Nitrogen and phosphorus fluxes in three soils fertigated with decentralised wastewater treatment effluent to field capacity

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ABSTRACT

The Decentralised Wastewater Treatment System (DEWATS) provides low cost onsite sanitation to residents living in informal settlements. Wastewater management through agriculture prevents environmental pollution and promotes sustainable agriculture. This study investigated the effects of fertigation with DEWATS effluent to field capacity in three South African soils under a banana crop. The experiment was conducted as a complete randomised design in a greenhouse with two irrigation water treatments (DEWATS effluent vs municipal tap water irrigation + fertiliser) × three soil types (Ia, Cf and Se) and four replicates over 728 days. Data were collected on crop growth, nitrogen (N) and phosphorus (P) uptake and dynamics in the soil. The DEWATS effluent significantly ($p < 0.05$) increased N and P uptake and soil NH_4^+-N and extractable P concentrations. Furthermore, DEWATS effluent fertigation significantly ($p < 0.05$) increased N leaching from the Ia soil and P leaching from the Cf soil. Nitrogen and phosphorus leaching from DEWATS was lower than the tap water irrigation + fertiliser treatment. There was, however, excess N and P accumulation from the DEWATS than the irrigation + fertiliser treatment, which would cause environmental concerns from runoff and leaching losses in the medium to long term.

Key words | crop evapotranspiration, irrigation depth, irrigation management, leaching, nitrates, orthophosphates

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INTRODUCTION

Municipalities in South Africa are considering provision of proper sanitation to all residents, including those in informal settlements, in a move towards the fulfilment of the millennium development goals (MDGs) (Roma *et al.* 2010). The eThekwini (Durban) municipality in KwaZulu-Natal (KZN) commissioned community ablution blocks that can be connected to a decentralised wastewater treatment system (DEWATS) as an interim solution to sanitation problems (Crous *et al.* 2013). The DEWATS is a modular water-borne sanitation system which consists of the settler, anaerobic baffled reactor (ABR) + anaerobic filter (AF) and planted gravel filters (Gutterer *et al.* 2009). The treatment process involves anaerobic degradation of organic matter within the ABR followed by the AF. The AF effluent is further passed to planted gravel filters which consist of vertical flow constructed wetland (VFCW) and horizontal flow constructed wetland (HFCW) for further polishing. The final effluent must comply with the stringent South

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African DWA (2013) discharge standards hence any failure to the wetland may lead to discharge of poorly treated wastewater.

The use of treated wastewater in agriculture has been recommended as a major way to fulfil MDG number seven of fighting against hunger (WWAP 2017). For an effective wastewater use programme in agriculture, practical guidelines that will be used to inform policy makers on how to maximise benefits and mitigate risks must be developed (Pescod 1992). Practical guidelines consider technical aspects such as land area requirements, effluent management in different seasons and environmental sustainability in different soils (Pescod 1992; USEPA 2012).

Effluent production occurs throughout the whole year and crop water requirements are variable with seasons. Therefore, crops that can fully utilise all the water and nutrient from effluent and irrigation methods that allow soils to absorb all the effluent produced are required. Fertigation using wastewater is done following irrigation scheduling which considers crop water requirements at different stages of growth (Pescod 1992; USEPA 2012; Qadir *et al.* 2013). Some of the most commonly used irrigation scheduling approaches include irrigating to field capacity, leaving room for rain, and irrigating with leaching requirement (Annandale *et al.* 1999). High volumes of effluent produced from the DEWATS may be utilised by crops with high water requirements if fertigated to soil capacity.

Fertigation to maintain soil field capacity, however, may load excess N and P into soils. The N and P retention, dynamics and movement in soils are affected by soil physical, chemical and microbiological properties (Feigin *et al.* 2012; Brady & Weil 2016). Some studies have been conducted on the behaviour of DEWATS effluent in three soils of KZN under laboratory column conditions (Bame *et al.* 2013), and with maize in pot experiments (Bame *et al.* 2014). Processes that allow nutrient retention, uptake and losses in different soils fertigated with DEWATS effluent to soil field capacity are not well understood. The aim of this study was, therefore, to investigate the environmental sustainability of fertigating banana (*Musa parasidiaca*) with DEWATS effluent to field capacity in terms of N and P transformations, retention, uptake and leaching in three dissimilar soils from KwaZulu-Natal. Specific objectives of the study were to: (i) investigate growth and nutrient uptake of banana irrigated with DEWATS effluent; (ii) investigate the effects of irrigating with DEWATS effluent to field capacity on N and P loading in soils; and (iii) determine the effect on soil chemical properties and potential N and P leaching.

