campbell (1989), while symbiotic N fixation is simulated after the approaches of Bouniols et al. (1991). Crop nitrogen uptake is modelled using a modified version of the Godwin and Jones (1991) approach, where crop nitrogen uptake is determined as the lesser of crop nitrogen demand and potential nitrogen uptake (Stöckle et al., 1994). A detailed description of the N module, including the major nitrogen transformation processes, can be found in Stöckle et al. (2003).

Model parameterization

Soil

Four major soil textural classes (clay, clay loam, sandy clay loam and sandy loam) were selected from our database to investigate maize crop yield and potential nitrate leaching from sludge-amended soils that received sludge based on crop N requirements adjusted for each agro-ecological zone, using inorganic fertilizer as a benchmark. Selected physical and

chemical properties of the four soil textural classes used for model simulation are presented in Table 1.

Sludge

The sludge used for simulations in this study was anaerobically digested and dried on conventional concrete beds. The sludge was digested to 33% volatile suspended solids (VSS) destruction under mesophilic conditions. The retention time was 15 days in primary and 2 days in secondary digesters. Sludge properties required for model parameterization to run scenario simulations are presented in Table 2.

Inorganic fertilizer

The amount and timing of inorganic fertilizer application for this modelling work was based on the Fertilizer Handbook (FSSA, 2007) to meet the target yield for each selected site. The fertilizer was applied at planting and top dressed 5 weeks later according to the FSSA (2007) recommendations presented in Table 3. Limestone ammonium nitrate (LAN) with 28% N content was used as a source of nitrogen to meet the crop N requirement in this study.

Crop

Maize was selected as test crop because it is one of the most widely cultivated crops across the globe and accounts for 51% of the cultivated land in South Africa (FAO, 2005). A well-studied maize cultivar, PAN 6966, was selected and certain crop model parameters are presented in Table 4.

Table 2. Selected properties of the anaerobically digested sludge used for model parameterization

Sludge parameter	Units	Value
C	%	17
Total N	%	2.81
NH ₄ -N	%	0.264
NO ₃ -N	%	0.051
P	%	3.02
pH (H ₂ O)	NA	5.86
Water content	%	30
Fast cycling fraction	kg·kg ⁻¹	0.3
Slow cycling fraction	kg·kg ⁻¹	0.3
Fast cycling half-life	days	3
Slow cycling half-life	days	60
C:N ratio	kg·kg ⁻¹	8

Table 1. Selected soil physical and chemical characteristics of the four soil textures used for model scenario simulations

Selected characteristics	Unit	Soil textures			
		Clay	Clay loam	Sandy clay loam	Sandy loam
Field capacity (FC)	m·m ⁻¹	0.479	0.328	0.255	0.196
Permanent wilting point (PWP)	m·m ⁻¹	0.131	0.139	0.096	0.107
Bulk density	Mg·m ⁻³	1.207	1.314	1.401	1.557
Sand	%	20	32	60	65
Clay	%	60	34	27	10
Organic matter	%	2.8	2.5	1.6	1.5
Ψ _{FC}	kPa	-30	-30	-30	-30
Ψ _{PWP}	kPa	-1 500	-1 500	-1 500	-1 500
Drain factor	-	0.3	0.5	0.8	0.9
Root depth limit	M	2	2	2	2

Table 3. Inorganic fertilizer application timing and amounts used for scenario simulation across selected sites in South African agro-ecological zones (FSSA, 2007)

Agro-ecological zone	Selected sites	Inorganic fertilizer (LAN) application timing and date			
		First split application (at planting)		Second split application (five weeks after planting)	
		Date	Amount (kg·ha ⁻¹)	Date	Amount (kg·ha ⁻¹)
Semi-arid	Bloemfontein	27 Oct	24	5 Dec	23
	Rustenburg	27 Oct	37	5 Dec	35
	Polokwane	27 Oct	33	5 Dec	33
Sub-humid	Johannesburg	1 Nov	60	10 Dec	60
	Port Alfred	27 Oct	45	5 Dec	45
	Bethlehem	1 Nov	45	10 Nov	45
Humid	Durban	1 Oct	75	7 Nov	75
	East London	27 Oct	65	5 Dec	65
	Cape Town	10 Nov	65	18 Dec	65
Super-humid	Nelspruit	10 Oct	85	18 Nov	85

Table 4. Selected properties of the maize used for model parameterization

Crop parameter	Units	Value
Emergence	day deg	50
Flowering	day deg	1 000
Maturity	day deg	1 700
Transition	day deg	10
Leaf senescence	–	1 300
Maximum crop height	M	3.20
Maximum root depth	M	1.20
Minimum leaf water potential	kPa	–1 500
Maximum transpiration	mm·day ⁻¹	9
Specific leaf area	m ² ·kg ⁻¹	15
Leaf-stem partitioning	m ² ·kg ⁻¹	0.80
Root fraction	–	0.02
Root growth rate	–	8
Grain N partition coefficient	–	0.30
Root N concentration	kgN·kgDM ⁻¹	0.01
Maximum grain N concentration	kgN·kgDM ⁻¹	0.02

Study site

Scenario simulations were run using the SWB-Sci model for 4 of the 6 major agro-ecological zones of South Africa (Table 5, Column 1) to predict maize grain yield and nitrate leaching from sludge-amended soils using inorganic fertilizer as price benchmark.

