INTEGRATING AGRICULTURE IN DESIGNING ON-SITE, LOW COST SANITATION TECHNOLOGIES IN SOCIAL HOUSING SCHEMES

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INTEGRATING AGRICULTURE IN DESIGNING ON-SITE, LOW COST SANITATION TECHNOLOGIES IN SOCIAL HOUSING SCHEMES

Report to the
Water Research Commission

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EXECUTIVE SUMMARY

BACKGROUND

The disposal of effluent generated from low-cost sanitation technologies such as the decentralized wastewater treatment system (DEWATS) poses challenges to the environment. Such effluent has been shown to contain high concentrations of essential nutrients necessary for crop production. Integrating agriculture in the planning and design of low cost sanitation technologies could provide safe and sustainable mechanisms for disposing of such effluent by retaining the nutrients for crop production and releasing water into hydrological systems. Existing guidelines (for pure waste materials and water) focus mainly on the potential harmful effects of heavy metals in water and do not consider the potential benefits of using nutrient-rich effluent from low-cost sanitation technologies. In addition, these guidelines do not allow for the soil's contribution in ameliorating potential pollutants in waste.

AIMS AND OBJECTIVES

The aim of this project was to build on previous work and to generate information on recycling of nutrients from DEWATS technology and other human excreta-derived materials (HEDM) that will inform policymakers and town planners in the design of new social housing developments that include an agricultural component. The specific objectives were:

1. To identify suitable agricultural areas in terms of liquid assimilation capacity, soil and climatic variables.
2. To evaluate the effect of wastewater, use on soils and crop production including risks of microbial contamination.
3. To assess the quality of wastewater and its effects on the environment.
4. To generate information that could be used to develop protocols that integrate agriculture in social housing development schemes.

SCOPE AND APPROACH

These objectives were achieved through field, tunnel and laboratory activities that focused on the “nutrient uptake” aspect with some attempt at achieving nutrient balances and thus estimates of nutrient loss. The soil processes that govern the two most critical elements in human waste for both plant growth and possible environmental problems, namely nitrogen (N) and phosphorus (P), were the main focus. This involved their behaviour when applied in liquid (effluent) and solid (HEDM) form. Effluent application considered both the nutrient and water demands of the crops as opposed to the solid waste which concentrated on the former aspect.

Other critical aspects of these materials examined were their pathogen content and their behaviour in soil as well as their acceptability for use by the target communities.

SUMMARY OF MAIN FINDINGS AND CONCLUSION

Effluent utilisation and impact on soils, crops and water bodies

Use of DEWATS effluent results in a twofold benefit, i.e. the water is used for irrigation and the nutrients in the effluent to meet the fertiliser requirement of crops. This combination is often termed 'fertigation'. At the field site at Newlands-Mashu, Durban, the incoming waste is treated in an anaerobic baffled reactor (ABR) and this then produces a range of possible effluents that could be used for fertigation. These include (a) effluent direct from the ABR with no further treatment (ABR effluent), (b) the ABR effluent that has then passed through a vertical-flow wetland (VFW effluent), (c) the ABR effluent that has passed through both the VFW and then a horizontal flow wetland (HFW) (HFW effluent). The yield of banana and taro in the field experiment demonstrated that the nutrients from both the ABR and the HFW effluents could sustain the crops in the same way as inorganic fertiliser (the effluent from the VFW was not used directly in this project). Depending on the source from which fertigation is carried out, the effluent could either supply or undersupply adequate nutrients to meet the crop requirements. However, the N in the leachate was found to be greater in high rainfall periods.

Land area requirements estimations

Based on crop water requirements during the present study, irrigation with the effluent for the crops translated to the need for about 0.97 ha (9 700 m^2) of land from a discharge of 35 KL of effluent daily which is the total output from the ABR. This amount of effluent is produced from 83 households and so the area required per household is about 117 m^2 or about 23.3 m^2 (0.002 3 ha) $person^{-1}$. This equates to the crop water requirements of 35.14 ML ha^{-1} over the 33 months growing period (12.8 ML ha^{-1} $annum^{-1}$) from a production of 12.5 ML $annum^{-1}$ of DEWATS effluent. This has considerable implications in terms of housing developments as more houses could be built and small parcels of land reserved for agricultural activity. The use of effluent directly from the ABR would not require wetlands for further treatment that take up more land. Furthermore, temporary storage facilities during high rainfall periods must be considered. Maintenance of such wetlands requires skilled persons which could be a problem in low income communities. The current restrictions on N and P application to land do not apply in this case as the present guidelines have no restrictions on these constituents as the amount of effluent produced by the DEWATS at Newlands-Mashu is below the threshold level of 50 m^3 of effluent per day. Although the levels of N and P at certain points were high in the wetting front detectors (WFDs) that were installed in the field experimental plots they may be utilised by plants if proper irrigation management is followed to prevent leaching beyond the root zone.

Nitrogen and phosphorus movement, uptake and use of DEWATS effluent by different crops.

Crop growth responses are influenced by an interaction between fertiliser application rate and irrigation water source. Irrigation with ABR effluent increased Swiss chard growth compared to tap water irrigation with fertiliser in all three soil types. The effluent can supplement fertiliser requirements due to its ability to increase crop growth especially at half optimum fertiliser rate compared to irrigation with tap water, especially in a maize crop. However, most of the growth responses were more evident in the sandy Cartref (Cf) soil for potato as compared to more response in the strongly acidic Inanda (Ia) soil with respect to Swiss chard. The clayey Sepane (Se) soil was most effective in retaining N and P and this was evident in the dry matter production and nutrient concentrations in plant tissue. Irrigation with ABR effluent increased soil pH in the Ia soil comparable to liming. The pH increment achieved with the ABR effluent improved soybean yield and nodulation as well as mineralisation of ammonium by microorganisms. Irrigation with effluent could be beneficial in soils of low fertility by improving their nutrient status. However, it must be well-adjusted to both the soil characteristics and the crop use within the growing season.

Nutrient release patterns from struvite, nitrified urine concentrate and LaDePa pellets and uptake by crops in a range of soils

Urine-based fertilisers have the potential to be a nitrogen soil amendment, particularly in soils that are able to mineralise urine-based ammonium sources. Soil characteristics need to be carefully considered when deciding to amend soil with urine-based fertilisers. Sandy soils with low clay and organic matter may mineralise the ammonium to plant-available nitrate but equally may lose large amounts of ammonium by volatilization and any nitrate produced may be lost by leaching unless immediately taken up by roots. A clay soil may reduce the amount of ammonium lost by volatilization but if its pH is low then no mineralisation will occur, or at best its rate will be very slow. Based on this, split application of urine-based nutrient sources is a more effective strategy to optimize dry matter production and to avoid losses of N, than a once-off application. Urine products, particularly the nitrified urine concentrate (NUC), proved to be as effective as mineral fertiliser for dry matter production of rye grass. A combination of struvite and LaDePa pellets as slow-release fertilisers with urea and diammonium phosphate as readily available fertilisers would likely give a more balanced nutrient release for both the early and the late stages of a crop’s growing period.

Modelling water and nutrient movement in soils irrigate with DEWATS effluent

The Soil Water Balance was used to estimate land area and nutrient dynamics based on water balances. The model was able to simulate banana growth and soil moisture dynamics accurately so it can be used reliably for irrigation scheduling on a Sepane soil (Newlands Mashu soil). The model was set to schedule irrigation following the room for rain approach, aiming to replenish 35% water depletion for banana crop. Land area required was then determined based on crop water requirements (evapotranspiration) during the growing season. The results showed that for a banana crop grown at Newlands Mashu, 17 100 m^2 (1.71 ha) of land was required which translated to 206 m^2 household^{-1} (41.2 m^2 person^{-1}), which can be half the land when bananas are grown with taro in an intercrop. The model was successfully calibrated to simulate banana growth and can be used reliably for estimating land areas required in different regions. However, the model was used to simulate nutrient (N and P) dynamics following irrigation with DEWATS effluent at Newlands Mashu. The simulated nutrient (NO_3^- and PO_4^{3-} concentrations) dynamics in the soil did not agree with data measured in the field due to high spatial variation. The soil irrigated with DEWATS effluent are at very high risk of NO_3^- and PO_4^{3-} accumulation when proper irrigation management practices are not followed.

Contamination of vegetables and risk of microbial infection

The DEWATS achieved a reduction of 4 Log10 units for *Salmonella* spp, while *Campylobacter* spp and Somatic coliphages recorded a 1 Log10 unit reduction. However, *Escherichia coli* concentrations remained fairly constant through the anaerobic treatment process, recording a 5 Log10 unit concentration, with the total elimination of soil transmitted helminths (STHs) and *Clostridium* spp. However, the data from this study site cannot be extrapolated to other sites, especially in lower income areas, because STH infection is mostly linked to poverty and therefore a higher prevalence is expected in such areas. Despite the reduction in microbial numbers achieved through the treatment, farmers using effluents from the ABR for irrigation have a high risk of infection (10^{-2}). Therefore, there is need for further interventions to reduce the concentration of these pathogens before irrigation. Contamination of vegetables irrigated with the ABR effluents differed between those with edible parts growing above the ground (spinach) compared to those with edible parts below ground (beetroot). Consumers of vegetables, such as spinach and beetroot, were at a similarly high risk of infection (10^{-2}) as the farmers.

Despite the reduction in microbial numbers throughout the ABR treatment the final ABR effluent still contains a high microorganism load that leads to a significant risk of infection for farmers and a high contamination of vegetables grown with the effluent which subsequently results in a high risk of infection for the consumers. However, as part of the WHO guidelines for reuse of wastewater in unrestricted agriculture a multi barrier approach would reduce this risk of infection. For instance, interventions such as washing and cooking of vegetables before consumption considerably reduces the concentration of some pathogens.

The use of spinach and beetroot are indicative of worst case scenarios where the effluent is applied directly to the crops. Crop selection and irrigation methods are therefore important factors to consider in the development of practical guidelines for the agricultural use of DEWATS effluent for irrigation. In the present study, banana and taro were selected because the edible parts are enclosed in a protective cover. The banana fruit is raised above the ground and the probability of contact with the effluent is low. The taro corm also grows underground. Sub-surface irrigation was also used to minimize contact between the effluent and the growing plants. The harvested crops are generally cooked for consumption. There were no colonies present on the banana fruit and only a few colonies were found on the banana peel.

Perceptions and social acceptability of DEWATS for use in agriculture

In similar sanitation projects that have been carried out it was noted that there were generally negative perceptions on the use of human excreta in agriculture. Barriers such as religion, culture, smell, lack of knowledge and negative attitudes towards excreta have been identified. In the present study, however, using effluent was considered acceptable to all the stakeholders that participated in the study. Concerns about theft of equipment, health risks and social stigma were identified among the participants. The high level of acceptability of effluent could be attributed to two factors. Firstly, effluent is treated (anaerobic digestion) and the end product which is a clear liquid is appealing compared to handling raw faecal matter and urine. In addition, the detailed explanation of the DEWATS also gave participants a clear understanding of how the system works thus allaying many of their doubts and concerns. With regard to the acceptability of effluent in agriculture, this study found highly positive attitudes as respondents noted that it was a good idea to use effluent in agriculture even though none was aware of the potential benefits prior to the focus groups discussions.

However, there is need for continued engagement and consultations between regulators, policymakers, technicians and communities with regard to the use of DEWATS effluent for agriculture in South Africa.

RECOMMENDATIONS FOR FUTURE RESEARCH

1. The present study has only considered the agricultural use of the effluent on a limited range of crops on only one soil type in the field and over a very short time period. More crops and a range of different over a longer time period are required to assess the full potential for using DEWATS effluent in order to monitor both positive and negative impacts. This will give more information on land area requirement estimations.

2. The SWB proved to be most useful for irrigation scheduling which enable more extensive estimates of land area and effluent usage to be arrived at. Nutrient (N and P) dynamics in the soil could not be accurately predicted by the model due to spatial variation hence more extensive research in different is required for more reliable results. Furthermore, more investigations need to be made on different cropping systems to produce a comprehensive knowledge of the practice.

3. Further studies will be required on the behaviour of pathogens in the effluents and the potential risks associated with them when the effluents are used on agricultural land.

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List of abbreviations

ABR	Anaerobic Baffled Reactor
CEC	Cation Exchange Capacity
COD	Chemical Oxygen Demand
DEWATS	Decentralised Wastewater Treatment System
DM	Dry Mass (kg m^{-2})
DM_i	Dry Matter Increment (kg m^{-2} day^{-1})
DWR	Dry Weight ratio (Pa)
E_c	Radiation use efficiency (kg MJ^{-1})
Eta	Crop evapotranspiration
ETo	Reference evapotranspiration
EWS	eThekwini Water and Sanitation
FAS	Fertiliser Advisory Service
GDD	Growing Degree Days
HEDM	Human Excreta-Derived Materials
HFW	Horizontal Flow Wetland.
Kc	Crop Factors
K_{PAR}	Canopy solar extinction
LA	Leaf Area (m^2)
LaDePa	Latrine Dehyration Pasteurisation pellets
LAI	Leaf Area Index
ML	Megalitres
NH_4^+	Ammonium
NH_4^+-N	Ammonium nitrogen
NO_3^- N	Nitrate nitrogen
NO_3^-	Nitrate
NUC	Nitrified Urine Concentrate
PAR	Photosynthetically active radiation
PET	Potential Evapotranspiration (mm)
PO_4^{3-}	Orthophosphate
PO_4^{3-}P	Orthophosphate phosphorus
PRG	Pollution Research Group
R^2	Coefficient of Determination
RD	Root Depth (m
RDM	Root Dry Mass (kg m^{-2})
RGR	Root Growth Rate (m^2 $kg^{-0.5}$)

R_s	Solar radiation for a particular day (MJ m^{-2})
Se	Sepane soil
SED	Standard Error of Deviation
SLA	Specific leaf area (m^2 kg^{-1})
SWB	Soil Water Balance model
T	Transpiration (mm)
T_{avg}	Daily average air temperature (°C)
Tb	Base temperature (°C)
T_{cutoff}	Cutoff temperature (°C)
TDM	Top Dry Mass (kg m^{-2})
T_f	Temperature factor for light limited crop growth (°C)
TLA	Total Leaf Area (m^2)
T_{lo}	Temperature for optimum light-limited crop growth (°C)
T_{max}	Daily maximum air temperature (°C)
T_{min}	Daily minimum air temperature (°C)
T_p	Potential transpiration (mm)
TransDD	Day degrees of transition period from vegetative to reproductive growth
Transl	Factor determining translocation of dry matter from stem to grain
UKZN	University of KwaZulu-Natal
VFW	Vertical Flow Wetland
VGI	Vegetative Growth Index
VPD	Vapour Pressure Deficit (Pa)
WFD	Wetting Front Detector
wsf	Water stress factor
yLAI	Leaf area index of senesced leaves
$yLAI_i$	Daily increment of leaf area index of senesced leaves

1 INTRODUCTION

1.1 Background and justification

Urban municipalities are faced with increasing challenges of providing many services to their populations. With current demographic trends and population projections suggesting that by the year 2050, 70% of the global population will be living in cities (UNFPA, 2007), it is clear that there will be huge pressure on municipal authorities to provide housing and related infrastructure. Currently the eThekwini Water and Sanitation Unit (EWS) is responsible for the provision of water and sanitation services to more than 3.6 million people within the eThekwini Municipality boundaries. The number of people residing within the municipality boundaries is expected to increase in the future and the vast majority would most probably reside in informal settlements located at the periphery of the main sewage system.

The eThekwini Municipality is currently considering new plans for social housing projects to cater for such communities. Previously the selection of wastewater treatment systems for similar housing projects has been limited to conventional treatment package plants and pond systems which discharge the treated water to the aquatic environment. The planning of new social housing projects will require high densities in order to prevent urban sprawl and necessitate a reticulated sewage system, as opposed to on-site disposal, acceptable to the communities. The Municipality is considering an alternative approach whereby metered potable water is provided through roof-tank, reticulated sewage, a BORDA Decentralised Wastewater Treatment System/Anaerobic Baffled Reactor (DEWATS/ABR), a vertical flow and/or horizontal-flow constructed wetlands and an adjacent agricultural area. The ABR system is successfully used in other developing countries such as Indonesia (Malisie, 2008; Reynaud et al., 2009) and India (Eales, 2012) and the wastewater from such a system has been found suitable for irrigation onto agricultural land. The potential use of the treated effluent for agriculture is significant because by definition the recipients of social housing are poor and the provision of employment and improving household security (including food security) are social aspects that need to be considered in parallel to the provision of housing. In addition, the ABR could allow for the capturing of biogas as an energy source for use in cooking.

1.2 Problem statement

The utilisation of effluent generated from low cost sanitation technologies such as the DEWATS still poses challenges to the environment. Such effluent has been shown to contain high concentrations of essential nutrients necessary for crop production (Bame et al., 2014). In a previous WRC project (**K5/2002)** the potential of nutrient uptake from the ABR effluent by Swiss chard at the field scale was clearly demonstrated. It has also been demonstrated that soils of different properties are able to retain nutrients from the ABR effluent (Bame et al.,

2013) and may meet the crop water requirements. Integrating agriculture in the planning and design of low cost sanitation technologies could provide safe and sustainable mechanisms for utilisation of such effluent by retaining the nutrients for crop production. Existing guidelines (for pure waste materials and water) focus mainly on the potential harmful effects that could arise from wastewater and waste utilisation and have not considered the potential benefits of using nutrient-rich effluent from low-cost sanitation technologies. In addition, these guidelines do not allow for the soil's contribution in ameliorating potential pollutants in such waste.

1.3 Objectives of the study

The overarching aim was to generate information on recycling of nutrients from DEWATS technology that will inform policymakers and town planners in the design of new social housing development that integrate agriculture.

The main objectives were to:

(1) develop models based on water and/or nutrient balance simulations to predict the outcome of the application of DEWATS effluent when growing selected crops under different climatic conditions;

(2) establish focused experiments in the laboratory and field, which will be used in calibrating and validating the respective models;

(3) determine (a) the amount of land required for agriculture; (b) the quality of run-off water and its management during the wet season; (c) the water and nutrient-uptake by different plants grown on a range of soil types;

(4) generate information that could be used to develop protocols that integrate agriculture into social housing development schemes and

(5) assess the use of other human excreta-derived materials (HEDM) as new fertiliser sources on different soils;

1.4 Approach to the study

The project originally was to be based at Kwadinabakubo near Hillcrest in KwaZulu-Natal, where the municipality was proposing a new social housing scheme which could potentially adopt a DEWATS plant as a sanitation solution. Due to delays in deciding which sanitation system was best suited for that site, the study was moved to Newlands-Mashu where a pilot DEWATS plant had already been constructed. Similarly, other products from excreta streams were assessed for agricultural use. The following activities were carried out within the project:

1.4.1 Literature review

A synopsis of the opportunities or problems that could be created from wastewater irrigation and utilisation of HEDM was undertaken. The implications of their use either directly or indirectly in agriculture have been elaborated on to further illustrate that agriculture could be a safer utilisation measure than disposal to aquatic bodies.

1.4.2 Field trial

A field experiment was laid out comprising of two main plots, a plot irrigated with municipal tap water + fertiliser and an ABR/HFW effluent irrigated plot. Within each plot banana (*Musa parasidiaca*) was planted as the main crop with taro (*Colocasia esculentum*) as the intercrop. The banana crop once established was maintained for the first crop and the subsequent ratoon crop. The irrigation was done by a modified drip system supplying effluent directly to the plant at the soil surface. The amount of effluent used during each irrigation period was recorded and the amount of nutrients applied with irrigation quantified. Banana leaf samples were collected at flowering while taro corms after harvest and they were analysed for macro and micronutrients. Irrigation was complemented with data collected from the on-site weather station. Leachates from within the root zone were collected via wetting front detectors (WFDs) installed in each plot. Piezometers were installed below the root zone within the plots, and above and below the experimental area. The leachates were analysed for nitrogen (N) as both ammonium-N (NH_4^+-N) and nitrate-N (NO_3^--N), and orthophosphate P (PO_4^{3-}-P) concentrations to determine their behaviour in the soil at different depths. At the end of each crop cycle, yield was measured and soil sampling done at the same depths as previously collected for fertility analysis.

1.4.3 Laboratory incubation and controlled environment plant growth studies

Laboratory incubation studies were carried out using HEDMs namely struvite, nitrified urine concentrate (NUC) and LaDePa pellets. The focus was on the N and P release from the HEDMs in comparison to manufactured commercial fertilisers. The rate of N mineralisation or immobilisation of the N fractions (NH_4^+-N and NO_3^--N) was analysed from incubating the HEDMs with soils of contrasting physicochemical properties.

Pot experiments were conducted in tunnels using a range of crops under controlled conditions. This was to investigate the use of ABR and HFW effluents as irrigation sources on soils of different properties compared to irrigation with municipal tap water with different fertiliser rates. Similarly, pot trials investigated the uptake of plant nutrients from HEDMs applied to different soil types.

1.4.4 Modelling

The land area required for irrigating with DEWATS effluent was determined using the Soil Water Balance-Sci model. The model was calibrated and validated using the field data collected at Newlands Mashu over a 33 month growing period. The land area required was based on banana crop water requirements (evapotranspiration). The model was also calibrated to simulate N and P dynamics in the soil over a 33 months period.

1.4.5 Quantitative Microbial Risk Assessment (QMRA)

Samples of the raw wastewater from the inflow, after the second ABR chamber and after the final ABR filter were analysed and the concentrations of *Escherichia coli*, *Campylobacter* spp (as surrogates for bacterial pathogens), somatic coliphages (surrogates for viral particles), *Clostridium* spp (as surrogates for spore forming bacteria and protozoan parasites) and soil transmitted helminths (STHs) were determined. These measurements were used to determine the log reduction in concentration achieved throughout the treatment process. Spinach (representing vegetables grown above the ground) and beetroot (representing vegetables with edible parts below the ground surface) irrigated with the effluents from the ABR were also sampled and their contamination with the selected pathogens determined. Using the QMRA framework the risk of infection for farmers was determined for a one-time exposure as well the annual risk (assuming 150 days of exposure) based on accidental ingestion of 1 mL of the effluent used for irrigation. Risk of infection for consumers of the vegetables (spinach and beetroot), based on the consumption of 10 g of vegetables, was also determined using the same QMRA framework.

1.4.6 Stakeholder consultations

Consultative meetings with relevant stakeholders took place to discuss the concept of waste and wastewater reuse in agriculture as a component of new social housing schemes. By undertaking consultations, real questions with regards to barriers to the integration of agriculture in the planning of new housing schemes were raised.

2 AGRICULTURAL UTILISATION OF HUMAN EXCRETA-DERIVED MATERIALS AS FERTILISER AND/OR A SOURCE OF IRRIGATION: A REVIEW

2.1 Introduction

Urbanization is one of the most important demographic trends of the twenty-first century, and growth is particularly rapid in lower-income countries (United Nations, 2001). The majority of urban growth is associated with the rapid expansion of smaller urban centres and peri-urban developments (United Nations, 1999). Much of this growth is unplanned and informal, resulting in the production of wastes that rarely receive adequate treatment. In peri-urban areas, increasing populations, combined with increasing water consumption and a proliferation of waterborne sanitation, create widespread wastewater disposal problems. In many cases, wastewater is discharged locally onto open ground and vacant plots, creating ponds of foul-smelling stagnant water. In the past, the conventional wisdom has been that centralized systems are easier to plan and manage than decentralised systems. However, experience shows that centralized systems have been particularly poor at reaching peri-urban areas, particularly those that fall outside municipal boundaries. In response to the deficiencies of centralized approaches to sanitation, in recent years there has been increasing emphasis on the potential benefits of adopting decentralised approaches to sanitation and wastewater management, which are particularly appropriate for peri-urban and rural areas.

2.2 The use of human waste in agriculture

Although human excreta have a number of potential benefits in agriculture, their social acceptance has been considered a key barrier to their use. Studies that have examined attitudes and perceptions towards human excreta in agriculture have shown that these differ across culture and religions. Primary arguments in these studies have identified five key obstacles to the use of, for example, urine in agriculture, i.e. lack of knowledge, traditional and religious beliefs, health concerns and smell (Foxon et al., 2004; Drangert, 2005; WHO, 2006; Duncker et al., 2007; Cofie et al., 2010; Mariwah and Drangert, 2011). A further concern raised in South Africa relates to the possible presence of menstrual blood and the transmission of HIV/AIDS through urine (Benoit, 2012).

In terms of knowledge about the value of human excreta in agriculture, a study in Ghana found that most of the study participants lacked knowledge of the value of urine in agriculture (Cofie et al., 2010). In a similar study, Mariwah and Drangert (2011) used a mixed research method (survey and focus group discussion) to examine the acceptability of human excreta among farmers in Ghana. The study found a significantly high negative attitude towards human excreta (Table 2.1). Participants in the study considered food grown with human effluent as being ‘unclean’ for human consumption (Mariwah and Drangert, 2011). A similar study by Roma et al. (2013) found that “social stigma attached to using dry sanitation and applying urine in agriculture and poor operational knowledge” are other barriers to the application of urine in agriculture.

Table 2.1 The acceptability of human excreta for agricultural use among farmers in Ghana (Source: Mariwah and Drangert, 2011)

Issue raised	Responses (%)		
	Agree	Disagree	Don’t know
Human excreta is a waste and suitable only for disposal	84.4	0.0	15.5
Handling excreta is great health risk	96.8	0.6	2.5
Human excreta should not be handled in any way	72.1	3.2	24.6
Human urine has no benefit to humans	74.0	8.4	17.5
It is a taboo to handle urine	37.7	11.7	50.7
Human faeces have no benefit to humans	70.8	5.8	23.4
It is a taboo to touch faeces	43.5	12.3	44.1
It is a taboo to touch treated faeces	38.9	13.0	48.0

A study by Roma et al. (2013) used the receptivity model to assess perceptions on the reuse of urine in agriculture and found a prevailing lack of knowledge about the nutrient potential of urine. In another study involving 420 respondents in Mali and Nigeria, Akeredolu et al. (1994) found that more than half of respondents were aware of the benefits of human excreta in agriculture in both Mali and Nigeria (52% in Nigeria and 58% in Mali, respectively). The study also found that 42% of respondents in Nigeria and 51% in Mali would use human excreta in agriculture. In addition, the study established that 51% of respondents from Nigeria would buy food grown using human excreta while 46% in Mali would. The lower percentage in Mali was attributed to the prevalent Islamic religion which abhors close contact with human excreta. A study by Benoit (2012) found that concerns about the smell of urine and the fear that the smell will be present in urine-grown food made farmers in South Africa conceal information about urine-grown food from buyers. In a similar study, Mariwah and Drangert (2011) found that smell is a barrier to the use of urine in agriculture in Ghana, Nigeria, South Africa and Kenya. The health implications of using human excreta in agriculture were cited as a barrier in most studies consulted (Foxon et al., 2004; Magida et al., 2006; Dunker et al., 2007; Okem et al., 2013; Roma et al., 2013). According to Roma et al. (2013), concerns “about the presence of micro-pollutants, hormones, pathogens, pharmaceutical residues and other contaminants in urine" have been identified as barriers to the reuse of urine in agriculture in both low and high-income countries. The study noted that the smell of urine is often associated with the presence of pathogens which makes people wary of using it in agriculture (Roma et al., 2013).

A study by Cofie et al. (2010) reported farmers' willingness to purchase urine-grown food on condition that they will be guaranteed that consuming such food will not have any negative health implications. In the study by Mariwah and Drangert (2011) it was noted that 97% of respondents were of the view that human excreta pose health risks. As a result, 72% reported that human excreta should not be handled.

From the foregoing, it is clear that fear about the health implications of human waste plays an important role in the adoption of human excreta in agriculture. Harnessing the agricultural potential of human excreta requires a paradigm shift both in the design of sanitation facilities and attitudes towards human excreta. Although perceptions and acceptability of human excreta vary across studies, there is a generally low acceptance across all studies. In view of the above discussion, if human excreta are converted into products that could be easily handled this could shift the attitude of people and encourage the use of waste from sanitation installations.

2.3 Wastewater use in agriculture

Wastewater use in agriculture has been established as the most viable reuse option as compared to other uses (Jimenez et al., 2010). Scott et al. (2010) reported that unplanned use of wastewater either directly or indirectly is an order of magnitude greater than planned use. In many low-income and middle-income countries, wastewater irrigation either involves the direct use of untreated wastewater or its indirect use from rivers and streams that receive untreated wastewater discharges. Case studies of city and country assessments of varying detail conducted in middle and low-income countries of Africa, Asia and Latin America have recognized that the use of untreated wastewater for the irrigation of high-value cash crops close to urban centres is a widespread practice. An estimated 20 million hectares is under agriculture using treated, partially treated, diluted and untreated wastewater (Scott et al., 2004; Marsalek et al., 2005; Hamilton et al., 2007; Keraita et al., 2008). For millions of poor households wastewater is a highly important productive resource used in profitable but often informal production systems that contribute significantly to the supply of perishable produce, notably fresh vegetables, to urban areas (Scott et al., 2004; Drechsel et al., 2006). Furthermore, interest in wastewater irrigation is viewed as a substantial and sometimes even primary source of income in addition to contributing towards urban food supply (Drechsel et al., 2006; van Veenhuizen and Danso, 2007). With the economic development of many countries towards large scale urbanization, industrial or domestic wastewaters are either used or disposed of on land for irrigation purposes and this creates both opportunities and problems. Opportunities exist as wastewaters from municipal origin are rich in organic matter and also contain appreciable amounts of macro and micronutrients (Feigin et al., 1991; Pescod, 1992; Gupta et al., 1998). For many wastewaters, it is their high content of plant nutrients (especially nitrogen (N) and phosphorus (P)) and total dissolved salts that make them able to be treated as waste products, although when recycled they can be used as a fertiliser source in irrigated agriculture (Toze, 2006; Scheierling et al., 2011). The nutritional value of wastewater in terms of its N and P contents can increase the productivity of farming and thus contribute to the livelihoods of peri-urban communities and provide another strong incentive for agricultural re-use. Other constituents may be critical in specific cases such as high organic matter content and biological oxygen demand, or high concentrations of particular chemicals. The use of treated wastewater in agricultural soils has been proposed as a sustainable management strategy and as an aspect of integrated water management for water-poor countries (Neubert, 2009). In such countries, the reuse of wastewater has, in recent years, been viewed as a strategy for the future and is being propagated as a concept by industrialized countries. In peri-urban areas of many developing countries, agriculture would be virtually impossible without the use of wastewater for irrigation. Farmers are dependent on it for their existence since it is their only reliable source of water (Friedler, 2001; Rutkowski et al., 2007).

2.4 Soil, plant and wastewater interrelationships

The objective of land application of wastes is to utilise the chemical, physical, and biological properties of the soil/plant system to assimilate the waste components without adversely affecting soil quality or causing contaminants to be released into water or the atmosphere (Loehr, 1984). The use of wastewaters centres on the need to maintain a productive soil environment for crop production, while minimizing or avoiding degradation of soil and water resources. Municipal wastewaters used for irrigation could influence the physical, chemical and biological properties of the soil (Feigin et al., 1991; Mathan, 1994; Schipper et al., 1996) which, in turn, play an important role in the transformation of nutrients present in the applied wastewater. Chakrabarti (1995) observed that rice crops gave a higher yield when irrigated with raw or partially diluted sewage compared to groundwater. While the additional elements can be a bonus as additional fertiliser, excess carbon (C) and N can have an adverse effect through excessive microbial activity and growth. Treated wastewater irrigation has supplied the necessary nutrients for growth of Chinese cabbage and corn plants as well as giving an improvement in soil properties in the Gaza Strip, Palestine (El-Nahhal et al., 2013).

2.4.1 Effect of wastewater irrigation on soil physical properties

The main properties that control soil hydraulic conductivity are soil texture, dry bulk density, soil structure, soil solution chemistry, soil cation exchange capacity (CEC) and the microbial activity (Halliwell et al., 2001; Goncalves et al., 2007). These properties tend to be modified during the application of wastewaters especially in tropical soils because of the effects of sodium (Na) which occurs in high concentration in many wastewaters (Goncalves et al., 2007). Studies by Magesan et al. (1999) and Halliwell et al. (2001) have shown that changes in the porous system of the soil seem to be the dominant factor for infiltration and hydraulic conductivity reduction. Decreases in soil hydraulic conductivity can result in surface runoff and flooding, which lead to superficial contamination by the effluents and soil erosion, especially in a tropical environment (Vinten et al., 1983). Intensive irrigation with treated wastewater in loam and clay soils has been shown to have resulted in a significant increase in "clay dispersion and eluviation from the upper soil layers" (Warrington et al., 2007). The potential risk associated with irrigation using treated wastewater is degradation of soil structure. This is manifested by deterioration of aggregate stability resulting in decreased soil hydraulic conductivity. As a result there is increased susceptibility to surface sealing, runoff and soil erosion problems such as soil compaction and decreased soil aeration (Mandal et al., 2008). Irrigation with water of a moderate sodium adsorption ratio (SAR) of about 6 leads to an exchangeable sodium percentage (ESP) of comparable value in the soil and can adversely affect soil physical properties such as soil hydraulic conductivity due to sodium-induced clay dispersion (Halliwell et al., 2001). Studies by Tarchitzky et al. (1999) have shown that the presence of dissolved organic matter in treated wastewater, coupled with its higher sodicity, increases clay dispersion and results in higher flocculation values for both specimen and soil clays.

Comparative studies on the effects of irrigation with either treated wastewater or freshwater have shown that irrigation with treated wastewater containing a high load of organic matter and nutrients decreased soil hydraulic conductivity due to pore blockage by the suspended solids present in the treated wastewater (Vinten et al., 1983; Magesan et al., 2000) and by the excessive growth of microorganisms (Magesan et al., 1999). Some studies that used wastewater with a greater degree of treatment and thus of better quality, have shown no negative effect on soil hydraulic conductivity (Levy et al., 1999), whereas Tarchitzky et al. (1999) reported a reduction in hydraulic conductivity after leaching with treated wastewater. The level of treatment of the wastewater then becomes a factor for consideration.

In other experiments, changes in soil hydraulic conductivity during leaching with deionized water were compared to soils subjected to long term irrigation with either treated wastewater or freshwater (Bhardwaj et al., 2007). Results from these studies showed that irrigation water quality and method of irrigation did not have conclusive effects on the aggregate stability of the soil which was used as an indicator of steady state hydraulic conductivity. Levy et al. (2005) found that the combined effects of salinity, wetting rate and sodicity on hydraulic conductivity were complex and should be considered simultaneously in estimating hydraulic conductivity. Similar studies compared the changes in infiltration rate, runoff and erosion during natural or simulated rainfall on such soils (Mamedov et al., 2001; Agassi et al., 2003). These properties were found to vary due to differences in treated wastewater quality, soil texture, calcium carbonate content, intensity of cultivation, irrigation method, and antecedent moisture content in the soil. An exception to these studies was that of Bhardwaj et al. (2008) who tested the hypothesis that replacing saline-sodic irrigation water that had been in use for many years, with the considerably less saline-sodic treated wastewater, although with higher loads of organic matter and suspended solids, may help the soil regain its structure and hydraulic conductivity. Bhardwaj et al. (2008) found significantly higher hydraulic conductivity and aggregate stability in the treated wastewater-irrigated samples than in those that were subjected to long term irrigation with saline-sodic water. This effect of irrigation with wastewater can be used as a check mechanism especially in monitoring leaching columns.

In an earlier study, effects of sodicity on soil hydraulic conductivity, permeability and seal formation were determined for dry soils that were subjected to rapid wetting either from below or from above, prior to their exposure to leaching or simulated rain. In this study, fast wetting led to aggregate slaking (Panabokke and Quirk, 1957). A similar study showed substantial reduction in aggregate slaking by using slow wetting rates (commonly ~2 mm h^{-1}) which lessened the susceptibility of soil to seal formation and maintained higher hydraulic conductivity values in comparison to cases where severe aggregate slaking occurred when using much faster wetting (~50 mm h^{-1}) (Moutier et al., 2000). Shainberg et al. (2001) and Mamedov et al. (2001) have also demonstrated the importance of aggregate slaking in determining susceptibility to permeability deterioration which depends on both soil sodicity and clay content.

2.4.2 Effect of wastewater irrigation on soil chemical properties

2.4.2.1 Plant nutrients

The ability of soils to immobilize nutrients from sewage effluents could enhance the fertility and productivity of effluent-irrigated soils (Asadu et al., 2008; Lin et al., 2008). However, as a result of long-term irrigation with reclaimed wastewater, many questions have been raised with regards to long-term, gradual changes in soil chemical properties, and accumulation of environmental contaminants in soils in and out of the irrigated area, which may consequently degrade the soil quality as well as contaminate water resources. There have been observed changes in soil pH as a result of effluent acidity (Smith, 2006; Rosabal et al., 2007), increased CEC, electrical conductivity (EC), soil compaction and a reduction in the soil's capacity to retain nutrients (Smith, 2006; Wang et al., 2003). The soluble inorganic constituents of irrigation waters react with soils as ions rather than as molecules. The principal cations are calcium (Ca^{2+}), magnesium (Mg^{2+}) and Na^+ with small quantities of potassium (K^+) ordinarily present, while the dominating anions are carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), sulphate (SO_4^{2-}) and chloride (Cl^-) (US Salinity Laboratory Staff, 1954). The availability status of N, P and K to crops has been shown to be higher in surface soils after receiving applications of sewage than in soils irrigated with water (Yadav et al., 2002). Similarly, the amounts of these nutrients in a clayey soil increased significantly after irrigation with municipal wastewater that was screened through filtration media in India (Singh et al., 2012). They reported that after one season of wheat cultivation the amounts of N, P and K in soil increased from 200, 13.0 and 280 kg ha^{-1} to 283, 23.9 and 343 kg ha^{-1}, respectively. Phosphorus deficiency, when limed soils were irrigated with ABR effluent has suggested an interaction effect between the lime and the effluent which hinders the uptake of P (Bame, 2012). The mechanisms responsible for P unavailability from the effluent are linked to its removal from wastewater by lime precipitation (Vanotti et al., 2002; Pastor et al., 2008). Excessive inputs of some elements would also have an adverse impact on plants. The high total N of reclaimed water from secondary treatment makes it unfavourable for crop growth (Chiou, 2008).

2.4.2.2 Salt accumulation in soil

Effluent irrigation can result in the addition to soil of large amounts of salts. An annual application of 1 000 mm of water with 500 mg L^{-1} of total dissolved solids (TDS) would add five tons of salt per hectare per year to the soil (Bond, 1998). Problems may arise through removal of water by evapotranspiration and accumulating salts to a concentration considered harmful. Effluent irrigation can be managed such that salt does not accumulate in the root zone, which invariably means it will impact on groundwater. The presence of soluble salts of Na, Mg and Ca in wastewater can increase soil EC (Mohammad and Mazahreh, 2003; Ghanbari et al., 2007) and enhance soil salinity which is a particular problem in arid areas. However, salt accumulation could be controlled by alternate wastewater and freshwater irrigation. It may be possible to store some salt between the root zone and the water table, if the underlying material is sufficiently porous. However, this is likely to be no more than six tons per hectare for each metre of the profile. Storage of salt from 10 years of irrigation contributing salt at the rate of five tons per hectare per year therefore requires about eight metres of profile between the root zone and the water table (Bond, 1998). Salts have been shown to accumulate in the deeper layers more than the upper layers as a result of leaching.

2.4.2.3 Trace elements

Heavy metals in wastewater are also a limitation to its utilization. Most of the studies concerning the introduction of effluent-associated contaminants to soils focus on heavy metal accumulation in wastewater-irrigated soils as a function of the source of wastewater. Although at trace levels in the treated effluents, these contaminants could accumulate in the soils if long-term irrigation occurs, which may result in environmental problems such as contamination of groundwater. Common treatment processes efficiently remove heavy metals and the larger fraction in raw sewage ends up in the biosolid fraction of the treatment process with very low metal concentrations present in the treated domestic effluents (Sheikh et al., 1987). Although the concentrations of trace elements in sewage effluents are low, long-term use of these waters on agricultural lands often results in the build-up of these metals to elevated levels in soils (Datta et al., 2000). Irrigation with wastewater has significantly increased the zinc, iron and molybdenum concentrations in soil even though lower than levels toxic to animals ingesting plant tissue (Galavi et al., 2010). These are microelements required in smaller quantities by plants so promoting their utilization. Therefore, heavy metals tend not to be a cause for concern when irrigating with treated effluent that is not from an industrial source but when present they could be of utmost importance because of their potential bioavailability to crops. Local conditions such as climate, soil and plant characteristics affect their uptake and it should therefore be determined whether they are within acceptable limits (Kiziloglu et al., 2008). In Bulgaria a study by Angelova et al. (2004) confirmed that fibre crops such as flax and cotton did take up heavy metals from heavily contaminated soils as levels were above maximum permissible concentrations according to Bulgarian standards. However, the concentrations detected in leaves and seeds were only a small percentage of the concentration present in soil. Contrary to this, untreated wastewater irrigation in Turkey did not significantly affect the heavy metal content in cauliflower and red cabbage on a short-term basis (Kiziloglu et al., 2008). The accumulation of cadmium, lead and zinc in broccoli (*Brassica oleracea* var. Italica) was observed where wastewater was employed for irrigation of the plants. In Kenya, Ofosu-Asiedu et al. (1999) examined the uptake of heavy metals by crops irrigated with domestic and industrial wastewater. They found that the levels in the crops were similar to background environmental levels and thus posed no health risks. The organic carbon present in recycled water can stimulate the activity of soil microorganisms. Magesan et al. (2000) noted that the organic and inorganic nutrients in treated effluent that had a high C: N ratio stimulated the soil microorganisms which, in turn, decreased the hydraulic conductivity of the irrigated soil. The reduction in hydraulic conductivity was by excess cell growth and the production of biofilm structures, which clogged the pore spaces between the soil particles.

2.5 DEWATS – Decentralised Wastewater Treatment System

The DEWATS is an effective, efficient and affordable wastewater treatment process as it does not depend on an external source of energy to operate and has low maintenance costs with minimal sludge production. The anaerobic baffled reactor (ABR), which is a form of DEWATS, is a high rate, anaerobic digester consisting of alternate hanging and standing baffles designed to treat wastewater and has undergone improvement in design over the years to make it suitable for treating a wide variety of wastewaters (Barber and Stuckey, 1999). Studies by Foxon et al. (2005) have shown that an ABR treating domestic wastewater will convert a large amount of wastewater chemical oxygen demand (COD) to methane gas, and will reduce pathogen loads in the wastewater. Despite considerable reduction of pathogen load, secondary treatment is required before any conventional irrigation methods are embarked upon. However, there is no nutrient removal, and the amount of pathogens removed is insufficient to render the effluent safe for human contact. The presence of significant amounts of ammonium (NH_4) and P in the effluent means that it cannot be discharged to surface or groundwater but, theoretically, can be used in irrigation of agricultural land, or disposed of in a soak-away (Foxon et al., 2004). Except in the case where sufficient area and infrastructure is available to build a sub-surface soak-away system, some post-treatment of the effluent is required before it can be reused. It has been recommended that the use of membrane bio-filters in conjunction with the ABR be considered since a bio-filter would remove virtually all COD and pathogens, while allowing nutrients, which have a real economic value as a fertiliser, to be retained for use in agriculture (Foxon et al., 2004). Embarking on membranes is very costly and would not be economically viable. Another post-treatment option is a constructed wetland. Results from the WRC project K5-2002 have indicated that the effluent, at its present microbiological quality, is not suitable for irrigation of food crops (Foxon et al., 2005).

The high nutrient levels of the effluent suggest that it holds potential as a fertilising solution, if the microbial quality can be improved. Guidelines for water use in irrigation have been formulated without considering the role of soil in converting it into a more useful resource as the concentrations of elements in the effluent are compared directly with the permissible limits. On-site sanitation in low income, peri-urban communities could then be linked to agriculture to improve food security which is in accordance with the millennium development goals (MDGs) (United Nations Millennium Declaration, 2000). This declaration focused on key challenges to human development globally without designing indicators and an integrated monitoring framework. The sustainable development goals of post-2015 adopted by the United Nations build on the MDGs by giving bolder targets while taking into account differing national circumstances and respecting national policies and priorities (United Nations, 2015). The effluent from ABRs is no exception to benefits that wastewaters contribute to agriculture.

In Asia, there is widespread utilization of effluent from DEWATS installations with a lot of work done to improve and optimize the reactor to produce effluent of better quality but very little is documented in terms of its effects on soil and crop uptake (Bame et al., 2014). Leaching column studies with ABR effluent have resulted in lower concentrations of major elements in the leachates suggesting that soil plays a major role in affecting the chemical composition of the effluent (Bame et al., 2013). Soil acidity improvement in effluent-irrigated soils has been observed and this is attributed to the high Ca accumulation which was not the same in freshwater-irrigated soils (Fonseca et al., 2005; Bame et al., 2013).

2.6 Urine and urine derived products

Municipalities in recent years have reported problems with high amounts of unmanageable wastewater, including urine (Udert and Wachter, 2011). Urine has reportedly caused pipe blockage through spontaneous formation of struvite crystals ($MgNH_4PO_4.6H_2O$) (Jaffer et al., 2002) and contamination of waterways (eutrophication) (Winker et al., 2009). Urine contains 80-90% N, 50-70% P and 60-80% K in plant available form (Schouw et al., 2002; Maurer et al., 2003). In response to this, technology has introduced urine diversion (UD) toilet systems that separate urine from faeces at source. This system helps to collect and store urine in large quantities. The eThekwini Municipality in KwaMashu, Durban, KwaZulu-Natal, South Africa, collects about 10 000 L of urine per month from UD toilets. The potential in urine as a source of nutrients for plants has innovatively and successfully been enhanced by removing P from urine by adding magnesium salts to precipitate struvite (El Diwani et al., 2006; Udert and Wächter 2011).

While struvite has the potential of being used as a P fertiliser, the process of its formation leaves large quantities of N in the effluent, which makes struvite-effluent a potential source of environmental contamination. In order to make good use of the N in urine, different approaches could be used to make a variety of fertiliser materials. Urine-based nutrient sources, including urine, struvite, struvite-effluent and nitrified urine concentrate (NUC), contain mineralisable N that can support plants (Murugan and Swarnam, 2013).

The low solubility of struvite (0.2 g L^{-1}) in water makes it an ideal slow-release fertiliser (Rahman et al., 2013). Struvite contains 5.7% N and 12.6% P by mass (Doyle and Parsons, 2002). Barak and Stafford (2006) showed that struvite performs better than diammonium phosphate on a unit to unit basis in terms of dry matter production and P uptake. After struvite formation, the supernatant solution is left with approximately 90% NH_4-N and 100% K from the process (Doyle and Parsons, 2002). Urine can further be nitrified directly to produce NUC with more NO_3^--N than NH_4-N. It contains about 21% N and its use could minimise N losses due to ammonia volatilisation as half of the ammonium is converted to nitrate.

The suitability of these materials as fertilisers depends on mineralisation of the nutrients present (Murugan and Swarnam, 2013). Mineralisation and immobilisation processes are biochemical in nature and are mediated through the activities of microorganisms. The resulting effects of these two processes are expressed as net mineralisation or net immobilization which determines the N and P supply to the growing crops. The mineralisation and immobilization processes are affected by properties such as temperature and pH (Murugan and Swarnam, 2013). When these are favourable the metabolism of microorganisms results in mineralisation or, inversely, immobilisation.

2.7 Conclusions

The success of effluent reuse lies in how its physical, chemical and biological properties can be assimilated through the soil/plant system. The diversity in properties of various wastewaters makes it difficult and inappropriate to assume they will behave alike when irrigated on soil. Different soils will assimilate nutrients differently depending on their properties and the success in irrigating crops will be determined by how many of the effluent properties can be tolerated by that crop. Irrigating with DEWATS effluent could be considered as an alternative to treatment aimed at achieving the stringent standards for wastewater disposal into watercourses. It allows for the soil's contribution in accommodating pollutants harmful to water bodies which is an aspect that is not factored into most guidelines on wastewater utilization for agriculture. The DEWATS effluent serves as a nutrient source for plants and this has implications for the amounts of fertilisers needed for field crops. Supplementing fertiliser application could have financial benefits especially for subsistence farmers who have to deal with the ever-increasing price of fertilisers. The water component gives an opportunity for dry season cropping especially in agricultural areas that depend on rainfall. In instances where the water cannot meet the nutrient requirements of the crops, HEDMs could make up for this deficit.

3 THE EFFECT OF WASTEWATER IRRIGATION ON SOIL AND PLANT NUTRIENT DYNAMICS AND LAND AREA REQUIRED FOR A BANANA/TARO INTERCROP

3.1 Introduction

Wastewater reuse in agriculture is increasingly gaining ground due to the advantages associated with this practice. It is recognized as an important supplement to municipality tap water and rainwater and additionally provides the soil with nutrients and organic matter. Wastewater farming has been viewed as one of the most environmentally friendly methods for disposing of sewage effluent. Although wastewater reuse in agriculture has both agronomic and economic merits, care has to be exercised to minimise unfavourable health and environmental impacts. The success of such irrigation starts with the characteristics of the wastewater, the soils/crops involved and the climatic variables where the activity is being practiced.

The most commonly used method to measure the impact of effluent irrigation on soil properties and accumulation of possible contaminants is to compare soil parameters and contaminant levels between effluent-irrigated and non-effluent-irrigated soils.

The field trial therefore was established with the objectives to assess 1) the changes in soil characteristics, 2) the nutrient uptake from effluent, 3) the leachate characteristics within the root zone and 4) the movement of water away from the experimental plot that may impact on surrounding surface waters as well as groundwater.

3.2 Materials and methods

3.2.1 Site description

The study site was at Newlands-Mashu (30°57'E, 29°58'S) in Durban where a pilot DEWATS (ABR) plant had been installed by eThekwini Water and Sanitation (EWS) in conjunction with the Pollution Research Group (PRG), University of KwaZulu-Natal (UKZN) for scientific research (Figure 3.1). This site currently has an office, laboratory space and a plastic tunnel for more controlled environment experiments. The site has a weather station that allows for the collection of soil, crop and climate data and has an annual rainfall of ~700 mm and a mean daily temperature of 20.3°C.