MATERIALS AND METHODS

Experimental site

The study was conducted under controlled conditions in a growing tunnel (greenhouse) at Newlands-Mashu Research Centre, Durban, KwaZulu-Natal, South Africa (29°58′S; 30°57′E). Durban is in the east coast of South Africa and experiences cool dry winters and hot wet summers.

Soils and analyses

Figure 1 shows all locations from which soils used during the study were collected. Three contrasting topsoil (0–300 mm) horizons were collected from a Cartref form (Cf; Typic Haplaquept), an Inanda form (Ia; Rhodic Hapludox) and a Sepane form (Se; Aquic Haplustalf) (Soil Classification Working Group, 1991; Soil Survey Staff, 2014, respectively). The Cf was sampled from KwaDinabakubo (29°44′S; 30°51′E) near Durban KZN under natural grassland. The Ia was collected from World's View (29°35′S, 30°19′E), Pietermaritzburg under commercial forestry and the Se from the Newlands-Mashu Research Centre.

Soil physical properties were analysed before planting while chemical properties were analysed before planting and after harvest (728 days after planting). Bulk density was determined from undisturbed soil cores collected from a depth of 0–300 mm. The field capacity and permanent wilting points for the respective soils were calculated based on particle size using a calculator from the SWB Sci model (Annandale *et al.* 1999) (Table 1). Soils were air dried, ground and sieved to pass through a 2 mm mesh. A representative sub-sample of each soil was analysed for soil properties chemical and physical properties at the Soil Fertility and Analytical Services Division (Department of Agriculture, Cedara, KwaZulu-Natal) following methods