The potential yield of maize for the representative sites and inorganic fertilizer recommendations for each site were obtained from FSSA Guidelines (2007) and Du Plessis (2003) (Table 5). Sludge application/recommendation rate was estimated based on the annual sludge N release rates adjusted to match the crop N requirements (Table 5, Column 6) using the SWB-Sci model (Ogbazghi et al., 2015).

Long-term weather records for the selected sites within each agro-ecological zone were obtained from the South African Weather Service (SAWS) for 1993–2013. SAWS collates, maintains and runs a quality control process of South Africa's meteorological and climatological data and related information. This archived data consists of daily rainfall values since 1936 as well as mean hourly and daily data of wind direction, wind speed, temperature, humidity, pressure

and sunshine since 1950. Two sites, Nelspruit and Port Alfred, were exceptions, since data were available only for 2002–2013. The annual rainfall figures (1993–2013) of the selected sites are presented in Table 6.

Simulation and statistical analyses conducted

Simulations of 80 scenarios were done based on fully factorial combinations of 4 agro-ecological zones with 3 sites for the semi-arid, sub-humid and humid zones and one for the super-humid zone, and 4 soil textures. Each scenario was run for 20 years of simulation time. The numbers of years were used as replicates, except in testing Hypothesis 2 (that under dryland maize cropping, nitrate leaching and maize grain yield from sludge-amended soils compared with inorganic fertilizer will not vary across seasons at a specific site), where the number of years was used as the main effect. Statistical analyses were done using general linear model (GLM) procedures of Windows SAS version 9.4 (SAS Institute, 2012).

RESULTS AND DISCUSSION

Maize grain yield and nitrate leaching across South African agro-ecological zones and sites

Model scenario simulation was carried out to predict maize grain yield and nitrate leaching from sludge-amended soils across 5 of the 6 South African agro-ecological zones. Findings from these model simulation results are presented in the following sections.

Maize grain yield from sludge-amended soils and inorganic fertilizer

Maize grain yield varied significantly across the 4 agro-ecological zones for both sludge and inorganic fertilizer-amended soils (Fig. 1). Generally, maize yield was higher from sludge-amended soils than lands receiving inorganic fertilizer (Fig. 1). The highest average grain yield of 12.6 t·ha⁻¹ was predicted for the super-humid zone (Nelspruit) under sludge treatment, while lowest yield of 4.1 t·ha⁻¹ was recorded in the semi-arid zone of Bloemfontein under inorganic fertilizer application. Generally, the predicted yield for the sites was within the ranges reported by FSSA (2007).

Table 5. Potential maize grain yield and annual inorganic nitrogen fertilizer and sludge application rate recommendations for selected sites across South African agro-ecological zones

Agro-ecological zone	Selected sites	Mean annual rainfall (mm)	Potential maize yield (t·ha ⁻¹) ¹	Inorganic N fertilizer (kg·ha ⁻¹) ¹	Sludge recommendation rate (t·ha ⁻¹) ²
Semi-arid	Bloemfontein	401	4.5	47	6.5
	Rustenburg	475	6.5	72	8.7
	Polokwane	391	6	66	7.7
Sub-humid	Johannesburg	790	8–9	120	13.8
	Port Alfred	726	7–8	90	10.3
	Bethlehem	705	7–8	90	10.3
Humid	Durban	965	10–10.5	150	13.5
	East London	816	8–9	130	11.7
	Cape Town	831	8–9	130	11.7
Super-humid	Nelspruit	1003	11–12	170	13.5

¹FSSA, 2007; ²Ogbazghi et al., 2015

The mean annual maize grain yield varied significantly ($P < 0.05$) between sites within an agro-ecological zone (Fig. 2). In the sub-humid zone, maize grain yield in Johannesburg was 20% higher under sludge-amended and 32% higher under inorganic fertilizer-amended soils than for Bethlehem. Similarly, in the semi-arid zone, maize grain yield in Rustenburg was 25% higher under sludge-amended and 20% higher under inorganic fertilizer-amended soils than in Bloemfontein. In the humid zone, maize grain yield in Durban was 20% higher under sludge-amended and 28% higher under inorganic fertilizer-amended soils than in East London (Fig. 2). These variations are attributed to the differences in rainfall and temperature between sites, which affected dry matter production and grain yield.