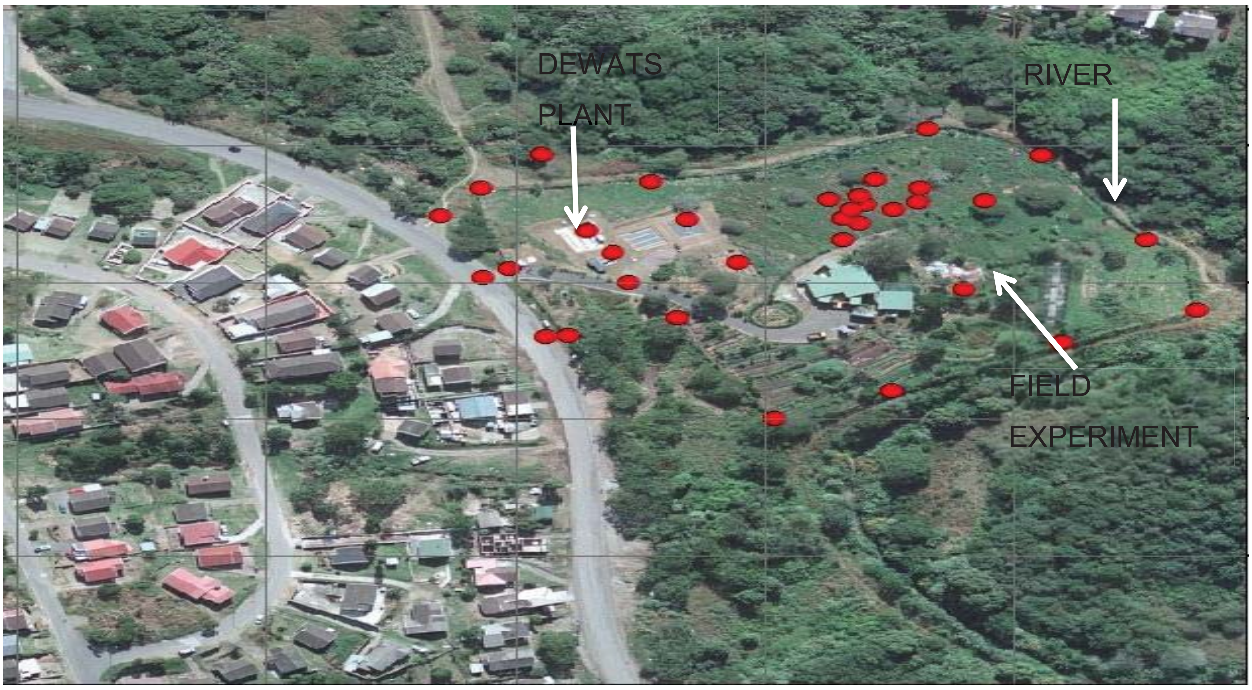

Figure 3.1 An aerial view of Newlands-Mashu site showing the DEWATS (ABR) plant, the experimental site, physical features (river) and some of the contributing houses. The red dots are GPS points

3.2.2 Experimental Design

The trial consists of two main treatments which are the irrigation sources namely DEWATS effluent and municipal tap water + fertiliser with three blocks resulting in six plots (Figure 3.2).

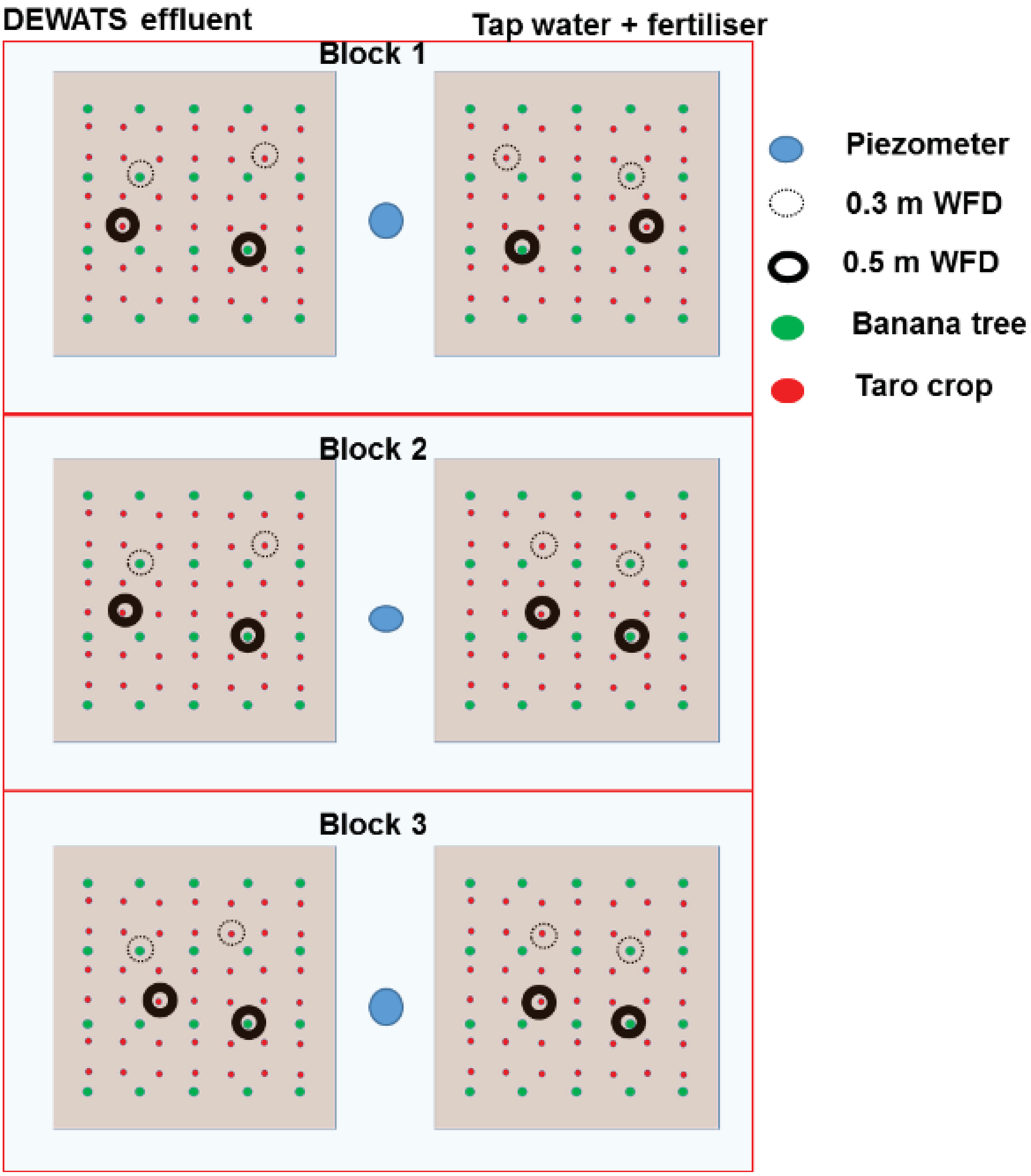

Figure 3.2 The field experimental plant for a banana/taro intercrop showing the positions of wetting front detectors (WFDs) and piezometers

3.2.3 Soil collection and analysis

Representative soil samples were collected from 0-0.3 and 0.3-0.6 m depths at the beginning of the trial. At harvest of the first crop soil samples representative of the experimental site were collected from the plots (90 m^2) which were ridged. Five samples were collected per plot at different depths (0-0.3 m, 0.3-0.6 m and 0.6-0.9 m) and bulked by depth. Composite samples were sent to the Fertiliser Advisory Service (FAS), KZN Department of Agriculture and Environmental Affairs; Soil Fertility and Analytical Service, Cedara for chemical analysis. The samples collected were also analysed for NO_3^--N, PO_4^{3-}-P and NH_4^+-N according to standard methods for wastewater analysis (APHA, 2005).

3.2.4 Trial establishment

3.2.4.1 Banana (Musa spp) establishment

Tissue-cultured banana plants of the Williams cultivar were planted in the field (Figure 3.3) on November 13th 2013. Bananas were planted in 90 m^2 plots at a spacing of 4.5 m^2 $plant^{-1}$ giving a plant population of 20 plants per plot. Holes of about 0.3 m were dug and plants of about 0.2 m tall housed in potting bags were transferred to the field. Fertiliser was applied based on fertility analysis results described in Table 3.1 as follows: urea: 31 g $matt^{-1}$ ($plant^{-1}$) $month^{-1}$ (14 g N $matt^{-1}$ $month^{-1}$ for 8 months), and KCl: 200 g $matt^{-1}$ $month^{-1}$ (104 g K $matt^{-1}$ $month^{-1}$ for 3 months). No P was applied since the soil test P was greater than twice the recommended soil target P. A banana is a tropical crop requiring warm, humid and frost free conditions. Water requirement for banana growth is 1 200-2 200 mm $annum^{-1}$ and soils with 30-55% clay are ideal. It is a crop with shallow roots that do not exceed 0.75 m in depth with most active roots concentrated in 0.3-0.5 m depth of the soil. Irrigation is a requirement for optimum banana growth especially in the winter months as it allows for about 35% moisture depletion. Bananas are an ideal crop for wastewater irrigation because the fruit is far above the soil and thus there is no or minimal contact with the fruit. Also, the fruit is covered in an inedible sheath minimising contamination from irrigation.

3.2.4.2 Taro (Colocasia sp) establishment

Taro, popularly referred to as 'madumbi', was established as an intercrop between the banana plants (Figure 3.3) at a planting distance of 1 m^2 with a plant population of 42 plants per plot on December 18th 2013. The taro was of the 'Dumbelomfula' landrace obtained from multiplication plots at the UKZN research farm. The planting method was the same as for the banana but with shallower holes. However, fertiliser was not applied to taro crops but the requirements are described in Table 3.1. Taro has an adventitious and shallow root system arising from the corm, a swollen underground stem. It has been categorized as one of the least water-efficient crops with a shallow root system. Taro is also a crop suitable for growth with wastewater irrigation as the edible part although found in the soil is covered in a sheath and the crop cannot be eaten raw.

Table 3.1 Nutrient (N, P and K) requirements for banana and taro during the growing period for season 1 (Nov 2013-May 2015) and season 2 (Jun 2015-July 2016) in respective irrigation treatments plots

Crop	Treatment	Year	N	P	K
			kg ha^{-1} yr^{-1}		
Banana	DEWATS effluent	1	250	0	262
		2	250	0	232
	Tap water + fertiliser	1	250	0	312
		2	250	0	45
Taro	DEWATS effluent	1	160	80	80
		2	160	80	80
	Tap water + fertiliser	1	160	80	80
		2	160	80	80

The layout of the banana/taro crops in an intercrop during the first growing season are shown in Figure 3.3.

Figure 3.3 Layout of banana/taro intercrop at Newlands-Mashu during the first main crop growing season

3.2.4.3 *Irrigation system*

The ABR consists of three streets (Figure 3.4) with streets two and three emptying into a holding tank at the end while street 1 delivers effluent into firstly a vertical flow wetland (VFW) and then into a horizontal flow wetland (HFW). As shown in the insert in Figure 3.8, the tank is not covered and so rainfall events will impact on the quality of the effluent.

The irrigation system was designed to supply effluent from the ABR via a submersible pump installed to deliver effluent into a 10 kL capacity irrigation tank. The effluent was then to be used to irrigate the field. The installations in the field are made up of a drip irrigation system using Netafim® drippers that were calibrated to deliver 8 L of effluent h^{-1}. Each of these drippers then split into four so that four plants were irrigated at any given time with each plant receiving 2 L h^{-1} (Figure 3.5). Equal volumes of effluent were supplied to each plant. The plots irrigated with municipal tap water had similar installations and were programmed to supply the same amount of water per plant as the effluent but from a standing tap.

Figure 3.4 Layout of the anaerobic baffled reactor at Newlands-Mashu

Figure 3.5 Drip irrigation installed in the field

3.2.4.4 Weather station

Climatic variables were collected from a Campbell Scientific automated weather station connected to the CR 1 000 data logger installed in June 2013 adjacent to the field experimental plot as shown in Figure 3.6. Meteorological data collected include wind speed and direction, rainfall, relative humidity, evapotranspiration (ETo), air temperature and solar radiation. Canopy temperature was measured by the Campbell infrared thermometers (IRT) which were connected to the weather station data logger. The CS 650 water reflectometers (Campbell scientific, Inc) installed at three different soil depths (0.3, 0.6 and 0.9 m) as shown in figure 3.6 were used to monitor soil moisture content.

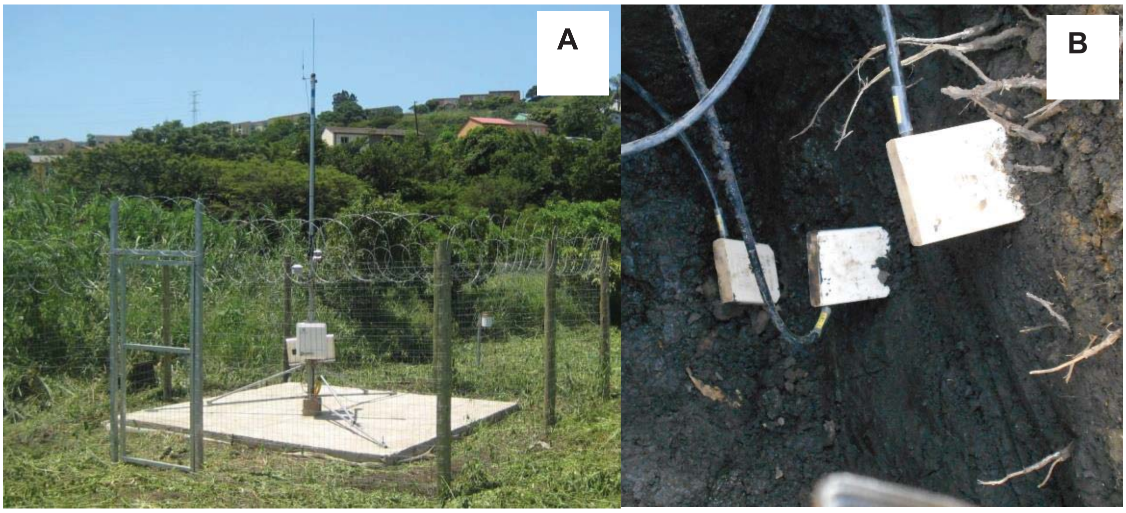

Figure 3.6 Automated weather station installed adjacent to the field experimental site at Newlands-Mashu (A) and the CS 650 soil water reflectometers inserted at different depths (0.3, 0.6 and 0.9 m)

Crop evapotranspiration (Eta) was calculated as a product of crop factors (Kc) and reference evapotranspiration (grass ETo) according to FAO (2015) see equation 3.2 below:

$$ETa = ETo \times Kc \qquad \text{Equation 3.2}$$

Banana crop factors for a humid sub-tropical climate like Durban were obtained from FAO (2015) and those for taro were obtained from Fares (2008).

3.2.5 Crop growth and yield

Data was collected randomly from crops within the inner quadrant leaving one row from the border of the field as shown in Figure 3.7.

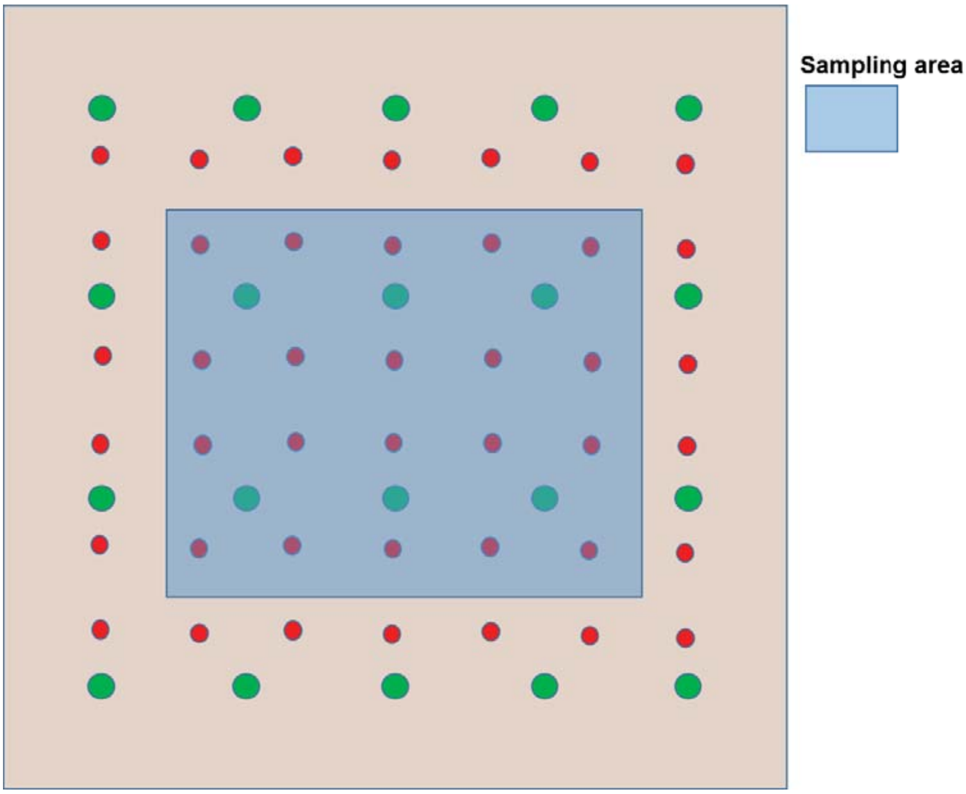

Figure 3.7 Sampling area from which all the crop growth, soil and leachates data was collected

Banana growth data measured during the vegetative stage include plant height, leaf area index (LAI) and chlorophyll content at three monthly intervals. Plant height was measured from the bottom of the pseudostem to the bottom part of the third uppermost leaf. Chlorophyll content was measured using a CCM 200 meter (Optisciences Inc, USA). Leaf area index was determined according to methods by Ghoreishi et al. (2008). Leaves for plant tissue nutrient analysis were collected from the third upper mature leaf. There was variability in flowering within the field as some plants flowered earlier than others. As such a first sampling was done at 10% flowering and the second sampling took place at more than 50% flowering. The leaf sample was taken midway and on both sides of the petiole. The samples collected were dried at 70°C for 72 hours and were ground to pass a 1 mm sieve before being taken to the Fertility and Advisory Services, Cedara for plant tissue analysis. The banana main crop was harvested 18 months after planting and the first ratoon crop was then harvested 33 months after planting. Yield parameters (number and mass of true fingers, bunch mass and peduncle mass) were used to calculate total yield according to Equation 3.1 below:

$$\textbf{Yield} = \textbf{Number of fruits bunch}^{-1} \times \textbf{bunches ha}^{-1} \times \textbf{mass of each fruit} \qquad \textbf{Equation 3.1}$$

Fresh mass was determined soon after harvest and each different plant part (pseudostem, leaves and bunch) was then sub sampled to determine dry mass since bananas are very succulent. Dry mass was determined by drying the sub samples in the oven at 70°C until a constant mass was attained. Total dry mass was determined by multiplying the proportion of dry mass to fresh mass by the total fresh mass.

Taro plant growth parameters measured included plant height, leaf area index (LAI), vegetative growth index (VGI) and chlorophyll content. Plant height in taro was measured from the base of the plant to the apex. The VGI was determined according to the equation 3.2 below:

$$\textbf{VGI} = [(\textbf{LAI}*\textbf{Plant height})/100] - (\textbf{suckers} + \textbf{stolons})^2 \qquad \textbf{Equation 3.2}$$

Fresh mass was measured from the harvested taro corms and these were dried to determine dry yield. The corms were dried in the oven at 70°C for 72 hours and the mass was measured repeatedly until a constant dry mass was attained as done to banana.

3.2.6 Installations

3.2.6.1 Piezometers and wetting front detectors

Piezometers were installed at 1 m depth (Figure 3.8) within the plots and above and below the plots. However, water could not be detected in some of the piezometers (below the field near the river) so more piezometers were installed to 2.5 m depth as shown in Figure 3.9 and each piezometer was coded according to Figure 3.8 colour codes. Ground water level was measured using a homemade water sensing device. The device is inserted into the piezometer and lights an indicator upon reaching water level. The water level is then determined by measuring the length of the cable from the ground level to the end of the sensor. A water sample was also collected from the piezometers and analysed for mineral nutrients (NO^{-}_{3}-N, PO_4^{3-}-P and NH_4^+-N) according to standard methods (APHA, 2005).

Wetting front detectors (WFDs) were installed at 0.3 and 0.5 m depths within a 0.2 m radius of both the banana and taro plants to collect soil water within the root zone (Figure 3.10). In the event of a rainfall event or an excess of irrigation they pop up as illustrated in Figure 3.10. The leachates were after heavy rainfall events and the when the indicator pop up in response to irrigation events. Leachates were analysed for NO^-_3-N, PO_4^{3-}-P and NH_4^+-N according to standard methods for wastewater analysis (APHA, 2005). Wetting front detectors responds to soil water potential of about 3kPa hence during saturation they remain full.

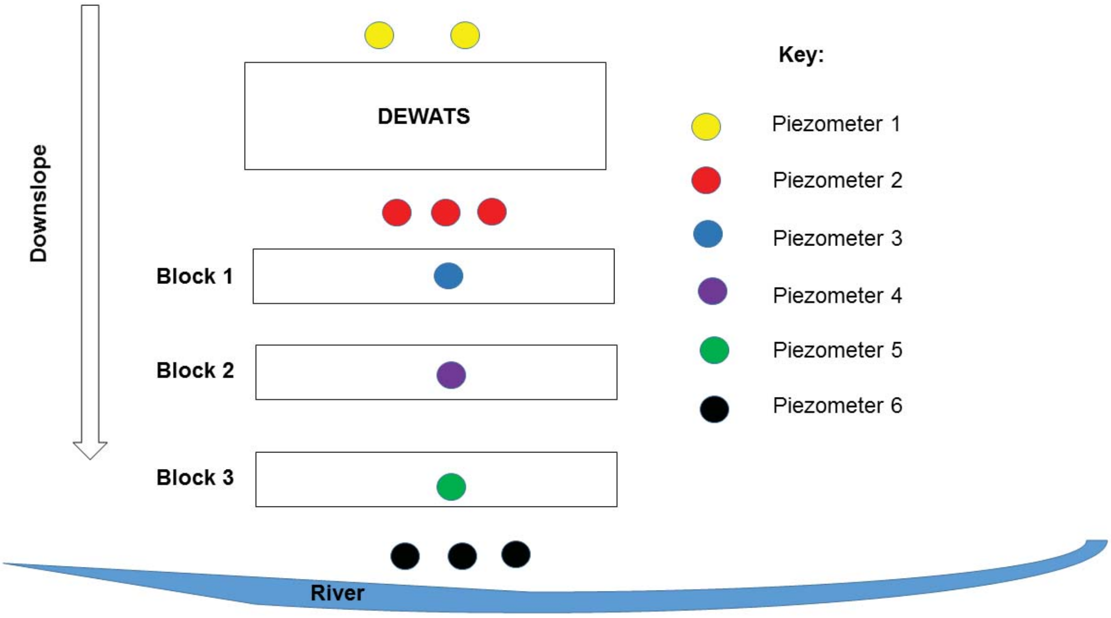

Figure 3.8 Field plan showing layout of the piezometers installed at 1 m depth

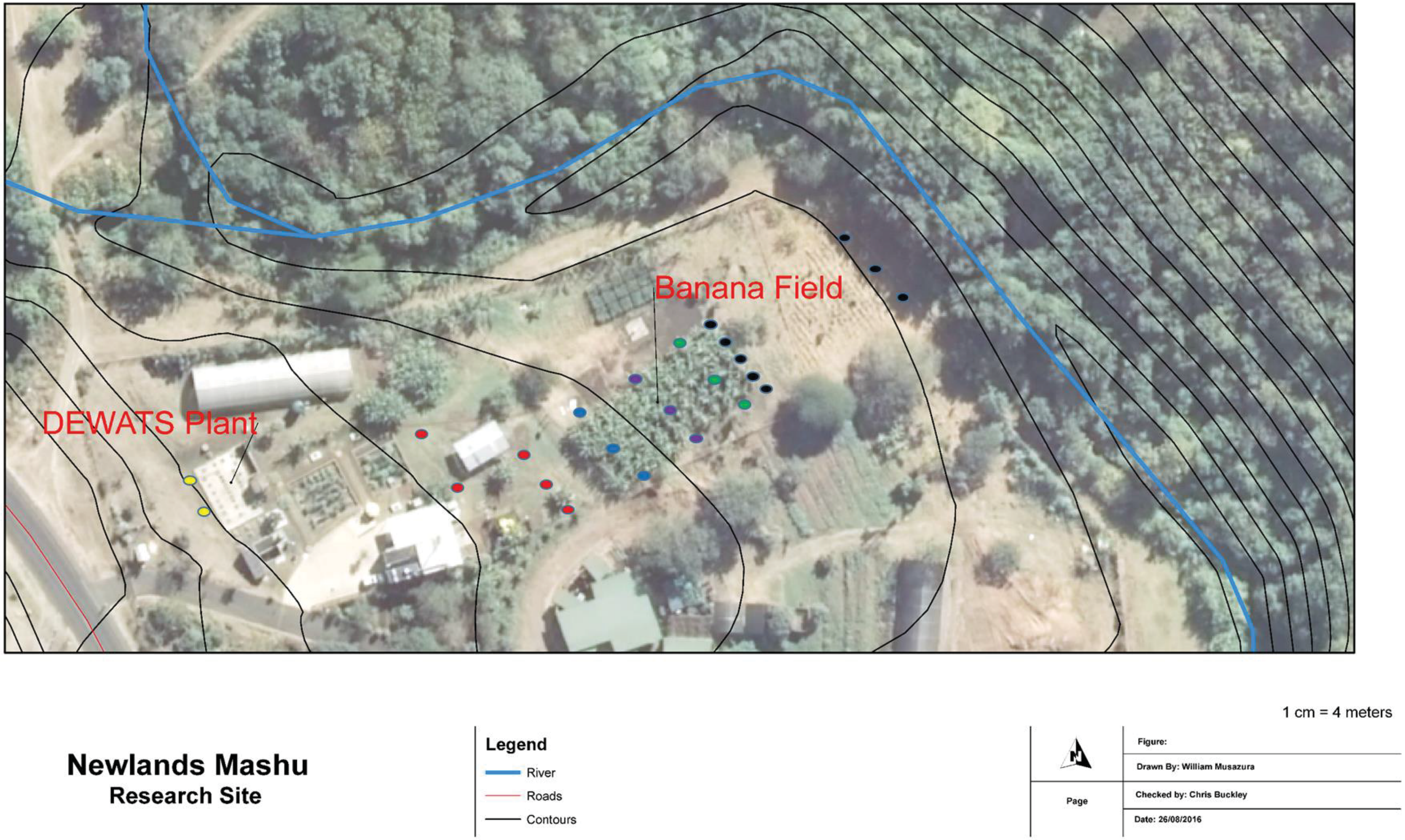

Figure 3.9 Site map showing locations of the piezometers (showed by coloured dots), river, DEWATS plant and the experimental field

Figure 3.10 Wetting front detectors at (A) 0.3 m and (B) 0.5 m; collection of leachates from the piezometers at 1 m to collect leachates from (C) within and (D) below the root zone

3.3 Results

3.3.1 Soil analyses before planting

The soil at the experimental site is classified as Sepane form, Katdoorn family (Se 1210) (Soil Classification Working Group, 1991); an Aquic Haplustalf, according to the USDA Soil Taxonomy (Soil Survey Staff, 2003). The results indicated in Table 3.2 show very slight differences between the two depths in most of the soil parameters. Phosphorus was clearly higher in the upper layer and being an immobile element it was expected to decrease with depth. Manganese was higher in the lower layer than in the top layer which was an exception when compared with the other minor elements. The soil has a clay loam texture and as such it was expected to retain water and solutes for plant uptake.

Table 3.2 Soil properties of the Sepane soil at the Newlands-Mashu field site

Soil parameter	Depth (m) 0-0.3	 0.3-0.6
Clay (%)	35	43
Silt (%)	42	31
Sand (%)	23	26
Organic C (%)	2.9	2.6
Total N (%)	0.29	0.27
Extractable P (mg kg^{-1})	39.3	11.9
Exchangeable K ($cmol_c$ kg^{-1})	0.30	0.18
Exchangeable Ca ($cmol_c$ kg^{-1})	12.2	8.1
Exchangeable Mg ($cmol_c$ kg^{-1})	7.8	7.4
Exchangeable acidity ($cmol_c$ kg^{-1})	0.05	0.07
Total cations ($cmol_c$ kg^{-1})	20.4	15.7
Acid saturation (%)	0	0
pH (KCl)	5.2	5.1
Zn (mg kg^{-1})	22.8	6.9
Mn (mg kg^{-1})	3.7	11.1
Cu (mg kg^{-1})	9.5	5.8

3.3.2 Leachate and after harvest soil analysis

Emphasis have been made on the analysis of leachates from the WFDs near banana plants rather than those close to the taro plants. The changes in PO_4^{3-}-P, NO_3^--N and NH_4^+-N in banana plants from September 2014 to August 2016 are described in Figure 3.11. Samples collected from September 2014 to October 2014 showed significantly higher concentrations of NO_3^--N due to high nitrification rate in disturbed soils after installation of wetting front detectors. During the study (October 2014 to April 2016) NO_3^--N was generally below 50 mg L^{-1} in all the treatments. However, very high values were recorded at 0.3 m for DEWATS effluent treatment in July 2016 (78 mg L^{-1}) due to large outlier (57.1 mg L^{-1}) recorded in block 1. Even from a period between April and August 2016, the NO_3^--N concentrations remained constant, sometimes higher at 0.3 m depth regardless of high rainfall events experienced in July 2016 (see Figure 3.25). This explains that NO_3^--N leaching due to rainfall was negligible as stated by Musazura et al. (2015) previously.

During the study NH_4^+-N was generally below 10 mg L^{-1} from September 2014 to December 2015. High concentrations of NH_4^+-N (> 10 mg L^{-1}) were observed in Tap water + fertiliser treatment at 0.3 m (March 2016), all treatments (April 2016) and Tap water + fertiliser treatment at 0.5 m (July 2016) due to variation within the data collected.

With regards to PO_4^{3-}-P dynamics over time, the leachates ranged > 16 mg L^{-1}, with the highest value of 15.9 mg L^{-1} being recorded in DW treatment at 0.3 m depth (10 December 2015). However, over time the concentrations remained constant and end up < 5 mg L^{-1} from a period between 29 April 2016 and 8 August 2016 despite the use of ABR effluent with more concentrations of PO_4^{3-}-P compared to HFW effluent. Even there were high rainfall events in July as described earlier (see Figure 3.25), PO_4^{3-}-P concentrations remained constant. This is expected since their movement in a clay loam soil type is slower than NO_3^--N, reported to not have leached much earlier. The data collected between October 2015 and March 2016 shows a lot of variability within blocks as described by large standard error bars, implying that the dynamics were different between contrasting blocks.

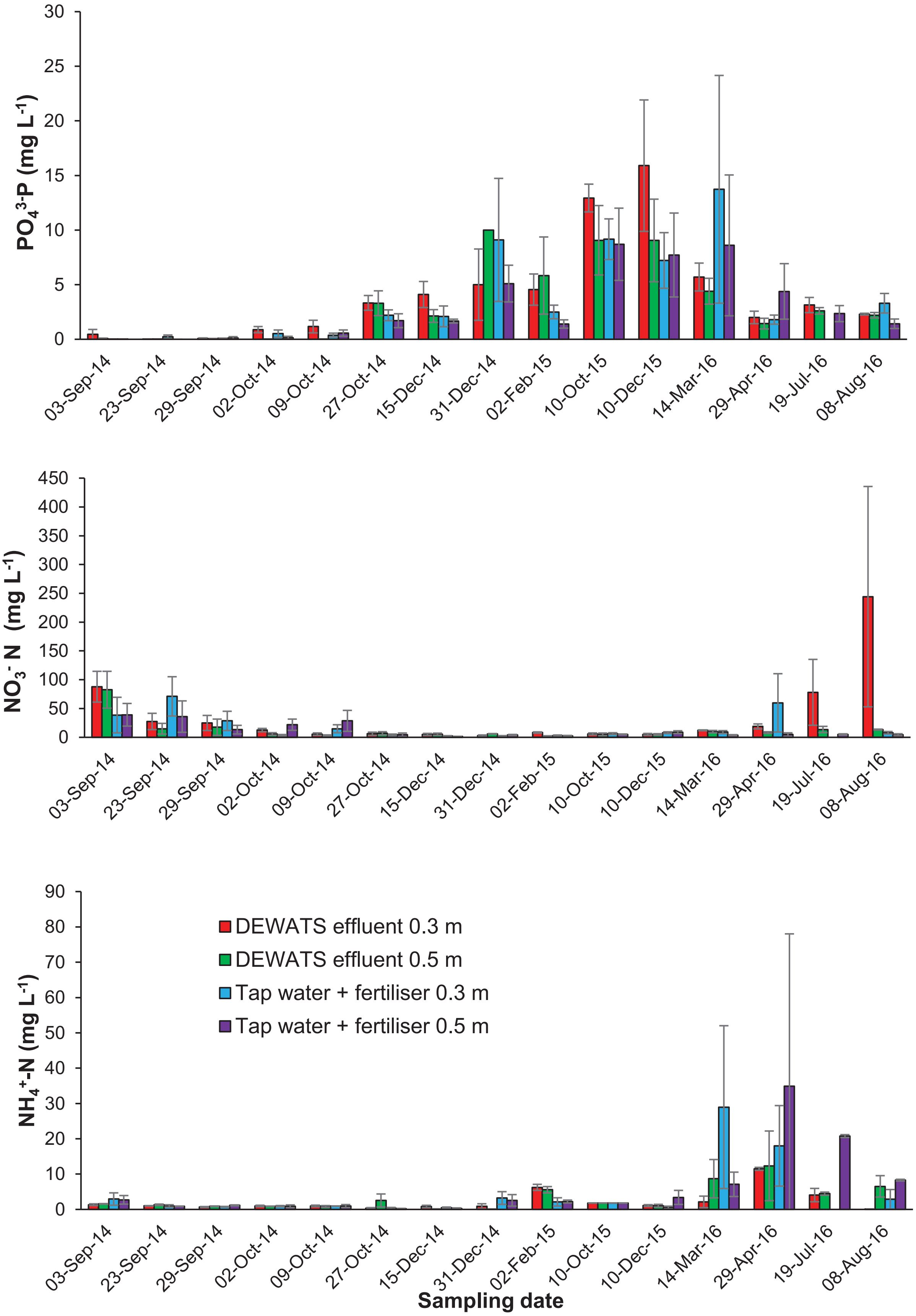

Figure 3.11 The NH_4^+-N in leachates from the wetting front detectors at 0.3 and 0.5 m depths near the banana plants between September 2014 and August 2016

For taro (Figure 3.12) the NO_3^--N was much higher than the NH_4^+-N in the leachates as was the case from the banana plants.

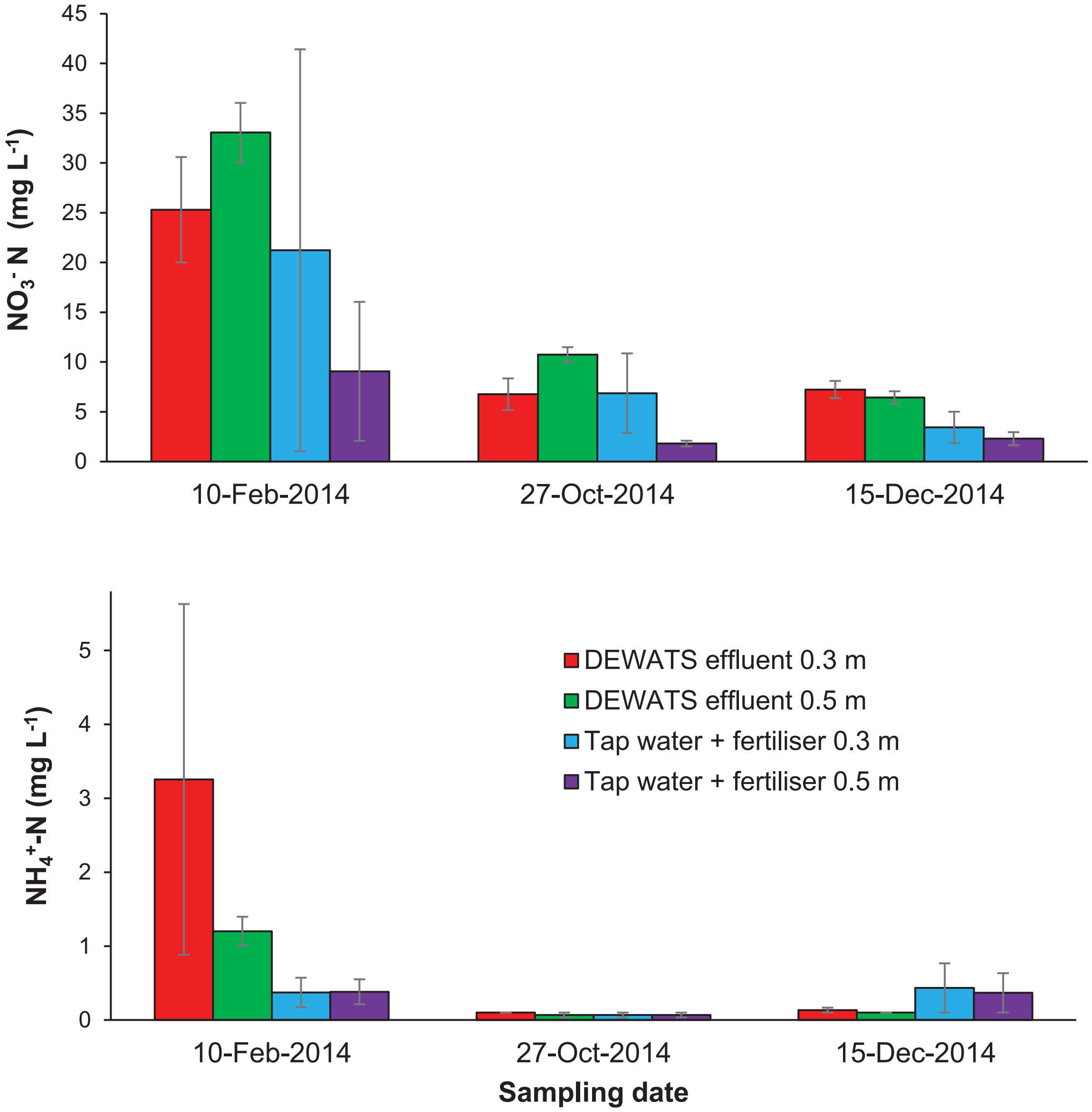

Figure 3.12 The NO_3^--N and NH_4^+-N in leachates from the wetting front detectors at 0.3 and 0.5 m depths near the taro plants in the three experimental blocks between October and December 2014

Figure 3.13 describes the average nutrient concentrations for NH_4^+-N, NO_3^--N and PO_4^{3-}-P collected from wetting front detectors during the entire experimental period. Higher NO_3^--N concentrations were observed in DEWATS effluent irrigation at 0.3 m compared to 0.5 m depth since the movement of solutes in a clay soil type of Newlands Mashu is generally slower as reported by Musazura et al. (2015) with respect to Swiss chard experiments. Highest NH_4^+-N value (19.7 mg L^{-1}) was observed in Tap water + fertiliser treatment at 0.3 m compared to other treatments. The mean deviation was very large and median values for all treatments were below 2 mg L^{-1} and there was an outlier which contributed to large variation (Figure 3.14).

Low concentration of < 2 mg L^{-1} for NH_4^+-N in leachates is expected in clay soil due to its capacity to retain cations. In comparison to NH_4^+-N results, NO_3^--N concentrations in leachates were generally higher (> 10 mg L^{-1}) as negative charged NO_3^--N repel from negatively charged soil colloids, allowing them to move passively in soil solution. No significant differences in PO_4^{3-}-P was observed between the two irrigation treatments and soil depths; the concentrations were generally < 5 mg L^{-1}. Regardless of PO_4^{3-}-P applied to the DEWATS effluent, the results remained comparable to Tap water + fertiliser treatment, implying that the clay soil could fix PO_4^{3-}-P as observed by Bame et al. (2013), leaving little amounts detectable in leachates.

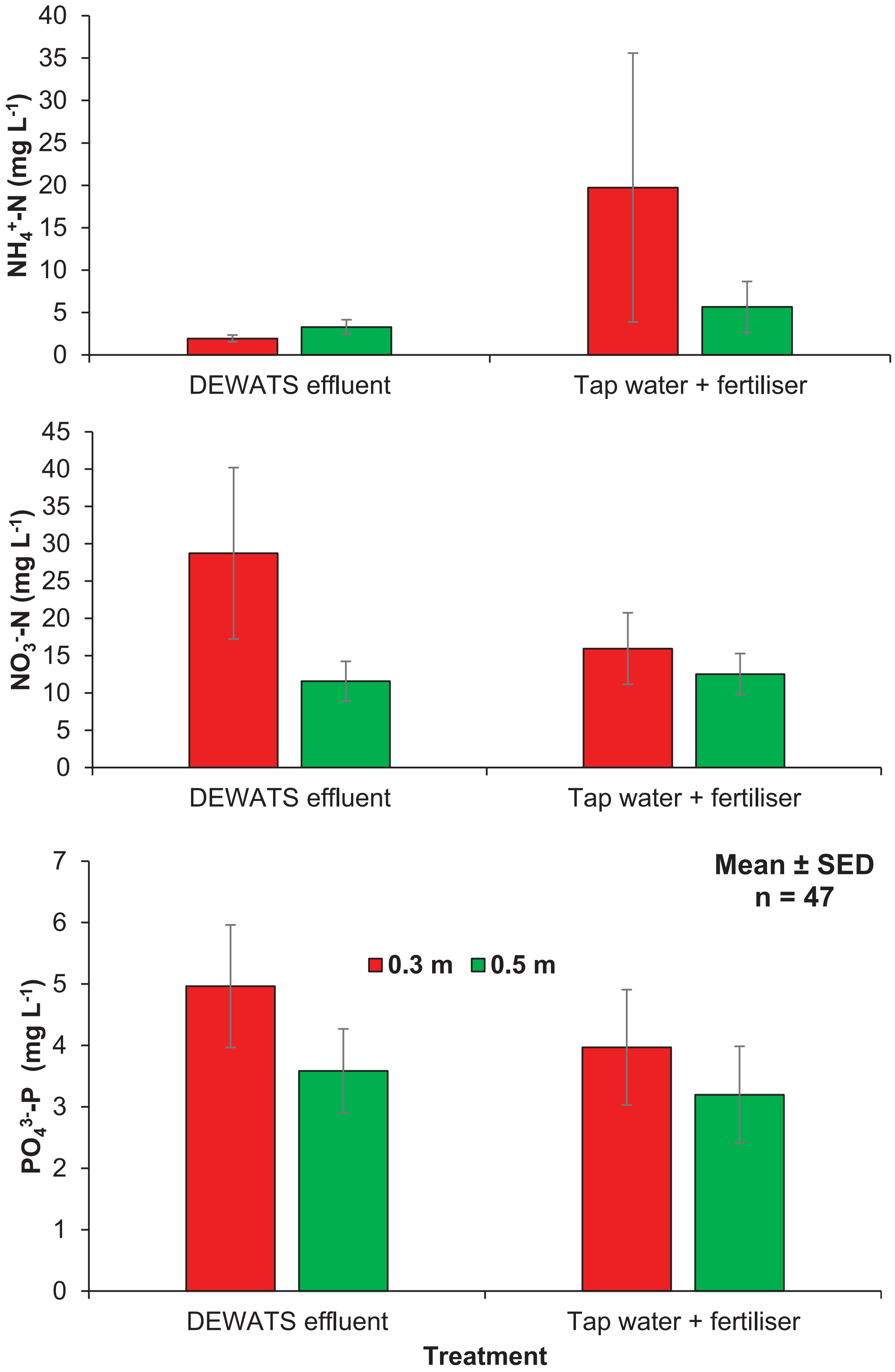

Figure 3.13 Concentrations of NH_4^+-N, NO_3^--N and PO_4^{3-}-P collected from wetting front detectors at different depths (0.3 and 0.5 m) between the two irrigation treatments showing the mean ± standard error of deviation (SED) and median values during the experimental period

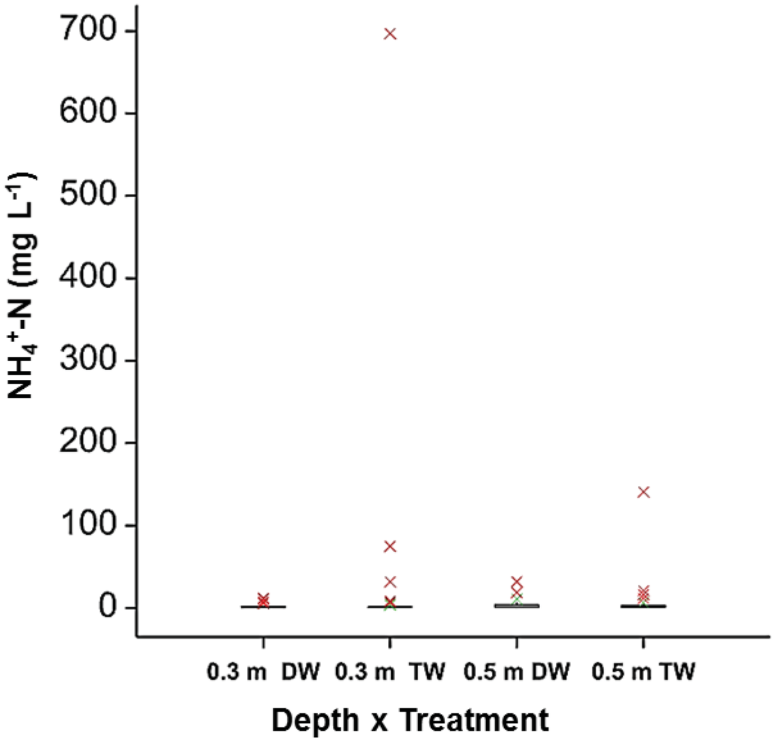

Figure 3.14 Boxplots for the NH_4^+-N concentrations measured during the experimental period between the two irrigation treatments (DEWATS effluent; DW vs Tap water + fertiliser; TW) and two soil depths (0.3 m and 0.5 m)

The concentrations of extractable NH_4^+-N, NO_3^--N and P from the soil analysis results after harvesting are presented in Figure 3.15. High concentrations of extractable in comparison to leached NH_4^+-N were observed. This explains the capacity of clay soils at Newlands in retaining NH_4^+ in their soil colloids. The opposite observation with regards to NO_3^--N was made; low concentrations of extractable were observed in comparison to free leaching NO_3^--N, implying that they are not adsorbed on the soil surface hence available for plant uptake. Very high extractable P were observed in top soil (0.3 m) compared to lower depths. This is because clay soils have a high P sorption capacity as described by Bame et al. (2013) and Levy et al. (2011). It is very important to agriculture as nutrients are retained in the soil, making them available for crop uptake.

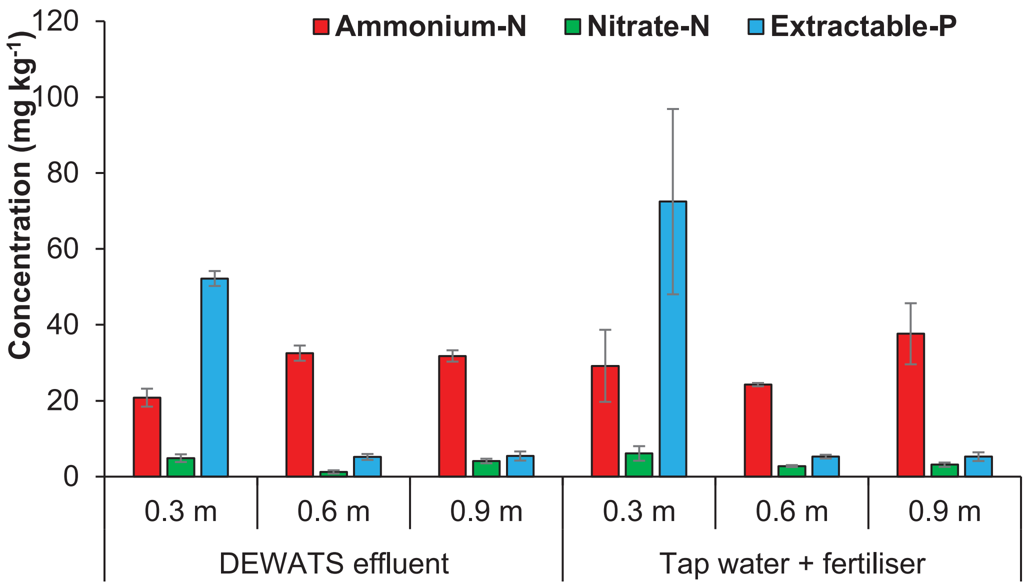

Figure 3.15 Amounts of NO_3^--N, NH_4^+-N and Extractable P in soil at three depths (0.3, 0.6 and 0.9 m) and two irrigation treatments measured after harvest of the banana crop at 18 months after planting

Figure 3.16 describes the concentrations of NO_3^--N, NH_4^+-N and PO_4^{3-}P from piezometers sampled during the experimental period. During the study leachates, could not be collected in some of the piezometers (Above the DEWATS from 27 October 2014 to 31 December 2014; Between the DEWATS and the experimental field on 27 October 2014). For the piezometers installed out of the experimental field, no sample was collected during the experimental field since it was not deep enough (1 m) to rich the water table level. Analysis of leachates showed the high concentrations of NH_4^+-N (above 10 mg L^{-1}) were detected above the DEWATS on 02 February 2015 (17.4 mg L^{-1}) and between the DEWATS and experimental field on 15 December 2014 (27.2 mg L^{-1}) and 31 December 2014 (11.35 mg L^{-1}).

High NO_3^--N concentrations were measured between the DEWATS and the field on 15 October 2016 (75 mg L^{-1}) and 15 December 2016 (36.4 mg L^{-1}). Some values > 10 mg L^{-1} were recorded in block 1 on 15 October 2015 (16.9 mg L^{-1}), block 3 on 27 October 2014 (21.4 mg L^{-1}), 15 December 2015 (13.9 mg L^{-1}) and 14 March 2016 (11.9 mg L^{-1}).

In the same figure (Figure 3.17) high concentrations of PO_4^{3-}P (> 10 mg L^{-1}) were observed above the DEWATS on 02 February 2015 (56.4 mg L^{-1}), between the DEWATS and the field on 15 December 2015 (14.9 mg L^{-1}), 14 March 2016 (10.9 mg L^{-1}), block 1 on 31 December 2014 (56 mg L^{-1}), block 2 on 15 December 2014 (10.4 mg L^{-1}), 31 December 2014 (10.5 mg L^{-1}) and 13 March 2016 (21.4 mg L^{-1}). In block 3 the highest concentration was recorded on 31 December 2014 (35 mg L^{-1}).