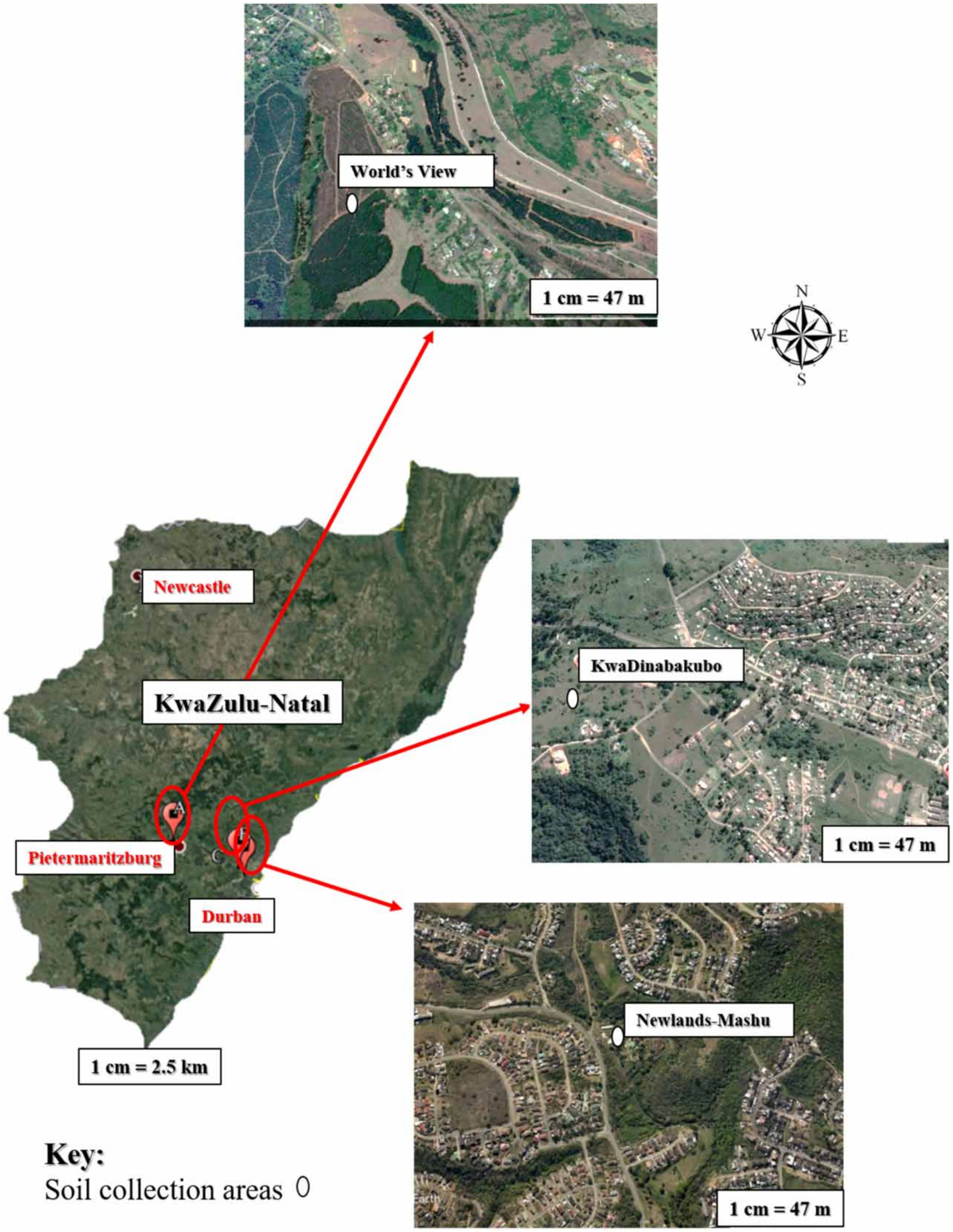

Figure 1 | Map showing the study site and areas where the soils used during the study were collected (Diagram by William Musazura: Sourced and modified from AfriGIS, Google Maps 2018).

given by the Non-Affiliated Soil Analysis Work Committee (1990).

Inorganic N (NH_4^+-N and NO_3^--N) was determined from freshly collected soil samples by extraction in 1:5 soil: 2M

Table 1 | Physical and chemical properties for the different soil types used for the pot experiment at Newlands-Mashu

Property	Inanda	Cartref	Sepane
Bulky density (kg m^{-3})	800	1,430	1,200
Clay (%)	23	12	37
Silt (%)	48	15	41
Sand (%)	29	73	22
Field capacity (m m^{-1})	0.40	0.24	0.43
Permanent wilting point (m m^{-1})	0.29	0.12	0.31
Organic C (%)	>6	<0.5	2.9
MIR-N (%)	0.56	0.05	0.29
Extractable P (mg kg^{-1})	12	0.7	39.3
pH (KCl)	4.11	4.21	5.20
Total cations ($cmol_c$ kg^{-1})	5.9	1.2	20.4
Acid saturation (%)	30	18	0
Exchangeable K (mg kg^{-1})	0.07	0.01	0.30
Exchangeable Ca (mg kg^{-1})	3.2	0.4	12.2
Exchangeable Mg (mg kg^{-1})	0.0	0.4	7.8
Exch. acidity ($cmol_c$ kg^{-1})	1.80	0.18	0.05
Extractable Zn (mg kg^{-1})	2.8	0.1	22.8
Extractable Mn (mg kg^{-1})	10.7	0.7	3.7
Extractable Cu (mg kg^{-1})	3.6	0.2	9.5

KCl and filtering using Whatman® No. 2 paper following methods by Mynard & Kalra (2008) and analysed using Merck Nova 60 Spectroquant® (Merck Millipore, Germany) following standard methods (APHA 2005). Phosphorus was extracted from freshly collected soil using the Ambic 2 solution followed by filtering using Whatman® No. 1 paper. Phosphorus was then determined from the filtrate using the molybdenum blue procedure following standard methods (Non-Affiliated Soil Analysis Work Committee 1990).

Experimental design management practices

A 2 × 3 × 4 factorial experiment was carried out in a complete randomised design. The experiment comprised of two irrigation treatments (DEWATS effluent vs municipal tap water irrigation + fertiliser) × three soil types (Cf; Typic Haplaquept, Ia; Rhodic Hapludox, Se; Aquic Haplustalf) × four replicates. Inorganic fertiliser was applied to the tap water + fertiliser treatment soils; they were mixed with urea (46% N), single superphosphate (10.5% P) and potassium chloride (52% K) based on soil analysis recommendations (Table 2). Dolomitic lime was added at a rate of 1.03 g kg^{-1} to the Ia and Cf soils to adjust soil pH to a permissible acid saturation of 1%. The soils had different bulk densities (Table 1) and 60 kg of soil were packed in each pot according to bulk densities measured in the field. The pots (90 L volume; 0.48 m diameter × 0.5 m height) were perforated underneath to allow free drainage and dishes were placed underneath to collect draining water, which was recycled back into the pot.