It was apparent from the simulations that maize grain yield from sludge-amended soils varied significantly ($P < 0.05$) across agro-ecological zones and sites compared with inorganic fertilizer. Maize grain yield was higher from sludge-amended soils than inorganic fertilizer, indicating the agronomic benefits of sewage sludge over inorganic fertilizer.

Nitrate leaching from sludge-amended soils and inorganic fertilizer

Henceforth, the simulation findings showed that nitrate leaching varied significantly ($P < 0.05$) across agro-ecological zones for both inorganic fertilizer and sludge-amended soils (Fig. 3). Cumulative annual nitrate leaching varied from 11.2 kgNO₃-N·ha⁻¹ (semi-arid) to 43.2 kgNO₃-N·ha⁻¹ (super-humid) for inorganic fertilizer-amended soils and from 5.6 kgNO₃-N·ha⁻¹ (semi-arid) to 32.7 kgNO₃-N·ha⁻¹ (super-humid) for sludge-amended soils. Generally, nitrate leaching within each agro-ecological zone was significantly higher ($P < 0.05$) from inorganic fertilizer-amended soils than sludge-amended soils (Fig. 3).

Simulations also showed that nitrate leaching varied between sites within an agro-ecological zone (Fig. 4). For instance, in the semi-arid zone, leaching was higher in Rustenburg (8.1 kgNO₃-N·ha⁻¹) than in Bloemfontein (4.1 kgNO₃-N·ha⁻¹) and Polokwane (5.6 kgNO₃-N·ha⁻¹); in the sub-humid zone, leaching was higher in Johannesburg (34.2 kgNO₃-N·ha⁻¹) than in Bethlehem (14.2 kgNO₃-N·ha⁻¹) and Port Alfred (8.3 kgNO₃-N·ha⁻¹); and in the humid zone, leaching was higher in Durban (40.2 kgNO₃-N·ha⁻¹) than in East London (13.2 kgNO₃-N·ha⁻¹) (Fig. 4).

The variation in nitrate leaching between agro-ecological zones generally follows a similar pattern to the rainfall for both inorganic fertilizer and sludge-amended soils. This concurs with previous findings that reported a direct relationship between water availability and nitrate leaching (Tsfamariam et al., 2015; Holland et al., 2018). Similarly, the difference in nitrate leaching between sites within an agro-ecological zone was attributed mainly to the variation in rainfall amount and distribution. For instance, in the semi-arid zone annual rainfall was 75 mm higher in Rustenburg than Bloemfontein; in the sub-humid zone, rainfall was 80 mm and 60 mm higher in Johannesburg than Bethlehem and Port Alfred; and in the humid zone, rainfall was 150 mm and 134 mm higher in Durban than East London and Cape Town (Tables 5 and 6).

This significant variation between sludge application and inorganic fertilizer was attributed mainly to the form of N. A large fraction of the N in sludge (> 70%) is organic, which is released gradually to plant-available form. In contrast, N in inorganic fertilizers is all inorganic and is potentially leachable under excessive rainfall.

Nitrate losses are low from sludge-amended soils compared with the conventional agronomic use of inorganic fertilizer. For instance, in the semi-arid zone of Rustenburg, only 2.3% of the organic N that is added with sludge was leached, compared with 11.1% for inorganic fertilizer. Similarly, in the sub-humid zone in Johannesburg, 6.2% of the organic N was leached from sludge compared with 28.5%. In the humid zone of Durban 7.9% of the organic N was leached from sludge compared with 26.7%. In the super-humid zone of Nelspruit, only 8.2% of the organic N that is added with sludge was leached as nitrate, compared with 25.4% of inorganic fertilizer. Therefore, using sludge in agricultural lands has a low risk of nitrate leaching compared with inorganic fertilizer. Therefore, the hypothesis that 'under dryland maize cropping, annual maize grain yield and nitrate leaching from sludge-amended soils will remain the same as inorganic fertilizer-amended soil across agro-ecological zones and sites' is not accepted.

Nitrate leaching and maize yield across seasons

Model scenario simulation was carried out to predict maize grain yield and nitrate leaching from sludge-amended soils across seasons within a site. Findings from these model simulation results are presented in the following sections.