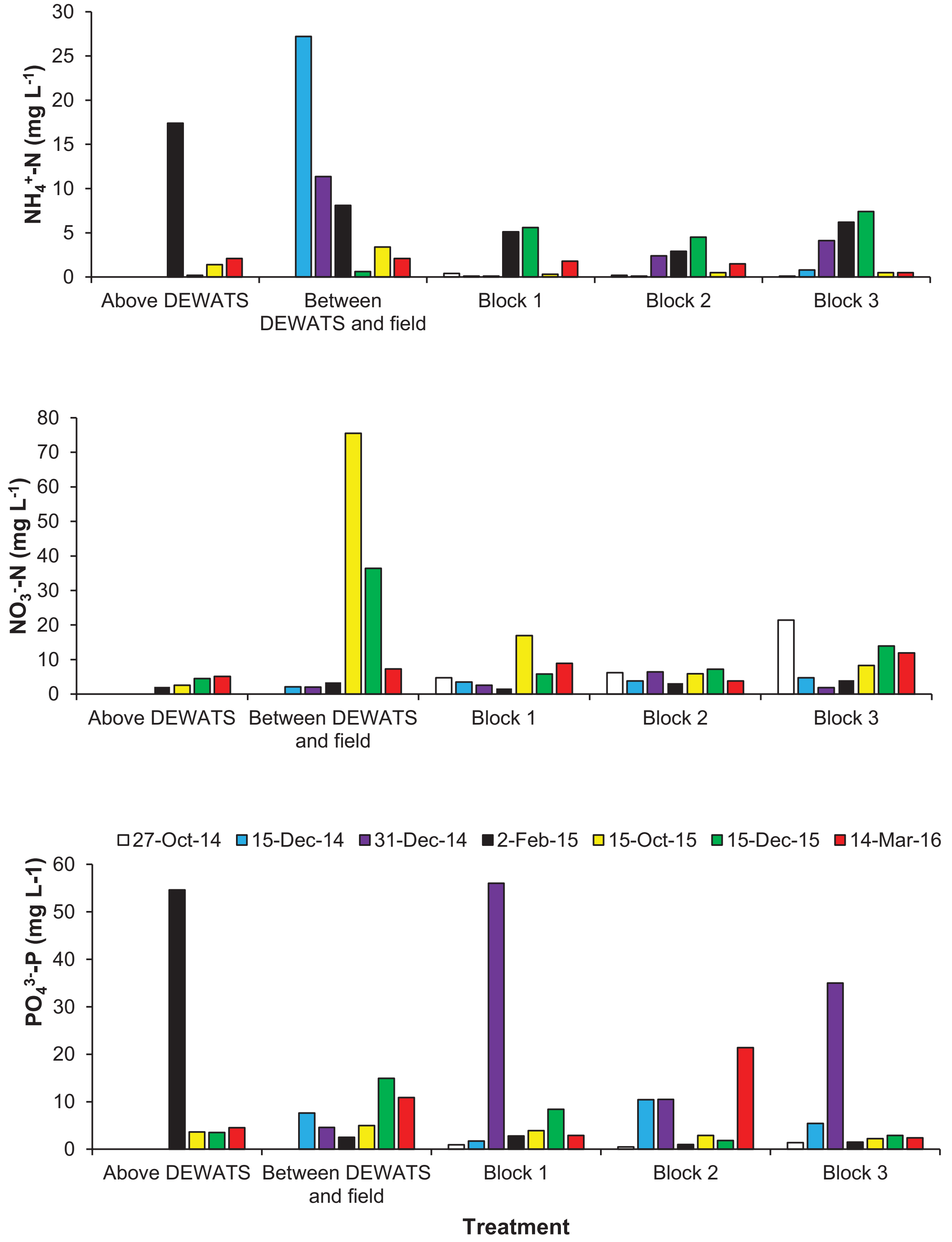

Figure 3.16 Concentrations of NO_3^--N, NH_4^+-N and PO_4^{3-}-P in leachates from piezometers sampled between October 2014 and March 2016

The mean ± SED and median values for the NO_3^--N, NH_4^+-N and PO_4^{3-}-P for the leachates collected in piezometers in different locations on the experimental site over the experimental period are described in Figure 3.17. Higher NH_4^+-N concentrations (8.8 mg L^{-1}) were recorded between the DEWATS and the experimental field in comparison to values observed in the experimental field (block 1;1.9 mg L^{-1}, block 2; 1.7 mg L^{-1} and block 2; 2.8 mg L^{-1}). Even though the mean value for NH_4^+-N concentration was 8.8 mg L^{-1}, the median value was < 10 mg mg L^{-1} (Figure 3.18).

The mean NO_3^--N value was high between the DEWATS and the field (21.1 mg L^{-1}). However, this was due to high variation of the data collected as the median value was 5.4 mg L^{-1}.

No significant differences on PO_4^{3-}-P concentrations recorded across all the treatments. The following mean values were recorded; above DEWATS (16.6 mg L^{-1}), between DEWATS and experimental field (7.6 mg L^{-1}), block 1 (10.9 mg L^{-1}), block 2 (6.9 mg L^{-1}) and block 3 (7.3 mg L^{-1}). However, the data was variable in all treatments except between DEWATS and experimental field as the median values were 4.1 mg L^{-1} (above DEWATS), 2.9 mg L^{-1} (block 1 and 2) and 2.4 mg L^{-1} (block 3).

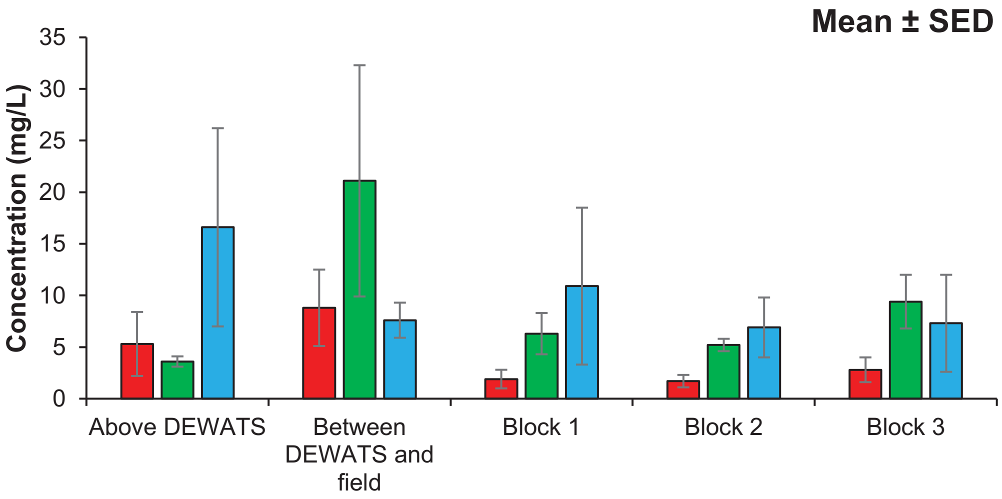

Figure 3.17 Nutrient concentrations for NH_4^+-N, NO_3^--N and PO_4^{3-}-P in different sampling positions of the piezometers (1 m deep) showing the mean ± SED and median values during the experimental period

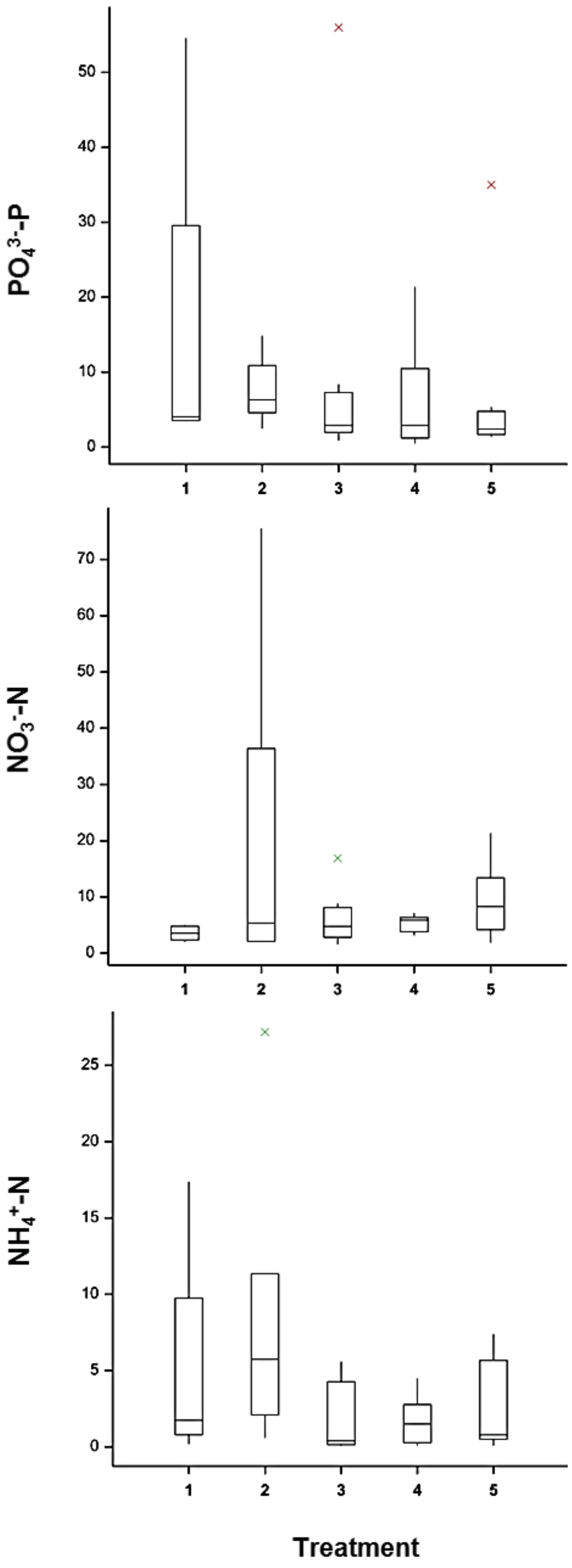

Figure 3.18 Boxplots for the NO_3^--N, NH_4^+-N and PO43$^-$P in different piezometers (1=Above DEWATS plant, 2=Between DEWATS plant and field, 3=Block 1, 4=Block 2, 5=Block 3) referred to as treatment

3.3.3 Climatic variables at Newlands-Mashu.

Climatic variables (relative humidity, air temperature and canopy temperature) are shown in Figure 3.19. Over the growing season, measured ambient temperatures were generally between the range of 7.9 to 30.5°C while the canopy temperatures were below 35°C, which are favourable conditions for the growth of both taro and banana.

3.3.4 Growth and yield variables

Taro growth variables (vegetative growth index, plant height and LAI) during its vegetative stage are shown in Figure 3.20 (September to November 2014 and January 2016 to March 2016). Irrigation with DEWATS effluent was characterised by higher growth (LAI and vegetative growth) compared to tap water + fertiliser. This was due to N and P supplied from the effluent since fertiliser in tap water + fertiliser treatment was only applied to banana plants. Lower growth in taro compared to the previous season was observed due to slow crop establishment due to some intermittent breakdown on irrigation system. Taro crops are very sensitive to water stress (Mabhaudhi et al., 2013) so they hardly establish in dry conditions.

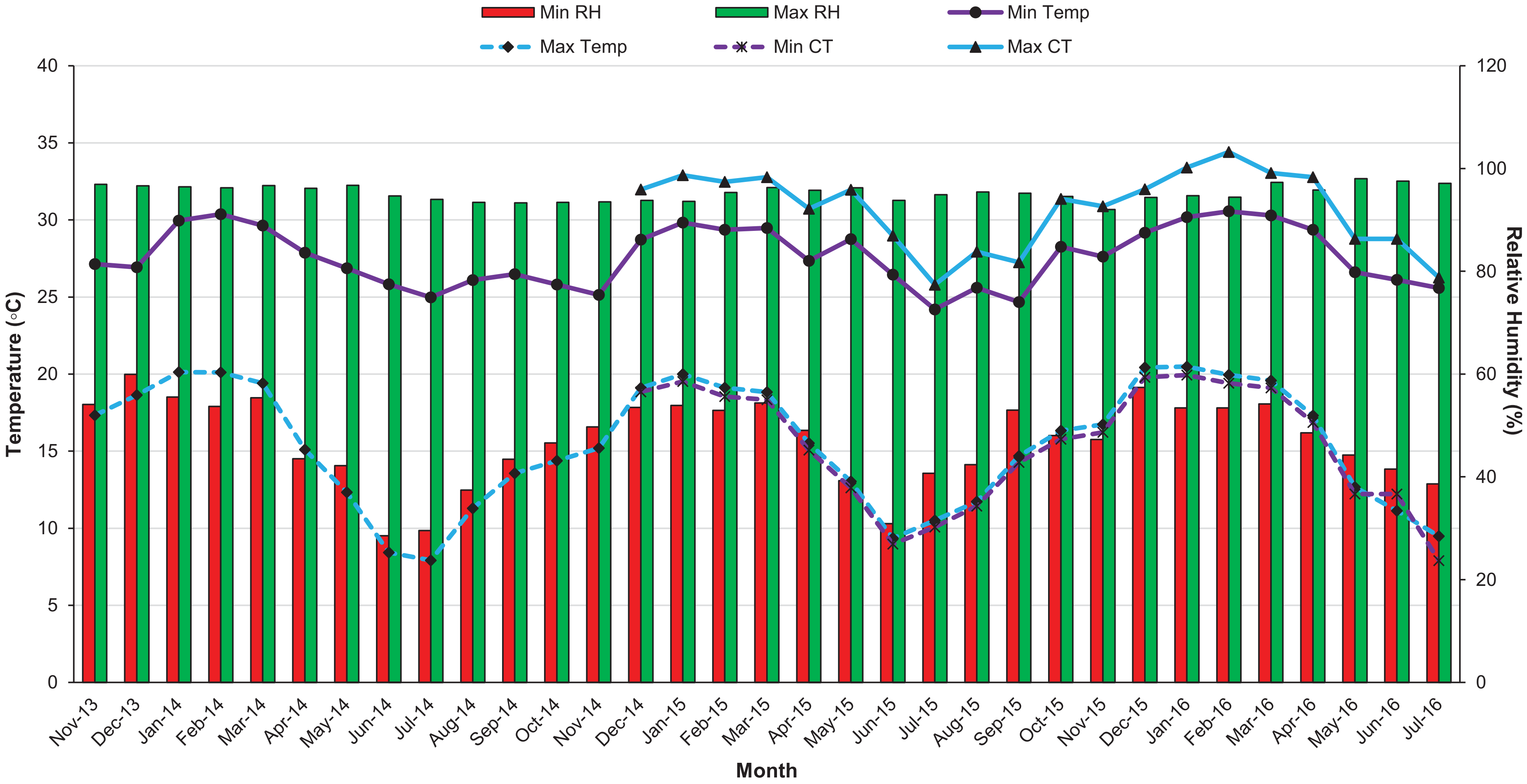

Figure 3.19 Monthly weather data during the 33 months experimental period showing the temperatures (maximum and minimum), canopy temperature (CT) and relative humidity (minimum and maximum)

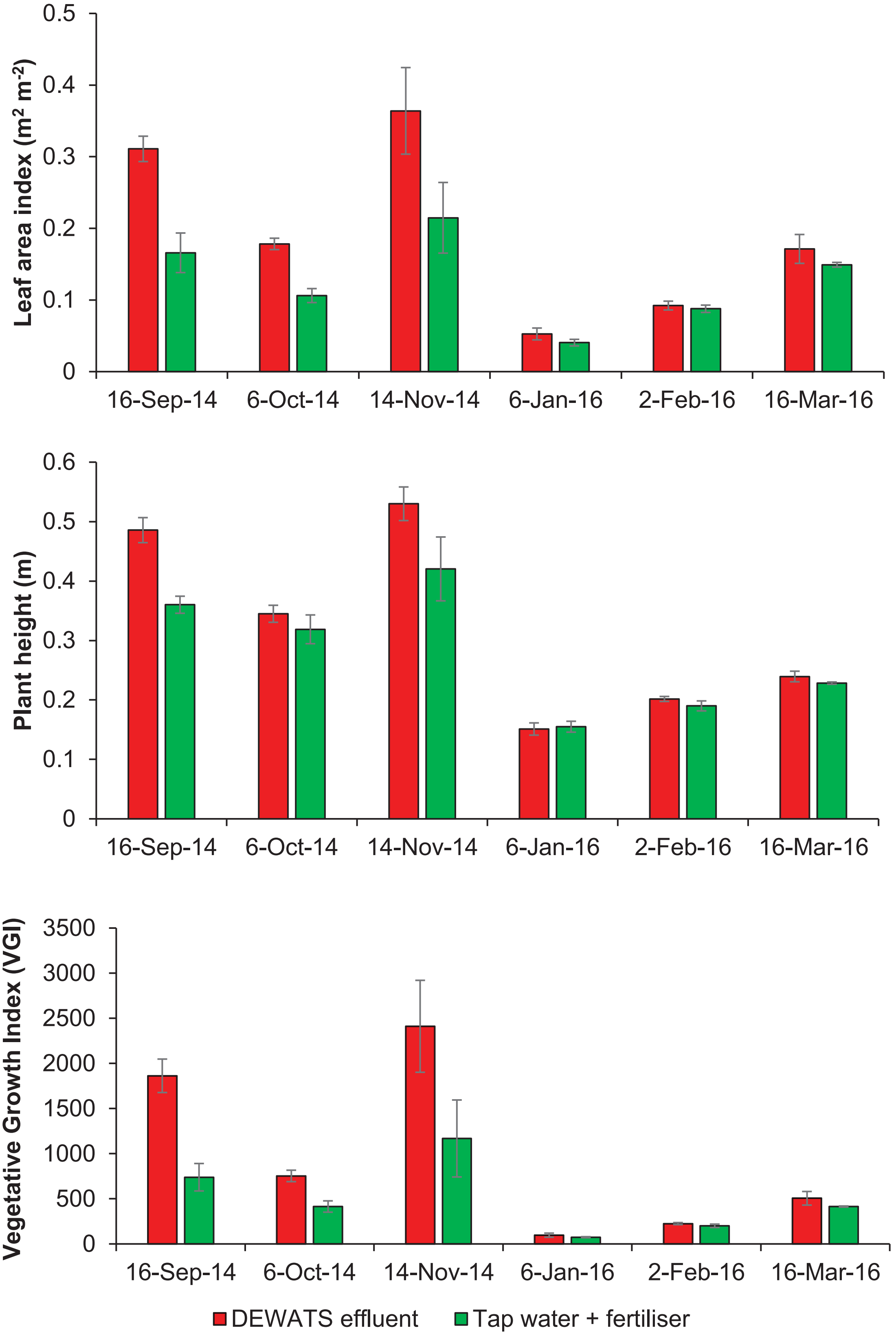

Figure 3.20 Growth indicators (averaged (n=3 ± SED)) (plant height, vegetative growth index and leaf area index) for taro plants after irrigation with tap water plus fertiliser and DEWATS effluent over two cropping seasons

The overall results for plant height, chlorophyll content index and LAI for the banana plants for the period November 2013 to April 2015 (main crop) and February 2015 to November 2015 (1st ratoon) are presented in Figure 3.21. The 1st ratoon crop had higher growth rates (plant height and LAI) compared to the main crop. The banana showed a gradual increase in growth (plant height and LAI) up to the ninth month and then a sharp increase to twelve months. The chlorophyll content index was variable across the seasons between the two crops (main crop and 1st ratoon). Chlorophyll content was generally higher in effluent-irrigated banana (main and ratoon crop) especially in the summer seasons. Chlorophyll content in crops is affected by different climatic and management factors such as nitrogen application (Sevik et al., 2012) and also lower winter temperatures in subtropical regions reduces banana chlorophyll content (Robinson and Saúco, 2010). In this study nitrogen was applied monthly in the tap water + fertiliser treatment and in the effluent treatment it was supplied from the effluent constantly. Higher chlorophyll content in the DEWATS effluent treatment in summer was due to higher temperatures, rainfall and a constant supply of nutrients (N and P) during the entire crop growing season. The period between 9 and 12 months after planting corresponded with the rainy period so the abundance of water shows the importance of water to the banana crop.

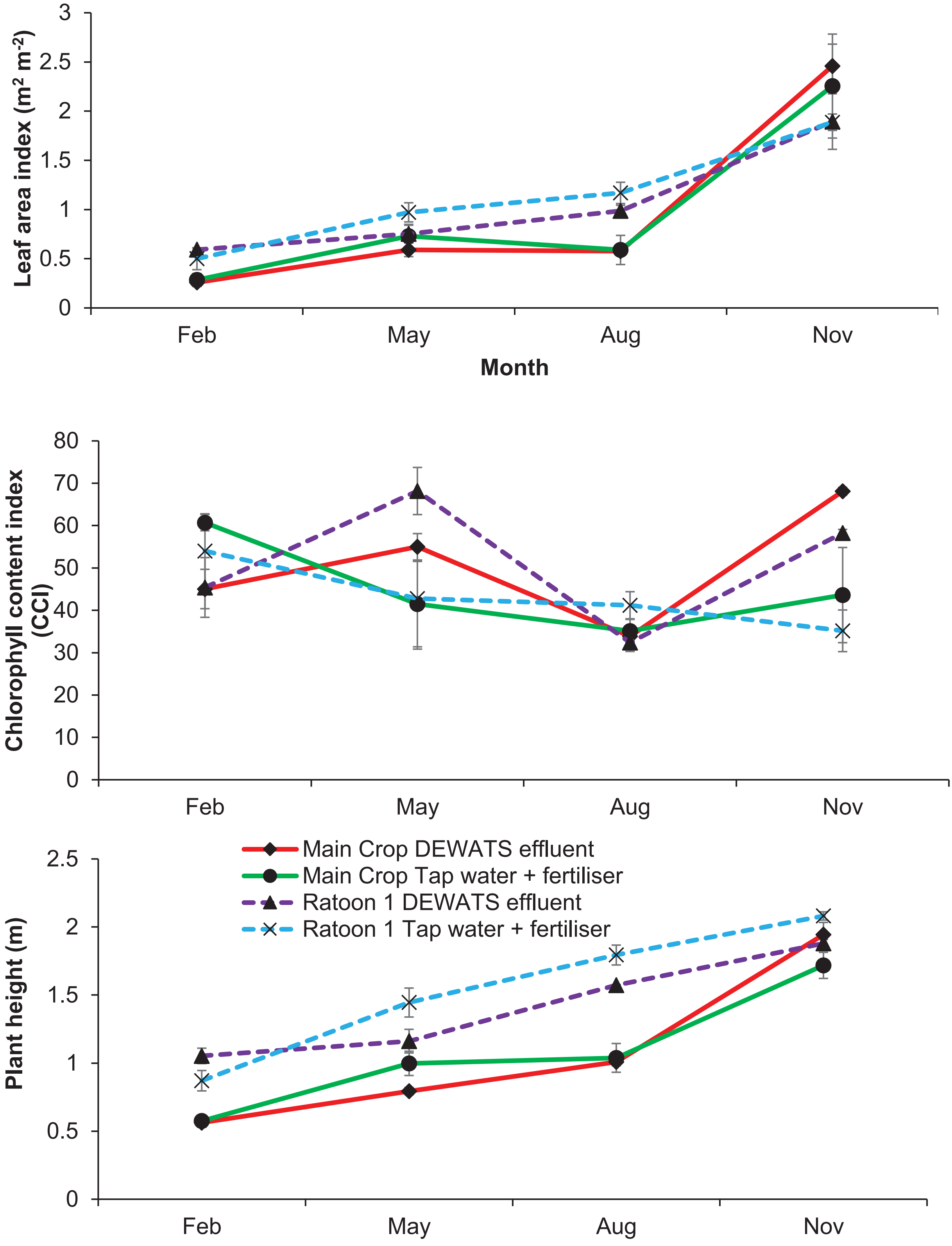

Figure 3.21 Vegetative growth indicators (plant height, chlorophyll content index and leaf area index) for banana plants (averaged (n=3 ± SE)) from tap water + fertiliser and DEWATS effluent from November 2013 to January 2016

Yield results (mass of each finger, bunch mass and number of true fingers per bunch) for the banana at 18 and 33 months after planting Figure 3.22. No significant differences in banana yield between the two irrigation treatments were observed during the first main crop. However, during the second planting tap water + fertiliser had higher yield compared to DEWATS effluent, despite large quantities of N applied through irrigation. One of the major factor reducing yield in banana is K deficiency (Robinson and Saúco, 2010). Furthermore, some of the symptoms related to K deficiency in banana; poorly filled banana fruits, lower number of fruits per bunch and thin fragile bunches were observed (Figure 3.23). Effective K must be applied before flowering and low K can also result in erratic flowering as observed on the trial. However, based on soil analysis results after first harvest, K fertiliser requirements in DEWATS treatment plots were very high (232 kg ha^{-1}) see Table 3.1. During the second cropping ABR effluent was used for irrigation, however could not meet the banana K requirements since more irrigation was applied after flowering, when the banana have attained their optimum K concentrations.

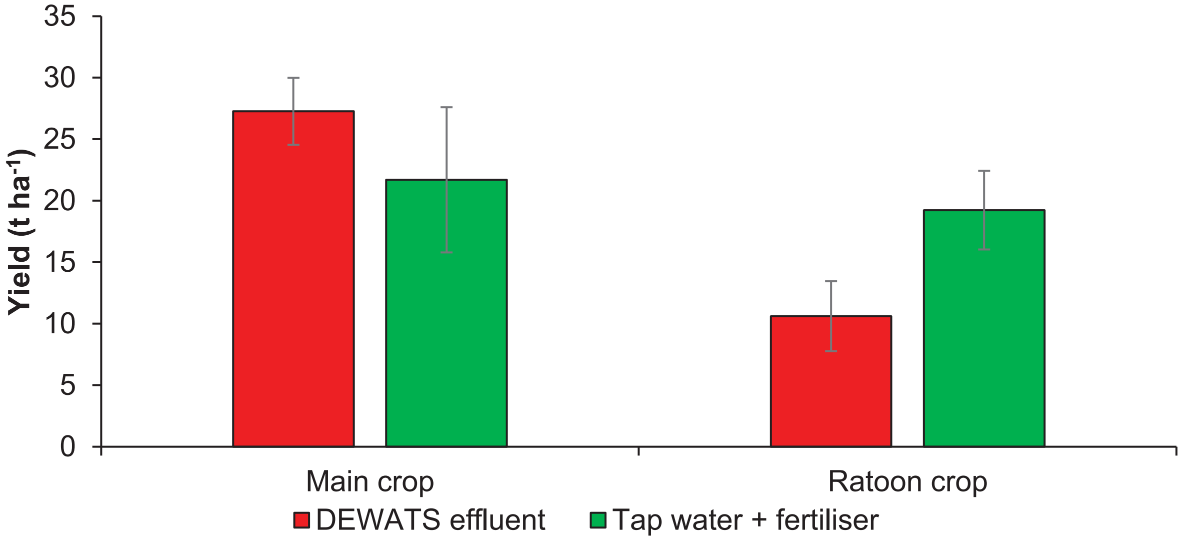

Figure 3.22 Yield results for the banana between 18 months after planting (main crop) and 33 months after planting (ratoon crop) between the two irrigation treatments (tap water + fertiliser vs DEWATS effluent)

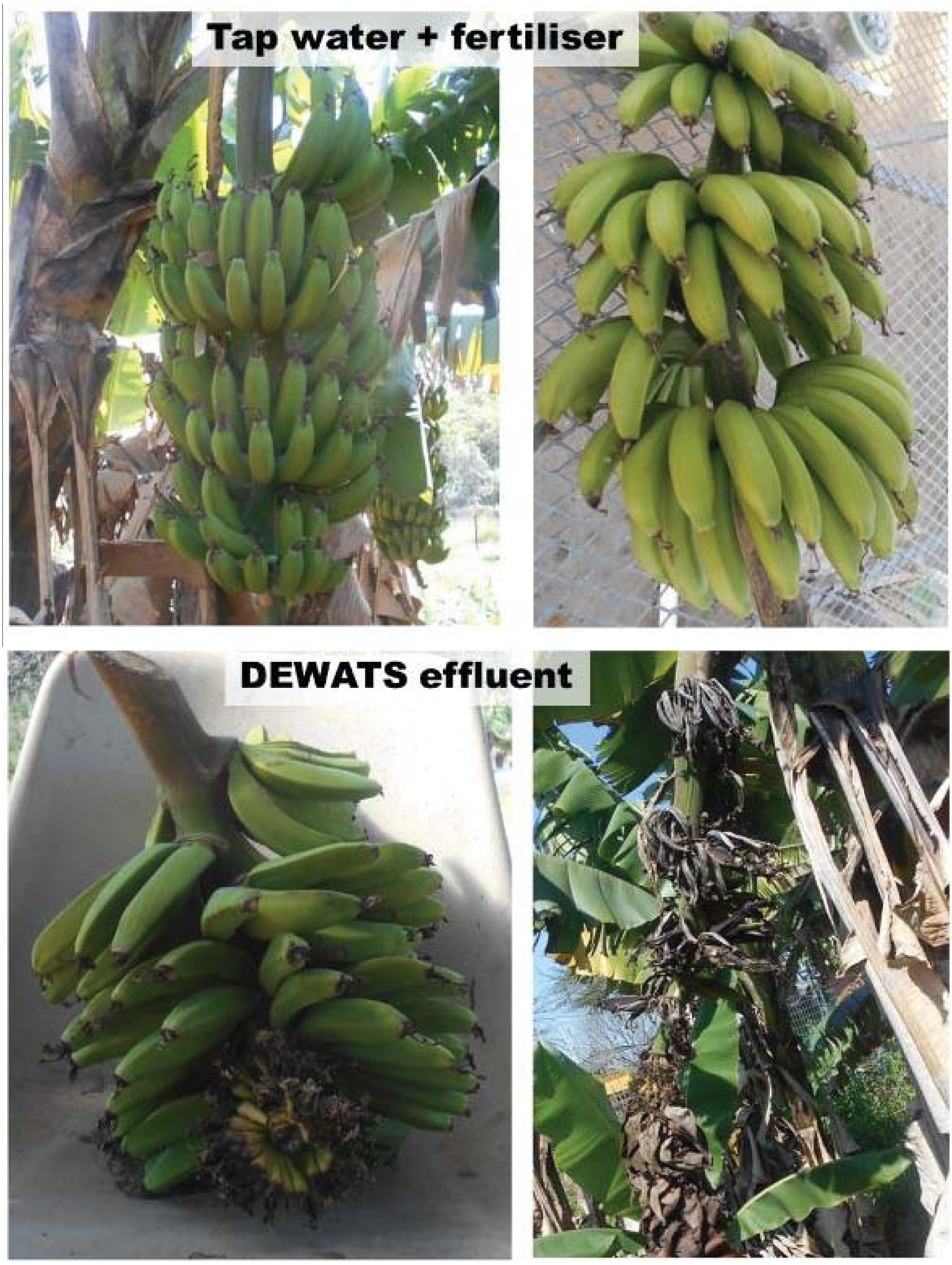

Figure 3.23 Comparing the banana yield and quality between the two irrigation treatments after harvesting the ratoon crop; pictures showing K deficiency effects

Taro yield results (fresh mass and dry mass) are shown in Figure 3.26. No significant difference in yield was observed between DEWATS effluent and tap water + fertiliser treatment (p>0.05) due to a higher standard errors of deviation variation in the tap water + fertiliser. Studies have shown that increasing nitrogen fertiliser application rate leads to prolific vegetative growth in taro (Hartemink et al., 2000) and an application of > 160 kg ha^{-1} of N gives high yields in taro (Mare, 2010) so we expected higher yields in DEWATS effluent treatment. Onwueme (1999) described corm and cormel initiation as driven by long days (especially in summer). During the second year taro yield was lower in both irrigation treatments, and this was consistent with results obtained from vegetative growth. Low vegetative growth reduces crop photosynthetic capacity and consequently reduced yields, furthermore, crop yields are driven by the number of yield sinks. In this study, low vegetative growth due to late establishment prolonged taro growth, pushing it away from summer. The crop was harvested end of July (winter) hence short daylength during the winter and retarded growth contributed to taro low yields.

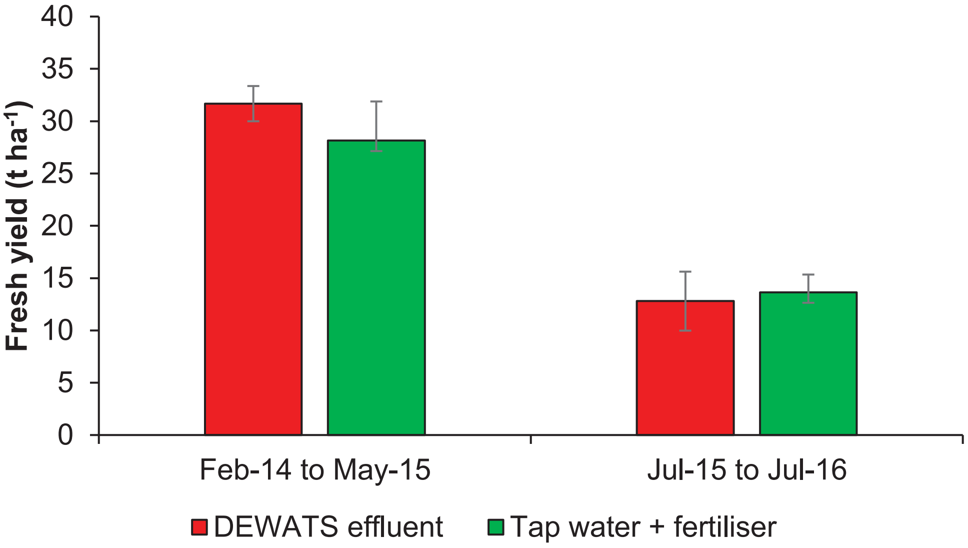

Figure 3.24 Yield results for the taro between the two irrigation treatments. Tap water: tap water + fertiliser; Effluent: horizontal flow wetland effluent

Generally, the level of macro and micro-nutrients was higher at 10% flowering than 50%. The values for both the effluent and tap water irrigation treatments were similar and consistent with respect to optimum nutrient levels for banana from other studies (Table 3.3). For example, recommended plant tissue nutrient levels of 3.5-4.5% N, 0.2-0.4% P and 3.8-5% K were reported for sampling leaf mid sections of banana plants in a production field in Hawaii (Silva and Uchida, 2000). These results are also consistent with typical leaf analysis for banana plants in the sub tropics (Appendix I). After flowering, photo-assimilates are transported to the reproductive parts (flowers) for fruit production (in this case towards bunch production). At the onset of flowering the nutrient levels were optimal for N and P but not for K. Potassium content ranged between 1.9 and 2.6% for both water and effluent treatments at 10 and 50% flowering which was considerably lower than the optimal requirement (3.1-4.0%) (Appendix I). Banana plants have a high demand for K and so the nutrient levels in the plant are expected to be very high. Leaf content of major plant nutrients did not differ between the effluent and the tap water irrigated plants at the respective flowering stages. The effluent supplied more than was required for banana growth in terms of N and P but not K. The P in the soil could meet banana requirements and so supplemental P was not required on the fertilised plots.

Taro plant tissue analysis results for the corms between the two irrigation treatments are described in Table 3.4. The DEWATS treatment had higher concentrations of Mg in taro corms compared to tap water + fertiliser treatment. On the opposite note, tap water + fertiliser treatment had significantly more concentrations of P compared to the DEWATS effluent irrigation. Based on the standard reference concentrations for plant tissue analysis stated by Bradbury and Holloway 1988 and later modified by Blamey 1996 (Appendix II), the concentrations of N in taro corms between the two irrigation treatments were generally lower than the minimum expected for the sufficient ranges. These results imply that soil P was sufficient for taro growth.

3.3.5 Plant tissue analysis

Results obtained from nutrient concentrations in the plants are reported in Table 3.2.

Table 3.3 Plant tissue analysis of banana plants at 10% and 50 flowering

Growth stage		**Macronutrients (%)**					**Micronutrients (mg kg^{-1})**				**Other elements (mg kg^{-1})**	
10% flowering		N	P	K	Ca	Mg	Zn	Cu	Mn	Fe	Al	Na
Tap water	Mean	4.3	0.3	2.6	0.8	0.5	16.3	9.6	77.7	222.7	148.0	296.5
	SED	0.0	0.0	0.0	0.1	0.0	0.7	0.3	7.8	11.8	8.2	33.7
DEWATS effluent	Mean	4.5	0.3	2.5	1.0	0.6	14.0	10.2	100.3	208.0	131.7	121.6
	SED	0.0	0.0	0.0	0.0	0.0	0.0	0.1	3.5	3.0	1.3	11.3
50% flowering												
Tap water	Mean	3.3	0.2	2.1	0.8	0.5	16.7	9.0	182.0	140.3	51.0	122.7
	SED	0.1	0.0	0.2	0.0	0.0	1.3	0.1	4.6	7.5	6.4	23.5
DEWATS effluent	Mean	3.3	0.2	1.9	0.8	0.6	16.0	9.3	101.0	167.7	90.0	156.9
	SED	0.1	0.0	0.0	0.0	0.0	0.0	0.1	19.6	20.2	16.0	17.7

Table 3.4 Taro plant tissue analysis results between the two irrigation treatments after crop harvest

		Macronutrients (%)					**Micronutrients (mg kg^{-1})**				**Other elements (mg kg^{-1})**	
		N	P	K	Ca	Mg	Zn	Cu	Mn	Fe	Al	Na
Tap water + fertiliser	Mean	2.1	0.6	1.7	0.3	0.2	189.4	13.7	32.8	656.6	641.2	626.3
	SED	0.1	0.0	0.0	0.0	0.0	11.8	0.5	1.3	28.8	40.5	49.5
DEWATS effluent	Mean	2.4	0.5	1.8	0.3	0.3	215.0	13.8	40.7	868.8	897.8	595.1
	SED	0.3	0.0	0.1	0.0	0.0	11.0	0.4	1.4	88.9	99.0	93.8

NB: SED is the Standard Error of Deviation

3.3.6 Rainfall and evapotranspiration

The rainfall and total evapotranspiration for the two crops (banana and taro) between planting (November 2013) and final harvest (July 2016) are presented in Figure 3.25. The data show a seasonal variation in rainfall and crop water demands typical of the sub-tropical climate at Newlands-Mashu in Durban. Higher crop water requirements were recorded during the summer months (September to April) compared to winter (May to August). During the study, highest winter rainfall was recorded in July 2016. There were two periods when irrigation deficit was very low (rainfall higher than evapotranspiration); July 2015 and 2016. Even though the crop water demands were higher in summer these were supplemented by high rainfall.

Over 33 months growing period the total effluent that could be irrigated to the banana/taro intercrop was 3 514 mm (35.14 ML ha^{-1}). Considering a total annual DEWATS effluent production rate of 12.5 ML annum^{-1} and the deficit of 12.8 ML annum^{-1} (35.14 ML per 33 months), all the effluent is likely to balance off banana/taro crop water requirements. Since irrigation is based on variable crop water requirements, temporary storage is required in periods when the irrigation deficit is negative. Since excess rainfall is received in July month; storage required during those periods was 211 mm over 33 months (767 KL annum^{-1}).

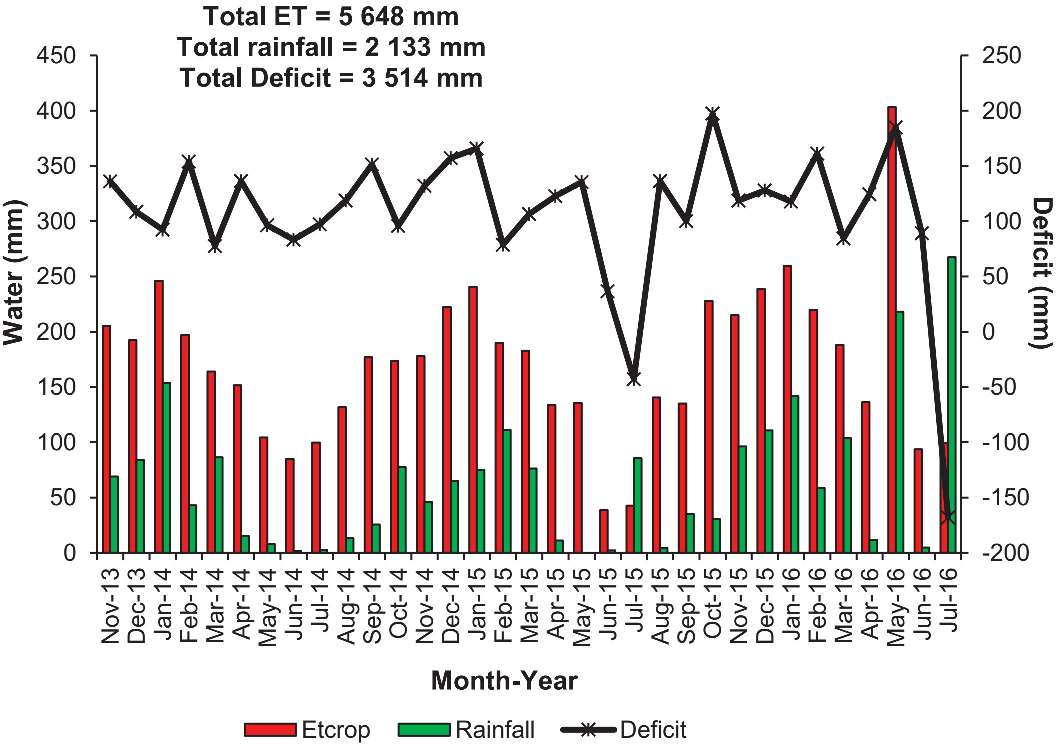

Figure 3.25 Rainfall and evapotranspiration (ET for both banana and taro) and irrigation deficits at the Newlands-Mashu field site showing irrigation water demands for the period between November 2013 and July 2016

3.3.7 Irrigation and drainage

The DEWATS plant at Newlands Mashu produces approximately 35 KL day^{-1} of effluent and 10 KL per day^{-1} (3.7 ML annum^{-1}) is directed through the wetlands and the rest 25 KL per day^{-1} is returned to the main sewer system. The data recorded for water added with regards to respective DEWATS effluent sources (after anaerobic baffled reactor; ABR and after horizontal flow wetlands effluent; HFW) are given in Table 3.5. During the study a total of 2 772 mm of effluent was used to irrigate crops instead of 3 514 mm required during the entire experimental period. Under irrigation of crops were due to delayed establishment (November 2013 to May 2014) and intermittent technical breakdowns of the irrigation system.

Table 3.5 Irrigation data at Newlands-Mashu field experiment for the period June 2014 to July 2016

Month-year	Days irrigated	Irrigation per plant (L)	Taro irrigation (mm)	Banana irrigation (mm)	Banana/taro irrigation (mm)
			Main crop		
Jun-14	12	96	45	21	66
Jul-14	31	248	116	55	171
Aug-14	30	240	112	53	165
Sep-14	30	240	112	53	165
Oct-14	30	240	112	53	165
Nov-14	20	160	70	36	106
Dec-14	26	208	97	46	143
Jan-15	12	96	45	21	66
Feb-15	0	0	0	0	0
Mar-15	10	80	37	18	55
Apr-15	5	40	19	9	28
Total	206	1 648	765	365	1 130
			First ratoon		
May-15	0	0	0	0	0
Jun-15	0	0	0	0	0
Jul-15	10	80	37	18	55
Aug-15	18	144	67	32	99
Sep-15	16	128	60	28	88
Oct-15	12	96	45	21	66
Nov-15	13	104	49	23	72
Dec-15	10	80	37	18	55
Jan-16	0	0	0	0	0
Feb-16	10	19	9	4	13
Mar-16	23	88	41	23	64
Apr-16	24	103	48	23	71
May-16	25	105	49	23	72
Jun-16	30	1 073	501	239	740
Jul-16	17	358	167	80	247
Total	208	2 378	1 110	532	1 642

Figure 3.26 describes the water levels measured below the ground at different locations on the experimental site. The piezometers above the DEWATS plant are annotated in yellow (1.1 and 1.2), between the DEWATS and the experimental field in red (2.1-2.5), block 1 in blue (3 TW, 3 DW and 3), block 2 in purple (4 TW, 4 DW and 4), block 3 in green (5 TW, 5 DW and 5) and after the experimental field in black (6.1 TW, 6.1 DW, 6.2 TW, 6.2 DW, 6 and before the river; 6.3-6.5) see Figure 3.8 and 3.9. Within the field (block 1, 2 and 3) the water level was generally < 0.6 m below ground. Although banana have a rooting depth of

0.5-0.8 m as described by FAO (2015), the effective rooting depth (87% of active roots) are concentrated in 0.3-0.4 m depth (Robinson and Saúco, 2010). Even taro has a shallow root system hence both crops required irrigation regardless of the ground water level. The results showed us that ground water level fell to 0.1 m with regards to block 1 in July 2016, which corresponds to high rainfall events in comparison to crop evapotranspiration (Figure 3.27). This explains the why irrigation was not required during that month. No water was detected down to 1 m in piezometers installed before the river (piezometers 6.3-6.5).

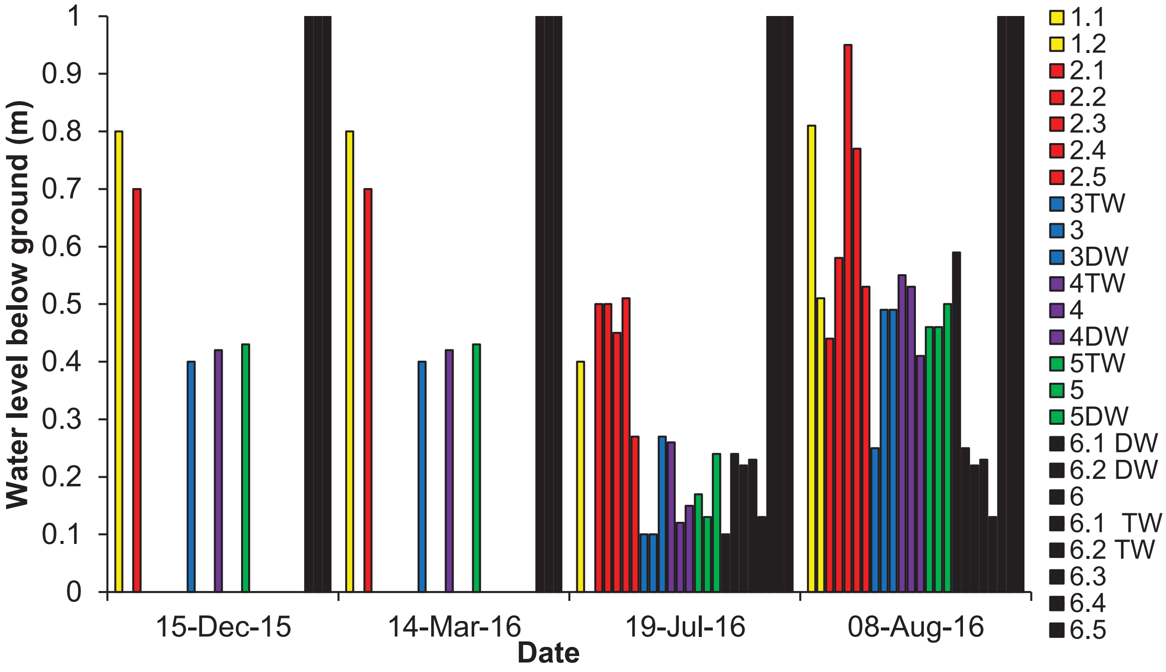

Figure 3.26 Water levels below ground in recorded in different piezometers installed at different areas around the experimental site (shown by distinct colours and numbering codes)

3.3.8 Effluent nutrient composition

The nutrient composition of the DEWATS effluent at three points, namely the effluent as it leaves the anaerobic baffled reactor (ABR effluent), after it has passed through the first wetland and after it has passed through the second wetland, is given in Table 3.4. The banana main crop was irrigated with water from the second wetland and the irrigation was switched to ABR effluent in June 2015 due to technical problems on the site.

Table 3.6 NH_4^+-N, NO_3^--N and PO_4^{3-}-P (mean ± SE and range) in wastewater samples from different sources at Newlands-Mashu for five sampling dates between February and August 2014. Department of Water Affairs (DWA) 2013 limits are given for reference

Wastewater	Ammonium-N	Nitrate-N (mg L^{-1})	Phosphate-P	K****
Limit (DWA, 2013) up to 2000 m^3 day^{-1}	3	15	10	
Limit (DWA, 2013) up to 500 m^3 day^{-1}	na*	na	na	
Limit (DWA, 2013) up to 50 m^3 day^{-1}	na	na	na	
ABR effluent**	55.34±5.67 range: 21.1-89	0. 63 ±0.27 range: 0-3	14.6 ±0.13 range: 7.6-19	14.2 ± 1.8 range: 8.34-19.4
Effluent after first wetland**	16.8 ±2.6 range: 4-28	22.7±5.2 range: 0.4-55.9	6.17±0.6 range: 3.3-10.7	
Effluent after second wetland***	6.7±1.02 range: 5-7.9	12.73±7.86 range: 3.1-24.9	4.13±0.55 range: 3-5.99	
Average total mineral N and P		N	P	K
ABR effluent		61.01	14.6	14.2
Effluent after first wetland		39.40	6.17	
Effluent after second wetland		19.43	4.13	

* not applicable

** Vertical flow wetland; n=10±SE

*** Horizontal flow wetland; n=3±SE

****Musazura et al. (2015)

3.3.9 DEWATS effluent sampling at the horizontal flow wetland

Sampling done of the DEWATS effluent after the HFW (Table 3.5) gives certain constituents considered for wastewater sampling. The DEWATS plant at Newlands-Mashu produces less than 50 m^3 per day and according to Government Gazette No 36820 of September 6, 2013 on *General Authorisations for Using Wastewater in Controlled Irrigation of Agricultural Land* the effluent meets the requirements for such an activity as there are no restrictions in terms of N and P. Nonetheless, this was compared with limits for the highest loading rate of 2 000 m^3. These values represent effluent from the second wetland; the point from which effluent was pumped into the irrigation tank. The ammonium concentration in the effluent ranged between 5 and 20 mg L^{-1} from the time of sampling with a sudden drop to below 1 mg L^{-1} at the beginning of 2015 (Table 3.5). Values of ammonium recorded between March and May 2015 (Table 3.5) were identical to the range within the effluent from the ABR (Table 3.4). The wetland was expected to impact on this concentration but minimal changes were observed.

Table 3.7 Monthly sampling results from the horizontal flow wetland effluent

Day/month/year	pH	COD (mg L^{-1} O_2)	Suspended solids (mg L^{-1})	Escherichia coli (cfu 100 mL^{-1})	Total coliform (cfu 100 mL^{-1})	Conductivity (mS m^{-1})	Ammonium (mg L^{-1} N)
Limits	6-9	5 000		100 000	nd	≤ 200	nd
28/05/14	6.65	45	1	1 000	5 500	81	4.2
23/06/14	6.75	46	2	3 500	6 500	82	9
03/07/14	6.47	45	1	<500	4 500	72	11
23/07/14	6.42	107	5	nd*	nd	70	15
29/07/14	6.57	159	1	nd	nd	68	18
04/08/14	6.49	86	2	15 531	nd	69	17
22/08/14	6.62	34	1	>24 196	nd	65	20
25/08/14	6.39	68	7	5 172	nd	65	15
04/09/14	6.34	103	1	17 329	nd	66	15
18/09/14	6.37	66	6	4 352	nd	76	12
14/11/14	6.50	45	3	70	420	63	14
20/11/14	6.47	91	1	3 255	nd	62	9.8
28/11/14	6.24	31	5	120	>800	93	7.4
17/12/14	6.32	36	1	<100	3 200	54	3.4
20/01/15	6.80	43	26	<100	>8 000	86	0.15
03/02/15	6.96	47	1	300	>8 000	83	0.23
03/03/15	7.11	77	3	4 900	>8 000	92	55
22/04/15	7.19	76	7	>8 000	>8 000	99	55
07/05/15	7.28	86	2	>8 000	>8 000	62	56

*nd – not determined

3.4 Discussion

3.4.1 Banana growth, yield and nutrient uptake

Banana plant growth parameters showed a gradual increase for the first nine months of the growing period followed by a rapid increase in the next three months. The irrigation was not available until June 2014 which was eight months after planting. The large increase (plant height doubled) in the last three months was almost certainly due to the added water since there was little difference between the DEWATS effluent treated plots and those with municipal tap water + fertiliser. When a farm is at its full production the plants are at different growth stages and have diverse nutrient needs. As such the nutrient uptake is more representative of a continuous demand and leaf analysis will reflect if the uptake is optimal as is the case presently.