Table 2 | Nitrogen (N), phosphorus (P), potassium (K) fertiliser and lime requirements for the three different soils used

Soil type	N	P (mg kg^{-1})	K	Lime
Inanda	100	10	104	1,030
Cartref	58	4.6	79	1,030
Sepane	70	0	51	0

Wetting front detectors (WFDs) were inserted in each pot to passively collect leachates at 0.2 m depth. Banana (*Musa parasidiaca*) suckers of 4–5 kg plant were planted in the pots on 3 April 2015 at a rate of one plant per pot. Irrigation was applied to maintain soil field capacity and a total of 2,770 mm was added to each pot over a period of 718 days and was stopped 10 days before final harvesting. Soil water content was determined by weighing the pot before each irrigation event. Temperature and relative humidity were monitored using iMini escort (CB-USB2-MINI5P) data loggers and the values were used to calculate reference evapotranspiration using the SWBSci model following algorithms by Allen (1998). Crop water requirements (Et_{crop}) (Figure 2) were calculated according to the Food and Agriculture Organisation (FAO) formula as a product of banana crop factors and reference evapotranspiration (Et_o) (Allen 1998).

Effluent characterisation

For the first 210 days after planting (3 April–29 October 2015), the pots were fertigated with DEWATS effluent from the horizontal flow constructed wetland (HFCW). Thereafter the effluent used was that obtained after the AF of the DEWATS. Effluent chemical oxygen demand (COD), suspended solids, pH, and nutrients (NH_4^+-N, NO_3^--N and P) were monitored throughout the growing

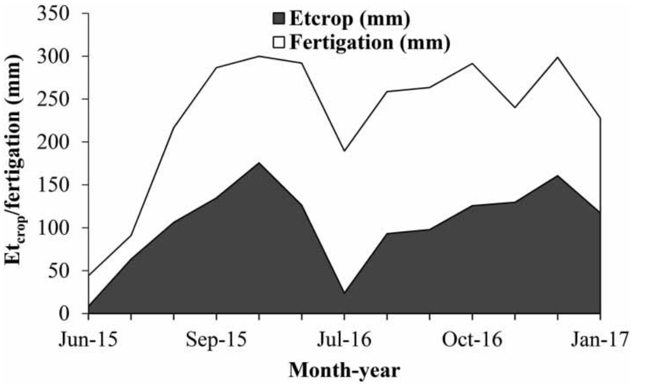

Figure 2 | Irrigation applied and crop water requirements for banana plants in the pots.

period and analysed following *Standard Methods for the Examination of Water and Wastewater* (APHA 2005).

Crop growth and nutrient uptake

Plant height and leaf area measurements were taken from each individual plant. Total leaf area was determined from the third uppermost leaf by measuring laminar length and width (Equation (1)):

$$\mathrm{TLA} = \mathrm{L}*\mathrm{N}*\mathrm{W}*\mathrm{c} \quad (1)$$

where TLA = total leaf area (m^2 plant^{-1}); L = leaf length (m); N = number of leaves per plant; W = leaf width (m); c = regression coefficient between independent values of leaf length and leaf width.

Plant height was measured from the soil surface to the third uppermost leaf. The whole plants were harvested, and fresh above-ground biomass was measured directly after harvesting. Plant tissue moisture content was determined by collecting subsamples from different parts of the banana plant and drying them at 70 °C for 72 hours. Total dry biomass was determined as a product of dry matter (%) and total fresh mass at harvest (Equation (2)):

$$\mathrm{TDM} = \sum(\mathrm{DM} \times \mathrm{FM}) \quad (2)$$

where TDM = total dry biomass of the whole plant (g); DM = plant tissue dry mass (%) for each plant part; FM = fresh biomass (g) for each plant part.