Table 6. Twenty year (1993–2013) measured annual rainfall (mm) of selected sites in South Africa (Source: South African Weather Service)

Zone	Site	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13
Semi-arid	Polokwane	296	401	487	401	346	401	298	386	272	478	223	388	341	513	341	420	389	480	481	421	457
	Rustenburg	496	520	440	521	489	521	389	491	435	585	405	440	435	585	305	440	474	490	398	480	443
	Bloemfontein	520	581	430	490	501	321	398	473	505	477	440	510	440	390	400	510	580	510	512	583	482
Sub-humid	Bethlehem	696	646	701	709	687	698	723	781	791	659	677	634	755	705	577	763	773	886	812	790	778
	Johannesburg	740	748	798	810	830	801	890	910	840	666	539	861	619	726	688	800	958	981	890	910	878
Humid	Port Alfred	-	-	-	-	-	-	-	-	-	636	749	671	574	696	638	944	901	890	689	795	897
	Durban	980	864	926	993	920	826	980	946	885	880	620	1004	1049	997	924	896	587	980	876	898	986
	Cape town	712	689	812	765	681	694	745	619	785	844	615	844	917	980	829	926	548	866	709	827	801
Super-humid	East London	895	864	896	775	793	812	932	873	927	948	627	863	959	918	880	1136	797	789	701	789	811
	Nelspruit	-	-	-	-	-	-	-	-	-	1026	903	964	941	1023	948	1253	977	1029	993	981	1001

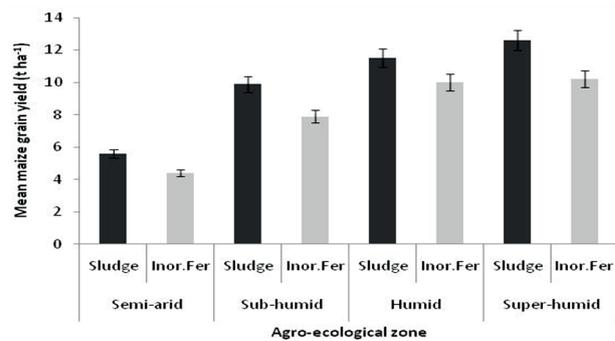


Figure 1. Model scenario simulations of maize grain yield from sludge-amended soils compared with inorganic fertilizer across agro-ecological zones in South Africa. Values presented are means of the values over 20 years. Error bars represent standard error with 5% value. Inor.Fer is inorganic fertilizer.

Maize grain yield over years within a site

Model simulations were conducted for over 20 years on 2 selected sites, namely, Johannesburg (sub-humid zone) and Durban (humid zone), to assess maize grain yield from sludge and inorganic fertilizer-amended soils. Maize grain yield varied significantly over years, both for inorganic fertilizer and sludge-treated soils (Fig. 5). Generally, maize grain yield was higher for soils fertilized with sludge than inorganic fertilizer in both Johannesburg and Durban. For instance, in the sub-humid zone of Johannesburg, maize grain yield from sludge-amended soil was predicted to be 10–15% higher than soils amended with inorganic fertilizer (Fig. 5a). Similarly, in the humid zone of Durban, maize grain yield was 15–20% higher in sludge-amended soils than those fertilized with inorganic fertilizer over 20 years (Fig. 5b).

The difference in maize grain yield between years was statistically significant ($P < 0.05$) when the difference in rain amount between years exceeded 241 mm (semi-arid zone), 362 mm (sub-humid zone), and 429 mm (humid zone). This event happened in 2 of the 20 years (2002 and 2004) of model simulation for both Johannesburg and Durban. Nitrate leaching in these 2 years was also lower compared with other years (Fig. 6). The low rainfall events of 2002 and 2004 led to low grain yield and nitrate leaching, because there is a direct relationship between water availability and maize grain yield (Nilahyane et al., 2019) as well as between high rainfall events and nitrate leaching (Holland et al., 2018). It is well documented that the presence of water plays a critical role in both nutrient uptake by plants and release of nutrients as plant-available inorganic forms from organic nutrient sources (Guntiñas et al., 2012, Ogbazghi et al., 2015).

Nitrate leaching over years within a site

Nitrate leaching varied significantly ($P < 0.05$) over the years under both sludge and inorganic fertilizer-amended soils (Fig. 6a and 6b). Nitrate leaching remained significantly higher under inorganic fertilizer-amended soils than those that received sludge. For instance, in the sub-humid zone of Johannesburg, the mean annual nitrate leaching from inorganic fertilizer was 15% higher than with sludge-treated soils (Fig. 6a). Similarly, in the humid zone of Durban, the mean annual nitrate leaching from inorganic fertilizer-treated soil was 20% higher than for sludge-treated soil (Fig. 6b). Similar to