3.4.2 Supply and demand

The total amount of effluent used to irrigate the main banana crop and the taro first year crop (June 2014 to May 2015) was 1 130 mm and thereafter ABR effluent was used for irrigation (June 2015 to July 2016) such that 1 642 mm were used for irrigation (Table 3.5). During the entire growing period (November 2013 to July 2016) including six months of no irrigation (November 2013 to May 2015) total effluent used for irrigation was 2 772 mm. The total amount of effluent produced by the DEWATS plant at Newlands-Mashu is about 35 KL day^{-1} (12.5 ML annum^{-1}). If the crops could have been irrigated during the whole experimental period, an amount of 3 514 mm (1 277 mm annum^{-1}) was required (Table 3.8). Thus to use all the effluent produced based on crop water requirements about 0.97 ha of land would be required. Considering that there are 83 households and five people per household there will be a need for 0.0117 ha household^{-1} (23.3 m^2 person^{-1}).

3.4.3 Crop water requirements

The water requirement for banana is 2 000 to 2 500 mm (rainfed) but they can grow with less water. The range is 1 200 to 2 500 mm with the lower amount required in humid regions and the higher amount in drier areas (FAO, 2015). Taro water requirements are between ≥ 1 500 (Onwueme, 1999). It is clear for the period from April to August 2014, which was particularly dry, that without irrigation to supplement the very low rainfall, neither crop could have survived. Table 3.8 shows the crop water requirements for both banana/taro in an intercrop, amount of irrigation applied, irrigation required taking into consideration rainfall and the surplus applied over the entire growing season (November 2013 to July 2016). The data obtained from the field experiment at Newlands-Mashu showed that the combined banana/taro crops were irrigated with 2 772 mm of effluent over the 25 months period (June 2014 to July 2016) since irrigation was delayed from November 2013 (planting) to May 2014. This has been a reason why there was a deficit of 743 mm irrigation. Due to technical problems and different crop water requirements in different seasons, management of excess effluent (through storage) must be implemented.

Table 3.8 Water supply and demand for a banana/taro intercrop at Newlands Mashu during the entire growing period (November 2013 to July 2016)

Etcrop	Irrigation Applied	Rainfall	Irrigation Required	Total deficit
		(mm)		
5 648	2 772	2 133	3 514	743

3.4.4 Nutrient utilisation

By using the data given in Table 3.5 and the average chemical composition of the DEWATS effluent given in Table 3.6, estimates can be made for major nutrients (N and P) that were added (or may be added) to each plot during the growing period three different scenarios depending on the source of water used for irrigation (Table 3.9).

Table 3.9 shows the N and P loading in the Sepane soil at Newlands Mashu after irrigation with different sources of DEWATS effluent during the 25 months of irrigation over the growing period of banana and taro. During the first 11 months of irrigation (June 2014 to May 2015) the crops were irrigated with HFW effluent and they received 220 kg ha^{-1} (N) and 46.7 kg ha^{-1} (P). During the second cropping season (June 2015 to July 2016) ABR effluent was used and supplied 1 000 kg ha^{-1} (N) and 239 kg ha^{-1} (P). Requirements for banana are between 200 and 400 kg N ha^{-1} and 45 to 60 kg P ha^{-1}. From the soil test results prior to planting, the banana required 257-320 kg N ha^{-1} and no P was required for that site (soil test P was > 40 mg L^{-1}). Both the N and P requirements for banana were thus met. These calculations, however, ignore the taro which may require up to 400 kg N ha^{-1} and 100 kg P ha^{-1} and there is no account taken for N losses. Therefore, it appears that for both banana and taro the HFW effluent was unable to supply sufficient of either N or P. Based on these data it would be possible to utilize the water from the first wetland and even directly from the ABR as N losses from this source of water will be much higher than from either of the wetlands due to the overwhelming dominance of NH_4^+-N in the DEWATS water (Table 3.5). Loss of NH_4^+-N could occur due to adsorption by the exchange complex in the soil, by replacement of NH_4^+ for interlayer cations in the expanded lattice of clay minerals and by nitrification and volatilization. However, the N value from the DEWATS may be underestimated due to the cleaning and restarting of the treatment plant during the sampling period.

Table 3.9 Nitrogen (N) and phosphorus (P) supply from three different irrigation sources during the 25 month irrigation period (June 2014-July 2016)

Irrigation source	N, P and K supply (kg ha^{-1})		
	N	P	K
ABR[#] effluent	1 000	220	232
Effluent after first wetland (VFW)[*]	0	0	0
Effluent after second wetland (HFW)[**]	239	46.7	-

[#] ABR – anaerobic baffled reactor

[*] VFW – vertical flow wetland

[**] HFW – horizontal flow wetland

Considering N limiting scenarios during the growing period based on the N requirements for the specific period when specific effluent source was used for irrigation (Table 3.10). During the first cropping when HFW effluent was used for irrigation, 1 130 mm was applied (November 2013 to May 2015) and supplied 220 kg ha^{-1} while 650 kg ha^{-1} was required to meet banana requirements. However, 2 787 mm was required to meet the banana and taro N requirements. During the second season (June 2015 to July 2016) ABR effluent was used for irrigation. The ABR effluent supplied 1 000 kg ha^{-1} (N) compared to 617 kg ha^{-1} required during that period at an application rate of 1 642 mm while only 657 mm was required to meet banana crop water requirements. Based on the effluent applied during the growing season 3 015 mm (728 mm of ABR effluent and 2 287 mm of HFW effluent) was required to meet banana N requirements compared to the actual amount applied of 2 772 mm (1 130 mm of HFW and 1 642 of ABR effluent).

Table 3.10 Comparison between the actual volumes of effluent applied during the whole growing season (November 2013 to July 2016) with the amount required when N is limiting

		Effluent volumes (mm)		**N supply (kg ha^{-1})**	
Irrigation source	Period of application	Actual applied	N limiting	Actual supplied	Required
Effluent after second wetland (HFW)**	Jun-14 to May-15	1 130	2 287	220	650
ABR effluent	Jun-15 to Jul-16	1 642	728	1 000	479
Total		2 772	3 015	1 220	1 129

NB. No effluent was applied during the first six months (November 2013 to May 2014).

3.5 Conclusions

Irrigation with DEWATS effluent results in a twofold benefit with the effluent able to make up for rainfall deficits and to supply nutrients to supplement the fertiliser requirements of crops. The yield of banana and taro has demonstrated that the nutrients from the DEWATS could sustain the crop in the same way as inorganic fertiliser but in some cases other nutrients can be supplemented. Depending on the source from which irrigation is carried out, nutrient supply could be adequate in terms of N and P when ABR effluent is used than when HFW effluent is used. The movement of N and P in leachates was very low due to the soil type. From the present study (33 months), irrigation with the effluent which was not at optimum capacity, required 3 514 mm (1 279 mm annum^{-1}) instead of 2 772 mm (1 008 mm) applied. From the study 0.97 ha of land would be required, which translate to 0.0117 ha household^{-1} (23.3 m^{2} person^{-1}). This would have implications for social housing development schemes as the effluent produced by the DEWATS plant can directly be used for agriculture in promoting sustainable agriculture. The use of effluent directly from the DEWATS will have no requirement for wetlands that take up more land and which could create problems of their management in low income communities. Furthermore, temporary storage is required during low irrigation demand periods. The restrictions on N and P do not apply in this case as the present guidelines have no restrictions on these constituents, given the output from the DEWATS plant. The DEWATS effluent is a valuable source of nutrients hence proper irrigation management that will consider crop water requirements at different growth stages will help manage nutrient utilisation in the soil.

4 EFFECT OF DEWATS EFFLUENT ON DIFFERENT CROPS GROWN ON SOILS OF CONTRASTING PROPERTIES IN POT EXPERIMENTS

4.1 Introduction

Different soils differ in physical properties such as texture depending on their parent material. This has implications for chemical properties such as nutrient content, pH and organic matter that are essential for nutrient recycling. Wastewater irrigation has variable impacts on soil properties and different crops have diverse nutrient uptake characteristics. The changes in soil properties are variable due to wastewater irrigation and plant uptake characteristics. However, depending on the soil type, irrigation with DEWATS effluent might have influence on the dynamics of soil N and P.

The objective of this section was to investigate the effects of irrigation with ABR effluent on maize, Swiss chard, and potato growth in three contrasting soils at different fertiliser rates. Furthermore, investigations on the uptake of nutrients from pot-grown bananas irrigated with HFW effluent on the same soil types as well as leachate properties from columns planted to perennial ryegrass were carried out.

4.2 Effect of ABR effluent on Swiss chard, potato and maize growth

The experiment was designed as a 2 x 3 x 3 factorial treatment in a randomised block design with the following treatment structure: Irrigation water (2 levels – ABR effluent and tap water); soil types (3 levels – Inanda, Cartref and Shortlands soils); and fertiliser (3 levels – zero, half recommended rate and full recommended rate) replicated 4 times giving a total of 72 experimental units for each crop. The crops used were maize – *Zea mays* (Mac Pearl), Swiss chard – *Beta vulgaris* (Fordhook giant), and potato – *Solanum tuberosum* (Nandi) representative of commonly grown cereal, leafy vegetable and root crops, respectively.

4.2.1 Soil collection, analysis and potting

Three contrasting soil types were used namely a Cartref E horizon (Cf; Typic Haplaquept), and the A horizon of an Inanda (Ia; Rhodic Hapludox) and a Shortlands (Sd; Typic Haplustalf) (Soil Classification Working Group 1991; Soil Survey Staff, 2014) (Appendix II). The Cf was collected from Kwadinabakubo (29^{o} 44.046’ S; 30^{o} 51.488’E) under natural veld, the Ia from World’s View, Pietermaritzburg under pine plantation (29^{o} 35.003’ S; 30^{o} 19.7404’ E) and the Sd from the Ukulinga Research Farm (30^{o} 24’ S; 29^{o} 24’E) of the University of KwaZulu-Natal in Pietermaritzburg. Soils were collected from the topsoil, air-dried, ground and sieved through a 2 mm mesh. Characterisation for their fertility status was carried out by the FAS. The sieved soils were mixed with urea (46% N), single superphosphate (SSP; 10.5% P), and potassium chloride (52% K) at the three different rates based on the soil analysis results for each soil and crop type. Pots were filled with the different soils and maize and potato were planted in 20 kg of soil and Swiss chard in 10 kg of soil.

4.2.2 Planting and trial establishment

Four seeds (tubers of potato) were planted and thinned to one plant per pot after two weeks. Before planting, soil water was brought to 70% of the field capacity of the soil with the required irrigation source. The pots were randomised within each irrigation source. The irrigation treatments were applied for eight weeks at an interval of five days until the plants reached the harvesting stage. However, during the experimental period the tunnel was damaged by heavy storm, which affected potato and maize under the Inanda soil so data could be collected from the respective treatments. On the other side a maize crop under Cartef soil was attacked by monkeys and we could not collect data from them.

4.2.3 Data collection

Parameters collected during growth included plant height, ear leaf sample and chlorophyll content for maize. Swiss chard parameters included leaf number, leaf area and chlorophyll content. Leaf area was measured according to Pokluda and Kuben (2002). The ear leaf samples from the maize and leaf samples from the Swiss chard were dried in a force draft oven at 70°C. Yield data collected included fresh and dry mass for Swiss chard and number of ears/plant, ear mass and dry mass of 100 grains for maize. Plant fresh mass (g) was determined by weighing plants directly at harvesting. The dry mass (g) was then determined by weighing plants which were oven dried as above.

For potato, chlorophyll content was measured and at harvest number of tubers/plant, tuber mass and diameter of each tuber were measured. All leaf, tuber and soil samples after harvest were taken to the FAS for analysis.

Statistical analysis was done using GenStat® 14th Edition (VSN International, Hemel Hempstead, UK).

4.2.4 Results

4.2.4.1 Soil and effluent characteristics

Soils differed in their clay contents as well as in their plant nutrient content. As such these soils have different abilities to retain water and nutrients from the effluent. The fertiliser requirements of the various crops are outlined in Table 4.1 with each of the soils having different nutrient needs for the specific crop. The ABR effluent characteristics are presented in Table 4.2. After about a month of irrigation the ABR plant was shut down for maintenance. As such effluent was stored in open tanks and changes recorded during storage are presented in Table 4.2. The total volume of effluent used to irrigate the crops is presented in Table 4.3.

Table 4.1 Recommended nutrient application rates (kg ha-1) for the soils and crops used in the experiments

Soil	Nutrient	Maize	Swiss chard	Potato
Cartref	N	200	100	220
	P	90	230	126
	K	100	365	568
Inanda	N	200	100	160
	P	30	195	80
	K	245	445	445
Shortlands	N	200	100	220
	P	30	195	80
	K	0	10	120

Table 4.2 Characteristics of the effluent used for irrigating the plants

Effluent	NO_3^--N	NH_4^+-N mg L^{-1}	PO_4^{3-}-P
At ABR outlet	not detected	100-116	21-22
After one week of storage	not detected	100	22
After one month of storage	not detected	nd*	27
After two months of storage	2.5	70	12

*nd – not determined

Table 4.3 Volume of effluent (L) used to irrigate the different crops

Soil	Swiss chard	Potato	Maize
Cartref	7.0	13.5	27.5
Inanda	9.5	nd*	nd
Shortlands	7.5	15.5	43.0

* nd – not determined

4.2.4.2 Effects of fertiliser application rates, soil type and irrigation source type on Swiss chard growth and nutrient uptake.

Fresh mass, dry mass, leaf number, leaf area

Significant differences in fresh mass were observed with regards to irrigation source ($p<0.01$), fertiliser application rate ($p<0.01$), interaction of soil type and irrigation source, fertiliser application rate and irrigation water source ($p<0.01$). The effluent treatment had a higher fresh mass value of 33.8 g as compared to 25.1 g after tap water irrigation. The interaction of soil type and irrigation source was significant ($p<0.001$) for fresh mass. For the effluent irrigation higher fresh mass (38.6 g) compared to tap water irrigation (10.6 g) in the Ia was recorded (Figure 4.1). The ABR effluent irrigation had a significantly higher fresh mass value of 12.4 g as compared to 0.3 g for the tap water irrigation in the unfertilised treatment (Figure 4.2).

The optimum fertiliser application rate for all the irrigation source treatments had the highest dry mass (4.9 g) which was significantly higher than the half optimum rate (1.9 g). The only significant difference in dry mass was observed in the Ia between the irrigation sources (Figure 4.1). Tap water irrigation had a significantly lower dry mass value of 0.8 g as compared to 2.6 g observed in ABR irrigation in the Ia (Figure 4.1).

The tap water treatment at optimum fertiliser application rate showed a dry mass of 4.9 g compared to tap water at half the recommended rate (1.8 g) and unfertilized (0.1 g). There were no significant differences in dry mass between the optimum and half optimum application rates in pots irrigated with ABR effluent. Within the optimum fertiliser application rate the Cf had the highest dry mass (0.6 g) as compared to the Ia and Sd soils. There were no significant differences in Swiss chard dry mass amongst the three soils for the unfertilized treatments (Figure 4.3).

A significantly higher ($p<0.001$) number of leaves was observed in Swiss chard irrigated with ABR effluent (8.3) as compared to tap water irrigation (3.8) (Figure 4.1). At optimum and half fertiliser application rates, the average leaf number was 7.6 and 6.0, respectively, compared to 2.3 for the unfertilized treatment (Figure 4.2). The unfertilised plants irrigated with ABR effluent did not differ from the fertilised treatments in leaf number for both tap water and effluent indicating the fertilising ability of the effluent (Figure 4.2).

A larger leaf area was recorded in Swiss chard irrigated with ABR effluent (116 cm^2) as compared to tap water irrigation (6.3 cm^2) in the Ia soil. The ABR effluent treatment had a significantly larger leaf area value (44.5 cm^2) at the zero fertiliser application rate as compared to tap water irrigation which had a leaf area value of 1.9 cm^2 (Figure 4.2).

These observations and differences are clearly established in Figure 4.4 where it can be seen that plants thrived better in the sandy Cf than the clayey Sd soil in the unfertilised treatments irrigated with ABR effluent than the tap water irrigated treatments.

Higher growth (dry mass and fresh mass) in ABR effluent in comparison to tap water irrigation, especially in Inanda soils implies that the effluent has a capacity to optimise soil pH and promote crop growth. The same observation was reported by Bame et al. (2004) when she used maize as a test crop. The ABR effluent contains mineral nutrients (N and P) that can supplement inorganic fertiliser as evidenced by higher crop growth in Swiss chard irrigated with ABR effluent and fertiliser was not applied.

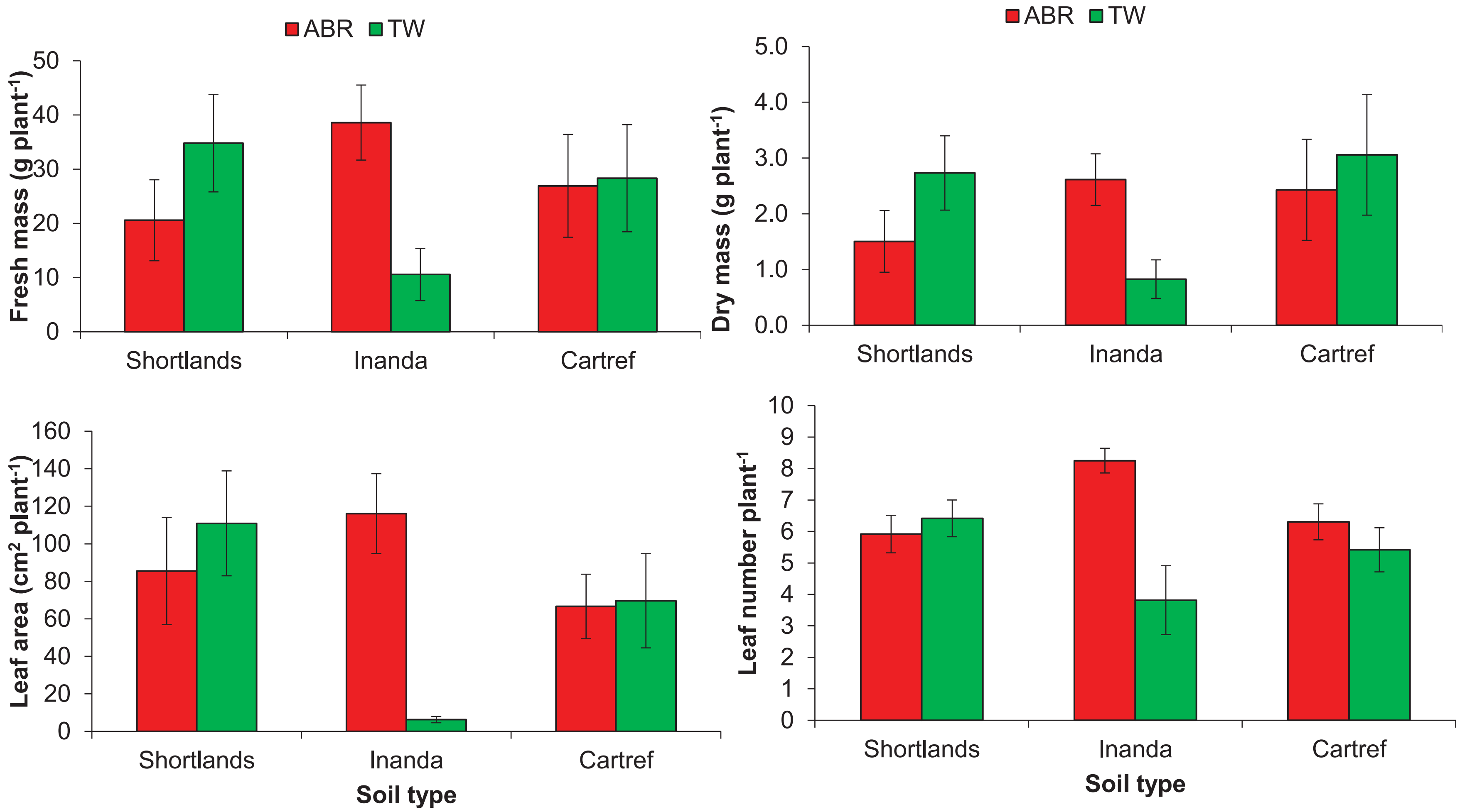

Figure 4.1 The interaction of soil type and irrigation water source on dry mass, fresh mass, leaf area and leaf number of Swiss chard for the three applied fertiliser rates. ABR – effluent; TW – tap water

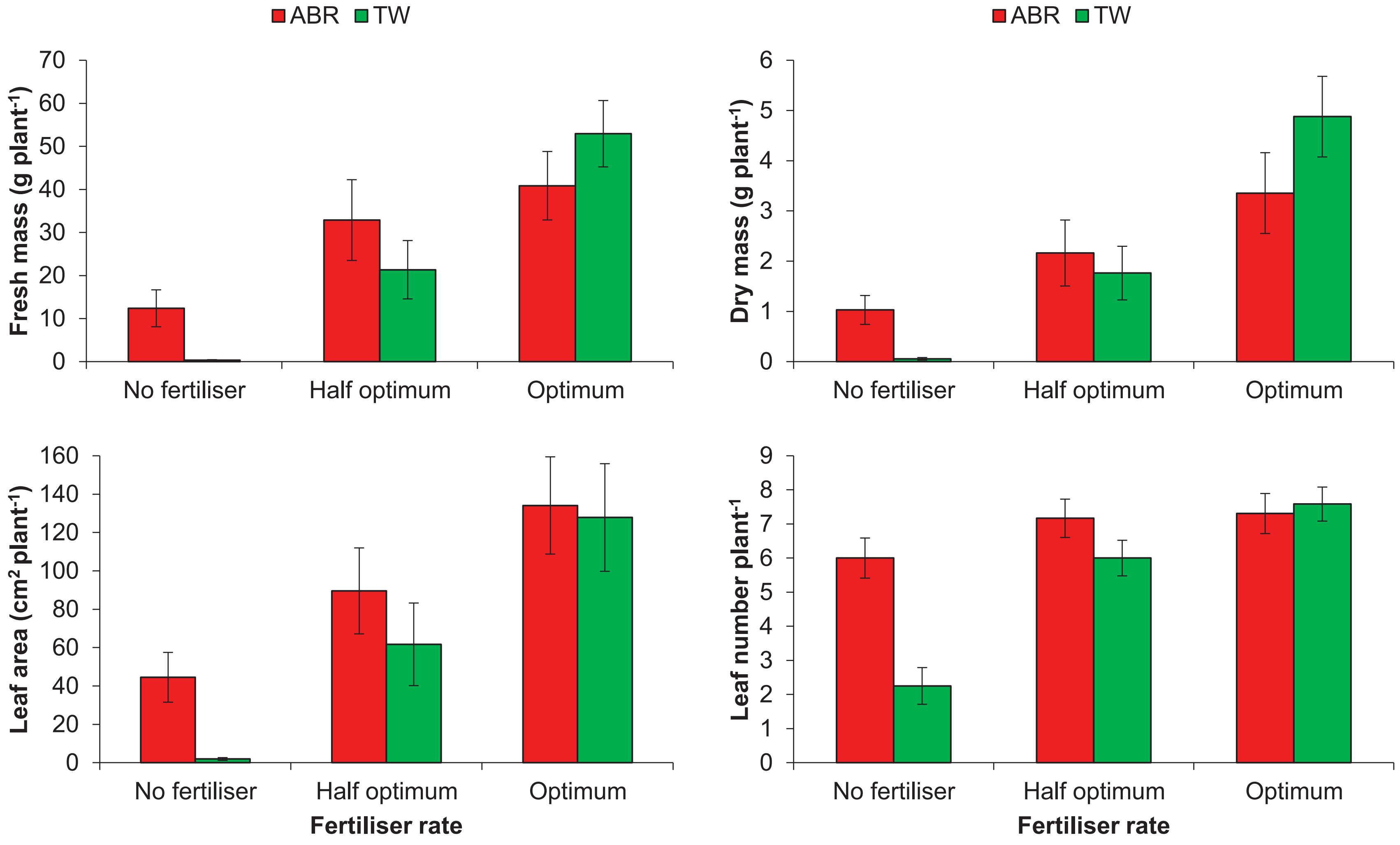

Figure 4.2 The interaction of fertiliser rate and irrigation water source on dry mass, fresh mass, leaf area and leaf number of Swiss chard for the three applied fertiliser rates. ABR – effluent; TW – tap water

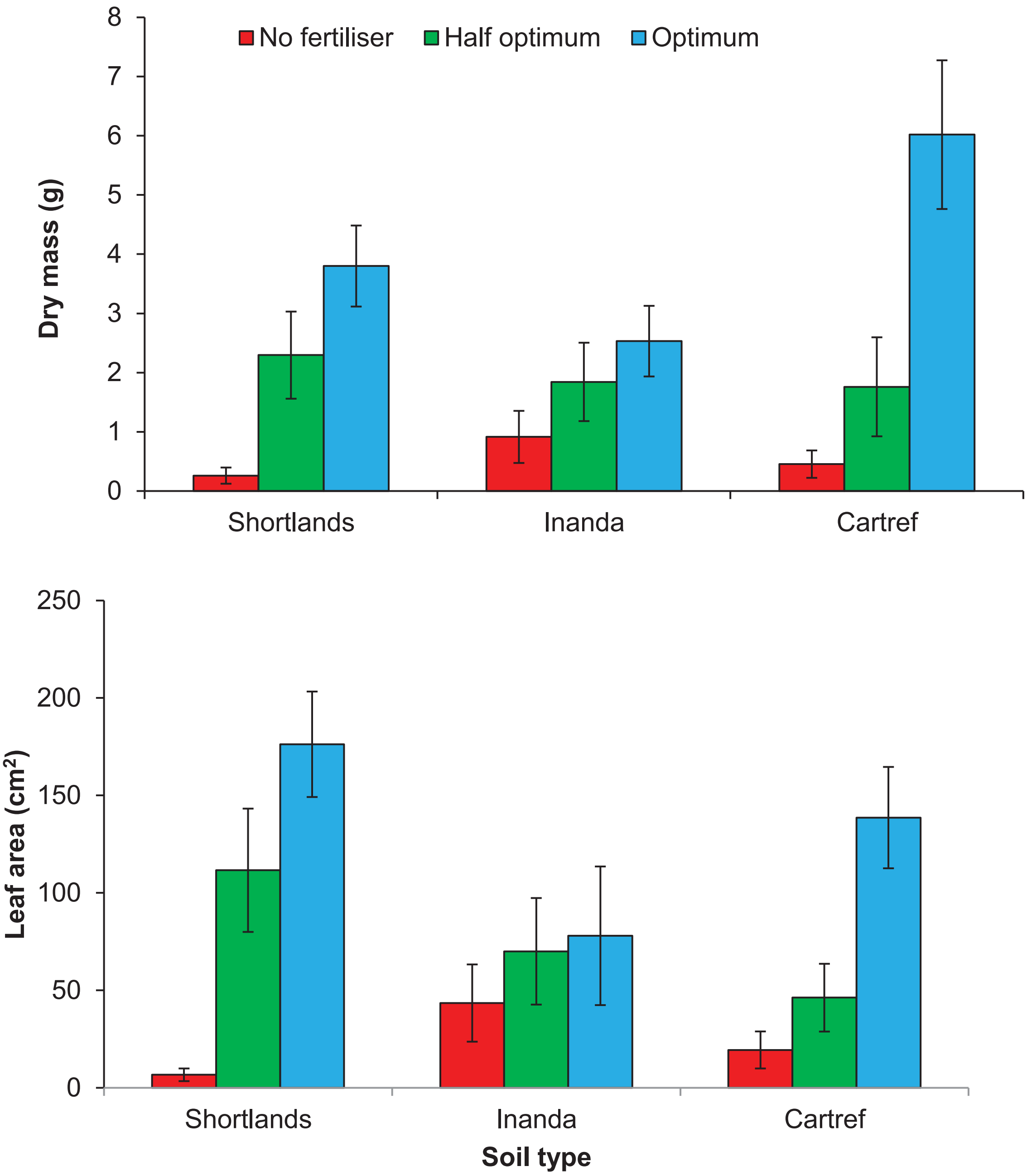

Figure 4.3 Interaction of fertiliser rate and soil type on dry mass and leaf area of Swiss chard across both irrigation water source treatments

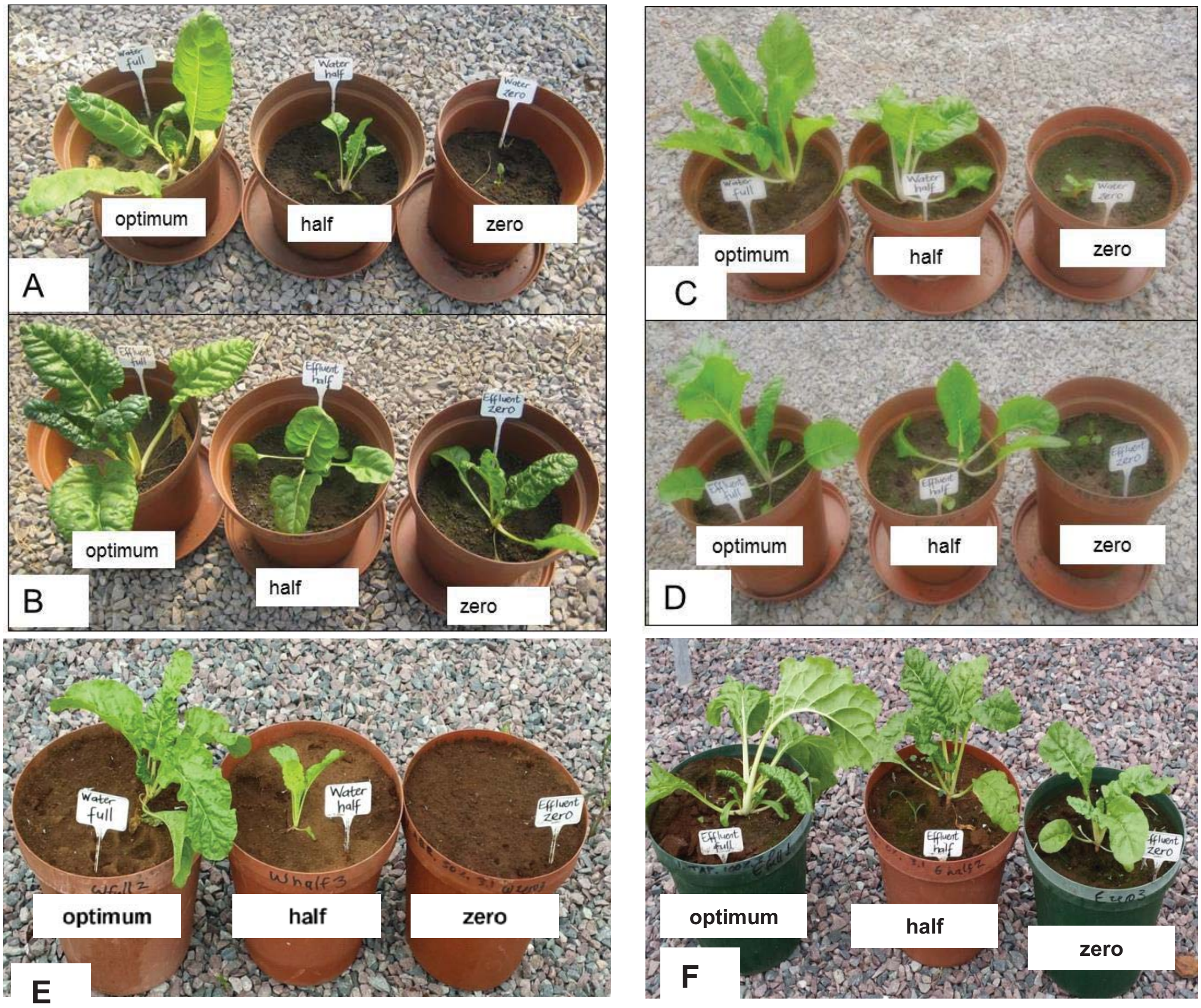

Figure 4.4 Swiss chard at harvest on the Cartref (Cf) soil after irrigating with A. water and B. effluent; C. Shortlands soil water and D. effluent; E. Inanda soil water and F. effluent at different fertiliser application rates

Plant tissue nutrient analysis

Plant tissue analysis was done on Swiss chard under three contrasting soils, fertiliser application rates and between the two irrigation treatments (Figure 4.5). In the study low nutrient uptake (N, P, K and Na) were observed with regard to Cf soil, which is generally low in mineral nutrient content and retention as discussed by Bame et al. (2014). A comparison between ABR effluent and tap water irrigation showed that more nutrients (N, P, K and Na) were taken up in ABR treatments under the Cf soil, implying that ABR effluent is a source of mineral nutrients in low fertile soils. All the Swiss chard plants with no fertiliser application under the tap water irrigation and could not be analysed for plant tissue as they were very small to meet the sample quantity required for plant tissue analysis. Plants from ABR effluent under no fertiliser application were bigger and produced adequate sample size for plant tissue analysis.

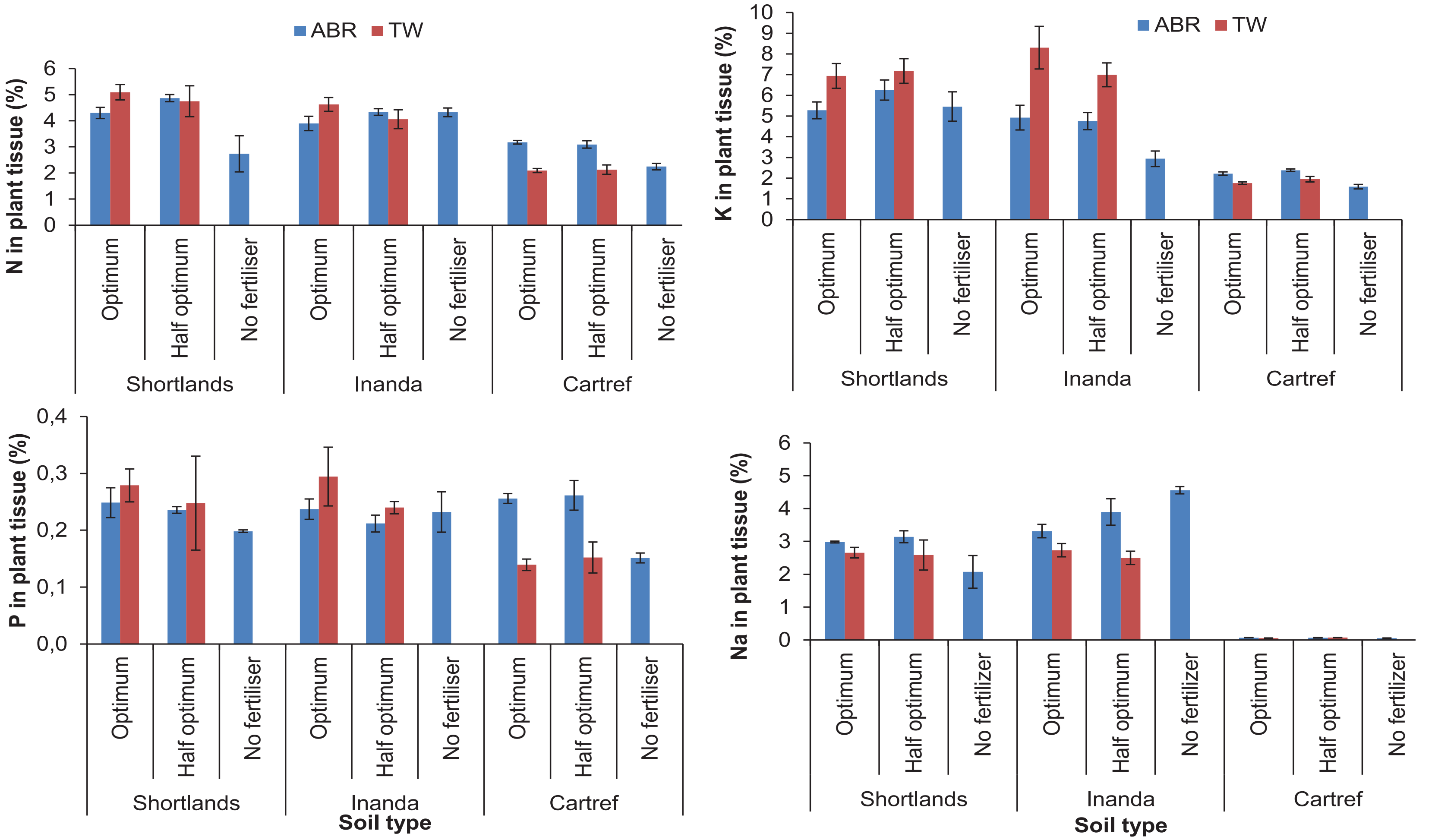

Figure 4.5 Swiss chard tissue concentrations of nitrogen (N), phosphorus (P), potassium (K) and sodium (Na) at different fertiliser rates as influenced by soil type and irrigation source. ABR – effluent; TW – tapwater

4.2.4.3 Effects of fertiliser application rates and irrigation source on maize growth in the Shortlands soil.

Growth parameters

Plant height and chlorophyll content were measured at tasselling. In Figures 4.6 and 4.7 it can be seen that plants from the tap water irrigated treatments presented yellowing symptoms as compared to the effluent irrigated plants. Additionally, the unfertilised effluent irrigated plants performed better than those irrigated with water. Similar results were recorded for the chlorophyll content between the zero and the optimum fertiliser application. In the tap water irrigated plants, chlorophyll content increased with increasing fertiliser application rate (Figure 4.8).

Figure 4.6 Maize plants on the Shortlands soil close to maturity irrigated with tap water (left) and effluent (right)

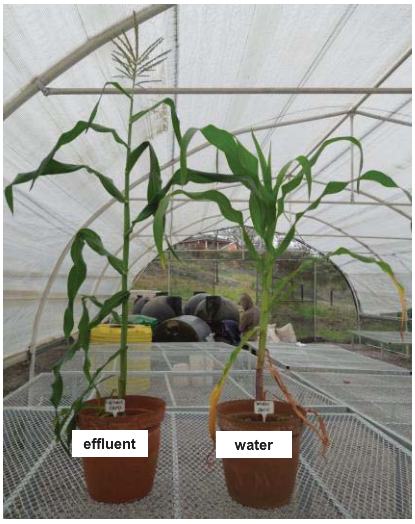

Figure 4.7 Comparison of maize plants between the unfertilized tap water and effluent irrigated Shortlands soil at tasselling

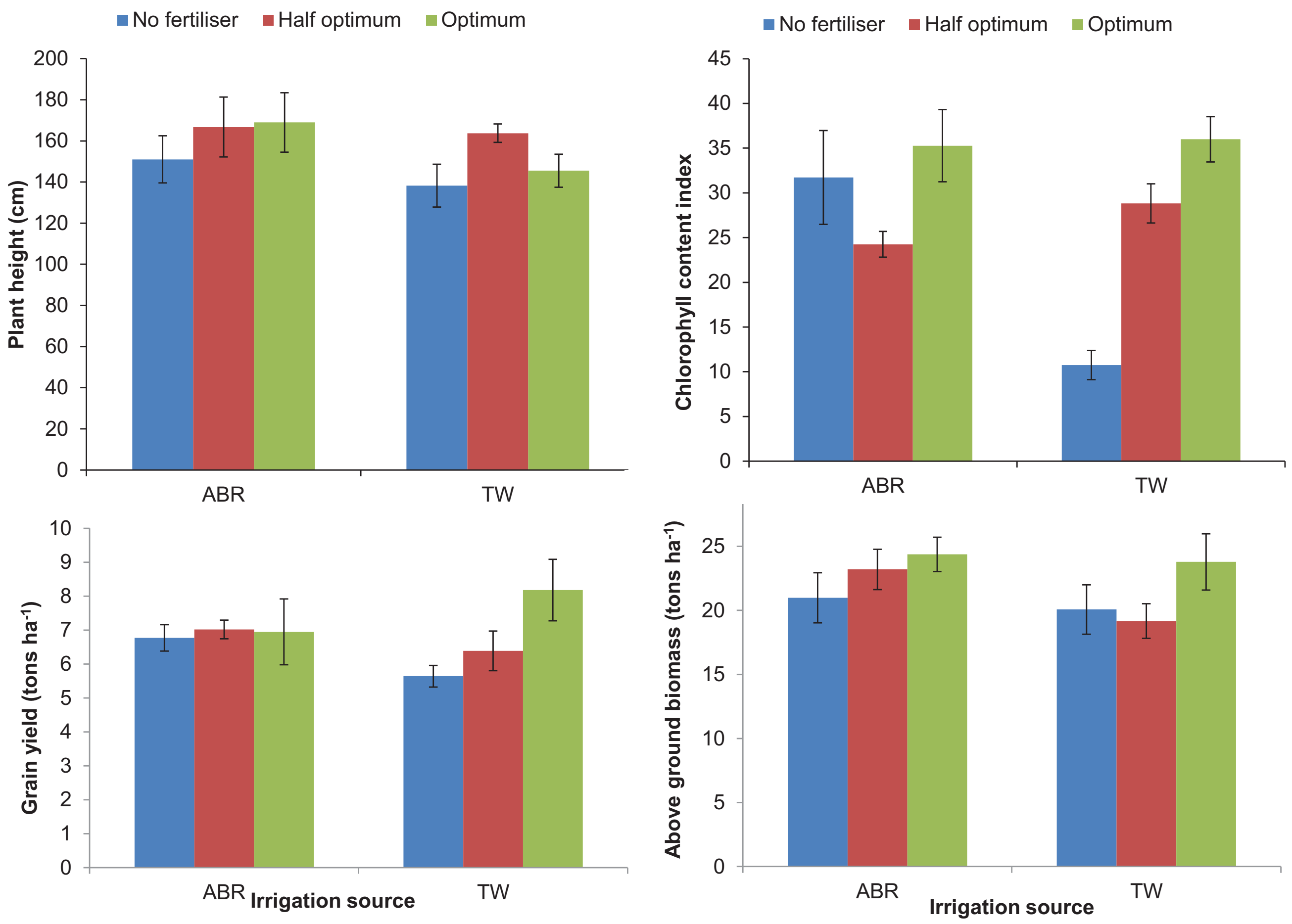

Figure 4.8 Effect of irrigation source and fertiliser rate on growth and yield parameters of maize on the Shortlands soil. ABR – effluent; TW – tap water

4.2.4.4 Yield parameters

There were no significant differences among the fertiliser treatments for the ABR irrigation with respect to grain yield and above-ground biomass (Figure 4.8). In the tap water irrigated plants, grain yield increased with increase in fertiliser application in contrast to the above-ground biomass as the unfertilised plants were not different from the optimally fertilised plants.

4.2.4.5 Effects of fertiliser application rates and irrigation source on potato growth in the Shortlands and Cartref soils

Yield parameters

A difference in number of tubers per plant was recorded only in the optimum fertiliser application for the ABR irrigation (Figure 4.9a). In this case the number of tubers was higher on the effluent than the tap water irrigated soil. Tuber yield was higher on the ABR irrigated than the tap water irrigated soil (Figure 4.9c). In the Shortlands, there were no differences among the fertiliser rates and irrigation source (Figure 4.9b and d). Figure 4.10 shows potato plants irrigated with effluent and tap water on the Cf soil. It can be seen that the unfertilised tap water irrigated soils had stunted growth as compared to the effluent.

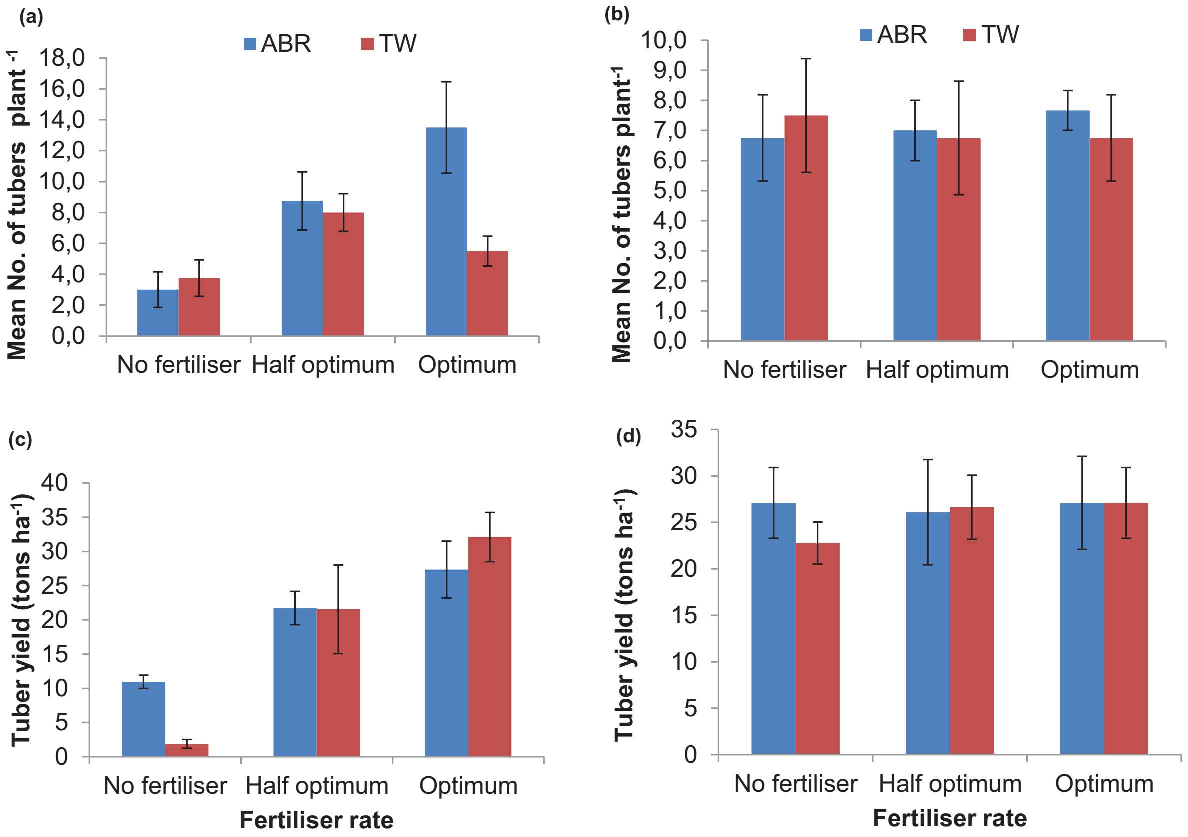

Figure 4.9 Effect of irrigation source and fertiliser rate on yield parameters of potato on (a) and (c) Cartref soil and (b) and (d) Shortlands soil. ABR – effluent; TW – tap water

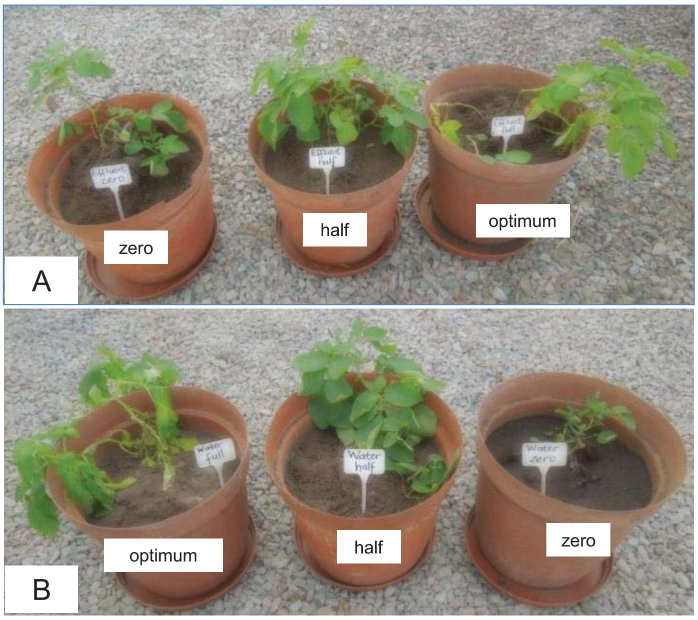

Figure 4.10 Potato plants on (A) effluent irrigated and (B) tap water irrigated Cartref soil at different fertiliser rates

4.2.5 Discussion

Irrigation with ABR effluent had a higher impact on growth than tap water irrigation. This is expected because ABR effluent contains plant nutrients such as N and P that impact on plant growth. Studies have confirmed that irrigation with treated wastewater can increase crop growth (Shahalam et al., 1998; Zavadil, 2009; Adewoye, 2010; Bame et al., 2014). Irrigation with ABR effluent increased Swiss chard growth at zero and half fertiliser recommendation rates as compared to tap water. This implies that ABR effluent provided nutrients which supplemented the deficit required to meet the fertiliser recommendation. Bame et al. (2014) showed that nutrients from ABR effluent can be retained within the plant rooting zone thereby supplementing fertiliser requirements in crops. The interaction of soil type and irrigation water source on Swiss chard showed that ABR effluent significantly increased its growth on the acidic Ia soil as compared to the sandy Cf and clayey Shortlands soils. The significant effect on the acidic soil is because ABR effluent contains cations that have a buffering action on soil pH (Bame et al., 2013). As expected, Swiss chard growth (biomass, leaf area and leaf number) increased with increase in fertiliser application rate. Furthermore, the Ia soil was most influenced by irrigation source for Swiss chard especially with the tap water irrigated plants. This was probably caused by the low soil pH which could not be moderated by tap water unlike the effluent that mitigated the acidity. At half optimum fertiliser application rate the Cf produced a significantly lower biomass and leaf area as compared to the heavier textured Shortlands soil. The relatively lower chlorophyll content on the Ia could be due to differences in the soil chemical properties as reported by Bar-Tal (2011). The rate of N mineralisation (ammonification and nitrification) is retarded when the C: N ratio is high. The Ia had a higher C: N ratio as compared to the Shortlands soil.

In the maize pots the optimum fertilised plants performed better with respect to certain parameters (chlorophyll content and yield) than the tap water. The unfertilised effluent irrigated plants were not different from the half optimal rate irrigated with tap water. This again shows the fertilising ability of the effluent in sustaining crop growth. The same observation was made in the potato crop, particularly in the Cf soil.

4.2.6 Conclusions

The interaction between fertiliser application rate and irrigation water source influenced crop growth responses were influenced. Irrigation with ABR effluent increased Swiss chard growth and chlorophyll content compared to tap water irrigation in all soil types and at all fertiliser application rates. The ABR effluent can supplement fertiliser requirements due to its ability to increase crop growth especially at half optimum fertiliser rate compared to irrigation with tap water. However, most of the growth responses were more evident in the sandy Cf soil for potato as compared to more response in the acidic Ia soil with respect to Swiss chard. Irrigation with ABR effluent could be beneficial in soils of poor fertility by improving their nutrient status. However, it has to be well-adjusted to the water requirement for the crop within the growing season.