Samples for plant tissue nutrient analysis were collected from the third uppermost leaf after harvest. Plant tissue samples were oven dried at 70 °C for 72 hours. Dried plant tissues were then crushed and sieved through a 1 mm sieve. The leaf tissues were analysed for total N using the LECO® TruSpec Micro CNS analyser and P using the acid digestion method followed by inductively coupled plasma optical emission spectroscopy (ICP-OES) Vista MPX following standard methods (Riekert & Bainbridge 1998).

Nutrient leaching and drainage

Sampling of leachates commenced 181 days after planting. Leachates were collected from the WFDs at random periods four hours after irrigation and analysed for NH_4^+-N, NO_3^--N and PO_4^{3-}-P using a Nova 60 Merck Spectroquant® (Merck Millipore, Germany) according to standard methods (APHA 2005). Soil drainage rates were quantified by measuring the volume of water leached 4 hours after random irrigation events.

Data analysis

All data were analysed using GenStat® 18th edition (VSN International, UK). The data were subjected to analysis of variance (ANOVA) and standard error of mean differences were used to separate differences between means at the 5% significance level.

RESULTS

Effluent characterisation

The N and P concentrations of effluents used during the study are reported in Table 3.

Crop growth and yield

The interaction between soil type and irrigation treatment on banana plant height, total leaf area, fresh and dry biomass are presented in Table 4. The plant height and total leaf area were significantly high in Se compared to other soils for both irrigation treatments (Appendix 1, available with the online

Table 3 | Inorganic N and P in different sources of DEWATS effluent (mean ± standard error of mean differences) used during the study

Effluent source		NO_3^--N (mg L^{-1})	NH_4^+-N (mg L^{-1})	PO_4^{3-} (mg L^{-1})	Total N (mg L^{-1})
Anaerobic filter	n	9	9	9	3
	Mean ± SE	2.1 ± 0.5	54.8 ± 1.6	10.5 ± 1.5	60.6 ± 2.7
	Median	1.8	55.6	8.7	59.8
	Range	0.2–4.1	48.1–60.1	5.9–19.5	51.2–68.4
HFCW	n	3	3	3	3
	Mean ± SE	12.7 ± 6.4	6.7 ± 7	4.1 ± 0.5	19.4 ± 7
	Median	10.2	7.2	3.9	18.1
	Range	3.1–24.9	5–7.9	5.9–19.5	8.1–32.1

HFCW = horizontal flow constructed wetland; SE = -standard error of mean differences ($p < 0.05$).

Table 4 | Banana plant height, total leaf area and fresh and dry biomass (728 days after planting) on three soils under different irrigation treatments ($n = 3$; mean ± standard error of mean differences)

Treatment	Soil type	Plant height (m)	Total leaf area (m^2)	Fresh biomass (g $plant^{-1}$)	Dry biomass (g $plant^{-1}$)
DEWATS	Cartref	0.92 ± 0.06^b	2.04 ± 0.29^b	$4\,480 \pm 559^d$	560 ± 65^d
	Inanda	0.90 ± 0.07^b	2.07 ± 0.19^b	$6\,500 \pm 284^c$	911 ± 124^c
	Sepane	1.12 ± 0.08^a	3.62 ± 0.45^a	$7\,188 \pm 210^b$	$1\,001 \pm 69^{bc}$
Tap water + fertiliser	Cartref	0.56 ± 0.08^c	1.29 ± 0.31^c	$2\,450 \pm 401^e$	359 ± 70^e
	Inanda	0.78 ± 0.09^b	1.88 ± 0.37^{cb}	$6\,767 \pm 775^{abc}$	$1\,171 \pm 131^{ab}$
	Sepane	1.15 ± 0.08^a	4.22 ± 0.64^a	$8\,113 \pm 633^a$	$1\,249 \pm 186^a$

Superscripts that are different within a column indicate significant differences ($p < 0.05$).

version of this paper). These plant growth variables were also comparable between the two irrigation treatments under Ia soil as well as to Cf soil fertigated with DEWATS effluent. Least plant height and total leaf area were reported in Cf soil in tap water + fertiliser treatment.

The fresh and dry biomass of banana measured at harvest (728 days after planting) are also reported in Table 4. Both fresh and dry biomass were significantly low in Cf soil under tap water + fertiliser treatment compared to other soil and irrigation treatment combinations (Appendix 2, available online). Highest fresh and dry biomass was recorded in Se soil under tap water + fertiliser treatment. Generally speaking, fresh and dry biomass under tap water + fertiliser treatment was significantly higher than DEWATS treatments planted to similar soil types. The only exception was for Ia soil, which was not statistically significant but was still higher under tap water + fertiliser.