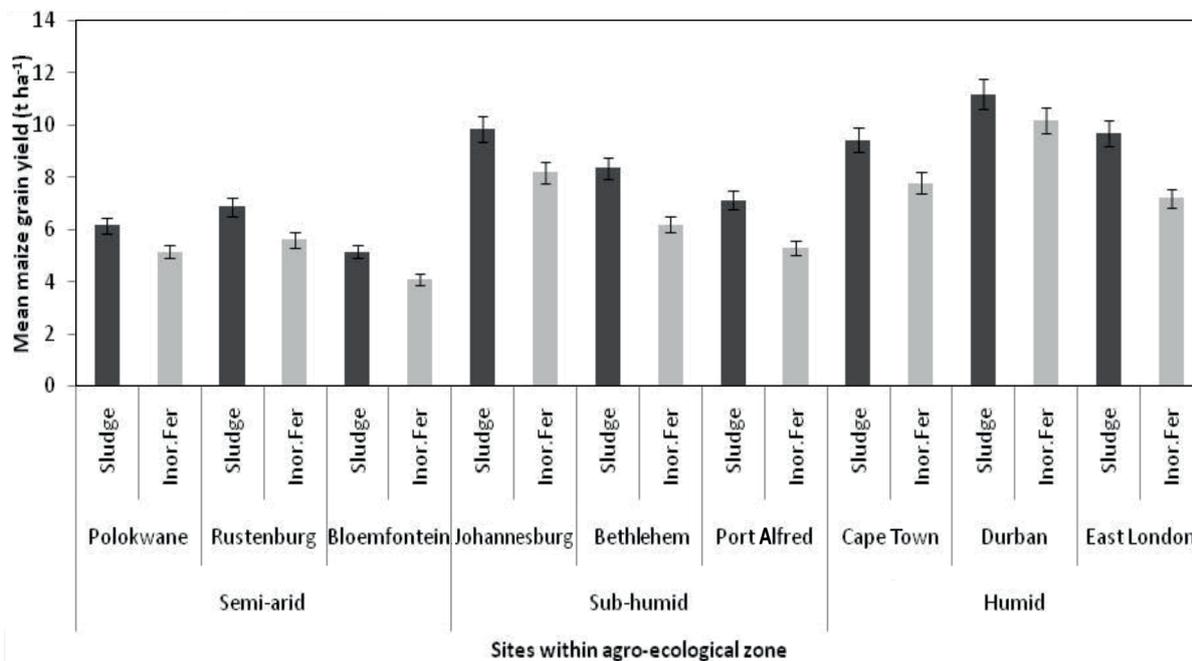


Figure 2. Model scenario simulations of maize grain yield from sludge-amended soils compared with inorganic fertilizer within selected sites in South African agro-ecological zone. Values presented are means of the values over 20 years. Error bars represent standard error with 5% value. Inor.Fer is inorganic fertilizer.

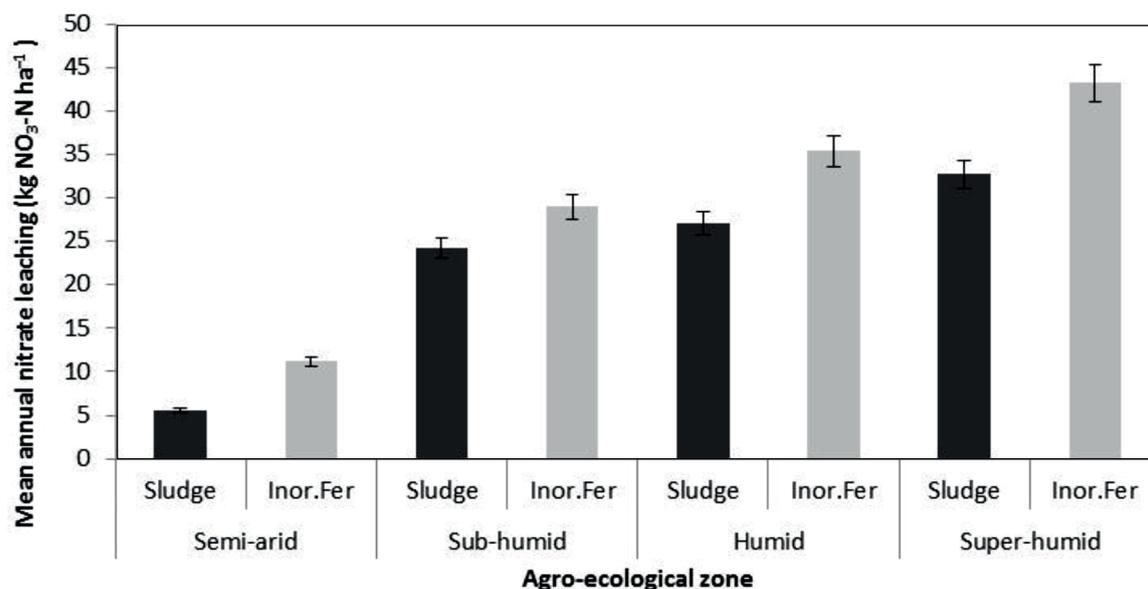


Figure 3. Model scenario simulations of nitrate leaching from sludge-amended soils compared with inorganic fertilizer across agro-ecological zones. Values presented are means of the values over 20 years. Error bars represent standard error with 5% value. Inor.Fer is inorganic fertilizer.

maize grain yield, the significant difference ($P < 0.05$) in nitrate leaching between years was observed in 2 of the 20 years.