4.3 Effect of ABR effluent on potted banana plants growing on three contrasting soil types

4.3.1 Experimental design and method

A tunnel experiment was conducted at Newlands-Mashu in Durban with three soil types namely Cartref, Inanda and Sepane. Factorial experiments were laid out in a complete randomised design with the following factors: 2 levels of irrigation water (ABR effluent (EF) and tap water + fertiliser (TW)) and three soil types, which were all replicated four times. In this study the effluent was sourced from the horizontal flow wetland (HFW) for the first seven months before being changed to ABR effluent. Soils were collected, air dried and sieved through a 2 mm mesh. Sieved soils (60 kg) were mixed with fertilisers for the TW treatments based on the recommended rates from the FAS. The fertilisers added were urea (14 g N pot^{-1}) and potassium chloride (78.2 g K pot^{-1}) to all soils on the 4/4/2015 and again on the 3/9/2015. Single superphosphate (20 g P pot^{-1}) was applied to only the Cf on the 4/4/2015. Dolomitic lime was added at a rate of 65 g per 60 kg pot (Ia) and 14 g per 60 kg pot (Cf) to moderate their pH to a permissible acid saturation of 1%. No fertiliser was applied to the EF treatments. The soils were packed into 90 L containers according to their field bulk densities (Ia: 0.77 g cm^{-3}, Se: 1.2 g cm^{-3} and Cf: 1.44 g cm^{-3}). Wetting front detectors were installed in the pots to collect leachates. Banana suckers (4-5 kg plant) were obtained from the field trial and planted in the pots at a rate of one plant per pot on 3 April 2015. The plants were irrigated with tap water until the soils reached about 70% field capacity. The pots were weighed before and after irrigation to estimate crop water requirements. Temperature and humidity were monitored using iMini escort (CB-USB2-MINI5P) data loggers. Plant growth parameters collected included plant height, total leaf area per plant and chlorophyll content. Leachates were collected and analysed for NO_3^--N, NH_4^+-N and PO_4^{3-}-P according to standard methods (APHA, 2005). All the methodologies for irrigation water analysis and data collection were done as described in the field experiment (Section 3.2.5).

4.3.2 Results

4.3.2.1 Chemical characteristics of effluent used for irrigation.

Table 4.4 gives the nutrient loading in the tunnel based on the volumes of effluent applied. From April 2015 to October 2015 crops were irrigated with HFW effluent, after which the irrigation was switched to irrigation with ABR effluent. The average concentrations of N and P were 19.4 and 4.1 mg L^{-1}, respectively, in the HFW water and 61.01 and 14.6 mg L^{-1}, respectively, in the ABR effluent. There was a total supply of 17.8 g N and 4.2 g P per 60 kg pot over the period of 11 months.

Table 4.4 The volumes of effluent used for irrigation and its content of nitrogen (N) and phosphorus (P) during the 11 months growing period of banana in the tunnel experiment

Month-year	Irrigation volume (L pot^{-1})	N	P
		(g per 60 kg pot)	
Apr-2015	5	0.1	0.02
May-2015	10	0.2	0.04
Jun-2015	13	0.3	0.05
Jul-2015	10	0.2	0.04
Aug-2015	40	0.8	0.16
Sep-2015	55	1.1	0.23
Oct-2015	45	0.9	0.19
Total	178	3.6	0.73
Nov-2015	60	3.7	0.88
Dec-2015	60	3.7	0.88
Jan-2016	75	4.6	1.10
Feb-2016	40	2.4	0.58
Mar-2016	60	3.7	0.88
Apr-2016	60	3.7	0.88
May-2016	60	3.7	0.88
Jun-2016	0	0	0.88
Jul-2016	60	3.7	0.88
Aug-2016	60	3.7	0.88
Sep-2016	60	3.7	0.88
Oct-2016	60	3.7	0.88
Nove-2016	40	2.4	0.58
Total	695	42.7	11.06
Cumulative total	873	46.3	11.79

During the experiment the amounts of N and P supplied were more than the recommended requirements in all the soils (Table 4.4).

4.3.2.2 Crop water requirements

Banana is a tropical plant with temperature requirements of between 16 and 38°C and a mean temperature requirement of 27°C for optimum growth (Eckstein and Robinson, 1996). During the study from June 2015 to November 2015 the monthly maximum temperatures were between 36.4 and 43.7°C and minimum temperatures between 19 and 32°C (Figure 4.11) which were very high for banana. Crop water requirements are based on the amount lost through evapotranspiration. Potential evapotranspiration (Eto) is affected by temperature, relative humidity, wind speed and solar radiation. Crop evapotranspiration (Etc) is affected by crop factors which change with different stages of growth. During the study, irrigation was based on the fixed amount irrigation approach. There are other irrigation approaches available which include crop water requirement and which allow for rainfall, leaching requirements and stress depletion level. In the study, irrigation was in excess of the crop water requirements. However, for soils with low water retention capacity, such as the Cf, the water was in excess if irrigation was based on leaching requirements.

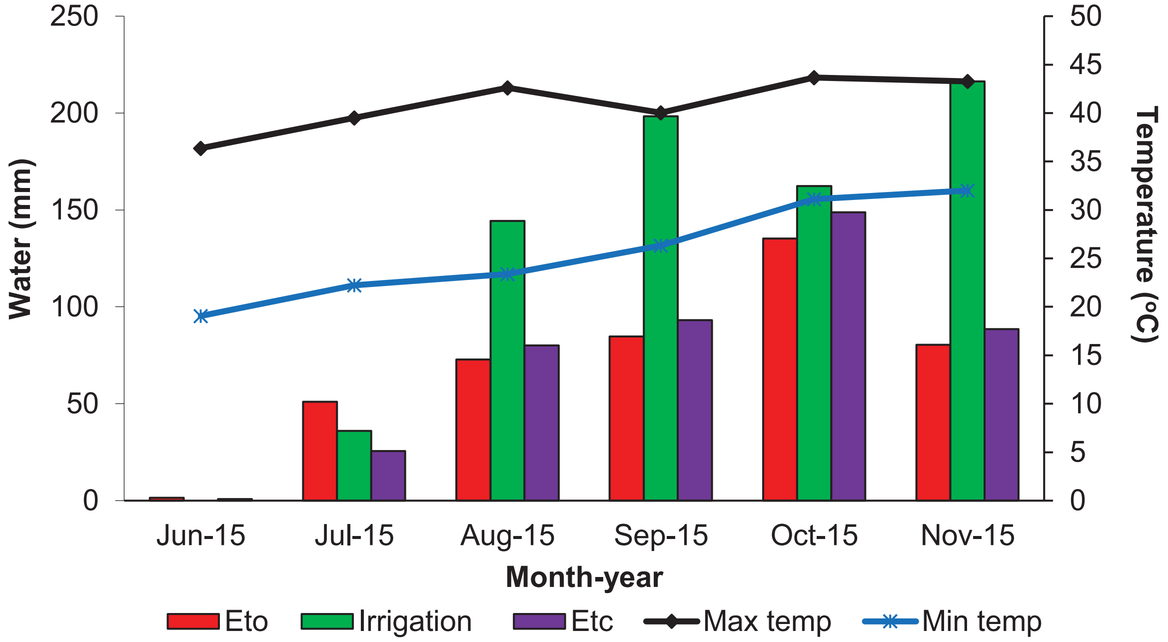

Figure 4.11 Relationship between potential evapotranspiration (Eto), crop evapotranspiration (Etc), irrigation and temperature (minimum and maximum) in the tunnel during banana growth between June and November 2015

4.3.2.3 Crop growth

Figure 4.12 shows plant growth (total leaf area per pot and plant height) results of banana plants from five to 18 months after planting between the two irrigation treatments and three soil types. The plant height increased in all the treatments over time; Sepane soil having the highest growth rate and attained the highest plant height in all irrigation treatments. Least plant height was attained in Cartref soil within the tap water + fertiliser treatment. The similar pattern has been followed with regards to total leaf area per pot; banana crops under the Sepane soil had higher leaf area growth compared to other treatments. This is due to ability of Sepane soil to retain nutrients such as N, furthermore the soil was obtained from the field at Newlands Mashu and it did not require any further P application. Irrigation with DEWATS effluent provided a constant supply of nutrients during the growing season as evidenced by higher final plant height in Cartref soil (DEWATS).

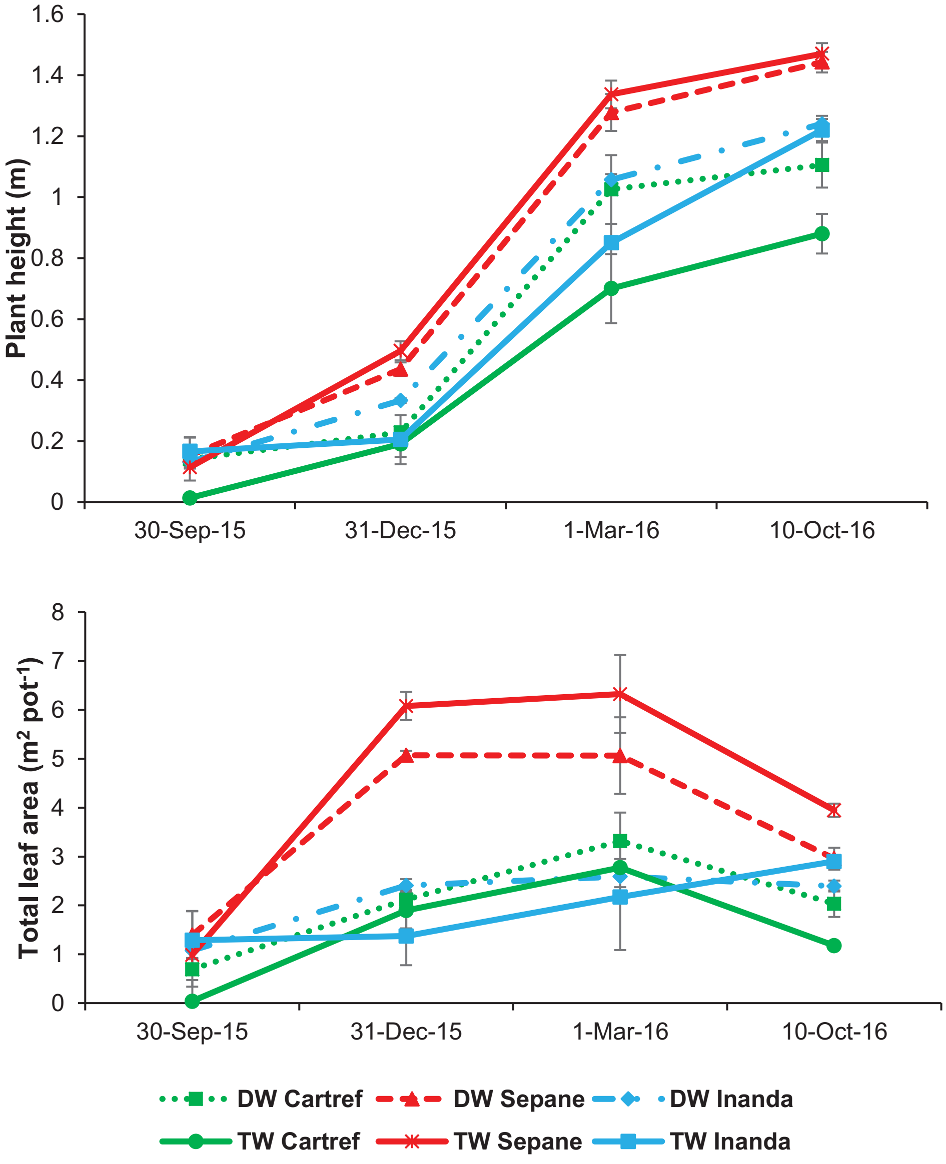

Figure 4.12 Banana plant growth parameters (total leaf area per pot and plant height) at 18 months after planting between the two irrigation treatments (DW – effluent; TW – tap water) and three soil types (Cartref, Sepane and Inanda)

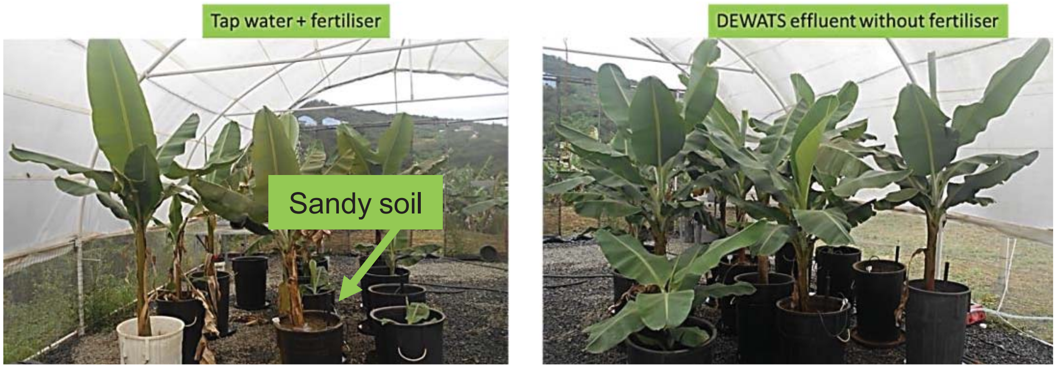

Figure 4.13 Differences in banana growth between the effluent and tap water treatments in the tunnel at 8 months after planting

4.3.2.4 Leachate analysis

The concentrations of NO_3^--N, NH_4^+-N and PO_4^3-P in the irrigation and soil treatments at five and eight months after planting are shown in Figure 4.14. Regardless of irrigation with DEWATS effluent, the NO_3^--N concentrations are declining with time even for the tap water + fertiliser treatment. The similar pattern is observed with regards to NH_4^+-N, which shows that total N is declining over time. Plants are utilizing nitrogen and, considering the volumes of effluent being applied some is being lost through denitrification. However, the total N (NO_3^--N and NH_4^+-N) are generally higher in the Inanda soil with regards to DEWATS effluent especially in March and November 2016. Thus mineralization rate was high in that soil due to organic matter. The PO_4^3-P concentrations observed in pot experiments were comparable No P was applied to Sepane soil in tap water + fertiliser treatment but PO_4^3-P concentrations remained constant during the season. Surprisingly PO_4^{3-}-P concentrations from the DEWATS treatment (all soils) were declining over time, ending up being lower than for Sepane (tap water + fertiliser treatment) in November 2016. This explains the influence of effluent in providing organic C which help retain P in complexes on the soil particles as described by Levy et al. (2011). Since PO_4^{3-}-P is retained, it will not be detected in the leachates as observed by Bame et al. (2013).

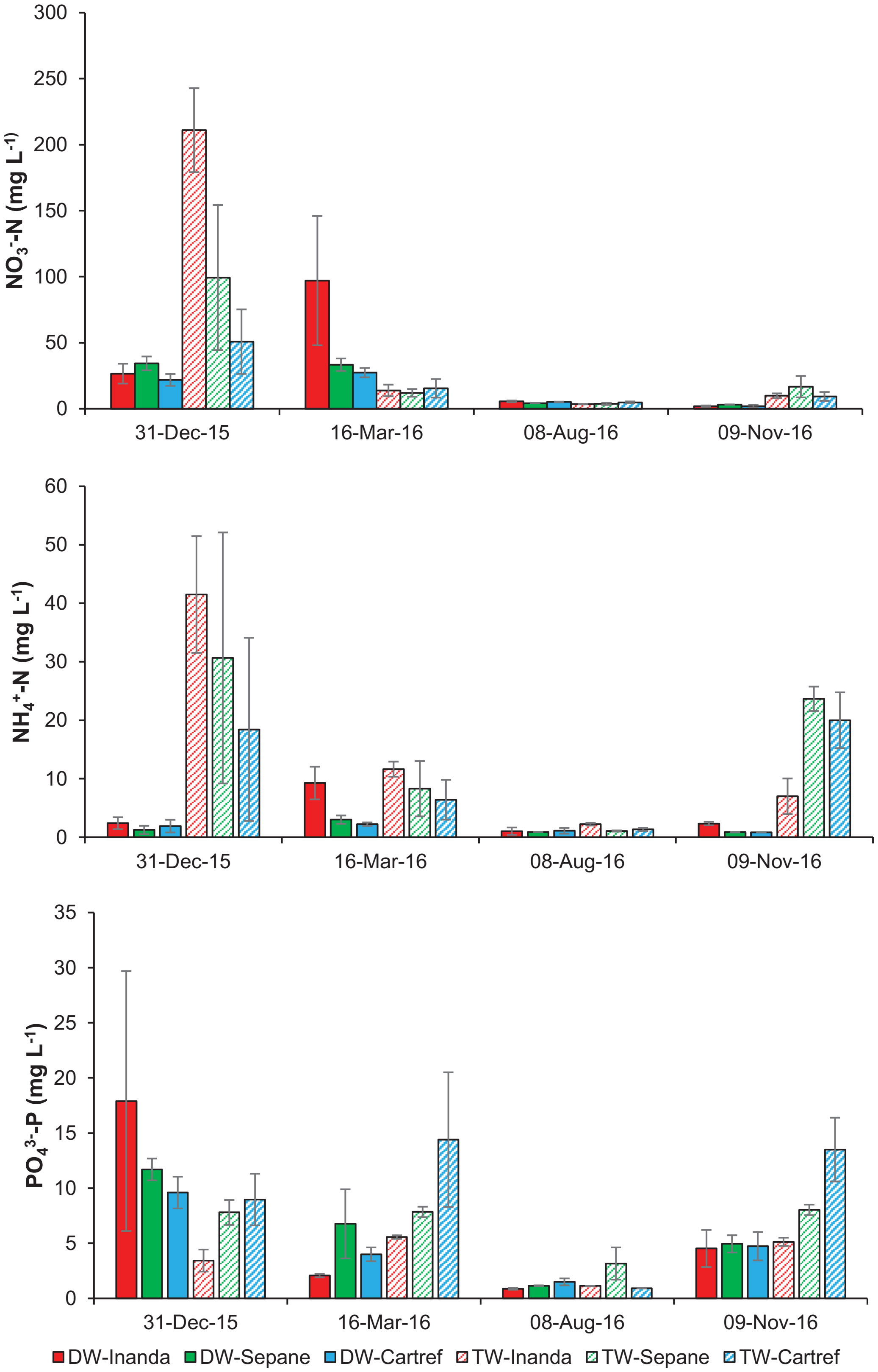

Figure 4.14 Concentrations of NO_3^--N, NH_4^+-N and PO_4^3-P in the leachates from the irrigation and soil treatments from eight to 18 months after planting banana in the tunnel pot experiment. DW-DEWATS effluent; TW-tap water

4.3.3 Conclusions

Bananas in the Sepane and Inanda soils had a better response to irrigation with effluent compared to the Cartref soil. The concentration of nitrogen species were lower in leachates from all soils in the effluent irrigated than in the tap water irrigated treatments. This could be attributed to the inorganic fertiliser applied. It was also observed that the mineral N was higher in Inanda soil with regards to DEWATS effluent irrigation due to high rate of mineralisation. Although high concentrations of N and P were applied from DEWATS effluent the concentrations detected in leachates were getting progressively lower due to fixation on soil particles (PO_4^{3}-P) and loss through denitrification.

4.4 Nitrogen and phosphorus retention in different soils irrigated with anaerobic baffled reactor (ABR) effluent and uptake by perennial rye grass (*Lolium perenne*)

4.4.1 Aim and Objectives

The aim of the study was to understand the processes and mechanisms that affect the ability of different soils to retain nutrients when ABR effluent is applied to soils to irrigate crops and how this may influence the plant nutrients in forms that are available for root uptake and their impact on crop production.

The broad objectives were:

(a) to determine the capacity of three different soils (Cartref (Cf), Sepane (Se) and Inanda (Ia)) to retain N and P from ABR effluent and their uptake by perennial rye grass;

(b) to determine the movement of N and P contained in ABR effluent through the Cf, Se and Ia soils.

4.4.2 Materials and methods

4.4.2.1 Experimental site

The study was conducted in a tunnel at the University of KwaZulu-Natal, Pietermaritzburg Campus. The soils used were the same types used in Section 4.3 except that the Cf was collected from near Ottos Bluff (29°29'52.23"S 30°23'505"E) (Appendix II).

4.4.2.2 Experimental set up and planting

The experiment was designed as a two-factor analysis using a completely randomised design with three soils either unplanted or planted with perennial rye grass (*Lolium perenne*) giving a total of six treatment combinations, replicated five times giving a total of 30 experimental units (columns). Columns made of polyvinyl chloride 360 mm long (i. d. = 100 mm) with a fine stainless-steel mesh attached to the base were used. Glass wool was placed on the mesh in order to minimize soil loss during leaching and a funnel fitted over the base to enable the collection of leachate (Figure 4.15). The soils were air dried and ground to pass a 2 mm sieve. Soils were packed into the columns to a height of 350 mm by constantly tapping on the bench to achieve bulk densities of 1.47 g cm^{-3}, 0.77 g cm^{-3} and 1.21 g cm-^{3} for Cf, Ia and Se, respectively.

Figure 4.15 Experimental unit for the soil column experiment

No fertiliser amendment was used and soil in each column was brought to 70% field capacity with ABR effluent.

Seeds of perennial ryegrass cultivar Nui were planted by broadcasting on the soil surface at a rate of 50 kg per hectare which was equivalent to 24 seeds per column. The columns were then mounted on tripod stands (Figure 4.15). The experiment had a duration of 18 weeks and the rye grass was harvested four times.

4.4.2.3 Data collection

Determination of nitrogen and phosphorus retention in soils

After 18 weeks a sample of each soil from each treatment was collected and prepared for chemical analysis. Nitrogen was determined after extraction in 2M KCl and P after extraction with ammonium bicarbonate.

Determination of nitrogen and phosphorus movement in soils

The volume of the effluent added to all columns at each irrigation time was recorded. Leaching was simulated three times by over-applying effluent to the column in order to collect about 550 mL of leachate from each column. Samples for N analysis were kept at 4°C prior to analysis to avoid losses and changes in the nitrogen forms. The samples were analysed for NH_4^+-N and NO_3^--N by steam distillation with magnesium oxide and Devarda's alloy. Phosphorus was determined by inductively coupled plasma (ICP) emission spectroscopy.

Determination of plant height and dry mass and uptake

Plant height was measured and recorded on a weekly basis. The first harvest was recorded six weeks after planting when the perennial ryegrass had reached a height of 20 cm by cutting to a height of 5 cm. Three more harvests were performed at 21-day intervals. The fresh mass after each harvest was recorded immediately after harvesting and the samples were oven dried at 60°C for 48 hours and the dry mass recorded. Dry plant samples were taken to Fertiliser and Advisory Services, Cedara for the analysis of N and P.

Determination of leachate pH and electrical conductivity

The pH and EC of the leachate samples and a sample of the effluent before leaching were measured at 25°C on a Radiometer PHM 210 meter and a CDM 210 electrical conductivity meter, respectively.

Determination of chemical oxygen demand (COD) in the leachate

Leachate samples equivalent to 50 mL of each of the three replications and the control for each treatment were analysed for COD using potassium dichromate as an oxidant.

4.4.2.4 Data analysis

The data were analysed using the statistical package Genstat 14th edition. Analysis of variance was used to determine whether treatments differed significantly at $p < 0.05$.

4.4.3 Results

4.4.3.1 Nitrogen and phosphorus retention

Significant differences at the end of the experiment were noted between the soils planted with grass and those without grass ($p < 0.05$). The Cf had the highest total N followed by the Se and the Ia which had the least (Figure 4.16). However, unlike the Se and Ia, the grass treatment for the Cf had a final soil N content that was higher than where there was no grass (Figure 4.16).

There were significant differences ($p<0.001$) between the soils in terms of P that remained in the soil at the end of the experiment. The Ia had the highest P as compared to the other two soils which had P concentrations that were similar (Figure 4.17). There were no significant differences between P concentrations in planted and unplanted soils. However, residual soil P in the unplanted columns was higher than in the planted treatments for all three soils (Figure 4.17).

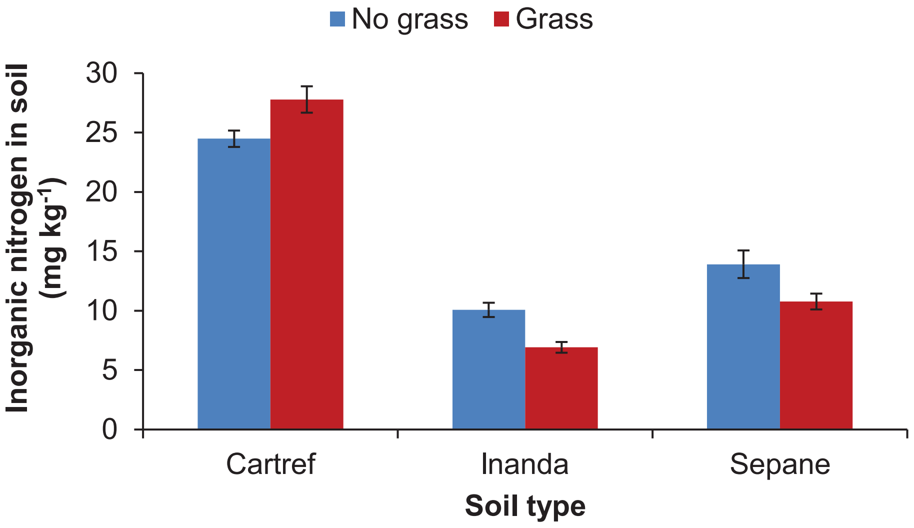

Figure 4.16 Final nitrogen concentration in the three soils with and without ryegrass

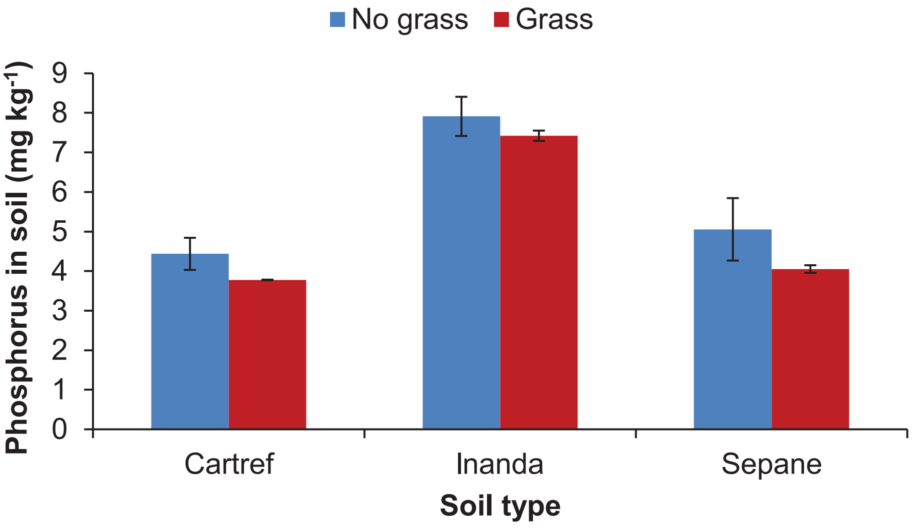

Figure 4.17 Final phosphorus concentration in the three soils with and without ryegrass

4.4.3.2 Nitrogen and phosphorus leaching

Total N that leached through the soils differed significantly amongst the three soil types over the three leaching periods ($p<0.05$). Comparison of the N in the leachate between planted and unplanted treatments also showed significant differences although there were no significant differences over time. The mean N in leachates from the planted Ia were higher compared to the unplanted treatment but this was not the case for the other two soils (Figure 4.18).

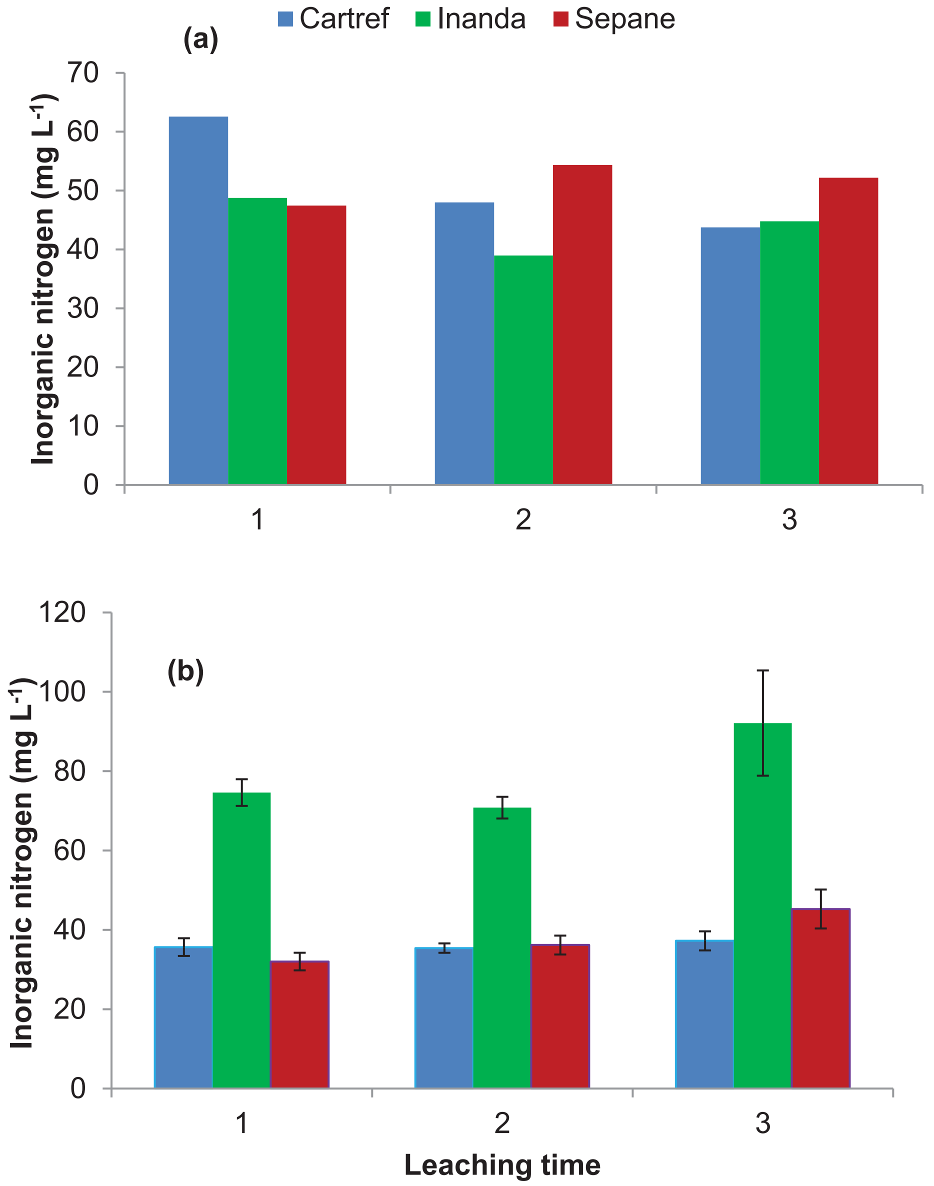

Figure 4.18 Amount of nitrogen leached through the three different soils (a) without grass and (b) with grass at three sampling times

The P leached through the three soils also varied significantly ($p<0.001$) and there were also significant differences between the planted and unplanted treatments for each soil ($p< 0.001$). More P was leached through the planted soils than where there was no grass (Figure 4.19) with the Se having the greatest amount of P loss.

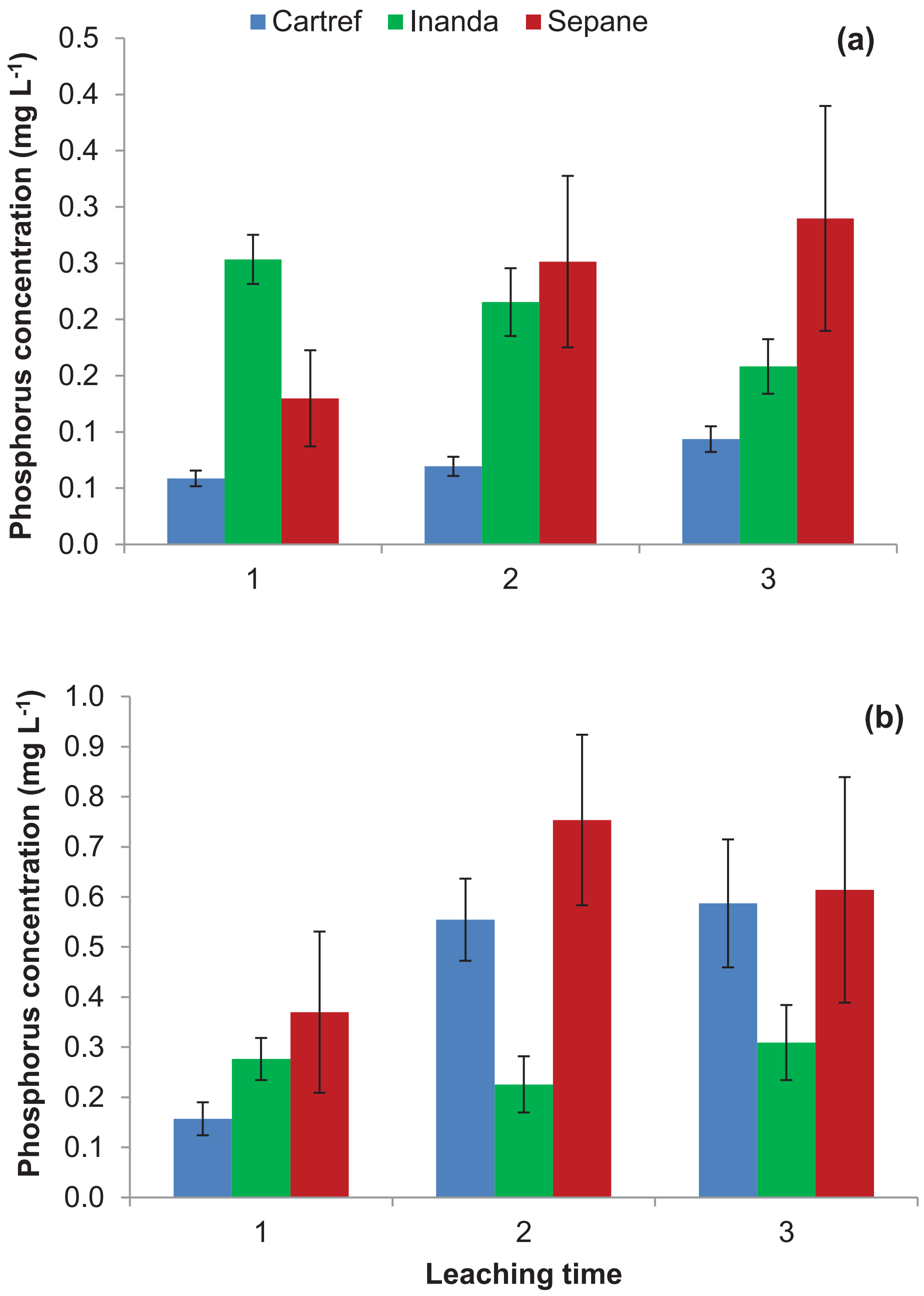

Figure 4.19 Amount of phosphorus leached through the three different soils (a) without grass and (b) with grass at three sampling times

4.4.3.3 Electrical conductivity and pH

Highly significant differences were noted between the three soils with regards to EC of the leachate ($p<0.001$). However, there were no significant differences within the soils with regards to time of leaching. The EC ranged from 0.75 to 2.1 dS m^{-1} with leachates from the Ia having the highest EC followed by Se and the lowest in Cf (Table 4.5).

Table 4.5 Electrical conductivity (dS m^{-1}) of the initial effluent and leachates from the planted and unplanted soils

Sample	No grass Leaching event			Grass Leaching event		
	1	2	3	1	2	3
Effluent initial	0.753	1.321	1.008	0.753	1.321	1.008
Cartref	1.080	1.012	0.773	0.831	1.079	0.851
Inanda	1.725	1.479	1.147	2.028	1.884	1.949
Sepane	1.270	1.146	0.943	0.832	1.051	0.756

Leachate pH varied significantly amongst the soils with change in time ($p < 0.001$). There were also significant differences between the leachate pH of the planted and unplanted soils. The leachate from the Se generally had the highest pH, followed by that from the Cf with the Ia leachate having the lowest pH (Table 4.6).

Table 4.6 pH of the initial effluent and leachates from the planted and unplanted soils after three leaching events

Sample	No grass Leaching event			Grass Leaching event		
	1	2	3	1	2	3
Effluent initial	6.81	6.75	7.45	6.81	6.75	7.45
Cartref	6.60	5.86	6.63	6.66	6.52	7.25
Inanda	6.59	6.48	7.02	6.53	6.05	6.47
Sepane	6.58	7.26	7.61	6.63	7.06	7.44

4.4.3.4 Chemical oxygen demand

There was a variation in COD of the leachates from the different soils (Figure 4.20). There were significant differences in COD amongst soils with time and also between the planted and unplanted treatments ($p < 0.05$).

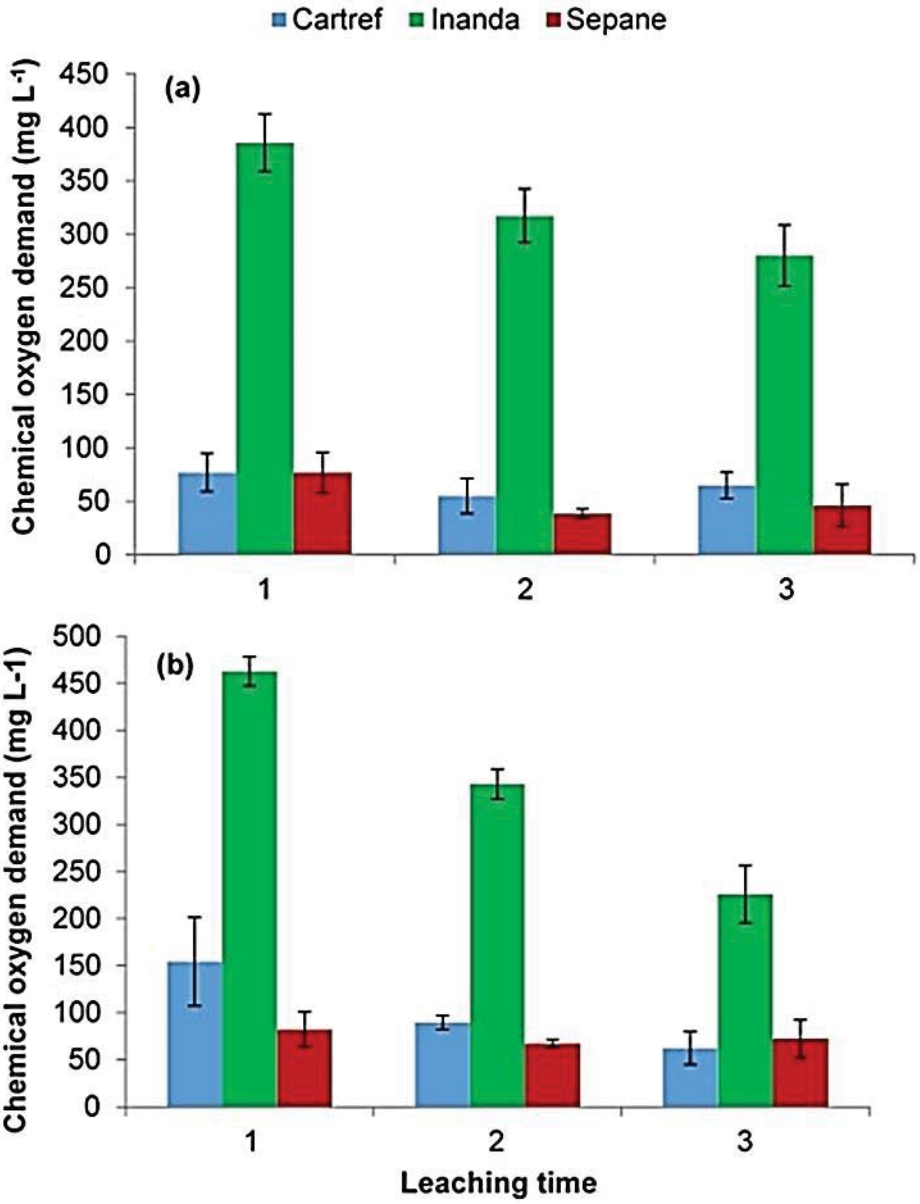

Figure 4.20 Chemical oxygen demand of the leachates from the three soils (a) without grass and (b) with grass at three sampling times

The leachate from the Ia had the highest COD for both planted and unplanted treatments. The Se and Cf had significantly lower COD in the leachates and there was a decrease in COD of the leachates from all the soils with time.

4.4.3.5 Crop growth variables

There were significant differences in plant height in the three different soils ($p<0.001$) with plant height following the order Se > Cf > Ia at all cuttings (Figure 4.21).

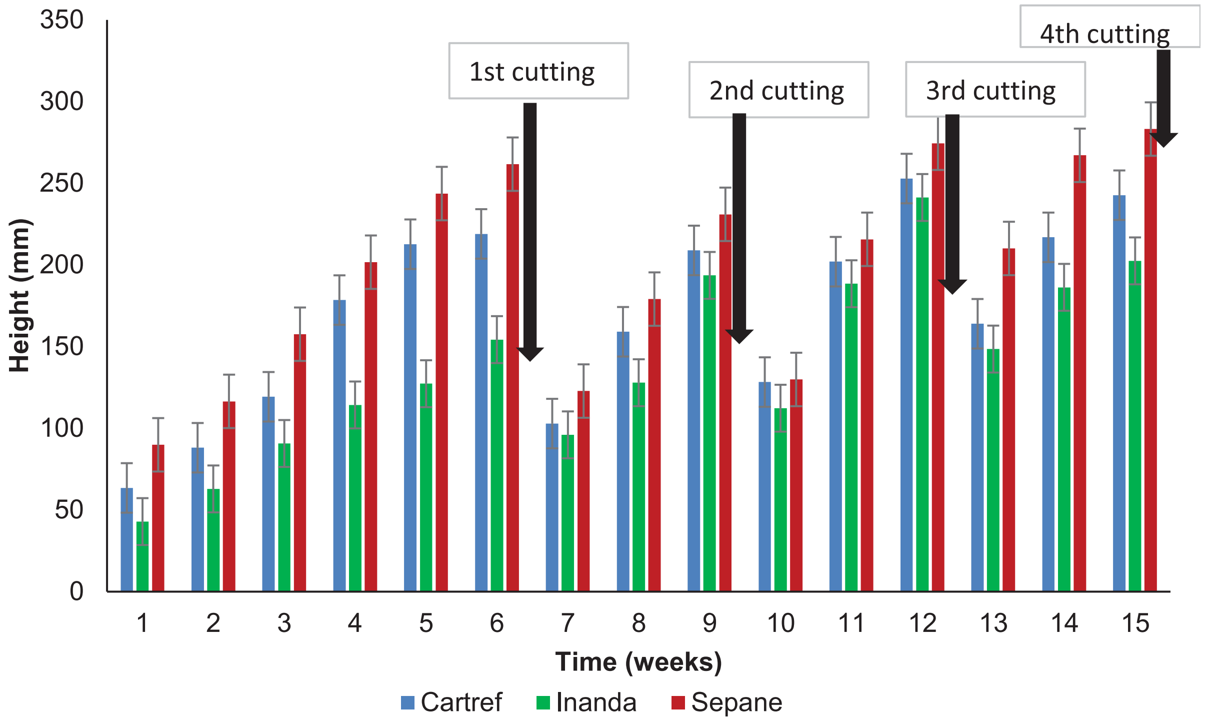

Figure 4.21 Change in plant height and regrowth with time in the three different soils

Regrowth of perennial rye grass was generally good for all the soils (Figure 4.21) and although a slight decrease was measured at the 4th cutting, the heights remained above those at the first cutting.

In addition to plant height, root length from a sample of each soil was recorded. Root length followed the order Ia > Cf > Se (Figure 4.22).

Figure 4.22 Root length of perennial rye grass grown in three different soils 18 weeks after planting

In general, plant dry matter increased with each harvest for all soils (Figure 4.23). The harvest yield expressed as kg per hectare differed significantly for the three soils ($p<0.001$).

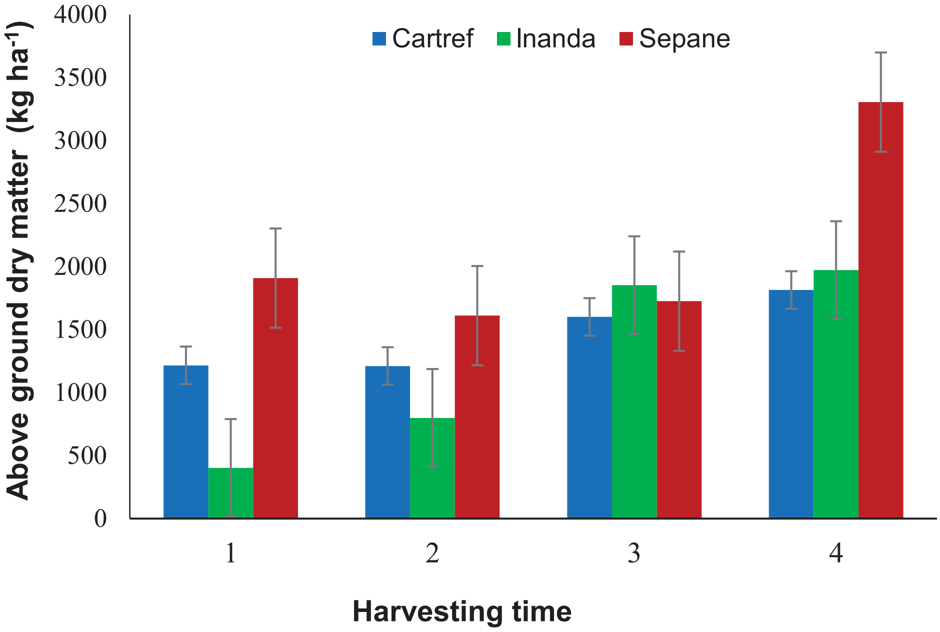

Figure 4.23 Dry matter at four harvest times in the three different soils

The highest plant dry matter for all the four harvest periods was recorded in the Se with a large increase noted from the third to the last harvest. In the Cf, plant dry matter increased steadily while in the Ia there was a large increase between the second and third harvests (Figure 4.23).

4.4.3.6 Plant nutrient uptake

With respect to N concentrations in plant tissue, there were significant differences among the soils with the Ia having the highest levels of N in plant material ($p<0.001$). There were also significant differences with time. In general, there was a decline in plant N from the first to the fourth harvest (Figure 4.24).

The high N concentration in plants growing in the Ia were reflected in the intensity of the green leaf colour as compared to plants in the other two soils (Figure 4.25) which showed slight chlorosis.

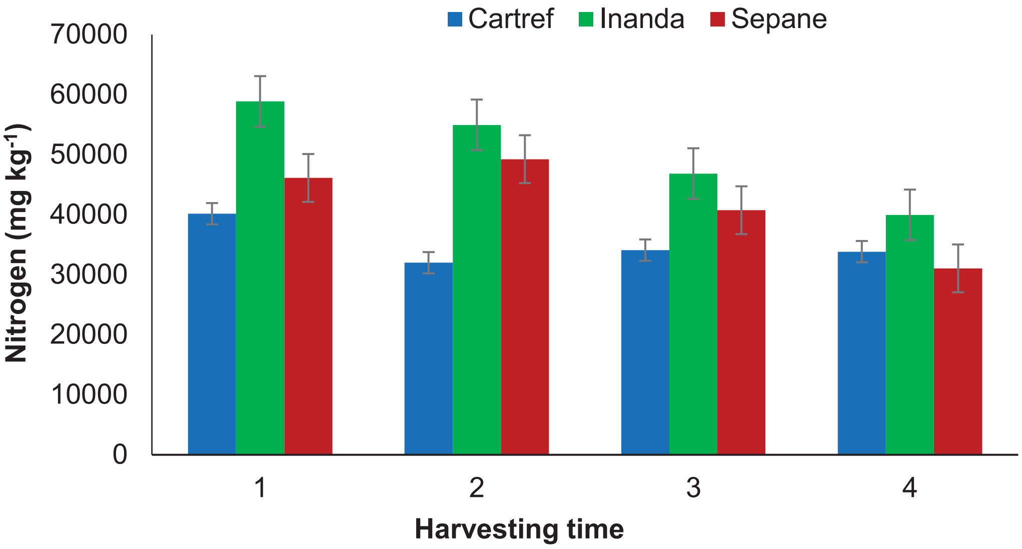

Figure 4.24 Plant tissue nitrogen at four harvest times in the three different soils

Figure 4.25 Leaf colour of perennial ryegrass grown in the Sepane (Se); Inanda (Ia); and Cartref (Cf) soils

Phosphorus uptake, on the other hand, increased with time (Figure 4.26). There were significant differences in P uptake between the three soils with the Se having the highest mean P uptake ($p < 0.001$). Inanda had the least P in plant tissue which is contrary to its N uptake although the P level declined with time following the trend in N. In the Se and Cf soils the plant P concentration increased from the first to the third harvest and then declined slightly in the final harvest.

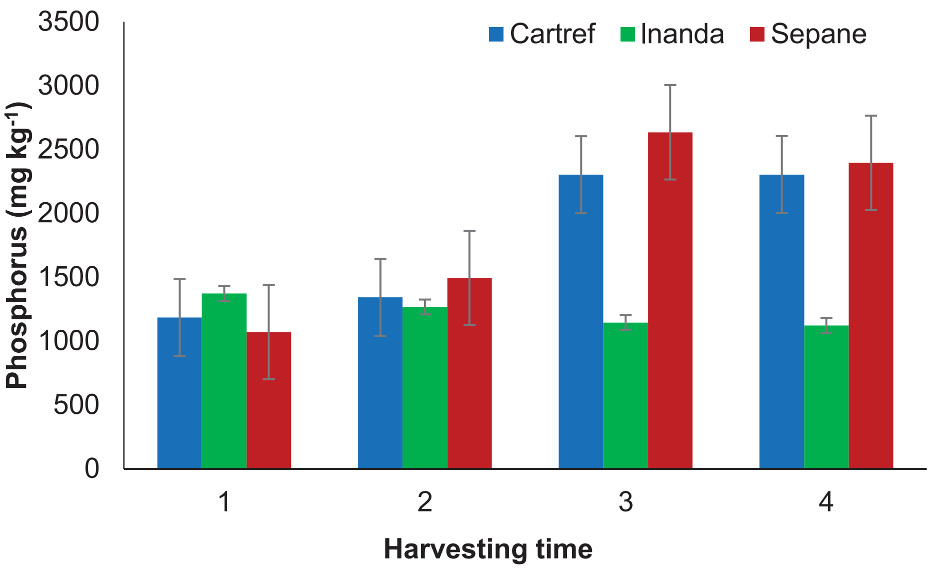

Figure 4.26 Plant tissue phosphorus at four harvest times in the three different soils

4.4.4 Discussion

With regard to nutrient balances, in the Ia and Se it is possible that mineralisation of the organic matter in the soils could account for the difference, by releasing N that was not measurable in the initial soil. However, the organic matter content of the Cf is very low and so this explanation seems less likely.

For P in the Cf the amounts of “in” vs “out” are almost the same which on such a sandy soil is perhaps reasonable since little P would be held in an unavailable form. In the Ia there is a large difference between the “in” and the “out” suggesting that the difference is being held in the soil in a form unavailable to either plants or chemical extractant. The high amount of sesquioxides and clay in the Ia could account for such ‘fixation’. The Se is the exception since it apparently released P. The reason for such release is not known but it could be that the effluent caused an increase in pH or that organic matter mineralisation released P in addition to N.