Soil chemical properties

There was a significant ($p < 0.01$) interaction between irrigation treatments and soil type on soil NH_4^+-N content (Appendix 3, available online). Irrigation treatments significantly differed ($p < 0.01$) with respect to extractable P (Appendix 3). The NH_4^+-N and extractable P concentrations in three different soils and irrigation treatments are described in Figure 3. Fertigation with DEWATS effluent significantly increased NH_4^+-N content in all soils compared to tap water + fertiliser treatment. The least NH_4^+-N concentrations values were found in the Cf and Se soils under the tap water + fertiliser treatment.

Nitrogen and phosphorus leaching and drainage

There were significant differences in P leached between the three soils ($p < 0.05$) see Appendix 4 (available online). A significant interaction ($p < 0.001$) between soil type and irrigation treatment on N leaching over time was also reported (Appendix 4). The amount of P leached from each pot amongst the three soils is shown in Figure 4. High P was leached from Cf soil compared to both Ia and Se.

The interaction between soil type and irrigation treatment over time on inorganic N leached is shown in Figure 5. Very high N leaching occurred in Se soil under

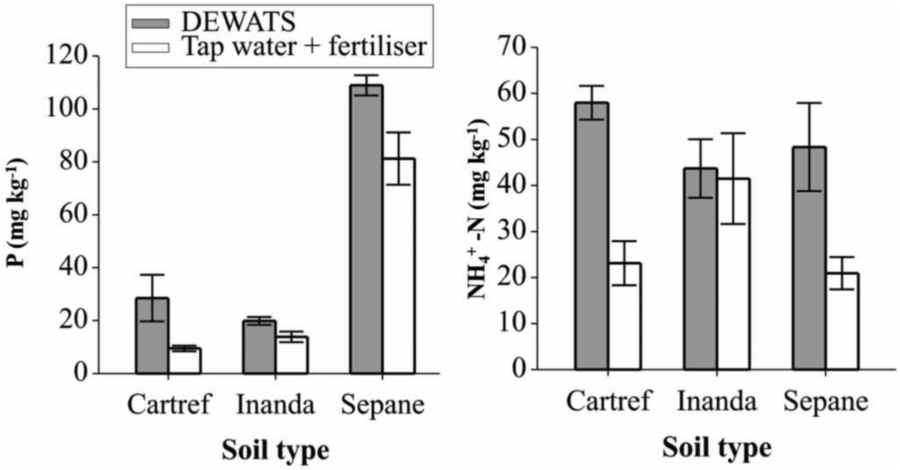

Figure 3 | Concentrations ($n = 4$; mean ± standard error of means) of ammonium N and extractable P in the three soils after harvesting from the two irrigation treatments.

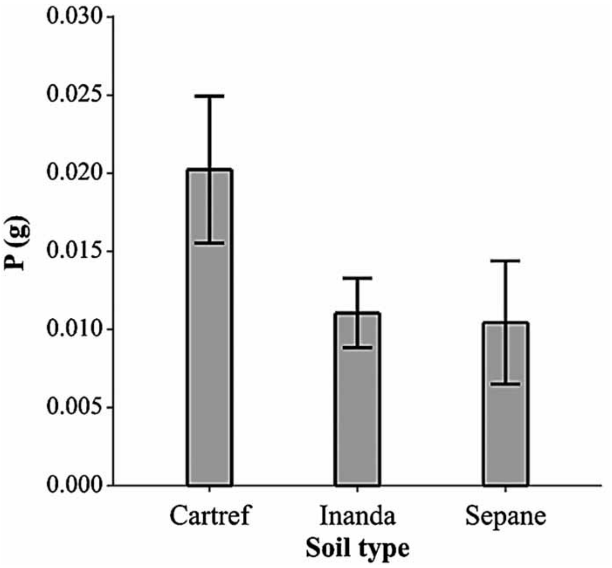

Figure 4 | Amounts of orthophosphate P leached from the three soils during the experimental period regardless of irrigation treatment ($n = 48$; mean ± standard error of mean differences).

the tap water + fertiliser treatment compared to DEWATS effluent. Comparisons amongst different soils within the DEWATS effluent treatment showed that N leaching was higher in Ia than the Se and Cf soils.