The observed increase in nitrate leaching as the rainfall increased is attributed to the increase in the mobility of nitrate within the profile, at a relatively faster rate than the rate of uptake by plants. Such interactive effects of both rainfall and leaching on uptake of N by plants are well documented (Banger et al., 2018). Holland et al. (2018) and Ogbazghi et al. (2016) reported a direct relationship between nitrate leaching and soil water availability. Therefore, the hypothesis that 'under dryland

maize cropping, annual maize grain yield and nitrate leaching will not vary across years both from sludge and inorganic fertilizer-amended soils' is not accepted.

Maize grain yield and nitrate leaching across soil textures

Maize grain yield and nitrate leaching varied significantly ($P < 0.05$) between soil textures for both sludge and inorganic fertilizer-amended soils (Fig. 7a and 7b). Maize grain yield was

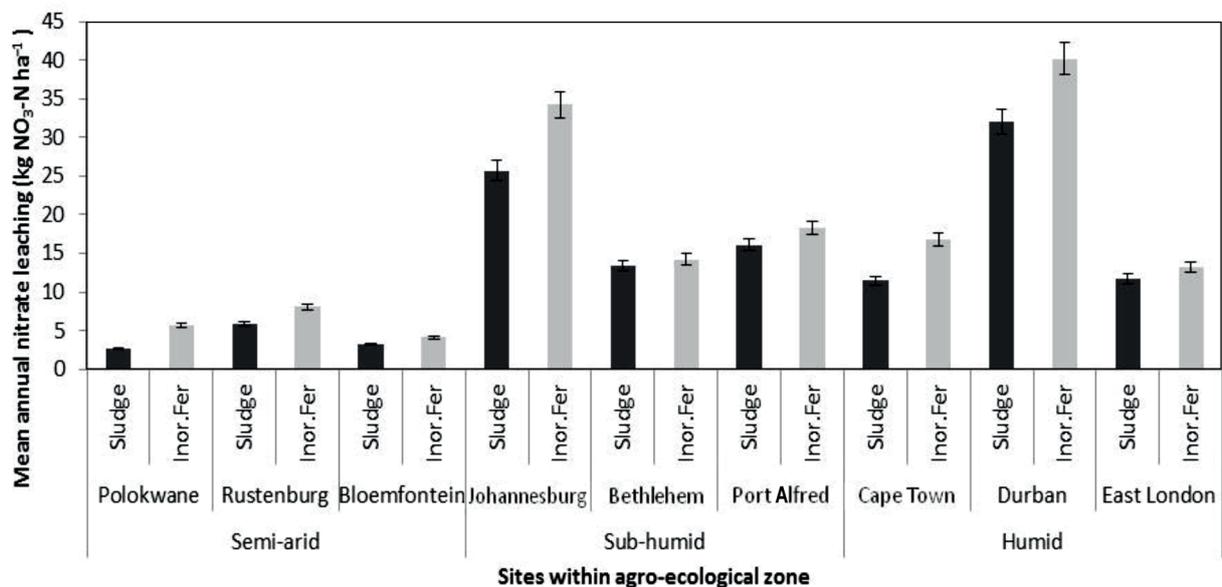


Figure 4. Model scenario simulations of nitrate leaching from sludge-amended soils compared with inorganic fertilizer within selected sites in South African agro-ecological zones. Values presented are means of the values over 20 years. Error bars represent standard error with 5% value. Inor.Fer is inorganic fertilizer.