Plant nutrient uptake and leaching are linked such that they both influence the retention of N and P in the soil. The Ia was least able to prevent N leaching from the soil especially in the planted columns. Possible reasons for this could be the higher amount of natural N in the soil due to its high organic matter content, reducing the demand for the effluent N that was added, coupled with the low bulk density of the soil and thus high porosity that reduced the N retention time. Creation of channels by the roots might have also allowed a faster flow of ABR effluent through the Ia. The clayey Se was the most efficient in reducing the leaching of N and despite having shorter rooting depth than either the Ia or the Cf the Se produced a higher biomass. The less N leached from the Cf is likely a result of the greater biomass produced on this soil than the Ia that counteracted the sandy and highly porous nature of the Cf soil.

Amounts of P leached from all the soils were very low due to the well-known immobility of P through soils. However, in all soils more P was measured in the leachates from the planted treatments again perhaps due to movement through root channels. The Se lost the greatest amount of P and this may reflect the presence of structural cracks in the soil due to its higher expansible clay content than either the Ia or the Cf, coupled with its shorter rooting depth.

The Se was most efficient in using plant available N and P, while uptake by the Cf was the lowest. The general inverse relationship between N and P uptake with time for all the three soils is related to the biomass production. The observed inverse relationship between N uptake and biomass production is probably a function of the dilution effect that occurs, especially with mobile elements such as nitrate, with increasing yield. That this was most pronounced in the Ia is a result of the soils high natural N content. The Ia also showed an inverse relationship between biomass and P uptake and again this is likely due to a dilution effect as increasing P became unavailable in this soil. In the Cf and Se, as biomass increased, in general so did the uptake of P reflecting that a greater proportion of the added P was plant-available in these soils.

Electrical conductivity of the leachate ranged from 0.75 to 2.10 dS m^{-1} which is low to medium in salinity rating. In this study, EC levels were considered to cause no harm although long term use might require some mechanisms such as leaching with freshwater to reduce salt accumulation. This study, of course, made no allowance for rainfall that would naturally affect crops grown in the field and thus may achieve the leaching of any build-up of soluble salts that might occur.

4.4.5 Conclusions

This study has shown that the ABR effluent has the potential to provide sufficient N and P for plant growth. Soil type plays a major role in determining retention of N and P allowing uptake by plants. The Se, a clayey soil with moderate pH, was the most effective in retaining N and P as indicated by the highest plant dry mater harvested and nutrient concentrations in the plant tissue. Perennial rye grass was able to efficiently absorb large quantities of N and P from the effluent as indicated by an increase in dry matter over time. However, leaching of these nutrients was more pronounced through the soils that had vegetation probably due to channel flow around roots as they grow.

5 LABORATORY EXPERIMENTS WITH HUMAN EXCRETA-DERIVED MATERIALS AS SOURCES OF NUTRIENTS FOR PLANT GROWTH

5.1 Introduction

Human waste, particularly urine, has been shown to contain nutrients equivalent to some plant requirements (Schouw et al., 2002). For many years famers in different parts of the world have been using urine to fertilise their crop lands to increase food production (Drangert, 1998). Reclaiming human waste (urine and faeces) is a potential strategy to both derive plant nutrients and solve sanitation problems while increasing food production in peri-urban areas. The aim of this chapter is to investigate the potential release of plant nutrients from human excreta-derived materials (HEDMs) and uptake of the nutrients by different plants.

5.2 Characterisation of human excreta-derived materials

5.2.1 Urine and its by-products

The urine fertiliser sources used in these studies were obtained from Newlands-Mashu, Durban. These consisted of stored urine collected from households around Durban, struvite processed from source-separated urine and the resultant struvite-effluent remaining after the precipitation of struvite. The struvite and struvite-effluent were processed at the reactor plant at Newlands-Mashu. There were two sources of the nitrified urine concentrate (NUC) namely that obtained from the Swiss Federal Institute of Aquatic Science and Technology (EAWAG) Switzerland and the other from the processing plant at Newlands-Mashu.

5.2.2 LaDePa pellets

Latrine dehydration and pasteurisation (LaDePa pellets) is a process which produces dry pasteurised pellets from sludge after emptying ventilated pit latrines. This process results in pellets that contain nitrogen and phosphorus. These were collected and sent to the FAS for nutrient analysis.

5.3 Nitrogen and phosphorus release from LaDePa pellets and struvite as fertiliser sources in an incubation experiment

5.3.1 Aim and objective

The aim of this study was to assess the potential of using struvite from source-separated urine and LaDePa pellets as plant nutrient sources when used singly, in combination or together with common commercial fertilisers (urea and diammonium phosphate (DAP)).

The broad objective was to determine the nutrient (N and P) release pattern of struvite and LaDePa pellets in two different soils.

5.3.2 Materials and methods

Soils (Shortlands (Sd) and Inanda (Ia)) were collected, air dried and sieved to pass a 2mm sieve. Each experimental unit consisted of 100 g soil and the materials were mixed, homogenised and brought to and maintained at 70% moisture content. The treatments included a control (C), struvite (S), LaDePa pellets (L), DAP (D), and urea (U) singly and in combination according to fertiliser recommendation for maize.

Destructive sampling was done weekly by extracting with 2M KCl and analysing with a Thermo Scientific gallery analyser for NH_4^+-N, NO_3^--N and P over a 70-day incubation period. The soil samples (5 g) were weighed into conical flasks, 50 ml potassium chloride (2M KCl) dispensed, and the flasks were shaken at 180 cycles per minute on the reciprocal shaker for 30 minutes (Carter, 1993). Samples were then filtered through Bowmen 250 mm filter papers, and soil sample extracts were then analysed using 2011 Thermo Scientific Gallery sample analyser.

5.3.3 Results

5.3.3.1 Nitrogen mineralisation

The main observations on N mineralisation were that:

(a) struvite and LaDePa pellets produced gradual changes in the release of both ammonium and nitrate whereas synthetic mineral fertilisers gave more rapid release (Figures 5.1 and 5.2).

(b) struvite and LaDePa pellets performed better when used with other fertilisers than when used singly.

(c) ammonium release occurred inversely to the release of nitrates in the Inanda soil (Figures 5.3 and 5.4).

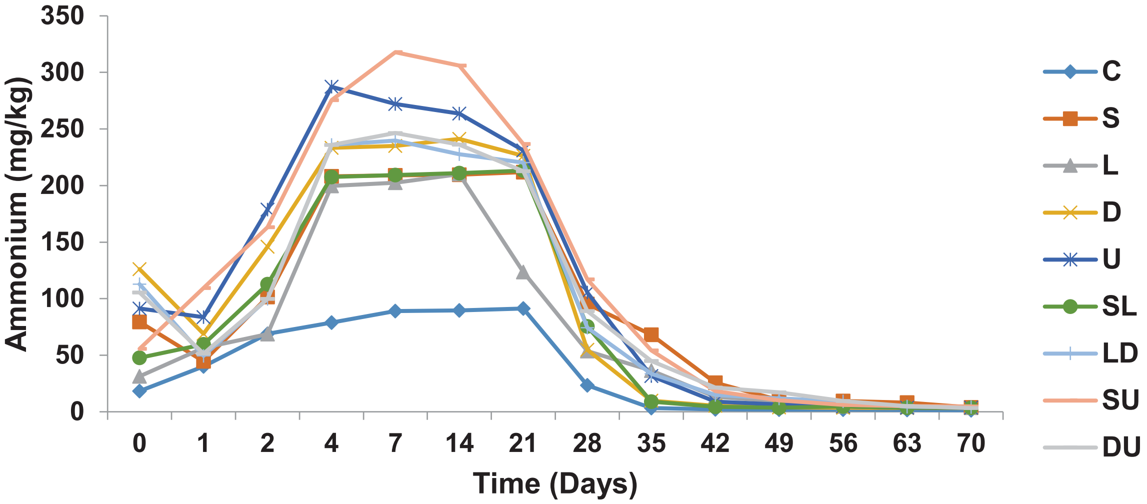

Figure 5.1 Ammonium release in the Shortlands from LaDePa pellets (L), struvite (S), diammonium phosphate (D) and urea (U) singly or in combination compared to the control (C) during 70 days incubation

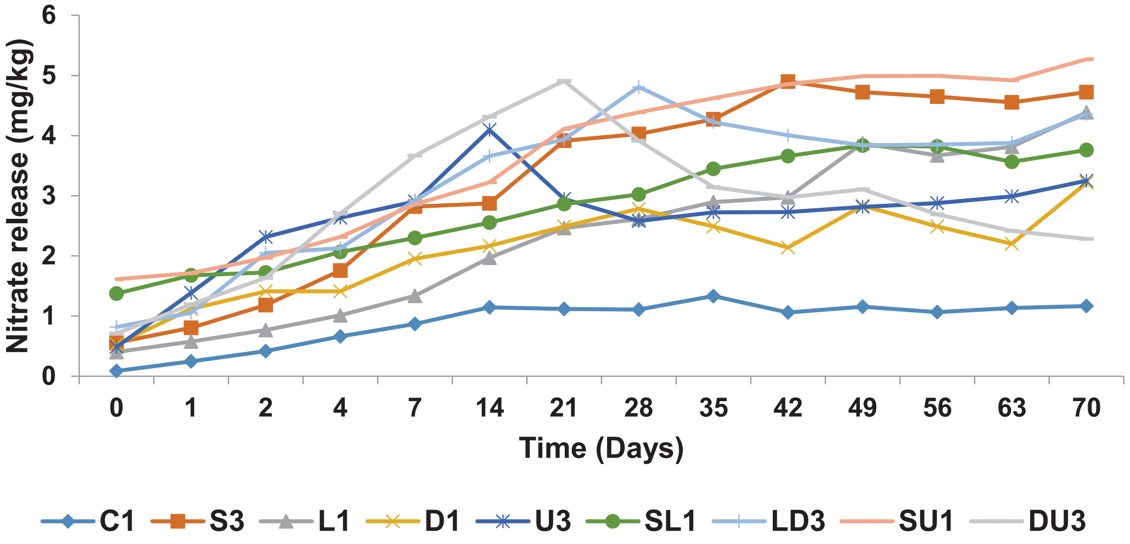

Figure 5.2 Nitrate release in the Shortlands from LaDePa pellets (L), struvite (S), diammonium phosphate (D) and urea (U) singly or in combination compared to the control (C) during 70 days incubation

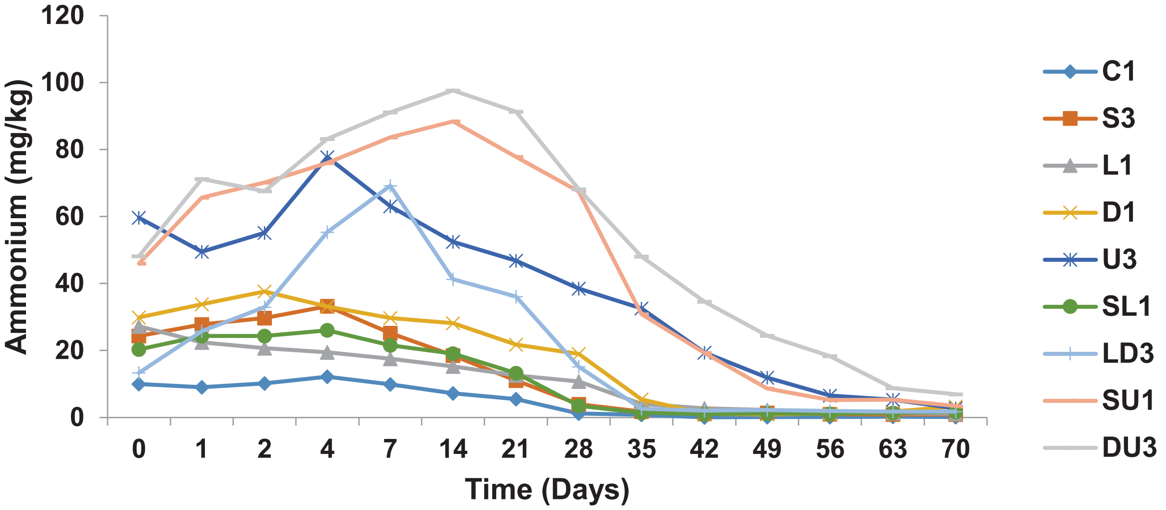

Figure 5.3 Ammonium release in the Inanda from LaDePa pellets (L), struvite (S), diammonium phosphate (D) and urea (U) singly or in combination compared to the control (C) during 70 days incubation

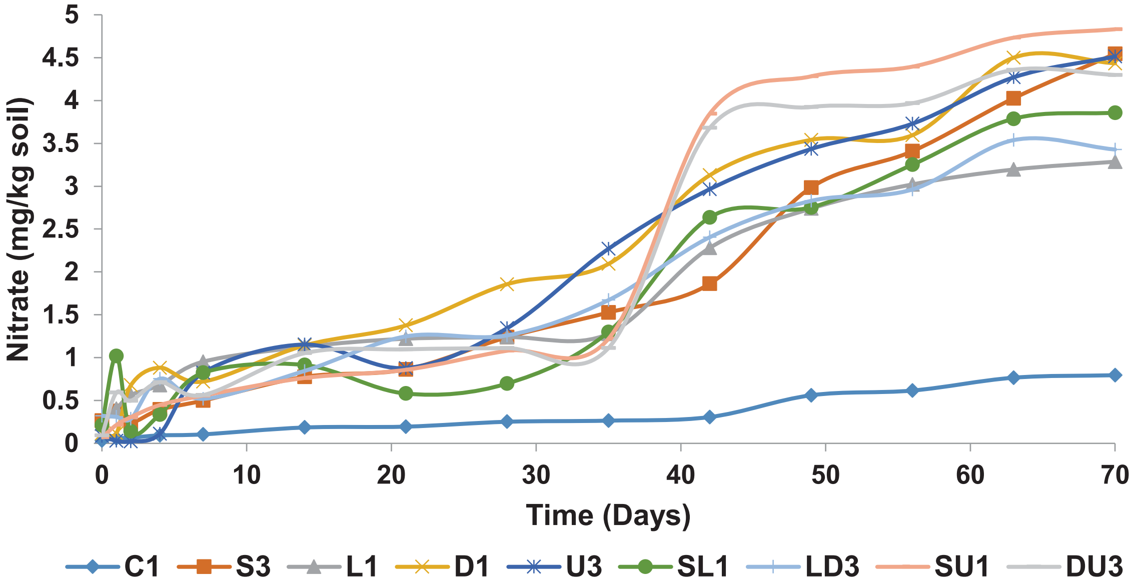

Figure 5.4 Nitrate release in the Inanda from LaDePa pellets (L), struvite (S), diammonium phosphate (D) and urea (U) singly or in combination compared to the control (C) during 70 days incubation

The process of N mineralisation converted the organic N contained in LaDePa pellets into plant-useable inorganic forms (ammonium and nitrate). A change in the release patterns of N hence reflects the net mineralisation of organic N. Compared to commercial nutrient sources, release of ammonium and nitrates by struvite and LaDePa pellets were more gradual as they are slow-release fertilisers. Hence, struvite and LaDePa pellets could continue releasing nitrates steadily even beyond the 70th day of the incubation period. Unlike the readily available commercial nutrient sources with high solubility, struvite has a solubility of only 0.2 g L^{-1} in water and when incorporated into the soil, nutrient release is largely the result of microbial nitrification of the ammonium constituent rather than simple dissolution. The slow-release characteristics of struvite and LaDePa pellets suggests that when a combination of struvite or LaDePa pellets with either urea or DAP is used, urea and DAP will release their nutrients earlier in the incubation period while struvite and LaDePa pellets will release their nutrients later. This is likely to be the reason why the best performance was observed when struvite and LaDePa pellets were used in combination with immediately available fertilisers than when used alone.

5.3.3.2 Phosphorus release

The main observations for P were that:

(a) larger quantities of available P were measured in the Sd than under the more acidic soil conditions of the Ia (Figures 5.5 and 5.6). This probably reflects the abilities of the two respective soils to retain P in a non-extractable form, rather than being a direct measure of the solubilities of the different fertiliser materials.

(b) at some times during the incubation period, struvite managed to supply more available P under acidic soil conditions than the commercial fertiliser.

(c) available phosphorus was greater where struvite and LaDePa pellets were used in combination with other nutrient sources than when used alone.

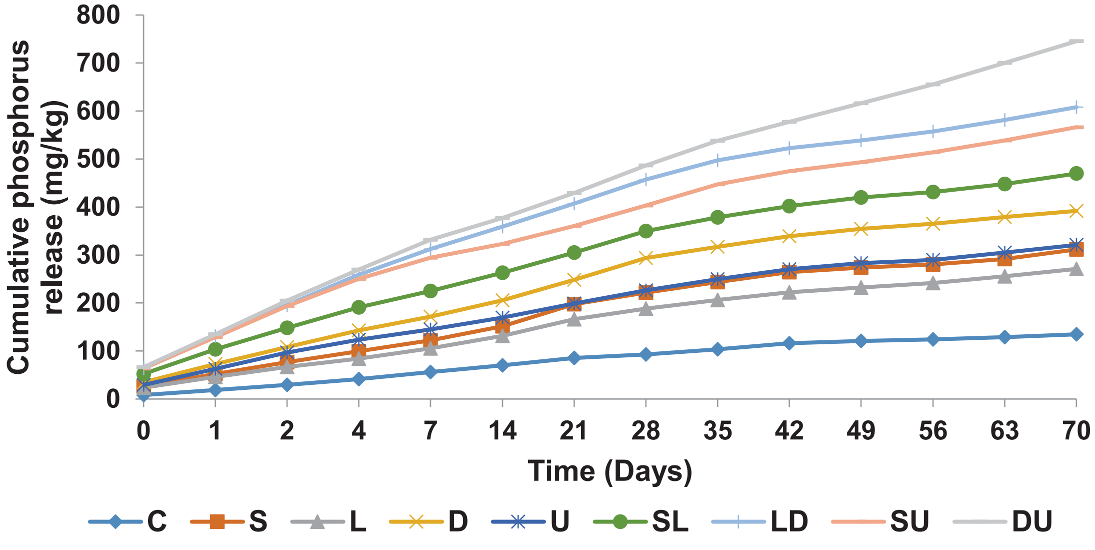

Figure 5.5 Cumulative total phosphorus in the Shortlands from LaDePa pellets (L), struvite (S), diammonium phosphate (D) and urea (U) singly or in combination compared to the control (C) during 70 days incubation

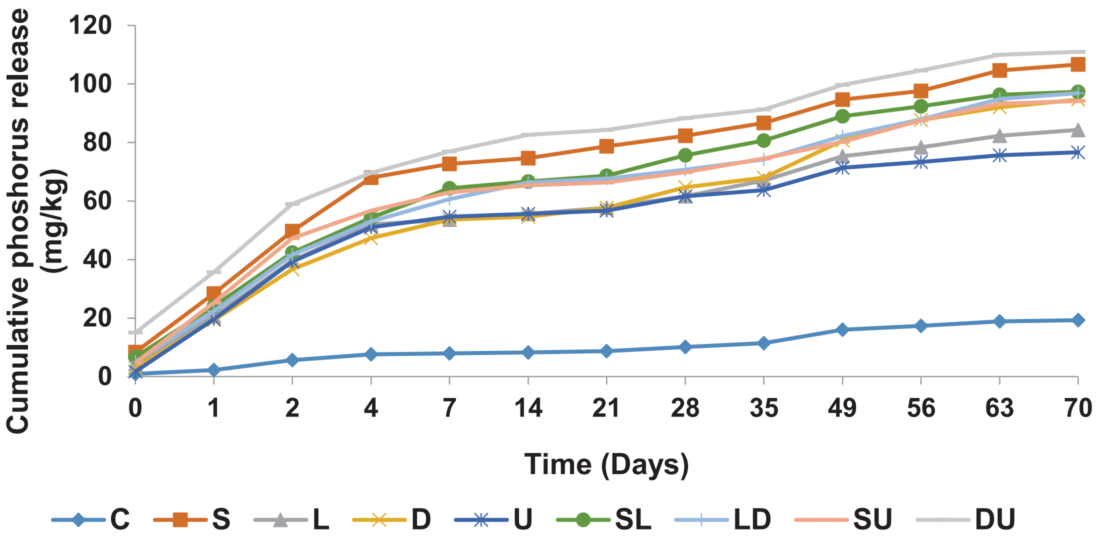

Figure 5.6 Cumulative total phosphorus in the Inanda from LaDePa pellets (L), struvite (S), diammonium phosphate (D) and urea (U) singly or in combination compared to the control (C) during 70 days incubation

5.3.4 Conclusions

Both struvite and LaDePa pellets were effective fertilisers, comfortably outperforming the control with no added fertiliser, even when added singly. They were, however, most effective as P and N sources when used in combination with commercial fertilisers (urea and DAP). As expected due to their greater solubilities, urea and DAP generally performed better than LaDePa pellets and struvite. Importantly, struvite and LaDePa pellets released nutrients more gradually throughout the 70-day incubation period and especially in the later stages of the incubation when the commercial sources were largely exhausted, whereas the urea and DAP showed a rapid release of N and P in the early stages of incubation.

A combination of struvite and LaDePa pellets as slow-release fertilisers with urea and DAP as readily available fertilisers would likely give a better balanced nutrient release throughout a crop’s growing period.

5.4 Effect of urine-based fertilisers on biomass production and yield of perennial ryegrass

5.4.1 Aim and objectives

The aim of this study was to assess the nutrient uptake and utilization by perennial ryegrass (*Lolium perenne*) in response to the application of urine-based fertiliser combinations (urine, struvite-effluent, struvite and NUC) on two different soil types.

The broad objectives were: (1) to determine the N release pattern from urine-based fertilisers in two contrasting soils; and (2) to determine the effect of urine-based fertiliser combinations on growth and biomass production of perennial ryegrass.

5.4.2 Materials and methods

Two experiments were conducted to accomplish the research aims and objectives, i.e. a soil incubation experiment and a pot experiment.

5.4.2.1 Experiment 1 – Soil incubation

The experiment was conducted in a controlled environment at the University of KwaZulu-Natal, Pietermaritzburg Campus. Environmental conditions were maintained at 25°C air temperature and 80% relative humidity throughout the experiment.

The nutrient sources were obtained from the Newlands-Mashu site and consisted of (a) stored urine (U; 4 656 mg N L^{-1}; 231 mg P L^{-1}); (b) struvite (S; 5.7% N; 12.6% P) processed from source-separated urine; (c) the resultant struvite-effluent (SE; 4 578 mg N L^{-1}; 7 mg P L^{-1}); and (d) nitrified urine concentrate (NUC; 35 483 mg N L^{-1}; 3 741 mg P L^{-1}). A zero fertiliser treatment was used as the control. Soils used were an Inanda (Ia) and a Cartref (Cf). Both were air dried and sieved to <2 mm.

Aerobic (2 kg ventilated containers maintained at 70-100% field capacity) incubation experiments were conducted for a period of 70 days. The experiment was designed as a 5 fertiliser sources (U, SE, S + SE, NUC, Control) x 2 soil types (Cf and Ia) x 2 nitrogen rates (recommended (R) and twice the recommended (2R) rate) factorial replicated three times giving 60 experimental units.

The soil samples (5 g) were weighed into conical flasks, 50 ml potassium chloride (2M KCl) dispensed, and the flasks were shaken at 180 cycles per minute on the reciprocal shaker for 30 minutes (Carter, 1993). Samples were then filtered through Bowmen 250 mm filter papers, and soil sample extracts were then analysed using 2011 Thermo Scientific Gallery sample analyser.

5.4.2.2 Experiment 2 – Pot trial

A pot trial was set up in a tunnel at the University of KwaZulu-Natal, Pietermaritzburg Campus at a temperature of 26°C and 65% atmospheric humidity to determine the effect of the application of the urine and urine products described in the incubation experiment (Section 5.4.2.1) on growth and biomass production of perennial ryegrass on a sandy soil. To 1 kg of the Cf soil the same fertiliser sources used for the incubation experiment were applied. The nutrient sources were either applied once off or split applied after each harvest resulting in three split applications. The fertiliser materials were applied at two rates (R and 2R except for the NPK control (2:3:2 NPK compound fertiliser) that was added only at the recommended rate) based on the N requirement of perennial ryegrass and replicated three times. Perennial ryegrass seeds were planted at the rate of 25 kg seed per hectare translating to one gram per pot. The different plant nutrient sources (fertilisers) calculated on the basis of N crop requirements for perennial ryegrass were added to the pots which were maintained at 70% field capacity with deionized water throughout the experiment. Plants were cut back to 1 cm above the ground after attaining a cutting height of 20 cm and were allowed to regrow resulting in four cuts.

Phosphorus was found to be highly deficient in these soils but fertiliser application rates were based on the crop N requirements. Therefore, P was corrected using single superphosphate (SSP; 10.5% P). However, in the (S+SE) treatment P was not limiting as extra P was supplied by the struvite (S). All additional P supplemented by SSP was applied immediately prior to sowing by mixing homogeneously into the soil.

Harvesting was done based on crop growth rates (20 cm plant height), at 35, 45, 63 and 79 days after sowing. At harvest the fresh mass of the plants was determined followed by drying at 60°C for 72 hours to obtain dry mass.

5.4.2.3 Data analysis

Data analysis was carried out using the General Linear Model, Repeated Measures using the Genstat 14 Statistical Package to compare treatment means and the interactions. Significance tests were done at the 5% level of significance.

5.4.3 Results

5.4.3.1 Incubation trial

Nitrogen mineralisaton in Cartref soil

Between Days 4 and 14 acute NH_4^+-N depletions from the system was observed (Figure 5.7) followed by a rather steady and gradual depletion between Days 21 and 70. By Day 70, the NH_4^+-N had decreased to about 3 mg kg^{-1} soil from about 1 000 mg kg^{-1} at the beginning of the incubation. At the same time nitrate production was very low (Figure 5.8). The highest nitrate was recorded at Day 70 where it was continuing to increase.

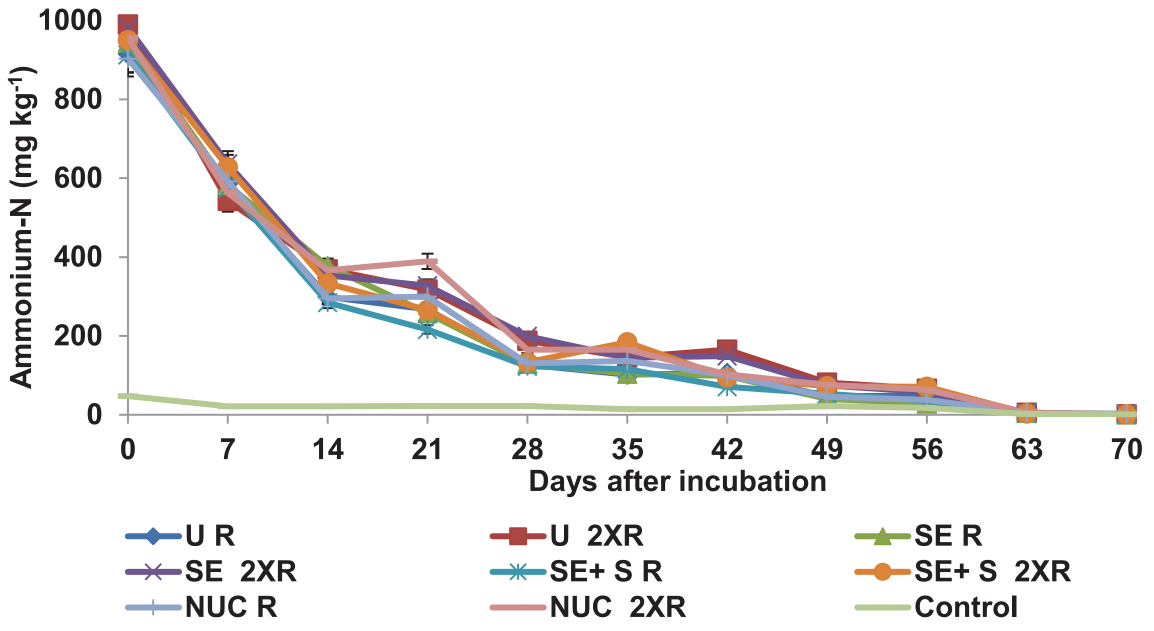

Figure 5.7 Ammonium-N concentration during the 70-day incubation study for the treatments: urine (U), struvite effluent (SE), struvite effluent + struvite (SE+S), and nitrified urine concentrate (NUC) at recommended (R) and double recommended (2XR) nitrogen rates and the control in the Cartref soil

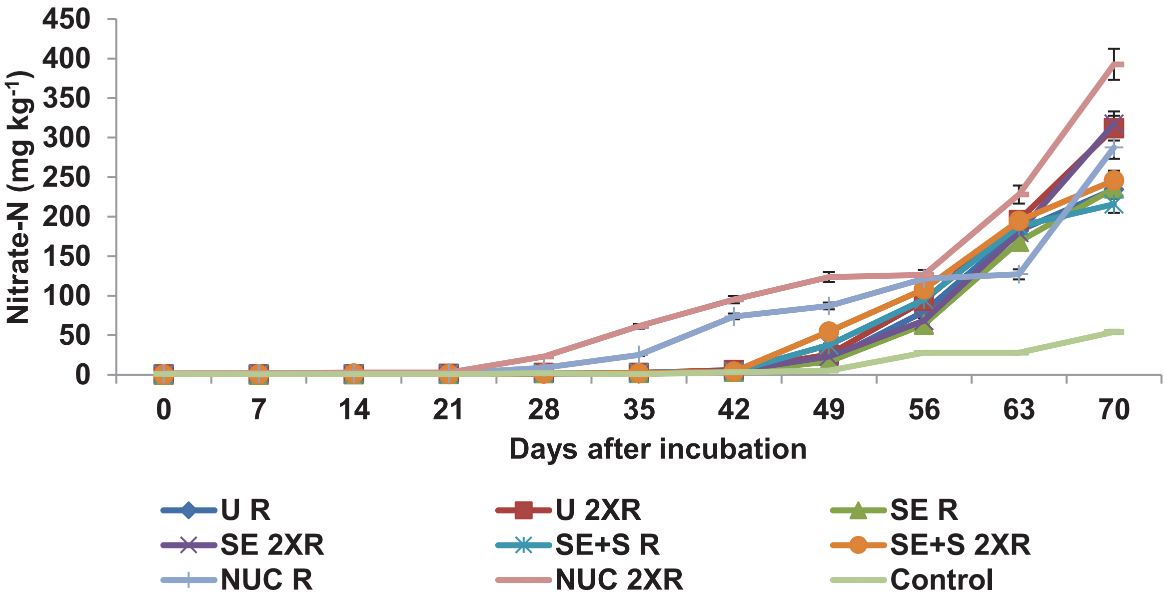

Figure 5.8 Nitrate concentration during the 70-day incubation study for the treatments: urine (U), struvite effluent (SE), struvite effluent + struvite (SE+S), and nitrified urine concentrate (NUC) at recommended (R) and double recommended (2XR) nitrogen rates and the control in the Cartref soil

Significant differences were observed between R and 2R treatments. There were no significant differences between U-R, NUC-R and SE-R in terms of ammonium depletion. However, the S + SE-R treatment was significantly different from the other R treatments. Similar trends were noted for the 2R treatments.

At Day 21 NUC was the first treatment to show a significant nitrate increase followed by the other treatments on Day 42 (Figure 5.8).

Nitrogen mineralisation in Inanda soil

In the Ia a significant depletion in ammonium was observed at Day 1 followed by a gradual depletion to Day 21. A sharper ammonium depletion was recorded between days 21 and 42 and thereafter was almost totally depleted by Day 70 (Figure 5.9) with no significant differences between treatments. For all treatments there was no significant difference between the R and 2R in the nitrate concentration during the 70 days (results not shown).

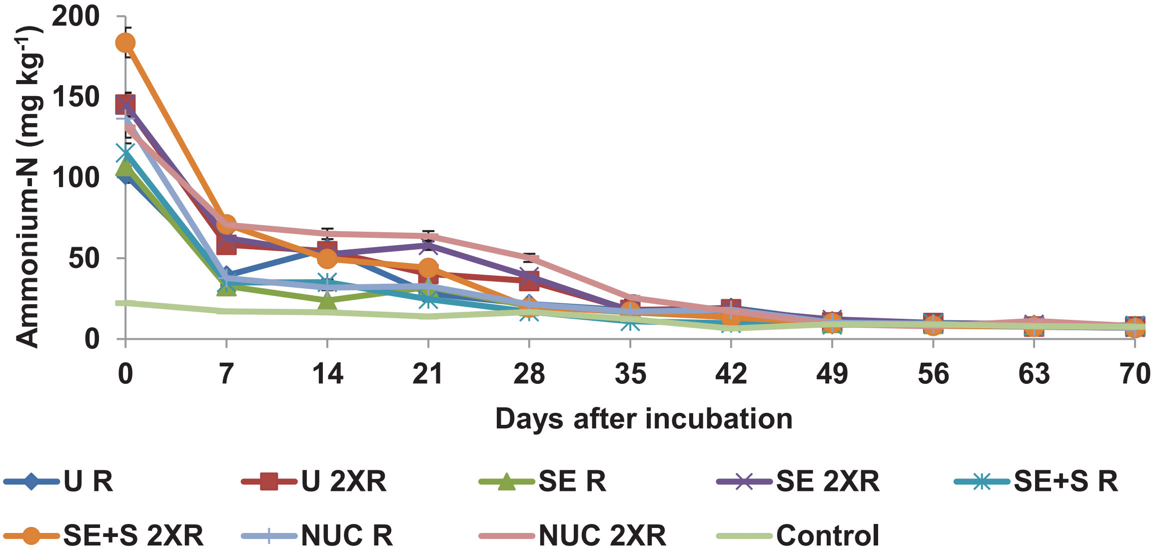

Figure 5.9 Ammonium-N concentration during the 70-day incubation study for the treatments: urine (U), struvite effluent (SE), struvite effluent + struvite (SE+S), and nitrified urine concentrate (NUC) at recommended (R) and double recommended (2XR) nitrogen rates and control in the Inanda

pH and electrical conductivity in soils

Although the pH increased with incubation time, the different treatments had similar effects on pH with the pH of the Ia increasing from 4.11 in the initial stages to 5.20 at Day 70. Increases in EC were observed and these occurred between Day 0 and Day 42 with no further increase thereafter in the Cf. However, treatments did not differ significantly from one another.

5.4.3.2 Pot trial

Dry matter yield

There were significant ($p<0.05$) differences in dry matter production among the treatments-with reference to application method and application rates. Dry matter production increased significantly with time after each cut before declining after the 3rd harvest (Figure 5.10). The 1st, 2nd, 3rd and 4th harvest differed significantly between each other with means of 150, 208, 481 and 321 kg ha^{-1}, respectively. Cumulatively the NUC at the recommended rate produced the highest dry matter yield (Figure 5.11). However, it was noted that even though dry matter declined significantly after the 3rd harvest, the split application method had a gradual decline whereas the once-off application method had a sharp decline. Split application had significantly higher dry matter production than once-off application (Figure 5.12) with means of 315 and 265 kg ha^{-1}, respectively. Dry matter production did not differ significantly between the R and 2R rates. Nevertheless, NUC had the highest dry matter production before the general yield decline. All treatments gave significantly higher dry matter than the zero fertiliser treatment although there were no significant differences in dry matter production between the NPK control and the urine and urine-derived products treatments.

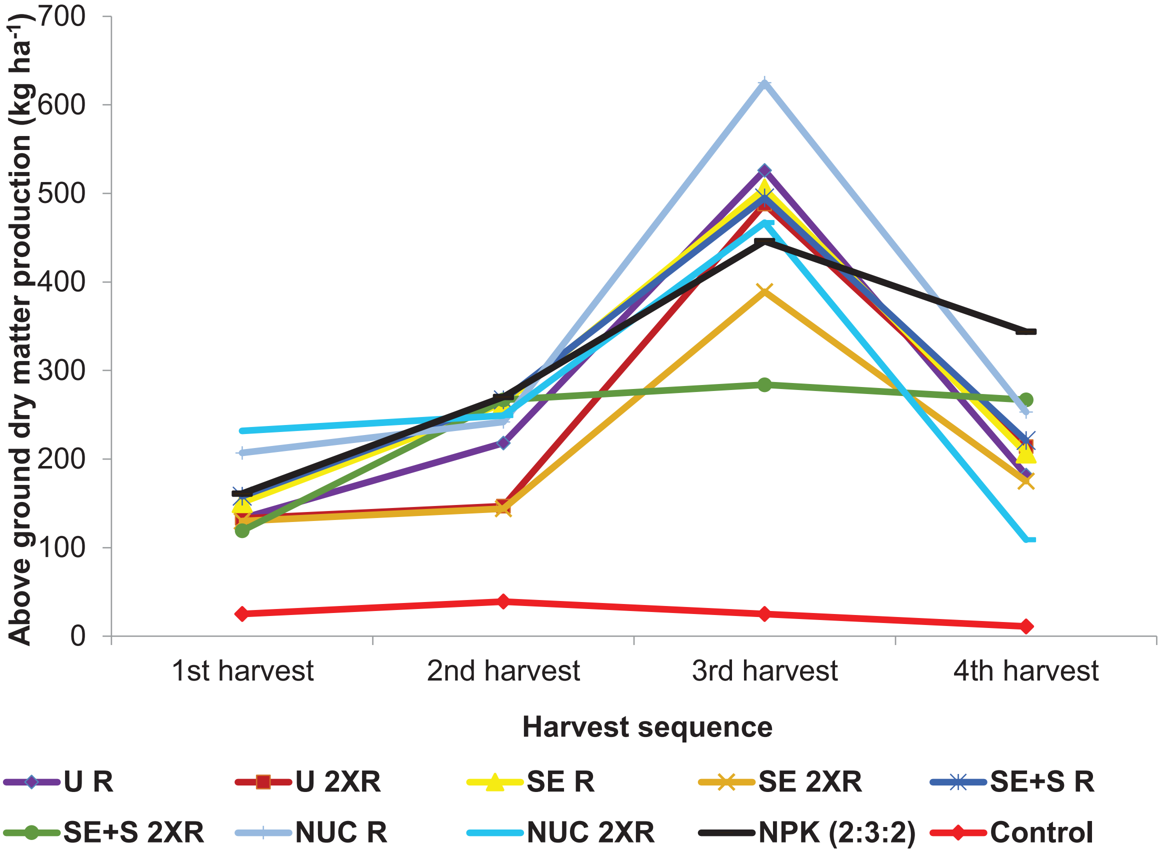

Figure 5.10 Above ground dry matter of perennial ryegrass with urine-derived plant nutrient sources: urine (U), struvite effluent (SE), struvite effluent + struvite (SE+S), and nitrified urine concentrate (NUC) at recommended (R) and double recommended (2XR) nitrogen) and double recommended (2XR) nitrogen rates and controls (NPK and zero fertiliser treatment (Control)

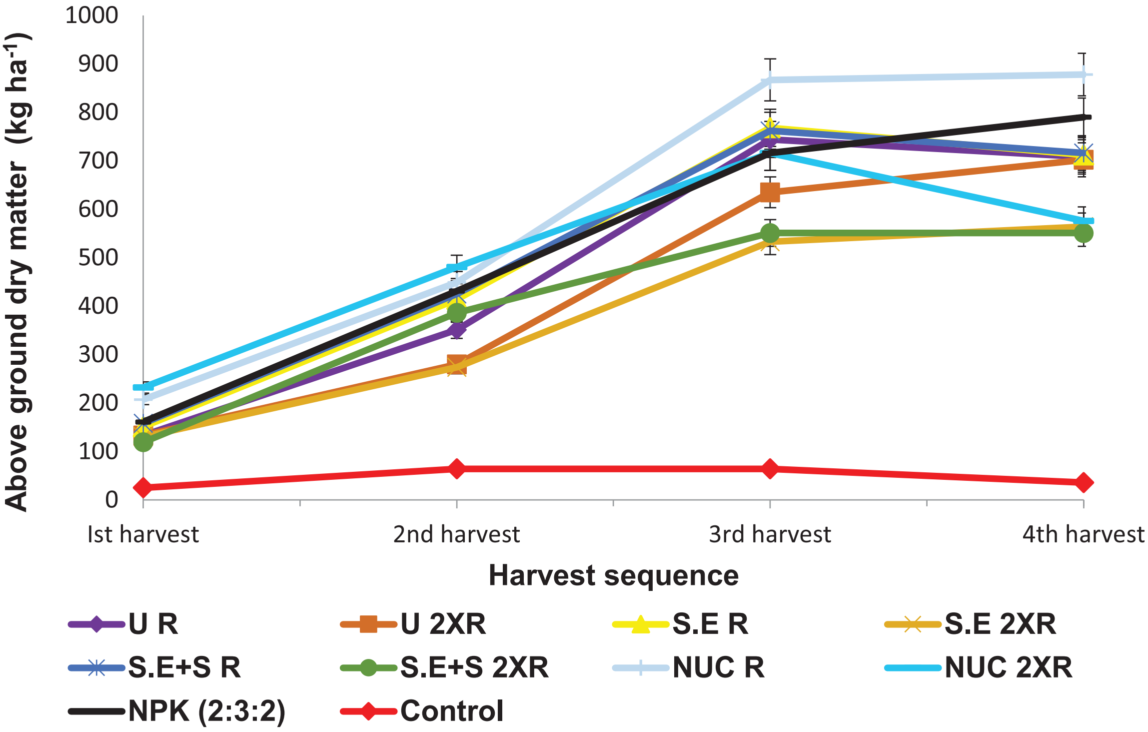

Figure 5.11 Cumulative above ground dry matter of perennial ryegrass with urine-derived plant nutrient sources: urine (U), struvite effluent (SE), struvite effluent + struvite (SE+S), and nitrified urine concentrate (NUC) at recommended (R) and double recommended (2XR) nitrogen rates and controls (NPK and zero fertiliser treatment (Control)

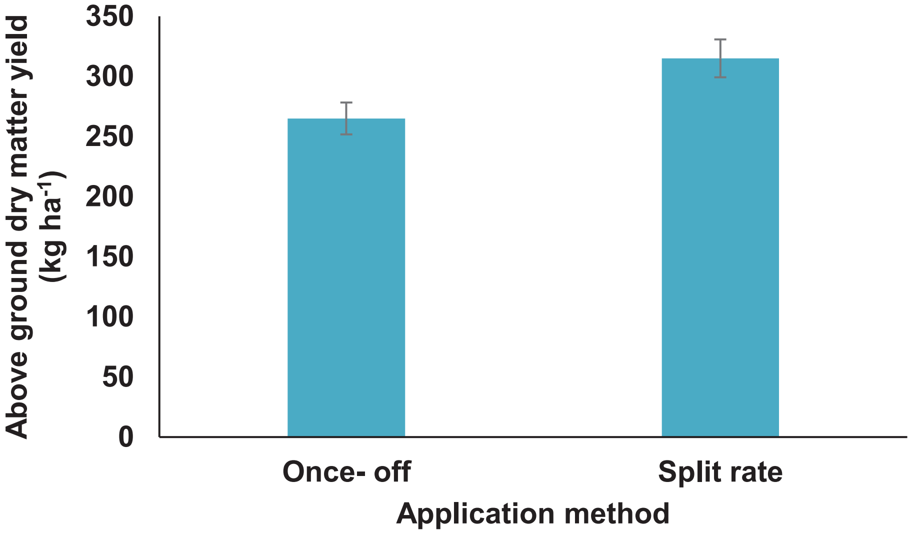

Figure 5.12 Effect of once-off and split rate fertiliser application method on above ground dry matter production of perennial ryegrass

Tissue concentration in perennial ryegrass

The different cuts were combined while maintaining replicates for tissue analysis. The concentrations of P, Mg, K, Na, Zn and Cu showed significant differences among certain treatments (Tables 5.1 and 5.2). All urine-based fertiliser nutrient sources had similar tissue P and Mg concentrations, the urine treatment had significantly lower P than NPK, with NUC and (S.E.+ S) having significantly higher levels of Mg than the NPK. The concentration of N, Al, Ca, Fe and Mn in perennial ryegrass tissue did not differ significantly among all treatments. All urine-based nutrient sources had significantly higher tissue Na and less Cu and K than NPK.

Table 5.1 Tissue concentration of macronutrients in perennial ryegrass

Treatment	N	P	K	Ca	Mg
	------------------------(%)------------------------				
Urine	5.29	0.51	3.31	0.41	0.51
Struvite-effluent	5.36	0.56	3.24	0.41	0.51
Struvite-effluent + struvite	4.95	0.59	3.27	0.39	0.58
Nitrified urine concentrate	5.28	0.58	3.05	0.40	0.59
NPK control	4.76	0.64	4.44	0.53	0.46
LSD (0.05)	0.73	0.08	0.62	0.29	0.06

Table 5.2 Tissue concentration of micronutrients and sodium (Na) in perennial ryegrass

Treatment	Na	Zn	Cu	Mn	Fe	Al
	---------------------------(mg kg^{-1})-------------------------------					
Urine	11.2	58.8	11.0	110	729	947
Struvite-effluent	11.5	55.0	11.9	102	671	836
Struvite-effluent + struvite	12.5	45.3	11.4	124	630	772
Nitrified urine concentrate	12.9	50.8	12.3	121	678	885
NPK control	6.1	49.8	14.3	130	873	944
LSD (0.05)	2.6	7.7	1.1	26	471	575

5.4.4 Discussion

5.4.4.1 Incubation trial

Ammonium loss

Between Days 4 and 14 there was a large loss of ammonium from the sandy Cf probably due mainly to volatilization. The pH increase observed may also have contributed via the ammonification process. In the Ia the loss of ammonium was more rapid initially (within 2 days) though smaller and there followed a more gradual decline than seen in the Cf, possibly due to the higher clay content of this soil. It was observed that doubling the rate of fertiliser application did not affect the amount of total N presumably due to the subsequent increase in volatilization from the extra amount of urea used.

Mineralisation

In the Cf there was little production of nitrate for the first 5 weeks of the incubation. The NUC treatment was the first to show a significant nitrate increase followed by the other treatments at Day 42. The delay for the other treatments was probably due to the need for the pH to rise sufficiently to allow mineralisation to occur. The lack of mineralisation in the Ia was probably due to the pH not increasing enough within the span of the incubation to allow conversion to nitrate, as even at 70 days the pH was still well below 5.50 which is considered to be the minimum value for mineralisation to take place.

5.4.4.2 Pot trial

The increase in dry matter with harvesting period was attributed to root access to nutrients for uptake. The gradual decline in dry matter in the split application method rather than the sharp decrease in the once-off application could be explained by the replenishing of nutrients every time the fertiliser material was added. The application could have been timed to meet regrowth needs after harvest by the split application method. The higher dry matter yield in the NUC treatment up to Cut 3 was attributed to more nitrogen being available as NO_3^--N in the NUC treatment. As the plant was taking up the readily available NO_3^--N, at the same time NH_4^+-N was being converted into NO_3^--N thus replenishing the source of uptake. The higher dry matter among treated pots compared to the control shows the importance of applying soil amendments and their effect on yield. The urine-based nutrient sources when applied at the recommended rate could be as effective as mineral fertiliser.

The sandy soil has low clay and organic colloids and as such NH_4^+-N has a low ability to form electrostatic bonds. Moreover, NH_4^+-N takes a minimum of 3-7 days to be converted into plant available NO_3^--N (Kizildag et al., 2013). During this time it is susceptible to volatilisation to ammonia. Nitrogen volatilization happens by urease enzymes in the soil converting the urea component to free ammonia gas, and is favoured at temperatures above 22°C (Wolkowski et al., 1995). This also suggests that the tunnel temperature that was kept at about 25°C also contributed to N volatilisation. These findings suggest that in once-off application all the NH_4^+-N could be lost by volatilization as ammonia. The lower dry matter production in treatments where the rate of fertiliser was doubled could be explained by toxicity which is brought about by high concentrations of nutrients in the soil solution (Barber, 1962; Britto et al., 2001). Urine has a high salt concentration, including sodium chloride, and so do products formed from it (Mamo et al., 1999. A high salt concentration in the soil inhibits water and nutrient uptake by plants thus leading to lower dry matter production (Kizildag et al., 2013). This is in agreement with the findings of this study that showed a significant Na uptake by perennial ryegrass as compared to the NPK treatment. The findings are also in agreement with Mnkeni et al. (2008) who reported similar findings on maize and selected vegetables (tomato, beetroot and carrot). The similarities in nutrient concentrations among urine-based nutrient sources could be also be explained by the source from which they are derived.

The similarities in tissue N, P and Ca concentrations between urine-based nutrient sources and NPK suggest that these nutrient sources are as effective as inorganic fertilisers. The lower concentrations of tissue Mg in NPK compared to (S.E.+ S) and NUC was expected and could be explained by the production process. When struvite is produced, additional Mg is added into urine which makes struvite a source of Mg thereby influencing the uptake of Mg. The NUC is a concentrated nutrient source and as such while concentrating the N, the Mg also becomes concentrated.

5.4.5 Conclusions

This study indicated that urine-based fertilisers have the potential to be a nitrogen soil amendment, particularly in soils that are able to mineralise urine-based ammonium sources. The study also showed that soil characteristics need to be carefully considered when deciding to amend soil with urine-based fertilisers. Sandy soils with low clay and organic matter may mineralise the ammonium to plant-available nitrate but equally may lose large amounts of ammonium by volatilization and any nitrate produced may be lost by leaching unless immediately taken up by roots. A clay soil may reduce the amount of ammonium lost by volatilization but if its pH is low then no mineralisation will occur, or at best its rate will be very slow. Thus neither of the two soils used for this study are ideally suited to urine-based N sources as one was too sandy and one too acidic. From this one could suggest that the “ideal” soil would be one with moderate clay content and a pH of between 5.50 and 6.50. Such a soil could be the Sepane at Newlands-Mashu. There is no yield advantage in doubling the application rate of the urine-based nutrient sources. Urine and urine products, particularly the NUC, are equally as effective as mineral fertiliser for dry matter production of rye grass. Split application of urine-based nutrient sources is a more effective strategy to optimize dry matter production than once-off application to avoid N losses.

5.5 Effects of excreta-derived plant nutrient sources on soil pH, nodulation and yield of soybean (*Glycine max*)

5.5.1 Objectives

The broad objectives were:

(a) to determine the effect of LaDePa pellets, nitrified urine concentrate (NUC), and horizontal flow wetland (HFW) effluent applied to different soil types (Sepane and Inanda) on soybean growth, pod yield and biomass; and
(b) to determine whether the HFW effluent has a liming effect on an acidic soil.

5.5.2 Materials and methods

5.5.2.1 Plant material

Soybean seed (cultivar PAN 1664R (A)) was obtained from Pannar. The soybean seed was inoculated with *Bradyrhizobia japonicum* (Eco Riz soya) which is a bacterial inoculant for fixing nitrogen in the root nodules of soybean and Eco-T which contains *Trichoderma harzianum* (C) which helps regulate root diseases and promotes growth of soybean.

5.5.2.2 Experimental setup and design

The first pot experiment was carried out in a glasshouse with controlled conditions at the University of KwaZulu-Natal, Pietermaritzburg Campus. The experiment was laid out in a randomised complete block design. Excreta-derived plant nutrient sources were the treatments. The N sources included latrine dehydration and pasteurization (LaDePa pellets), NUC, and HFW effluent. The control was treated with urea and single superphosphate. Each treatment was replicated four times in two blocks to give a total of 32 experimental units.