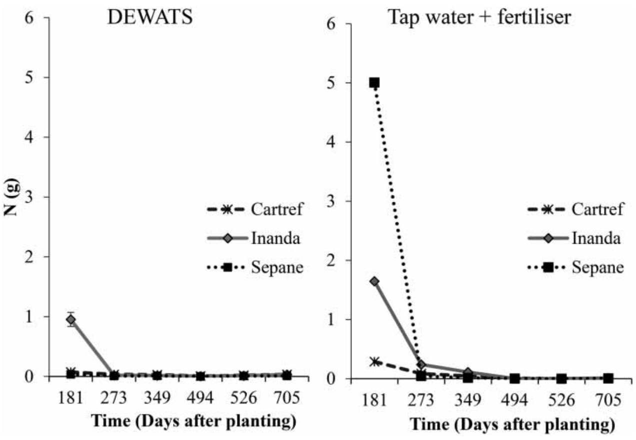

Figure 5 | Interaction between irrigation treatment and soil type on the amount of nitrogen (N) leached during the study ($n = 4$; mean ± standard error of mean differences).

Table 5 | The N and P applied through fertigation using DEWATS effluent over 728 days in comparison to crop fertiliser requirements

	Required		Applied	
Soil type	**N (mg kg^{-1})**	**P**	**N**	**P**
Cartref	58	4.6	837	148
Inanda	100	10	837	148
Sepane	70	0	837	148

Irrigation and nutrients

The quantities of N and P supplied through fertigation using DEWATS effluent in relation to the crop fertiliser requirements are shown in Table 5. Fertigation using DEWATS effluent to maintain soil field capacity added excessive N and P, more than was required by the crop.

There was a significant difference ($p < 0.001$) in P uptake between soils and N and P uptake between the irrigation

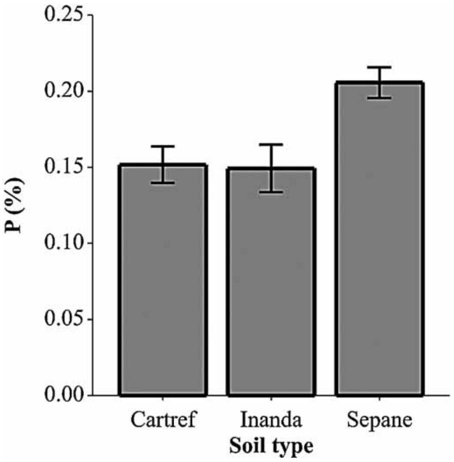

Figure 6 | Phosphorus (P) leaf tissue concentrations in banana grown on three different soils ($n = 6$; mean ± standard error of mean differences).

treatments (Appendix 5, available online). The differences in P concentrations taken up by banana plants between the three different soils are shown in Figure 6. The plants grown on the Se had the highest P concentrations (0.2%) compared to those on the Ia and Cf soils which had 0.15%.

Table 6 shows the N and P concentrations of banana leaf tissue irrigated with two irrigation sources. There were significantly ($p < 0.01$) higher banana plant tissue N and P concentrations in plants grown in the DEWATS effluent treatment compared to the tap water + fertiliser treatment.

DISCUSSION

Crop growth and yield

The DEWATS effluent increased banana vegetative growth (plant height, dry mass and leaf area) in the Cf soil, although highest growth occurred in the Se soil (Table 4). This was due to nutrients supplied through fertigation (Table 5) and their subsequent uptake by crops (Table 6), which agreed with several studies using the same type of wastewater (Bame *et al.* 2014). Banana yield could not be determined due to delayed and erratic flowering exceeding the experimental time frame, probably due to excess N from the effluent (Table 5).

Table 6 | Banana plant tissue nitrogen (N) and phosphorus (P) concentrations as a function of irrigation treatment ($n = 9$; mean ± standard error of mean differences)

Treatment	N (%)	P (%)
DEWATS	2.9 ± 0.12^a	0.19 ± 0.01^a
Tap water + fertiliser	2.5 ± 0.12^b	0.15 ± 0.01^b

Superscripts a and b indicate significant differences ($p < 0.05$).