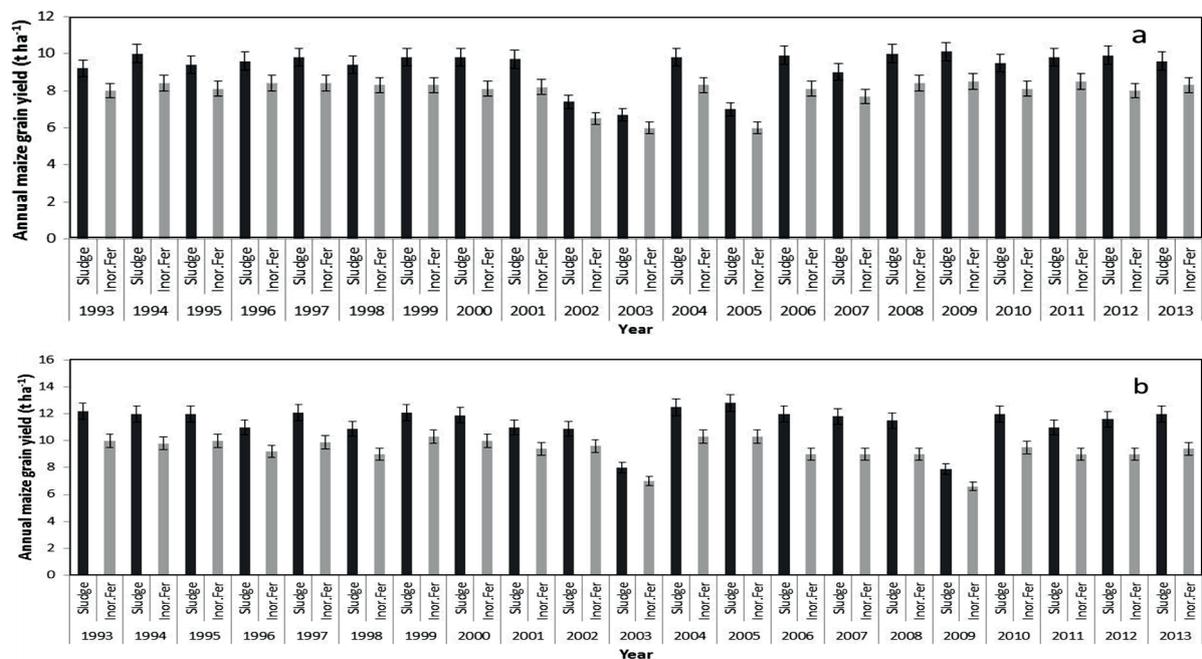


Figure 5. Model predictions of maize grain yield from sludge-amended and inorganic fertilizer applied to meet the crop N requirement in the (a) sub-humid zone of Johannesburg and (b) humid zone of Durban over 20 years of simulations. Values presented are means of the maize grain yield from clay, clay loam, sandy clay loam and sandy loam soils. Error bars represent standard error with 5% value. Inor.Fer is inorganic fertilizer.

predicted to be higher for clay loam and sandy clay loam soils than for clay and sandy loam soils (Fig. 7a). It was also apparent that maize grain yield was higher from sludge-amended than inorganic fertilizer-amended soil across soil textures (Fig. 7a). This is mainly due to the higher nitrate leaching from inorganic fertilizer compared with sludge-amended soil (Fig. 7b).

Nitrate leaching from inorganic fertilizer-amended soils was generally higher than from sludge-amended soils (Fig. 7b).

Nitrate leaching was lower in clay and clay loam soils than in sandy clay loam and sandy loam soils in both sludge and inorganic fertiliser soils. This agrees with the general literature in which nitrate leaching from sand-dominated soils is reported to be higher (Elasbah et al., 2019; Fang and Su, 2019). Therefore, the hypothesis that ‘under dryland maize cropping, annual maize grain yield and nitrate leaching will remain similar across soil textures’ is not accepted.