A second pot experiment was carried out at the same location for the liming experiment. The experiment was laid out in a randomised complete block design. Twelve pots were amended with dolomitic lime at the rate of 12 t ha^{-1}. Another 12 pots were treated with HFW effluent.

5.5.2.3 Soil preparation, potting and planting

Sepane (Se) and Inanda (Ia) soils were collected, air dried and ground to pass through a 2 mm sieve.

Experiment 1

The Ia soil was mixed with dolomitic lime two weeks before planting. The pots were filled with 10 kg of each soil and watered to field capacity to allow for reaction of the lime. Both soils were treated with the N sources (LaDePa pellets, NUC, HFW effluent and urea) at a rate of 30 kg N ha^{-1} according to soil analysis and soybean requirements. The seed was planted at a depth of 30 mm. Single superphosphate was banded 30 mm to the side of the seed at rates of 20 kg P ha^{-1} and 40 kg P ha^{-1} in Se and Ia, respectively, in the urea treatment. Plants were watered to 70% field capacity.

Experiment 2

A set of 12 pots were filled with Ia soil, limed and watered to field capacity to allow for reaction. A second 12 pots were filled with Ia soil and watered with HFW effluent to field capacity. Urea was applied in the limed treatments at a rate of 30 kg N ha^{-1}. Single superphosphate was applied to both the limed and HFW effluent treatments at a rate of 40 kg P ha^{-1}. Irrigation with water or HFW effluent was according to the water needs of the plant.

5.5.2.4 Soil pH determination

Soil from the control treatment and from the HFW effluent treatment of Experiment 2 were allowed to air dry prior to the measurement of pH in distilled water.

5.5.2.5 Data collection and analysis

During growth, plant height to the apical bud was measured on a weekly basis. Pod number was recorded. Plant height of the entire plant was measured. Dry mass was also measured after plants were allowed to dry in an oven at 60˚C for 48 hours. Soil pH was determined for Experiment 2. Genstat 14th edition was used to perform analyses of variance and the differences between means were compared using Least Significant Differences (LSD) at $p \leq 0.05$. For Experiment 2 an unpaired two way t-test was used to analyse the data.

5.5.3 Results

5.5.3.1 Experiment 1

Highly significant differences ($p < 0.001$) were observed between soils, nutrients and the interaction of soil and nutrients. Plant height at harvest in the Se was generally higher than in the Ia in all treatments (Figure 5.13). In the Se, plant height order was HFW effluent > NUC > control > LaDePa pellets. This was in contrast to the Ia which followed the order LaDePa pellets > HFW effluent > control > NUC and the difference between them was not significant. Plants in the Ia showed dense and extensive roots, thin stems and less vegetation while plants in the Se showed sparse and deeper roots, thicker stems and denser vegetation (Figure 5.14).

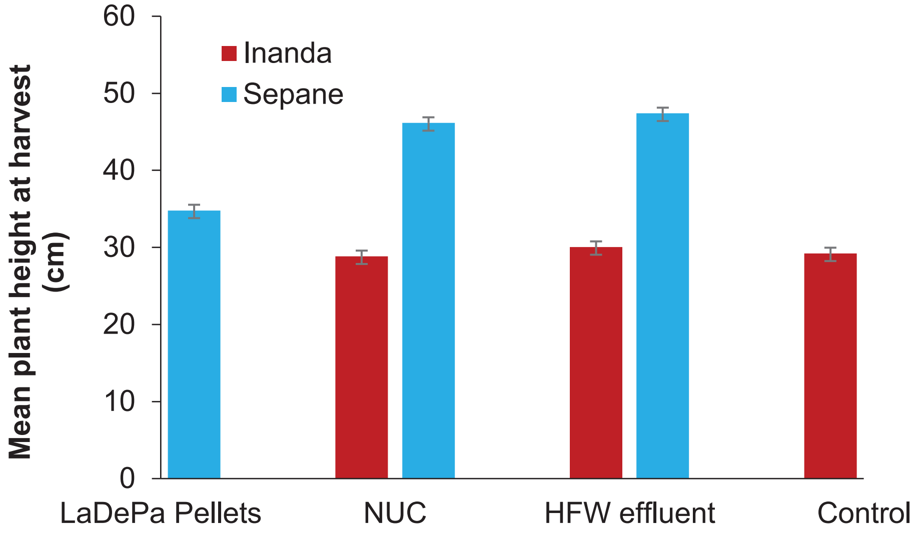

Figure 5.13 Effects of human excreta-derived plant nutrient sources on plant height at harvesting in Inanda and Sepane soils. NUC – nitrified urine concentrate; HFW – horizontal flow wetland

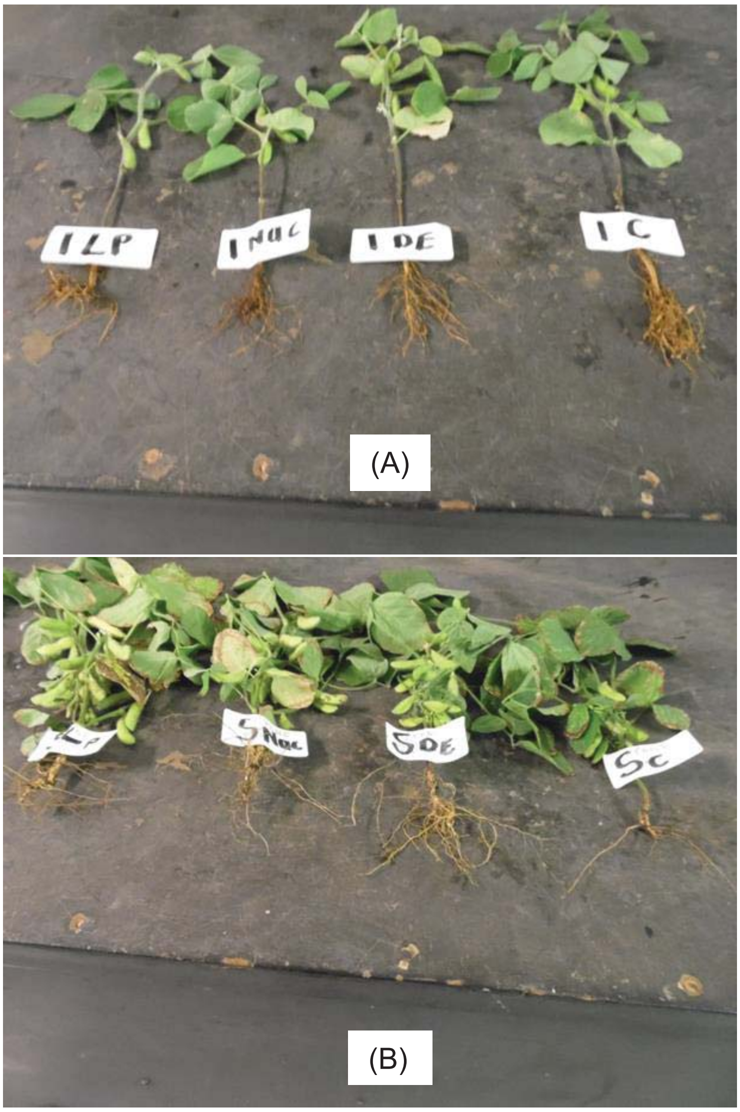

Figure 5.14 Difference in appearance of soybean plants grown in different soils at harvest in (A) Inanda and (B) Sepane. From the LHS: LaDePa pellets; nitrified urine concentrate; horizontal flow wetland effluent; Control

Pod mass and pod number differed significantly ($p<0.001$) between soils. In the Ia the order of pod mass was control > LaDePa pellets >NUC > HFW effluent (Figure 5.15). In the Se, the order was LaDePa pellets > NUC > HFW effluent > control. Pod mass and number were higher from plants grown in the Se than in the Ia. In the Ia pod number followed the same trend as pod mass while in the Se the highest number of pods were on the LaDePa pellets treatment followed by HFW effluent, NUC and the control (Figure 5.15).

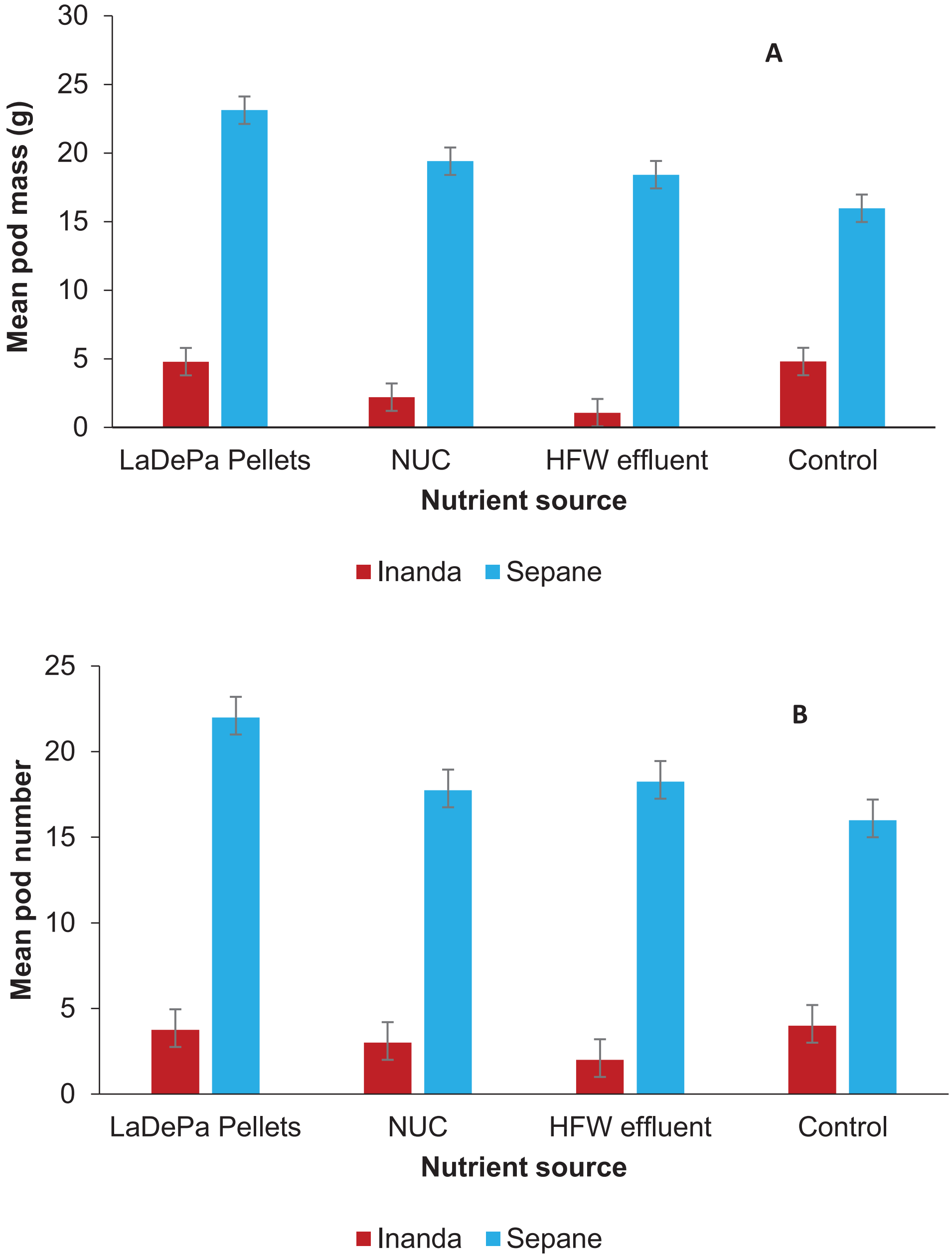

Figure 5.15 (A) Pod mass and (B) pod number of soybean plants grown on the Sepane and Inanda soils with excreta-derived nutrient sources. NUC – nitrified urine concentrate; HFW – horizontal flow wetland

5.5.3.2 Experiment 2

To determine whether the HFW effluent had a liming effect on the acidic Ia soil, dry mass, and soil pH were analysed. The HFW effluent treatment showed extensive, long roots with nodules unlike in the control (Figure 5.16). Stems of the plants from the HFW effluent treatment were thicker than from the control. Although both treatments showed an increase in soil pH above the initial value of 4.20, the final soil pH was higher in the HFW effluent treatment (5.64) than in the limed control (4.88).

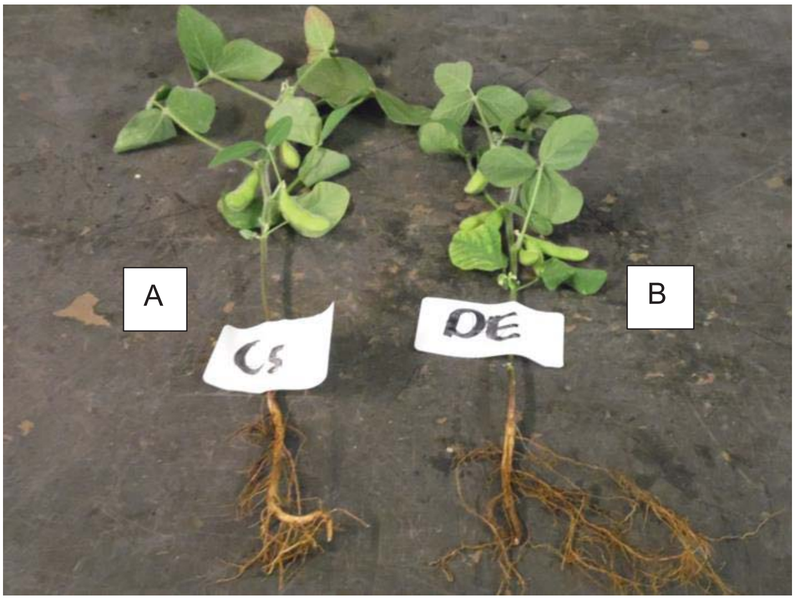

Figure 5.16 Difference in appearance of soybean plants from (A) control (limed); and (B) horizontal flow wetland effluent treatments on the Inanda soil

5.5.4 Discussion

5.5.4.1 Experiment 1

The results showed significant differences in relation to plant height over time as a function of soil type. The Se soil resulted in taller plants in all treatments. However, there were no significant differences between the treatments and this implies that the effectiveness of these excreta-derived plant nutrient sources depends on the soil's chemical and physical properties. It also suggests that the excreta-derived plant nutrient sources used are comparable nutrient sources to inorganic fertilisers such as urea and single superphosphate which were used as the control treatment. High variability in plant height over time could mean that plant height is not a good parameter to indicate plant growth in soybean plants.

There were significant differences in relation to dry mass on the two soils. The Se had higher dry mass than the Ia reflecting that the Se soil releases nutrients more efficiently making them easily available for uptake. Comparing the control to LaDePa pellets, NUC and HFW effluent showed no significant differences.

Pod number and pod mass were highly variable in both Ia and Se soils. Although there was no difference between the three N sources and the control, the Se soil gave higher pod number and pod mass than the Ia.

5.5.4.2 Experiment 2

The liming experiment showed that roots in the HFW effluent treatment were more extensive and had more nodules than those from the control treatment. Generally, nodule formation is more sensitive to soil acidity than other aspects of plant growth. This therefore shows that the

HFW effluent had a liming effect which led to nodule development. Nitrogen fixation, nodule formation and plant growth have been shown to be compromised in soils deficient in Ca and having Al and Mn toxicity (Eaglesham and Ayanaba, 1984). Rhizobia will fix nitrogen effectively at neutral to slightly acidic pH and nodule formation will fail at pH below 5 (Bordeleau and Prevost, 1994). Nodulation In low pH soil has been reported to be reduced by 90% and dry mass by 50% in soybean. Since the dry mass was higher in the HFW effluent treatment than the control, this study confirms that the effluent has an important role as a liming agent.

5.5.5 Conclusions

Excreta-derived materials (LaDePa pellets, NUC and HFW effluent) have been shown to be as effective as N and P fertilisers for soybean and this study suggests that they could become valuable alternatives to commercial manufactured plant fertilisers. It was also confirmed that the HFW effluent has a liming effect and was able to increase nodulation and yield in soybean in a strongly acid soil.

6 USE OF THE SOIL WATER BALANCE MODEL TO PREDICT EFFLUENT BEHAVIOUR IN SOILS

6.1 Introduction

To achieve robust guidelines for the use of DEWATS effluent for irrigation of agricultural crops trials at a number of field sites in different environments (climate, soils, topographic situations, etc.) need to be undertaken so that the practical impact of such irrigation can be measured and quantified. Within the constraints of the present project such data are only available for the short duration (18 months) field experiment carried out at Newlands-Mashu using banana with intercropped taro. In order to suggest possible scenarios, it is necessary to investigate if the use of a model can assist in the prediction of effects of irrigation with DEWATS if carried out under (a) the conditions at Newlands-Mashu and (b) different environmental conditions. The first of these will essentially field-test the model using measured data and the second will attempt to extend the prediction to unknown conditions. In broad terms three aspects will be considered namely (1) the management of the DEWATS effluent in different seasons, (2) the environmental risk in terms of nitrogen (N) and phosphorus (P) pollution when DEWATS effluent is used for irrigation, and (3) the land area required for each household for the full use of the DEWATS effluent to be achieved.

To examine these effects, the Soil Water Balance (SWB) model has been used. This is a mechanistic, irrigation scheduling and nutrient simulation model (Jovanovic et al., 2000; Tesfamariam et al., 2015) that makes use of weather, soil and crop databases to simulate crop growth, and water and nutrient balances. Several crop parameters have been included in the SWB model (Jovanovic et al., 1999) but there are no parameters for modelling banana and so one of the main objectives was to generate crop parameters required for simulating banana growth and nutrient uptake. The model was calibrated and validated based on the experimental data measured at Newlands-Mashu. The water mass balances were used to determine the land area required for each household when DEWATS effluent is used for irrigation. The SWB model has been used previously to simulate N and P leaching losses in agricultural fields (Van der Laan et al., 2010). In the present study the model was tested for its ability to simulate N and P dynamics in soil irrigated with DEWATS effluent and its potential effects on environmental pollution.

6.2 Materials and methods

The experimental site and the field methodology applied at Newlands-Mashu have been described in detail in Chapter 3.

6.2.1 Model description and parameterization

The Soil Water Balance (SWB) is described as a real time, generic crop growth, mechanistic, soil water and nutrient simulation model (Van Der Laan, 2010) developed from a crop version of the NEWSWB (Campbell and Diaz, 1988), which was used for irrigation scheduling. The model gives a plant-soil-atmosphere interaction using weather, soil and crop databases. The model has three different units; the crop growth unit, soil unit and the weather unit (Annandale et al., 1999; Jovanovich et al., 1999).

The weather unit requires site specific inputs and weather data including the daily relative humidity, rainfall, wind speed and temperatures (maximum and minimum). In the absence of solar radiation data, the model can estimate solar radiation, vapour pressure deficit (VPD) and grass reference evapotranspiration (ETo). The model can separate soil evaporation and crop transpiration using Penman-Monteith grass reference evapotranspiration (ETo) and crop potential evapotranspiration (PET) (Jovanovic et al., 2000). Actual evapotranspiration is limited either by water soil supply or crop water demand (Campbell and Norman, 1998).

The model can simulate crop growth mechanistically using the specific crop parameters. Dry matter increment is simulated as either water or radiation limited as they contribute to partitioning of assimilates to different organs (Jovanovic et al., 2000). Different parameters for modelling different crops have been included in the SWB (Jovanovic et al., 1999; Jovanovic and Annandale, 2000) although there are no parameters for modelling banana growth; which will be covered in this study.

Different sub models for modelling N and P have been included hence the latest version is referred to as the SWB Sci and they have been tested their suitability to suit South African conditions (Van der Laan, 2010). Nitrogen simulation using the SWB Sci follows the same principles in Cropping Systems Simulation Model (Crop Syst) (Stöckle et al., 2003; Tesfamariam et al., 2009) and Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) (Van der Laan, 2010).

The use of Decentralised Wastewater Treatment System (DEWATS) effluent in agriculture is one of the sustainable option for its reuse. However, long term impacts on the crop and environment in terms of nutrient management is one of the considerations of the study. Therefore, in the study the SWB Sci model will be calibrated and validated for simulating banana growth. The model will further be tested for simulating N and P uptake in banana and dynamics in the soil to assess the effects of DEWATS effluent on crops, soil and the environment.

6.2.2 Banana growth model calibration

Weather data used for model parameterization

The weather station (Section 3.2.5.2) situated 10 m away from the experimental field was used to monitor atmospheric weather conditions. The variables measured were relative humidity, air temperature, solar radiation, reference evapotranspiration (ETo), wind direction, wind speed and soil moisture. The parameters given in Table 6.1 were used to create the simulated weather station for the SWB model.

Table 6.1 Newlands-Mashu weather station information used to create the simulated weather station for the Soil Water Balance model

Parameter	Value
Weather ID	Newlands-Mashu, Durban, KwaZulu-Natal
Latitude	29.27°
Longitude	30.95°
Altitude (m)	14
Location	South
Height of instruments (m)	2

Crop growth parameters

Crop growth parameters for calibrating the banana growth model were collected from the Tap water + fertiliser treatment from the experiments conducted in over a period of 33 months as described in Chapter 3. The model was then validated using the data from both treatments (DEWATS effluent and tap water + fertiliser). Some of the parameters that were not measured were obtained from Literature. The parameters included in the model were: extinction coefficient, DWR (Dry Weight Ratio) in Pa, radiation use efficiency (kg MJ^{-1}), base temperature (°C), optimum temperature when light is limiting (°C), cut off temperature (°C), degree days (emergence, flowering, maturity and transition from vegetative to reproductive stage and, leaf senescence), maximum height (m), maximum root depth (m), stem to leaf translocation of dry matter (dimensionless), canopy storage (mm), minimum leaf water potential (kPa), maximum transpiration (mm day^{-1}), specific leaf area (m^2 kg^{-1}), leaf stem partitioning (m^2 kg^{-1}), total dry mass at emergence (m^2 kg^{-1}), root fraction (dimensionless), root growth rate (m^2 kg$^{-0.5}$), stress index (dimensionless), % depletion allowed (initial, development, mid-season and late season), N fixation, grain N partitioning coefficient, photoperiod sensitivity, critical photoperiod, photoperiod parameter, N:P ratio, root N concentration (kg N kg^{-1} dry mass), maximum grain (fruit) N concentration (kg N kg^{-1} dry mass), slope, photosynthetic pathway (C3 or C4), increased root active biomass, optimal P concentrations in mg kg^{-1} (emergence, vegetative and reproductive) and crop P uptake factor.

Soil parameters

The physical properties of soil used to run the SWB model are presented on Table 6.4.

Table 6.4 The average (n = 3) soil physical properties measured at different locations at the experimental site in the different soil layers (each 0.1 m thick) used in the Soil Water Balance model

Field	Layer	Depth (m)	Field capacity (m^3 m^{-3})	Initial Water Content (m^3 m^{-3})	Permanent Wilting Point (m^3 m^{-3})	Bulk density (g cm^{-3})
Banana 2014	1-3	0-0.3	0.402	0.402	0.286	1.348
Banana 2014	4-6	0.3-0.6	0.405	0.405	0.289	1.390
Banana 2014	7-11	0.6-1.1	0.428	0.428	0.313	1.035

Field management

The field management practices were included in the model and these included: irrigation scheduling, model type (growth), crop type, planting and starting date, field size (ha), weather ID, irrigation timing (% depletion), soil profile management (root zone), water balance approach (cascading), irrigation system (drip), emitter delivery (L h^{-1}), wetted diameter, root fraction, irrigation capture (mm), system efficiency (%) and storage efficiency (%). The soil parameters were included per each layer (0.1 m) for 11 layers. These included field capacity (m m^{-1}), initial water content (m m^{-1}), permanent wilting point (m m^{-1}), saturation point (m m^{-1}) and soil bulk density Mg m^{-3}). The irrigation and precipitation (mm) received were also included. Crop growth simulation was done following irrigation scheduling to replenish soil moisture at 35% depletion level.

6.2.3 N and P Modelling

The model was calibrated for N and P modelling using literature and measured data. The initial parameters for modelling N and P were: soil texture (%), organic matter (%), soil pH (H_2O), cation exchange capacity [CEC mmol (+) per 100 g], base saturation (%), $CaCO_3$ (%), Bray I test P (%), NO_3 (mg kg^{-1}), NH_4 (mg kg^{-1}), residues (kg ha^{-1}), annual average air temperature (°C), half annual temperature amplitude (°C), phase of sine temperature function (days), standing stubble mass (kg ha^{-1}), surface mass (kg ha^{-1}), bypass coefficient (dimensionless), cultivation depth (m), soil group type, C fractioning (≤ and . 0.3 m). The rain and irrigation water quality (NH_4^+-N, NO_3^--N and PO_4^{3-}-P in mg L^{-1}) were entered with regards to DEWATS effluent. The fertiliser and tillage management were entered for the tap water + fertiliser treatment. The plant residue parameters were also included in the sub model.

Other additional physical and chemical properties used to parameterize the model are presented on Tables 6.5 and 6.6.

Table 6.2 The initial soil physical and chemical properties in different soil layers (each 0.1 m thick) required to initialise the nitrogen (N) and phosphorus (P) simulation using the Soil Water Balance model

Layer	Depth	Sand	Clay	OM*	Soil pH	CEC**	Base satn	Test P	NO3-	NH4+	Residues
	(m)		(%)		(H_2O)	(mmol (+) 100 g^{-1})	(%)		(mg kg^{-1})		(kg ha^{-1})
1 to 3	0-0.3	18.1	35.7	3.2	5.6	19	99.9	52.2	4.9	20.8	10
3 to 6	0.3-0.6	20	41.2	2.6	5.9	16.8	99.8	5.2	1.7	36.7	0
6 to 11	0.6-1.0	21.6	42.7	1.9	5.5	21.5	99.7	5.4	4.1	31.8	0

* OM – organic matter

** CEC – cation exchange capacity

Table 6.3 Initial soil parameters required to initialise nitrogen (N) and phosphorus (P) simulation using the Soil Water Balance-Scie model

Parameter	Value	Source
Standing stubble mass (kg ha^{-1})	1	Measured
Surface mass (kg ha^{-1})	1	Measured
Bypass coefficient	0.6	Measured
Annual average air temp. (°C)	21.1	Measured
Half annual temperature amplitude (days)	170	Measured
Cultivation depth (m)	0	Measured
Soil group	Slightly weathered	
Soil P test type	Ambic	
Initial C fraction to microbial biomass (≤ 0.3 m)	0.03	Default
(> 0.3 m)	0.005	Default
Initial C fraction to active labile SOM* (≤ 0.3 m)	0.02	Default
(> 0.3 m)	0.000	Default
Initial C fraction to active metastable SOM (≤ 0.3 m)	0.450	Default
(> 0.3 m)	0.014	Default
Initial C fraction to passive SOM (≤ 0.3 m)	0.5	Default
(> 0.3 m)	0.985	Default

* SOM – soil organic matter

6.2.4 Model validation

The model was validated using independent data set and accuracy of the model was tested using the statistical parameters: Mean Absolute Error (MAE), the correlation coefficient (R^2) and the coefficient of agreement (D) according to De Jager (1994). The following statistical criteria are used to determine the model accuracy; $R^2 > 0.8$, MAE < 0.2 and D > 0.8.

6.3 Results and discussion

6.3.1 Soil Water Balance model calibration for banana

Crop specific parameters for banana used by the SWB model are presented in Table 6.2. The data collected from two fields Tap water + fertiliser (DTAPW2014) was used to calibrate the model and this was validated using the data from DEWATS effluent irrigation (DEFF2014) over a period of 33 months.

Table 6.4 Banana crop specific parameters included in the Soil Water Balance model based on measured and literature data

Parameter	Value	Source
Canopy solar extinction coefficient for PAR* (K_{PAR})	0.7	(Nyombi et al., 2009)
DWR** (Pa)	2.1	Measured
Radiation use efficiency (kg MJ^{-1})	0.0015	Measured
Base temperature (^{o}C)	12.5	(Chaves et al., 2009)
Optimum temperature (^{o}C)	25	(Chaves et al., 2009)
Cut off temperature (^{o}C)	38	(Chaves et al., 2009)
Emergence (day degrees)	0	Measured
Flowering (day degrees)	2568	Measured
Maturity (day degrees)	4950	Measured
Transition (day degrees)	260	Measured
Leaf senescence (day degrees)	3189	Measured
Maximum height (m)	2	Measured
Maximum root depth (m)	0.8	(FAO, 2015)
Stem to grain translocation	0.5	Measured
Minimum leaf water potential (kPa)	-1 500	(Robinson and Bower, 1988)
Maximum transpiration (mm day^{-1})	6	(Freitas et al., 2008, FAO, 2015)
Specific leaf area (m^2 kg^{-1})	12	Measured
Leaf stem partitioning (m^2 kg^{-1})	2	Measured
Total dry matter at emergence (kg m^{-2})	0.0130	Estimated (Nyombi et al., 2009)
Root fraction	0.05	Estimated (Nyombi et al., 2009)
Root growth rate (m^2 /√(kg))	3.1	Measured
Stress index	0.95	(Steduto et al., 2012)
Depletion allowed (Initial, Development, Mid-season, Late season)	35%	(FAO, 2015)

* PAR – photosynthetically active radiation

**DWR – leaf dry weight ratio corrected for vapour pressure deficit

6.3.1.1 Banana thermal time requirements

The SWB simulates plant growth using FAO model or growth model. The growth model uses thermal time approach (Monteith and Moss, 1977) to determine crop growth and development stages unlike the FAO module, which uses the number of days. The growing degree days (GDD) are calculated from the onset of crop growth and they are accumulated as the crop grows over time (Δt). These are calculated based on the difference between daily average and base temperatures according to Equation 6.1:

$$\mathbf{GDD_i = \sum (T_{avg} - T_{base}) \times \Delta t} \qquad \textbf{Equation 6.1}$$

The growing day degrees increment (GDD_i) are calculated for the entire growing period. The T_{avg} is the average daily temperature (°C) and the T_{base} is the minimum temperature required for banana growth. When T_{avg} is below the cut-off temperature the GDD_i is set to zero.

6.3.1.2 Dry Weight Ratio (DWR)

The relationship between transpiration limited growth and dry matter production can be calculated as the ratio of dry mass (DM in kg m^{-2}) corrected for the vapour pressure deficit (VPD in Pa) (Sinclair et al., 1984) and transpiration. The DWR was determined according to Equation 6.2:

$$\mathbf{DWR = \frac{DM\ x\ VPD}{Et}} \qquad \textbf{Equation 6.2}$$

Where Et is total evapotranspiration (mm).

Banana total dry mass (kg m^{-2}) was measured after crop harvest. However, the dry mass partitioned to roots could not be accounted for since only the above-ground material was harvested. Due to complexities in determining the total dry mass of banana, this was then estimated according to Nyombi et al. (2009) using Equation 6.3.

$$\mathbf{Y = ce^{ax}} \qquad \textbf{Equation 6.3}$$

Where Y is the total dry biomass at harvest including root, stem, bunch and leaves, c (0.066) and a (0.085) are constants, e is the exponential function, and x is the variable stem girth (cm^1).

The vapour pressure deficit (kPa) used to determine the DWR was calculated using the SWB weather unit following Equation 6.4 adopted from the Food and Agriculture Organisation (Smith, 1992).

$$\mathbf{VPD = \frac{[(esTmax + esTmin)]}{2\text{-}ea}} \qquad \textbf{Equation 6.4}$$

Where e_{sTmax} is the saturated vapour pressure (kPa) at maximum air temperature, e_{sTmin} is the saturated vapour pressure (kPa) at minimum temperature, and e_a is the actual vapour pressure (kPa).

Water loss through soil evaporation cannot be related to crop physiology (Jovanovic et al., 2000) although dry mass can be related to evapotranspiration. Evapotranspiration (mm) was determined as a product of the reference evapotranspiration (Eto) and crop factors (FAO, 2015).

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[1] The banana model developer expressed values consistently in cm.

6.3.1.3 *Dry mass accumulation*

Total dry matter (TDM) at emergence is usually equivalent to seed mass but in the present study the banana plants were planted as suckers and hence the sucker dry mass was measured. The root dry matter (kg m^{-2}) at emergence was estimated from Equation 6.5:

$$\mathbf{RDM = \frac{fr \times TDM}{1-fr}} \qquad \textbf{Equation 6.5}$$

Where fr is the partitioning fraction to root biomass, and TDM is the total dry mass (kg m^{-2}).

6.3.1.4 *Canopy extinction coefficient*

The SWB model is able to separate water loss through transpiration and evaporation. The transmission of light through the canopy follows Bouguer's law (Campbell and Van Evert, 1994). Fractional interception of radiation through the canopy can be determined according to Equations 6.6 and 6.7.

$$\mathbf{FI_{transpiration} = 1 - exp\ (- K_{PAR} \times LAI)} \qquad \textbf{Equation 6.6}$$

$$\mathbf{FI_{evaporation} = 1 - exp\ [-K_{PAR}\ (LAI + yLAI)]} \qquad \textbf{Equation 6.7}$$

Where K_{PAR} is the canopy solar extinction coefficient for photosynthetically active radiation and was derived from Nyombi et al. (2009) as 0.7, LAI is the leaf area index, and yLAI is the leaf area index of the senesced leaves.

The LAI is the total area covered by leaves per unit area (m^2 leaf area m^{-2} land area) and in banana it was measured using the length x breadth method as given in Equations 6.8-6.10 (Obiefuna, 1979, Nyombi et al., 2009).

$$\mathbf{LA = L \times W \times c} \qquad \textbf{Equation 6.8}$$

Where LA is the leaf area (m^2), L is the laminar length, W is the laminar width, and c is the regression coefficient obtained from the correlation between the independent values of lamina length and width.

$$\mathbf{TLA = LA \times LN} \qquad \textbf{Equation 6.9}$$

Where TLA is the total leaf area, LA is the measured leaf area, and LN is the number of functional leaves.

The LAI was then calculated as given in Equation 6.10.

$$\mathbf{LAI = \frac{TLA\ (m2)}{Land\ area\ (m2)}} \qquad \textbf{Equation 6.10}$$

6.3.1.5 *Dry matter accumulation under radiation limited conditions*

Under radiation limited conditions dry matter increment (DMi) was calculated following Equation 6.10 (Monteith and Moss, 1977).

$$DM_i = E_c \times T_f \times FI_{transp} \times R_s \qquad \textbf{Equation 6.11}$$

where E_c is the radiation use efficiency (kg MJ^{-1}) which is usually 0.0015 kg MJ^{-1} for banana (Chaves et al., 2009). However, in this study it was measured using the total dry mass (kg m^{-2}) per total solar radiation received as recorded by the on-site weather station. R_s is the solar radiation (MJ m^{-2}) for a particular day, and T_f is the temperature factor for radiation limited growth and was determined according to Equation 6.12.

$$T_f = \frac{Tav - Tb}{Tlo - Tb} \qquad \textbf{Equation 6.12}$$

Where Tav is the average daily temperature (°C), T_{lo} is the banana optimum temperature for light limited growth (25 °C), and Tb is the base temperature (12.5°C) (Chaves et al., 2009).

6.3.1.6 Root growth rate

Root growth rate (RGR) was calculated from Equation 6.13.

$$RD\ (m) = RGR\ (m^2\ kg^{-0.5}) \times RDM^{0.5}\ (kg\ m^{-2}) \qquad \textbf{Equation 6.13}$$

Where RD is the maximum rooting depth (0.8 m) as derived from FAO (2015), and RDM is the root dry matter. Since the banana was not destructively harvested the root biomass at harvest could not be measured. It was therefore estimated following Nyombi et al. (2009) allometric equations as given in Equation 6.14.

$$Y = c(x)^a \qquad \textbf{Equation 6.14}$$

where Y is the root dry mass (kg m^{-2}), c (1×10^{-4}) and a (1.863) are constants, and x is the variable banana stem girth (cm) at harvest. Equation 6.14 differs from Equation 6.13 because Nyombi et al. (2009) developed different equations for different parts of the banana at different growth stages.

6.3.2 Model calibration of crop parameters for N and P uptake

Crop parameters for nutrient uptake were based on the CropSyst algorithms (Boote et al., 2013). These simulate crop nutrient uptake based on root N concentration and above-ground N concentrations at different stages of growth (van der Laan et al., 2010). The model was calibrated using the data collected from the tap water + fertiliser treatment and some parameters were obtained from literature as described in Table 6.3.

Table 6.5 Nitrogen (N) and phosphorus (P) uptake related crop parameters for banana

Parameter	Value	Source
N Fixation	No	
Grain N partitioning coefficient	0.4	Estimated (van Asten et al., 2003)
Photoperiod sensitivity	No	(Robinson and Saúco, 2010)
Critical photoperiod	na*	
Photoperiod parameter	na	
N: P ratio	5	
Root N concentration (kg N kg^{-1} DM**)	0.0108	(Ahumuza et al., 2015)
Maximum fruit N concentrations (kg N kg^{-1} DM)	0.2075	(Ahumuza et al., 2015)
Slope	-0.405	
C3 or C4	C3	(Robinson and Alberts, 1986)
Increased root active biomass (kg m^{-2})	0.05	Estimated (Nyombi et al., 2009)
Optimal P concentration (Emergence) (kg P kg^{-1} DM)	0.00297	Measured
Optimal P concentration (Vegetative) (kg P kg^{-1} DM)	0.003	Measured
Optimal P concentration (Reproductive) (kg P kg^{-1} DM)	0.00245	Measured

* na – not applicable
** DM – dry matter

6.3.3 Validating the Soil Water Balance model for banana

The model was successfully calibrated as it met all the statistical criteria described by De Jager (1994). However, the model showed to accurately simulate crop growth with regards to top harvestable dry mass in DEWATS effluent. Although the mean absolute error (MAE) in DEWATS effluent leaf area index (LAI) was slightly above 20% (22**%**), other statistical parameters (r2 and D) were above 80%. This implies that some other factors which could not be catered by the model could have contributed, this might include K application since it is a limiting resource in banana production.

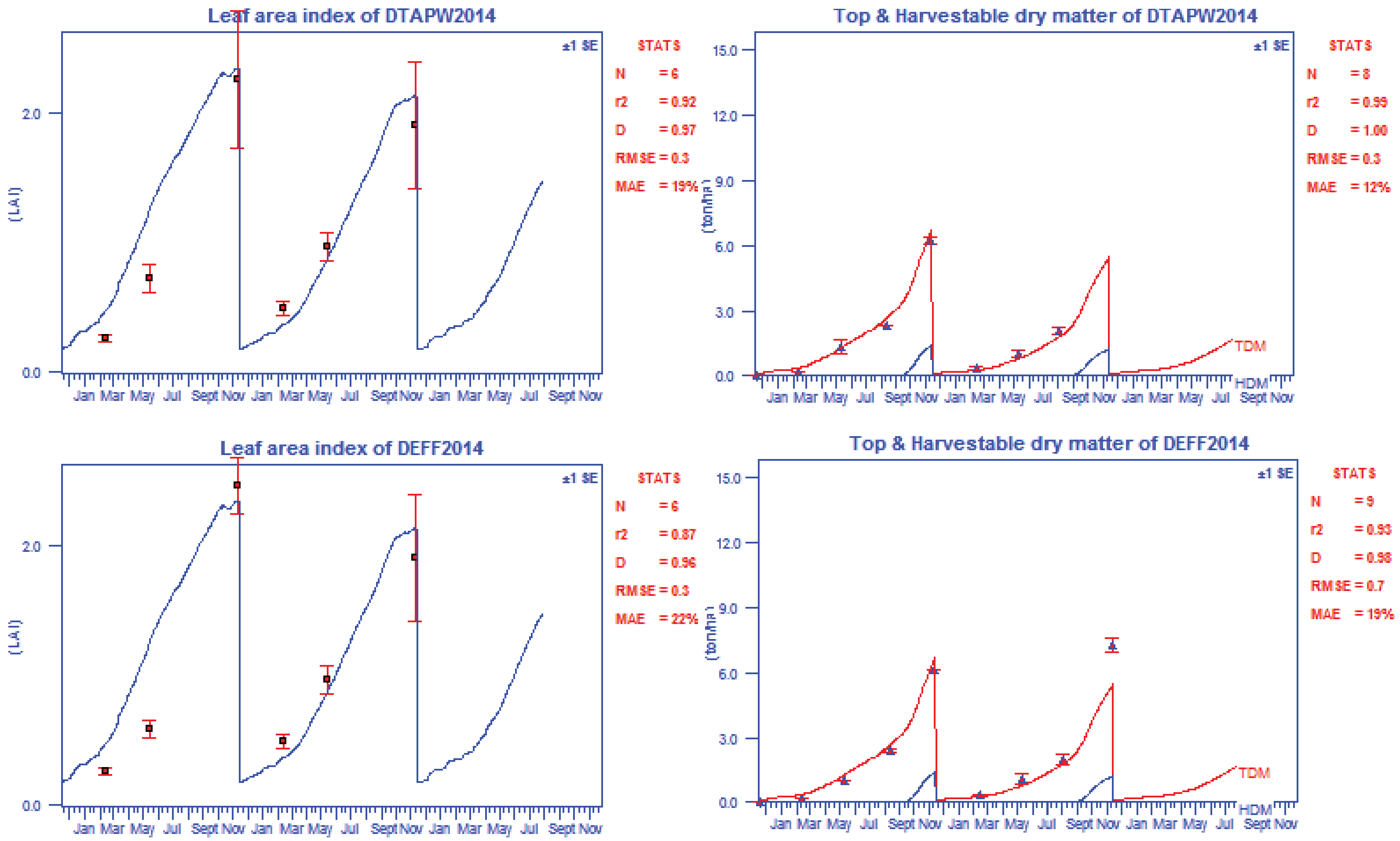

Figure 6.1 Simulated banana leaf area index (m^2 m^{-2}) and top dry mass (t ha^{-1}) of the DEWATS effluent irrigation (DEFF2014) tap water irrigation + fertiliser treatment (DTAPW2014) at Newlands-Mashu over the two growing seasons (Nov 2013 to July 2016)

The measured soil profile water content during the 33 months period was plotted against the simulated water content as described in Figure 6.3. The measured soil water content followed a similar pattern with simulated soil moisture content except from June to August 2015 when the profile water content was overestimated. This was due to low rainfall and irrigation during that period, furthermore no leachates were even detected from the wetting front detectors.

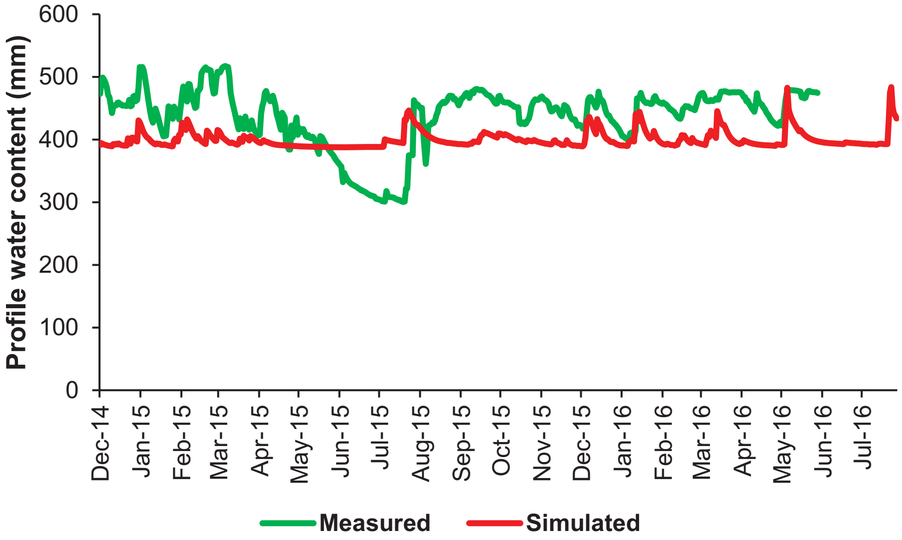

Figure 6.2 Soil water content (WC) measured by the CS 650 Campbell soil moisture reflectometers and simulated profile water content at the Newlands-Mashu field experiment (Profile water content in the model is expressed as mm)

6.3.4 Determination of land area required for irrigating banana

The Soil Water Balance model was set to irrigate after 35% depletion of soil moisture content with a room for rainfall approach. The SWB model has the capacity to separate evaporation from transpiration and crop water requirements must account for losses through evaporation and transpiration. The banana crop grown at Newlands Mashu, Durban under the Sepane (clay loam soil) used 907 mm (transpiration) and 1 096 mm (evaporation) thereby giving evapotranspiration value of 2 096 over 33 months (Figure 6.3). Based on those figures and a DEWATS production rate of 12.5 ML annum^{-1}, 17 100 m^2 (1.7 ha) of land was required which translated to 206 m^2 household^{-1} (41.2 m^2 person^{-1}). In areas where land is limiting, effluent storage is required. In the study different soil types with different physical characteristics (Cartref, Sepane and Inanda) are being used. The cartref is typically a sandy loam soil and the Inanda soil has high organic matter and low bulk density. Irrigation using DEWATS effluent in different soils must consider scheduling to meet the crop water requirements. In sandy loam soils, frequent application with low volumes can be done while in Sepane soil type more effluent can be applied less frequently.

Banana and taro have similar annual water requirements (Onwueme, 1999; FAO, 2015), thus this results implies that the amounts simulated regarding banana modelling can be extrapolated for taro. An intercrop between banana and taro can help utilise more effluent on a unit area.

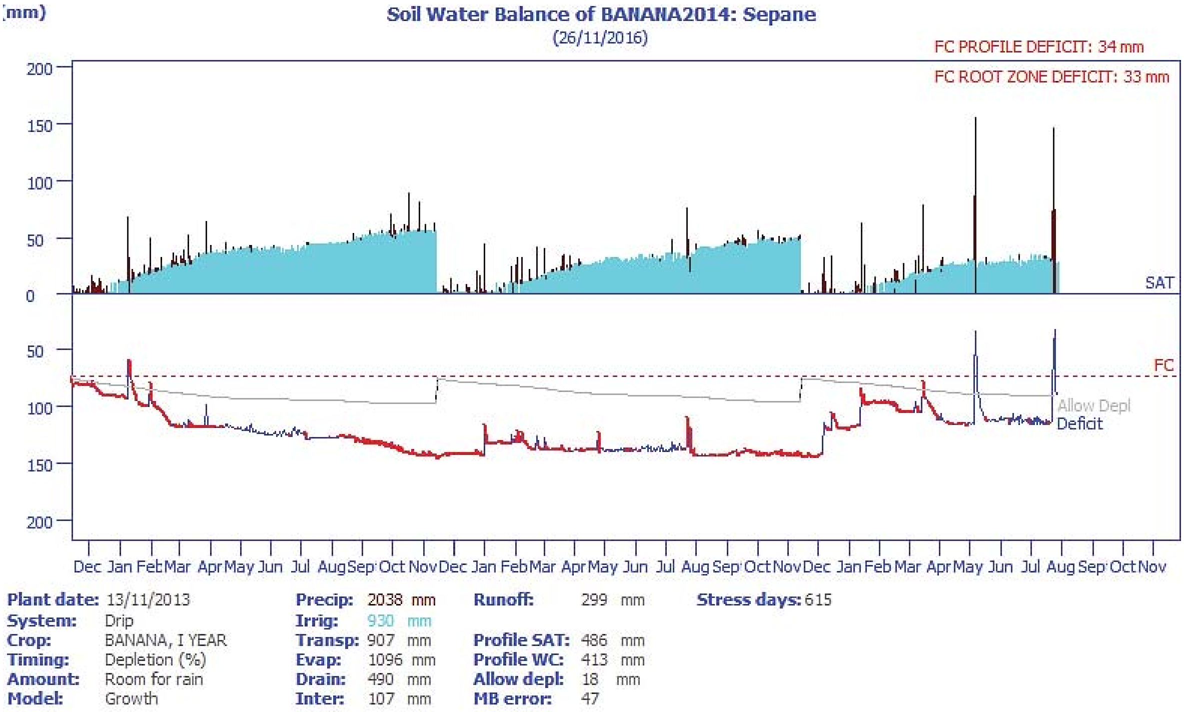

Figure 6.3 Soil water mass balances for the banana simulated by the SWB model over a period of 33 months At Newlands Mashu

6.3.5 N and P Modelling

The SWB N and P sub model was calibrated using the data collected on the tap water + fertiliser treatment during the two banana growing seasons (33 months) as described in Figure 6.7. The model was successfully calibrated to simulate N uptake in banana for the first year crop (r^2 = 0.94) and second year crop (r^2 = 0.97).

The model was validated using the data collected from the DEWATS treatment. The data shows that the model could successfully simulate top N uptake for the DEWATS effluent treatment as the r^2 = 0.9 (first year crop) and r^2 = 0.995 (second year crop). Generally, the model showed to better predict N uptake during the second year since the crop has established thereby efficiently utilising resources such as water and radiation through higher leaf area index and denser root system.