Soil chemical properties

High soil P content in Se soil compared to Ia and Cf reported in Figure 3 was probably due to low drainage of the soil and retention by soil Al/Mn/Fe minerals. According to findings by Bame *et al.* (2013), Ia soils retain more P due to their high organic matter content while Cf loses more due to its course texture, but Figure 3 showed that P content was comparable between Ia and Cf soils. Comparisons between the irrigation treatments showed that soil P content significantly increased in the DEWATS treatment compared to tap water + fertiliser treatment regardless of soil type (Figure 3). Therefore, fertigation with DEWATS effluent to field capacity increased soil P content regardless of soil type. Such excess accumulation of P above crop nutrient requirements warrants for DEWATS effluent application according to crop nutrient requirement instead of crop water requirement.

The NH_4^+-N concentrations increased significantly in all soils under DEWATS effluent fertigation (Figure 3). This is expected in soils with high cation exchange capacity (CEC) due to adsorption by the soil colloids as reported by some authors (Bame *et al.* 2013; Hernández-Martínez *et al.* 2016). On the other hand, NH_4^+-N content also increased in the low CEC Cf, probably due to increased fertigation which applied more N into soils (Table 5). This could lead to enhanced volatilisation, especially at soil pH exceeding 7 (Dendooven *et al.* 1998). The pH values of all soils used in this study ranged between 4.11 and 5.20 (Table 1), hence pH driven volatilisation losses are expected to be very low.

Nitrogen and P leaching

The leaching of P was high in Cf compared to the other two soils (Figure 4) due to low P sorption capacity of sandy soils. High organic matter in Ia soils and clay loam soils (Se) retain soil P thereby leaving less available for leaching. Similar results were also reported by Bame *et al.* (2013).

High amounts of N were leached from the tap water + fertiliser treatment on the Se soil at 181 DAP (Figure 5) due to fast hydrolysis of the urea fertiliser. In DEWATS effluent fertigated soil, the low N leaching losses from the Se and Cf soils compared to the Ia were probably due to the lower N content in these soils (Table 1). According to Egiarte *et al.* (2006), high concentrations of NO_3^- in leachates results from nitrification, especially in acidic soils. Therefore, high N leaching from the Ia soil (DEWATS) was likely caused by fast nitrification resulting from acidity of that particular soil, as also reported by Bame *et al.* (2013).

Irrigation and nutrients

High banana leaf tissue N and P concentrations in DEWATS effluent treatment (Table 6) are directly linked to nutrients applied through fertigation (Table 5) and retained in the soil (Figure 3). Critical ranges for banana plant tissue nutrient sufficiency are 2.7–3.6% N and 0.16–0.27% P (de Mello Prado & Caione 2012). Despite receiving high amounts of N and P through DEWATS irrigation (Table 5), the N and P concentrations in banana did not exceed 2.9 and 0.19%, respectively. This may be because plants take up nutrients during their growing period until an optimum concentration is attained (de Mello Prado & Caione 2012), as well as leaching and volatilisation of N and non-availability of P (Bame *et al.* 2013, 2014).

CONCLUSIONS

Crop growth significantly increased in Cf soil fertigated with DEWATS effluent. Fertigation with AF effluent up to soil field capacity loaded more N and P to the soil, which even exceeded crop fertiliser requirements. Soil extractable P and NH_4^+-N increased significantly in all DEWATS effluent fertigated soils. Soil P leaching differed between soils, Cf soil losing more compared to Ia and Se. There was a significantly high N leaching in tap water + fertiliser treatment than in DEWATS effluent treatment. Therefore, the use of DEWATS effluent to fertigate banana according to crop water requirement may potentially lead to excess accumulation of N and P in the soil profile which could eventually enhance leaching below the root zone. This warrants for crop nutrient requirement based DEWAT effluent application under the given climatic conditions and soil types for sustainable recycling of resource. Nitrogen leaching differed amongst three soils under DEWATS effluent fertigation, highest leaching was reported in Ia soil compared to other soils. The banana leaf tissue N and P concentrations were significantly higher in DEWATS effluent compared to tap water + fertiliser implying that banana plants may benefit with nutrients supplied by the effluent. Care must be taken, especially in high drainage soils such as Cf and Ia, where irrigation scheduling with room for rainfall can be opted to prevent N and P leaching. Considering that the study was conducted under controlled conditions, further investigations are recommended at field scale to accommodate various climatic zones, soil forms and crop types.

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