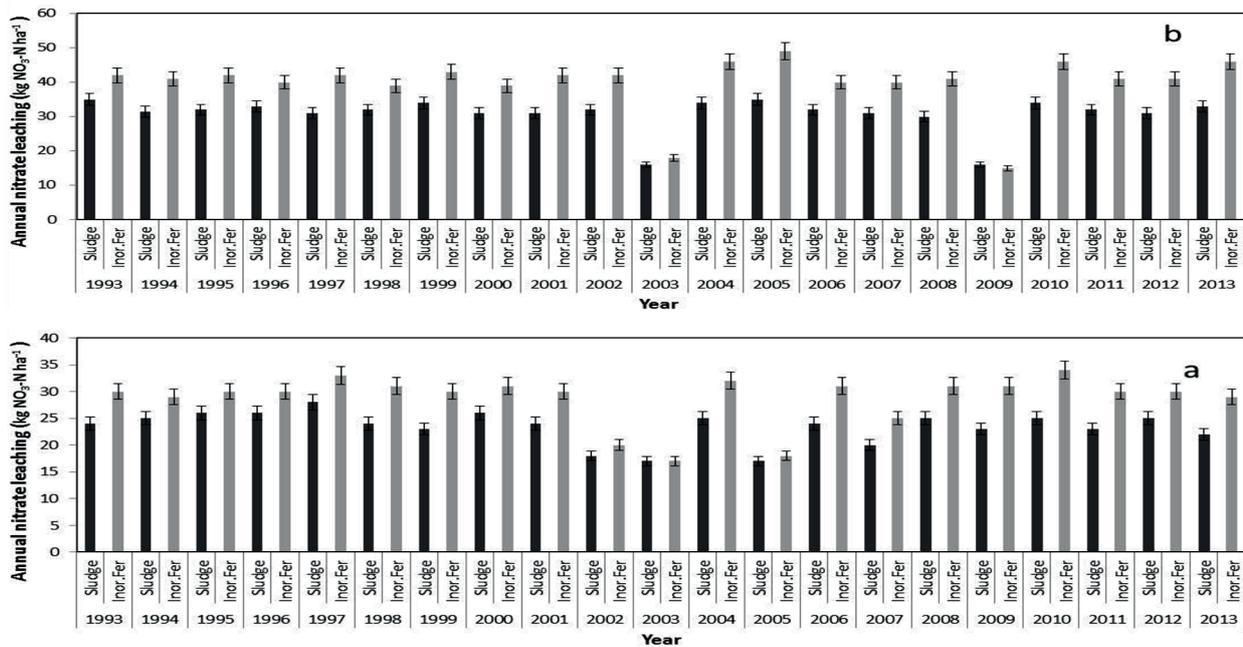


Figure 6. Model predictions of nitrate from sludge-amended soils and inorganic fertilizer applied to meet crop N requirement in the (a) sub-humid zone of Johannesburg and (b) humid zone of Durban over 20 years of simulations. Values presented are means of the nitrate leaching from clay, clay loam, sandy clay loam and sandy loam soils. Error bars represent standard error with 5% value. Inor.Fer is inorganic fertilizer.

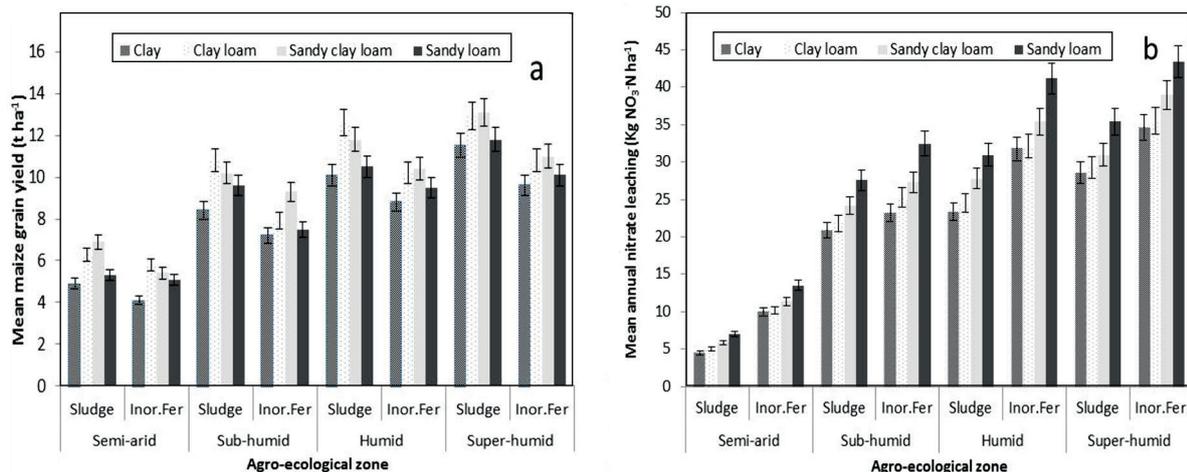


Figure 7. Model scenario simulations of (a) maize grain yield and (b) nitrate leaching from sludge-amended soils compared with inorganic fertilizer across South African agro-ecological zones as affected by soil texture. Values presented are means of the values over 20 years. Error bars represent standard error with 5% value. Inor.Fer is inorganic fertilizer.

CONCLUSIONS

Predicted maize grain yield and nitrate leaching varied significantly across 4 agro-ecological zones, for both sludge-amended and inorganic fertilizer-amended soils. Similarly, maize grain yield and nitrate leaching, were predicted to vary significantly across seasons and soil textures for both the sludge- and inorganic fertilizer-amended soils. However, nitrate leaching losses were lower from sludge-amended soils compared with those receiving inorganic fertilizer across all agro-ecological zones. Predicted maize grain yield was higher from sludge-amended soils than for inorganically fertilized crops, while nitrate leaching was

higher with inorganic fertilizer than with sludge, indicating the agronomic and environmental benefits of municipal sludge over inorganic fertilizer. Further validation of these findings using field experiments and monitoring potential P accumulation for soils that received sludge according to crop N requirements is recommended.

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