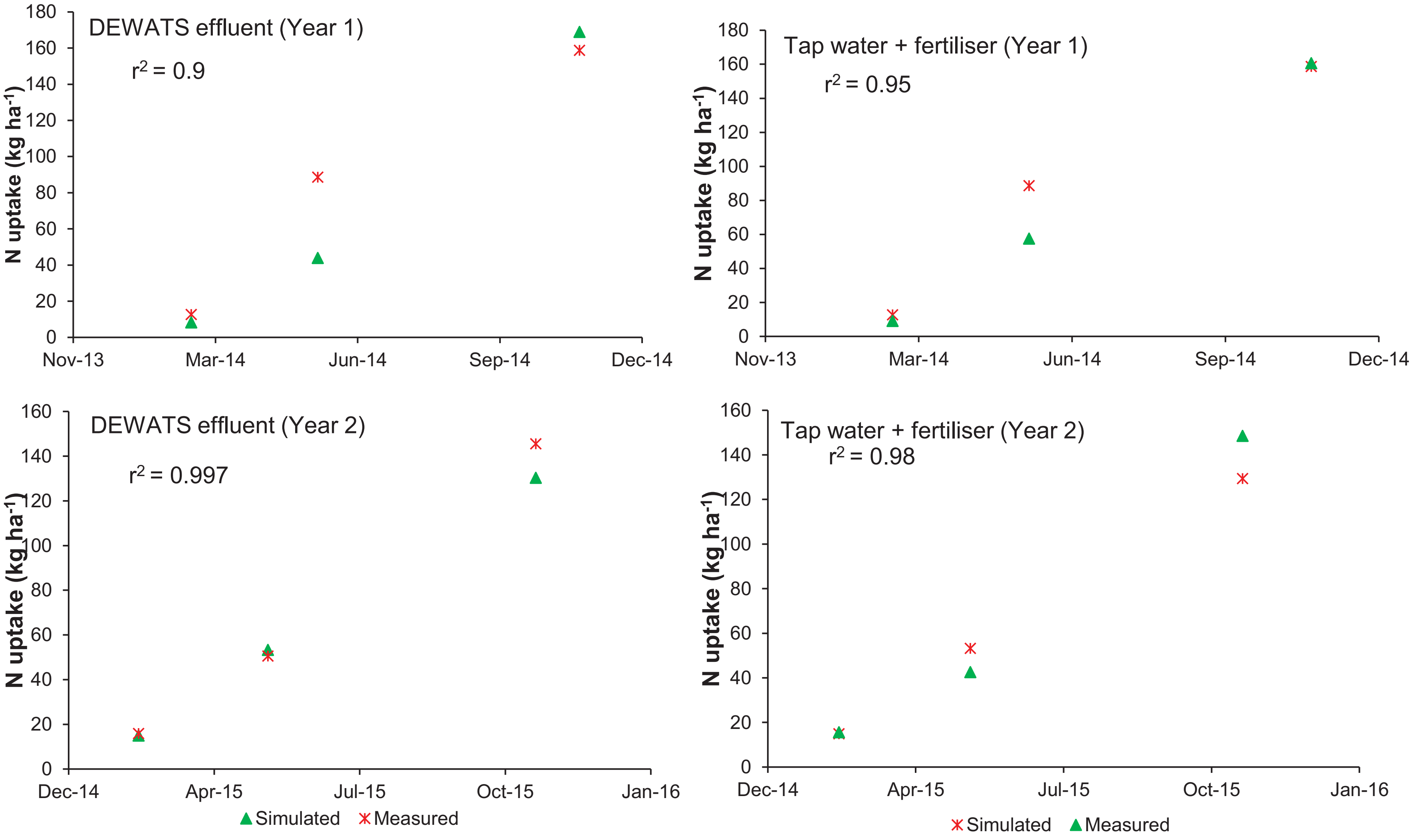

Figure 6.4 Comparison of simulated vs measured top nitrogen (N) uptake by a banana crop during the two growing seasons

6.3.5.1 Inorganic N and P modelling

Inorganic N (NO_3^-) and P (PO_4^{3-}) dynamics in the soil irrigated with DEWATS effluent in comparison to irrigation with tap water and fertiliser application are shown in Figures 6.5 and 6.6, respectively. The model overestimated NO_3^- concentrations in DEWATS effluent (0.3 and 0.5 m depths) and tap water + fertiliser treatments at 0.3 m depth. In tap water + fertiliser treatment at 0.3 m depth the simulated data followed almost a similar pattern with measured data but initially NO_3^- concentrations at 0.5 m depth were underestimated. When WFDs are installed during the early days, nitrification rate is faster but later stabilise. Furthermore, inorganic fertiliser (Urea) applied nitrifies faster than DEWATS effluent, explaining why the NO_3^- in tap water + fertiliser at 0.5 m depth were overestimated.

The model showed a variable PO_4^{3-} pattern between the two treatments (DEWATS effluent and tap water + fertiliser). The PO_4^{3-} concentrations in DEWATS effluent (0.3 m) treatment were overestimated during the early days since irrigation was just beginning. The pattern was almost similar in December 2014 but as time progressed PO_4^{3-} were overestimated (October to December 2015). Although PO_4^{3-} were overestimated, the pattern showed an increase over time due to irrigation with ABR effluent than HFW effluent. As the time progressed (January to July 2016), PO_4^{3-} concentrations declined sharply and it was not increasing further despite irrigation with ABR effluent. This could be due to the ability of clay soil to fix P, probably aided by dissolved organic C from ABR effluent as observed in pot experiments (Chapter 4).The pattern observed in tap water + fertiliser (0.3 m) was contrary to DEWATS effluent (0.3 m). The simulated PO_4^{3-} concentrations were generally below 23 mg L^{-1}, while the measured values were varying over time and sometimes getting over 40 mg L^{-1} (March and July 2016). In DEWATS effluent at 0.5 m depth the simulated values were below 11.5 mg L^{-1} but the measured values were varying over time, sometimes getting over 30 mg L^{-1}. We don't expect PO_4^{3-} to move enough within the soil but this sometimes occur through preferential flow in soil cracks, considering the cracking ability of the Newlands Mashu soil.

Modelling inorganic nutrients in the field is difficult due to spatial variation under field conditions (van der Laan et al., 2014). The WFDs used collects mobile nutrients which are passing through the soil layers. However, the SWB model assumes that the concentration of nitrates moved to the next layer is related to the concentration within the preceding layer. This is sometimes not the real situation due to certain factors. Leachates collected in WFDs may be diluted when the water table rises and sometimes delayed sample collection might result in a change from its initial concentration. In some heavy clay soils, preferential flow through cracks prohibit accurate interpretation of results. For better monitoring of inorganic N and P in the soil, WFDs can be used in parallel with suction cups (van der Laan et al., 2010). Furthermore van der Laan et al. (2014) concluded that in field conditions with high spatial variations, initialization of the model must be continually done and frequent monitoring of field data is recommended for more accurate simulations.

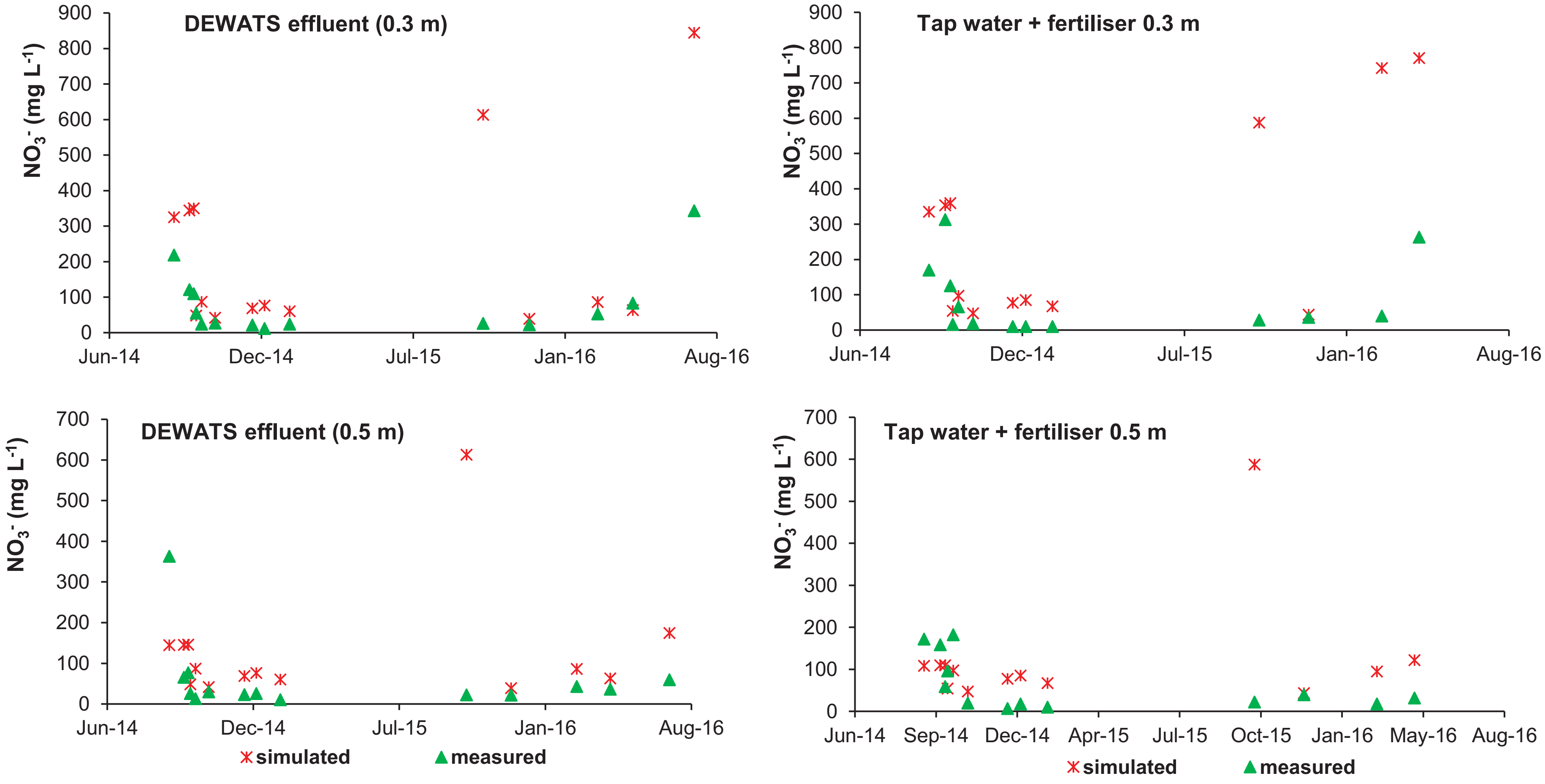

Figure 6.5 Simulated and measured nitrate concentrations at 0.3 and 0.5 m soil depths between the two irrigation treatments (DEWATS effluent vs Tap water + fertilizer)

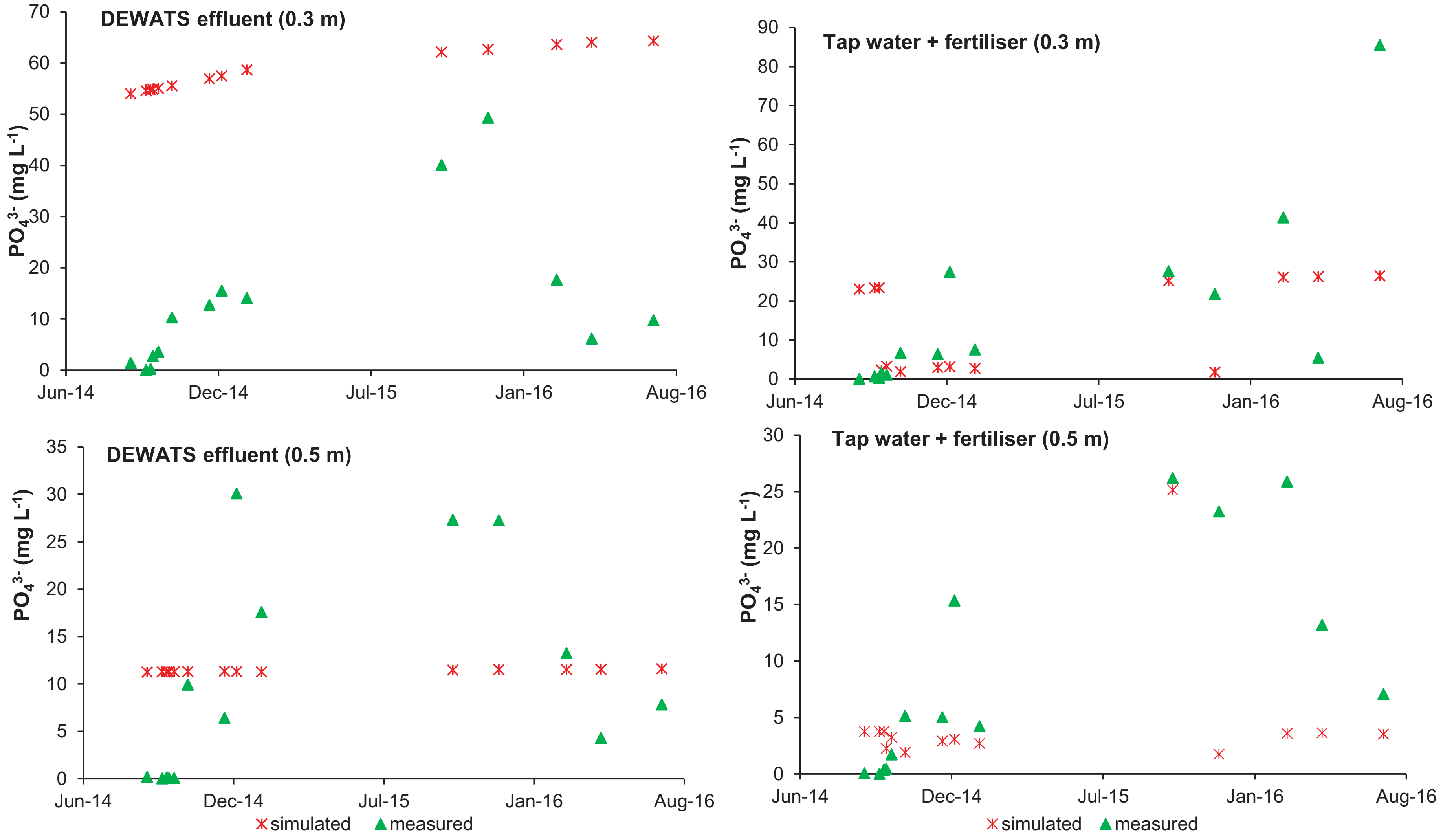

Figure 6.6 Simulated and measured orthophosphate (PO_4^{3-}) concentrations at 0.3 and 0.5 m soil depths between the two irrigation treatments (DEWATS effluent vs Tap water + fertilizer)

6.3.5.2 Soil residual nitrate and labile phosphorus loading

Residual NO_3^- in the soil refer to the concentrations residing in different soil layers that can be moved down the profile when a mass of water passes through a soil layer (van der Laan et al., 2010). The SWB model was used to estimate residual nitrate at the Newlands Mashu experimental site over a period of 33 months (Figure 6.7). The model shows that there was a high accumulation of NO_3^- within top 0.2 m in all treatments. The loading was very high on the DEWATS irrigated treatments (> 15 000 mg kg^{-1}) over a period of 33 months. The N loading implies that there are risks of environmental contamination through leaching when there is enough water to push it down. Furthermore, in the Sepane soil, through irrigation to field capacity we might get some losses through denitrification when anaerobic conditions prevail. However, in a worst-case scenario soil cracking may promote preferential flow to lower layers.

Figure 6.7 shows that the predicted residual PO_4^{3-} loading is expected to reach about 900 mg kg^{-1} over a period of 33 months in DEWATS irrigated soil. The Sepane (Newlands Mashu soil) had very high extractable P, which initially prevented the application of P fertiliser during the study. In such poorly managed soils, crops such as turfgrass sod may be grown since it is able to remove large contents of N and P (Tesfamariam et al., 2009).

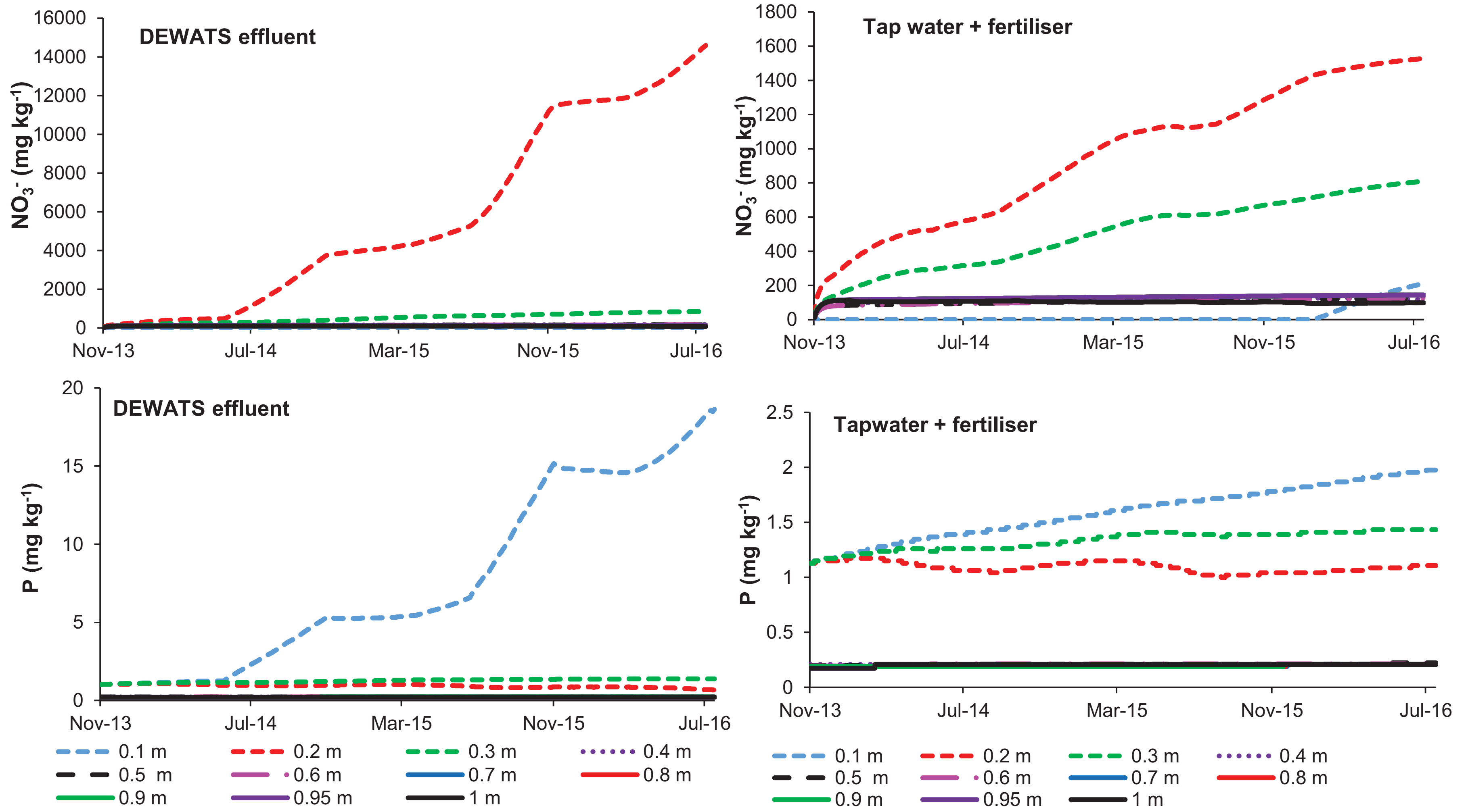

Figure 6.7 Simulated residual nitrate (NO_3^-) and labile phosphorus (PO_4^{3-}) concentrations for irrigation with DEWATS effluent (DW) and tap water + fertiliser (TW) at different depths in the Sepane soil at Newlands-Mashu over a period 33 months

6.3.5.3 Mobile NO_3^- dynamics

Figure 6.8 shows NO_3^- dynamics in the soil between the two irrigation treatments over a 33 months period at Newlands Mashu. The patterns was associated with increasing NO_3^- concentrations within the 0.2 m zone. Sudden drops in their concentration means that the NO_3^- has moved to the next layer. During the study, high nitrate movement in the soil with regards to irrigation with DEWATS effluent occurred as from April 2015 when the irrigation was switched from HFW effluent to DEWATS effluent. In both treatments, there has been significant NO_3^- accumulation in all soil layers from March to May 2015, probably due to low irrigation and rainfall. In March and July 2016 high NO_3^- shooting and falling coincided with high rainfall regimes which caused leaching. In comparison with tap water + fertiliser irrigation, NO_3^- concentrations at 0.2 m depth in the DEWATS treatment were periodically increasing over a period of time, expected to reach about 14 000 mg L^{-1}. Since the soil is at high risk of NO_3^- accumulation proper irrigation management practices that will ensure a reasonable water and nutrient balance must be considered.

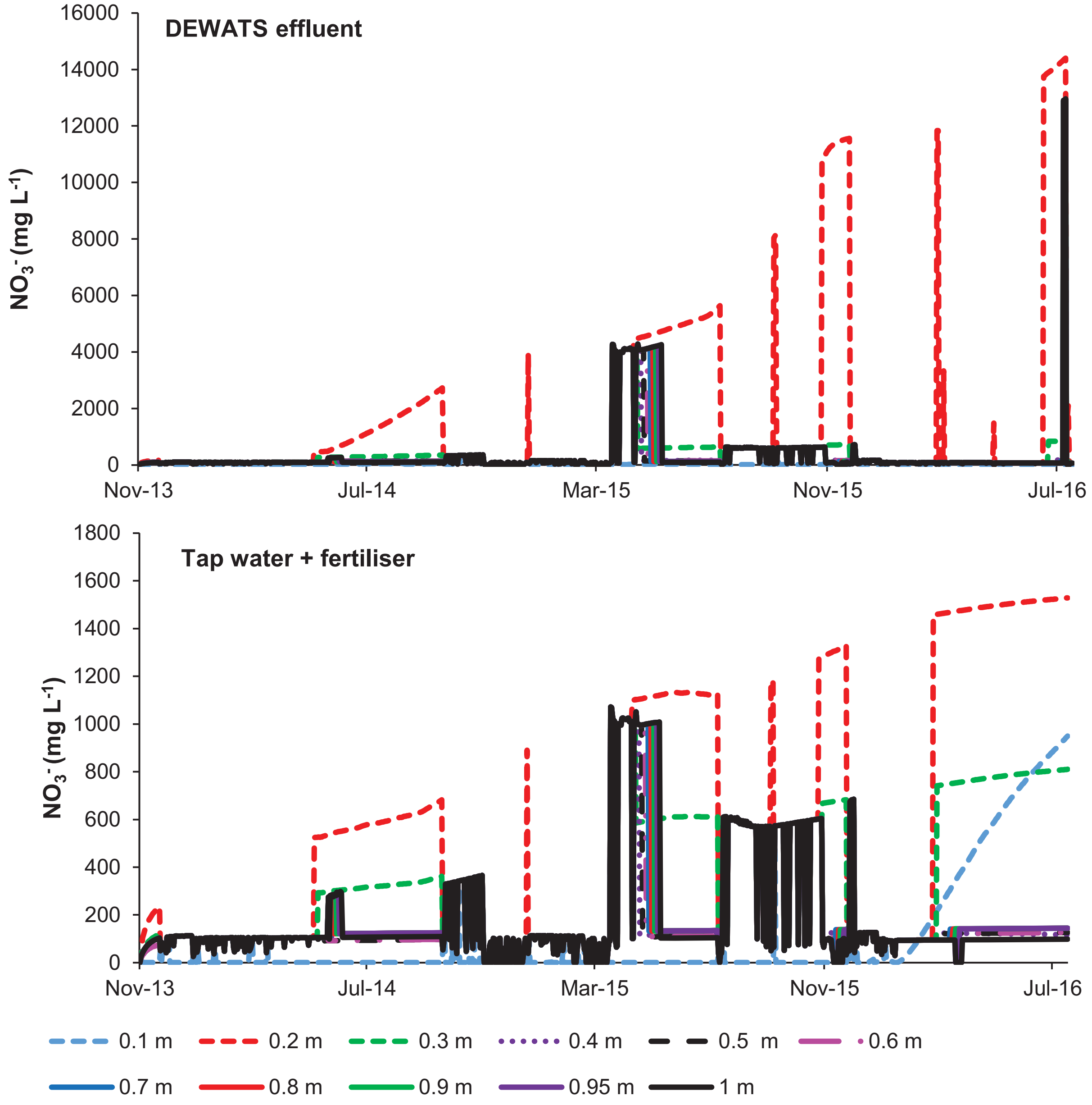

Figure 6.8 Simulated mobile nitrate at different depths in the Sepane soil at Newlands-Mashu irrigated with (A) DEWATS effluent and (B) tap water + fertiliser over a period of two years

6.3.5.4 Leaching of NO_3^- over time

The masses of NO_3^- leached from the Sepane soil irrigated with DEWATS effluent over 33 months are shown in Figure 6.9. From November 2013 to March 2016, the masses of NO_3^- leached in DEWATS effluent were progressively lower than tap water + fertiliser. Higher leaching losses in DEWATS effluent irrigation (up to 13.4 kg ha^{-1}) compared to tap water + fertiliser (up to 9.7 kg ha^{-1}) were observed in July 2016. The reasons behind were high irrigation rates and heavy rainfall regimes reported in chapter 3 (Table 3.5 and Figure 3.25). Furthermore, irrigation was switched from HFW to ABR effluent in June 2015 but this could not affect the leaching rate until March 2016. Nitrogen in DEWATS effluent is predominantly in the form of NH_4^+-N which is held and retained by negatively charged soil particles and can later be nitrified when exposed to conducive conditions (Bame et al., 2013). Therefore, irrigation with DEWATS effluent load more inorganic N in the soil which later leach when exposed to high irrigation and rainfall.

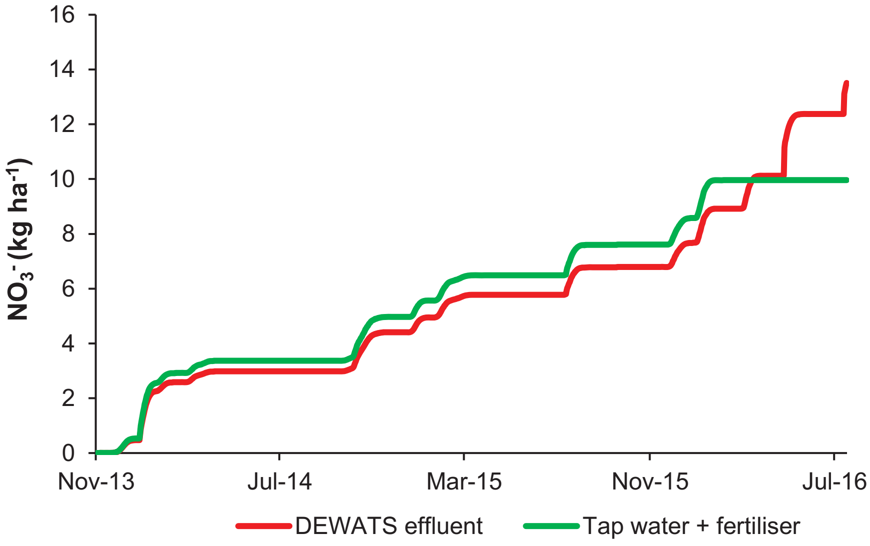

Figure 6.9 Simulated concentration of nitrate leached from the Sepane soil at Newlands-Mashu when irrigated with DEWATS effluent (DW) and tap water + fertiliser (TW) over a period of two years

6.4 Conclusions and recommendations

Parameters for modelling banana growth and nutrient uptake were developed for the SWB model. The model was successfully calibrated and validated; thereby meeting all the statistical criteria for simulating banana growth and nutrient uptake with high accuracy ($R^2 > 0.8$, $D > 0.8$ and $MAE < 0.2$). The predicted land required for irrigating banana was 206 m^2 household^{-1} (41.2 m^2 person^{-1}), which can be half the land when bananas are grown with taro in an intercrop. However, different irrigation scheduling programs can be employed in different soils, ensuring that crops are irrigated based on crop water requirements rather than soil storage capacity. The simulated nutrient (NO_3^- and PO_4^{3-} concentrations) dynamics in the soil did not agree with data measured in the field due to high spatial variation. The soil irrigated with DEWATS effluent are at very high risk of NO_3^- and PO_4^{3-} accumulation when proper irrigation management practices are not followed.

More studies are required on crop modelling, which include the parameterisation of taro growth model. The study was conducted at Newlands Mashu with a clay (Sepane) soil, other areas are being extrapolated under pot experiments. More field studies are required to validate the findings from the model and pot experiments since field scenarios are more complex. Nutrient accumulation at the site over time is of great concern, it is important to investigate hoe different cropping systems can help resolve problems such as residual N and P accumulation over time.

7 RISK OF MICROBIAL INFECTION DUE TO IRRIGATION WITH EFFLUENTS FROM THE DEWATS PLANT

7.1 Introduction

All pathogens of viral, bacteria, parasitic and protozoan origins can be found in wastewater; and can be transmitted to farmers using the wastewater for irrigation and the consumers (Asano, 1998). It is worth noting that diseases are linked to the nature of the pathogen in the wastewater and therefore vary greatly due to the local public-health pattern. The most vulnerable of exposed populations are children and the elderly. Contamination of crops with pathogens mostly occurs via direct contact, though there are some reported cases of uptake by plants (Hamilton et al., 2007). The primary concern for consumption-associated risk is the eating of uncooked vegetables such as raw salad dishes (Harris et al., 2003). However, risk of infection with spore forming bacteria as well as soil transmitted helminths (STHs) is still high for cooked vegetables due to their tolerance of high temperatures (van Gerwen and Zwietering, 1998). Enterotoxigenic *Escherichia coli* (ETEC) is often associated with diarrhoea (commonly referred to as Travellers' diarrhoea) in developing countries (Gupta et al., 2007) and several diarrhoeal outbreaks have been associated with wastewater-irrigated vegetables (WHO, 2006). Therefore to protect public health and rationalise the use of wastewater in agriculture, the World Health Organization developed a document on the reuse of effluents that relies on the thresholds of pathogen levels in irrigation water (100 coliforms 100 mL^{-1}) which should not be exceeded for unrestricted irrigation to achieve the tolerable disease burden of $\leq 10^{-6}$ DALYs per person per year (Havelaar et al., 2001). Traditionally, microbial analysis and epidemiological studies have been extensively used in evaluating risks in wastewater-irrigated agriculture, especially among affected farmers. The Quantitative Microbial Risk Assessment (QMRA) framework has been used extensively in recent times in the estimation of risk. In this report this framework was used to determine the risk of infection with different groups of pathogens representing bacterial, viral particles, parasites (both helminths and protozoan parasites). The risk of infection was estimated for farmers using effluents from the DEWATS plant for irrigation and for consumers of irrigated vegetables.

7.2 Sampling and laboratory analysis

Water samples, 100 mL for bacterial and coliphage analysis and 5 L for parasite analysis, were taken from the inflow of raw wastewater into the plant (inflow), within the second anaerobic baffled reactor chamber (ABR 2) and from the anaerobic filters, the last stage of the anaerobic treatment (effluents). Sampling was carried out from January to May 2016.

Sampling of the planted growth filters (PGFs) (horizontal flow wetland) was carried out in October 2015. However, during this sampling period the PGFs were not functional for most of the time and hence irrigation was carried out with effluents from the ABR. Bacterial concentration was determined using standard methods, bacteriophage concentration was determined using the double agar layer method (APHA, 1992). Soil transmitted helminth concentrations were determined using a modified version of the USEPA method (Schwartzbrod, 1998).

Vegetables were sampled from beds irrigated with the effluents from the DEWATS plant as well as from control beds irrigated with tap water. Each vegetable head was aseptically sampled and placed in a sealed sterile bag, kept on ice and transported to the laboratory for analysis. Contamination with different pathogens was determined with the methods mentioned above. Prior to microbiological analysis, each vegetable was weighed and then washed three times with 500 mL of distilled water and the third wash water was analysed.

7.3 Health risk assessment

According to Haas et al. (1999), QMRA involves a sequence of four interrelated steps: a) hazard identification; b) exposure assessment; c) dose-response assessment and d) risk characterisation. These different steps are presented.

7.4 Hazard Identification

In this report five pathogens, *E. coli* (representing bacterial pathogens), *Campylobacter* spp, somatic coliphages (as surrogates for viral pathogens), *Clostridium spp* concentration (as surrogates for protozoan parasites) and soil transmitted helminths (STHs) were selected for the risk assessment for farmers and consumers. Several studies have shown a close relationship between different types of infections and wastewater irrigation (Cifuentes, 1998; Peasey, 2000; Blumenthal and Peasey, 2002). The biggest threat to public health is infection with helminths, as these can survive for long periods of time under severe adverse environmental conditions (Feachem et al., 1983) and *Ascaris* has therefore been suggested for QMRAs in developing countries by the WHO (2006). However, in this study risk of helminth infections was only assessed for consumers because no viable helminth eggs were recorded in the effluents used for irrigation.

7.5 Exposure assessment

Exposure assessment involves the determination of the “amount or number of organisms that correspond to a single exposure (termed the dose) or the total number of colonies, plaques or ova that will constitute a set of exposures” (Haas et al., 1999). In this study, two pathways namely (a) accidental ingestion of the effluent by farmers during irrigation, and (b) consumption of contaminated vegetables were assessed. The basis for each of these scenarios is presented below.

7.5.1 Exposure framework

Figure 7.1 presents the exposure framework for both farmers and consumers. Risk of infection is determined separately for (1) effluent after the anaerobic filter (ABR effluent) used for irrigation and (2) effluent from the horizontal flow wetland (HFW) used for irrigation. These different effluents would result in different risk of infections due to different concentrations of pathogens.

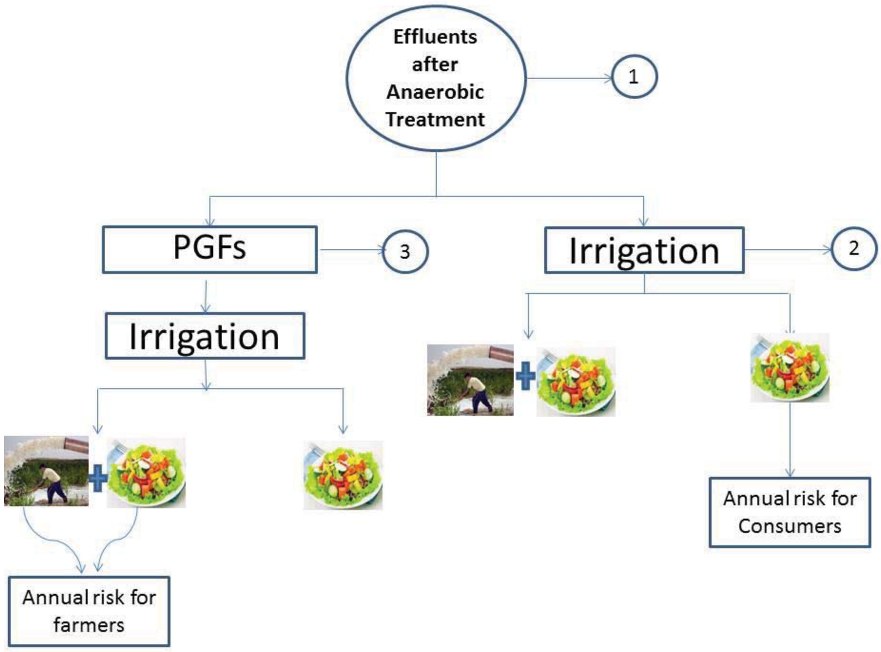

Figure 7.1 Exposure framework for health risk assessment. PGF – effluent after the horizontal flow wetland

7.5.2 Farmer's exposure scenario

Irrigated vegetable farming is a labour intensive exercise, exposing farmers to the effluents used for irrigation. It is common practice for small scale/subsistence farmers not to use personal protective clothes (e.g. boots, mouth covers, gloves, etc.), so therefore they are exposed to pathogens in the water. It is assumed that farmers would accidentally ingest 1 mL of the effluents (Ottoson and Stenström, 2003) for 150 days in a year (Seidu et al., 2008).

7.5.3 Consumer's exposure scenario

The risk of infection is calculated from the consumption of 10 g of vegetables (Seidu et al., 2008), and in this assessment spinach (representing leafy vegetables growing above ground) and beetroot (representing vegetables growing below ground) are considered as the vegetables of choice.

7.6 Dose-response assessment

Dose response assessment was undertaken to assess the relationship between the dose of pathogen ingested by the farmers and consumers and the probability of infection. In this report, the beta-Poison dose response model developed by Navarro et al. (2009) was used.

7.6.1 *Beta-Poisson dose response model*

The Beta-Poisson model takes into account the variations which exist in pathogen-host interactions and the parameters for this model were arrived at using the MLE method. A dose response model is acceptable when Y_{min} is less than the tabulated chi-square value X^2 at k-j degrees of freedom (Haas et al., 1999). The probability of infection was therefore calculated based on the Beta-Poisson model given in Equation 7.1.

$$\boldsymbol{p(inf) = 1 - \left(1 + \left(\frac{N}{\beta}\right)\right)^{-\alpha}} \qquad \textbf{Equation 7.1}$$

where p(inf) is the probability of infection, *N* is the dose of the pathogens (cfu for bacterial, pfu for bacteriophages and eggs L^{-1} for parasites) in a known consumed amount of irrigation water or vegetable consumed, and β and α are dose-response parameters which are determined by the infectivity organism provided that β is large compared α (Furumoto and Mickey, 1967). The parameters of the dose model for each pathogen are presented in Table 7.1.

Table 7.1 Parameters for the Beta-Poisson model used for the risk assessment

Pathogen	Reference pathogen	Parameters		Reference
		β	α	
E. coli	*E. coli 0157*	8.7 x10^3	0.22	Powell et al. (2000)
Somatic coliphages	Enterovirus	227.2	0.401	Tuenis et al. (1996)
Campylobacter spp	*Campylobacter jejuni*	7.59	0.145	Tuenis et al. (2005)
Helminths	Ascaris	0.044	0.104	Navarro et al. (2009)
Cryptosporidium	Clostridium	0.176	0.115	Tuenis et al. (2002)

7.7 Risk characterisation

In the risk characterisation all the outcomes of the hazard identification, exposure assessment and dose response assessment are combined to characterise the risk of infection for farmers and consumers.

The risk of infection (P_1(A)) associated with multiple exposures was determined from Equation 7.2.

$$\mathbf{P1(A)=1-\left(1-P1(\mathit{d})\right)^{\mathit{n}}} \qquad \textbf{Equation 7.2}$$

where P_1 (d) is the risk of infection from a single exposure to a dose ***d*** of the pathogen, and ***n*** is the number of days of exposure to the single dose ***d*** (Sakaji and Funamizu, 1998).

7.8 Results and discussion

7.8.1 Pathogen reduction efficiency

Reduction in concentration of microorganisms varied between the groups with the highest reduction of 4 Log10 units achieved for *Salmonella* spp, while *Campylobacter* and Somatic coliphages recorded a 1 Log10 unit reduction. However, *E. coli* concentrations remained fairly constant through the anaerobic treatment process, recording a 5 Log10 unit concentration (Figure 7.2). Several processes could contribute to the removal observed, such as adsorption onto settleable solids and other factors such as predation by antagonistic organisms, physicochemical conditions and toxins excreted by certain algae could also affect the removal of microorganisms (Plumb et al., 2001). A further 1 Log10 unit reduction was achieved with the planted gravel filters (first round of sampling), this might be due to the increase in hydraulic retention time and the further removal of particles (Table 7.2).

Table 7.2 Concentration of selected pathogens in effluents from the planted gravel filters (PGFs) and the anaerobic filter (AF) during the preliminary study

Pathogen	Concentration PGFs (100 mL)	Concentration AF (100 mL)
E. coli (cfu)	1 300 ± 532	40 000 ± 257
Salmonella (cfu)	1 650 ± 650	33 000 ± 845

The WHO guidelines for wastewater reuse in agriculture recommends a 4 Log10 unit reduction in pathogen concentration when effluents are intended for the cultivation of low growing crops (such as spinach and beetroot) using drip irrigation. Therefore, the DEWATS treatment process achieved this recommended reduction guideline for all pathogens studied except *E. coli*. Including the further reduction achieved through the PGFs an additional 3 Log10 units reduction is necessary before the use of reuse of the effluents if the concentration of *E. coli* is to be reduced to the recommended guideline for irrigation. This further reduction could be achieved through on-farm interventions such as storage before use. Effluent storage in reservoirs has been found to result in further reductions in pathogen concentration through die-off as well settling of cysts and ova. Bacterial numbers are expected to reduce by between 1-6 Logs, helminths by 1-3 Logs, viruses by 1-4 logs and cysts by a further 1-4 Logs (Pearson et al., 1996). Therefore, inclusion of such strategies would further reduce the concentration of these pathogens and result in reduced risk for exposed populations.

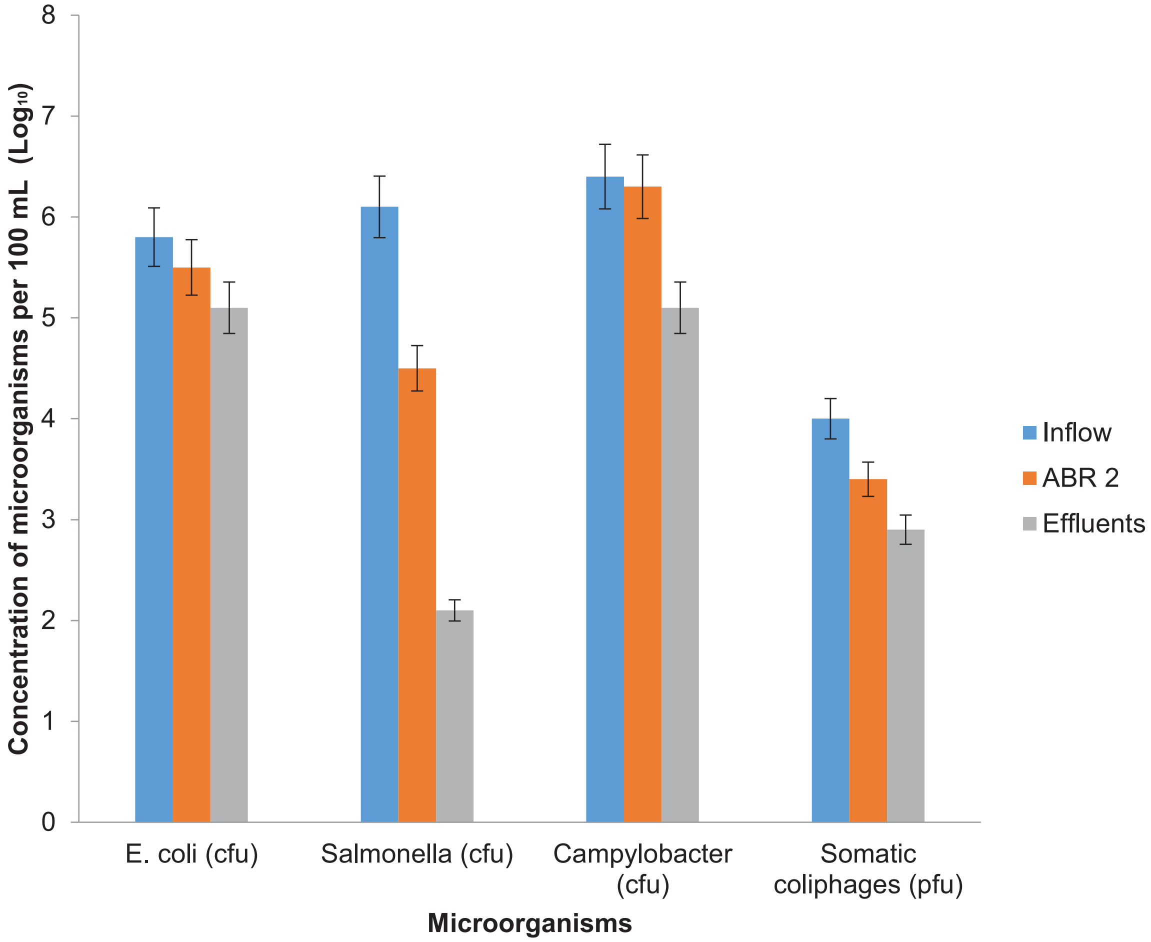

Figure 7.2 Concentration of selected pathogens at the sampling points.

However, higher removal efficiency was recorded for STHs and spore forming bacteria such as *Clostridium* spp. The prevalence of STHs in the influent was low, with samples only from the months of February, April and May 2016 being positive. *Ascaris* spp (42.51%), Hookworm (44.35%) and *Teania* spp (13.14%) were the species of STH eggs recovered from the influent, however, no viable eggs were recovered from the effluents. The wastewater influent contained 2Log10 units of *Clostridium* spp with a further 1 Log10 unit removed during treatment

(Figure 7.3). Removal of protozoan cysts and helminth eggs is strongly attributed to sedimentation, which is enhanced by relatively long hydraulic retention times (HRTs) (Wu et al., 2016). With an HRT of about 20 hours, most cysts, spores and eggs would settle into the bottom sludge (which was not analysed). A recommended guideline of <1 helminth egg L^{-1} is needed for unrestricted agricultural use (WHO, 2006). However, in this study there were no viable helminth eggs in the effluents which might be due to the low concentration and prevalence of these parasites in the influent even before treatment. Helminth infections are linked to poverty (Bethony et al., 2006) and so wastewater from poor communities is expected to have a much higher concentration than was observed in this area, which is a middle income area. Therefore, although no viable eggs were recorded, indicating their complete elimination, the results obtained here cannot be extrapolated to other areas. The *Clostridium spp* concentration was used in the risk assessment to represent probability of infection with protozoan parasites due to the strong correlation between these two groups of pathogens (Reinoso et al., 2008) and their similar survival rates.

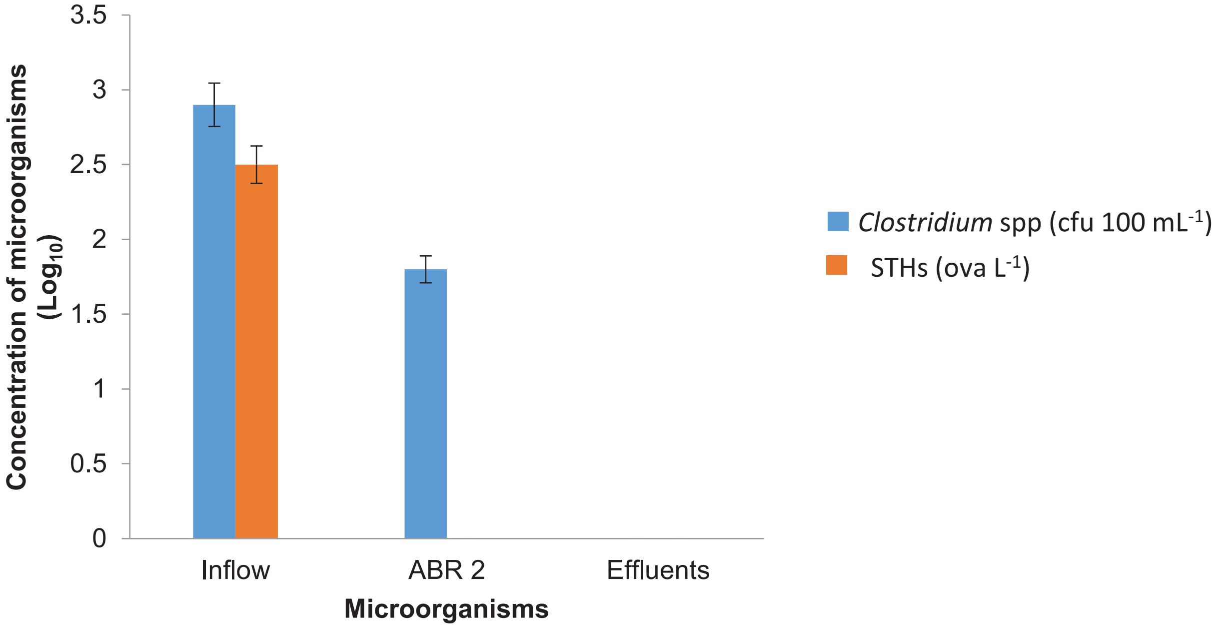

Figure 7.3 Concentration of Clostridium spp and soil transmitted helminths (STHs) at the various sampling points

7.8.2 Contamination of vegetables and probability of infection for farmers and consumers

The probability of infection with the different groups of pathogens was found to be high for the farmers due to the high concentrations in the effluents used for irrigation, with the lowest risk of 10^{-2} reported for accidental ingestion of water containing *E. coli* and somatic coliphages per day and an annual risk of 10^{-1}, which is higher than the WHO tolerable limit of 7.7×10^{-4} per farmer per year (WHO, 2006). Therefore, additional measures are needed to reduce the risk of infections. As stated above a further reduction is possible in pathogen concentration with storage of effluents before use and this intervention could reduce the risk further, to between 10^{-2} to 10^{-4}, depending on the duration of storage (Blumenthal et al., 2000). A functional PGF for instance could further reduce the bacterial concentration by 1.5Log10 units as observed in the preliminary study. In addition, the use of personal protective equipment could provide an additional protection against infection for farmers.

Contamination of farm produce with pathogens is a major source of infection especially for consumers. The mean concentrations of all bacterial pathogens and phages were significantly higher ($p>0.05$) for *E. coli* in the spinach samples (2740 ± 620 cfu $10g^{-1}$) compared to the beetroot samples (1450 ± 340 cfu $10g^{-1}$) (Table 7.3). This could be due to higher retention of irrigation water in the spinach. However, *Clostridium* spp and STHs recorded higher concentrations in the beetroot samples than the spinach samples (Table 7.3). Eggs of STHs and spores of *Clostridium* spp are more resistant to adverse environmental conditions than bacterial pathogens and therefore these pathogens could be accumulated in the soil due to continuous irrigation and might have higher concentration in the soil than in the irrigation (Seidu et al., 2008). With beetroot growing below the soil surface contact with these pathogens would therefore be higher than the spinach growing above the ground. In comparison with the control vegetables irrigated with tap water, wastewater irrigated vegetables recorded higher contamination levels (Table 7.4) and the differences in concentrations were statistically significant for *E. coli* and somatic coliphages ($p > 0.05$). Contamination levels for *Campylobacter, Clostridium* and STHs eggs were not significantly different for vegetables irrigated with the two types of irrigation water (ABR effluents and tap water). Further reduction of pathogen contamination of vegetables is achievable through washing. Amoah et al. (2007) found that the concentration of faecel indicator organisms on lettuce irrigated with wastewater was reduced by 0.5 Log when washed with salt, 0.2-4.7 Log with vinegar and 2.3-2.7 Log when washed with chlorine. A 1-2 log10 reduction of *Ascaris* on lettuce can be achieved with washing of vegetables with detergents (Seidu et al., 2008) resulting in a greater than 90% reduction in risk. Cooking the vegetables would also result in the inactivation of most of these pathogens, especially *E. coli* and *Campylobacter* spp,, although spore forming bacteria, such as *Clostridium* spp, *Bacillus* spp, etc. as well as helminths are more resistant and therefore a lesser reduction would be achieved as compared to the bacteria (van Gerwen and Zwietering, 1998). However, incorporation of these post-harvest interventions as well as good hygiene would result in a much reduced contamination if not complete elimination of pathogens on produce before consumption.

Table 7.3 Concentration (± standard deviation) of different pathogens in irrigation water and vegetables

Sample	*E. coli*	*Campylobacter spp*	Somatic coliphages	*Clostridium spp*	STHS*
Effluents (cfu 1 mL^{-1})	1 242 (±580)	1 140 (±549)	9.56 (±3.4)	0	0
Spinach (cfu 10 g^{-1})	2 740 (±620)	1 740 (±124)	32 (±12)	12 (±7)	8 (±3)
Beetroot (cfu 10 g^{-1})	1 450 (±340)	100 (±34)	28 (±10)	23 (±18)	24 (±12)

* STHs – soil transmitted helminths

Table 7.4 Concentration (± standard deviation) of different pathogens on vegetables irrigated with tap water

Sample	*E. coli*	*Campylobacter spp*	Somatic coliphages	*Clostridium spp*	STHS*
Spinach (cfu 10g^{-1})	1 275 (±523)	895 (±201)	21 (±8)	9 (±3)	10 (±4)
Beetroot (cfu 10g^{-1})	968 (±320)	101 (±16)	9 (±2)	20 (±6)	23 (±11)

* STHs – soil transmitted helminths

The probability of getting infected with *E. coli* due to onetime consumption of spinach and beetroot was found to be similar to risk of infection with the same pathogen for the farmers (6.0 x 10^{-2} and 3.33 x 10^{-2}, respectively). A similar trend was found for all pathogens except for risk of infection with *Cryptosporidium* (determined with contamination loads of *Clostridium* spp) and STHs. A risk of 4.17 x 10^{-1} and 4.80 x 10^{-1} (Table 7.5) for helminth infections due to the consumption of spinach and beetroot, respectively, were found. Helminth infection remains the biggest public health concern in wastewater reuse in agriculture due to their high survival rate in the environment and the low infection dose (Hotez et al., 2003).

Irrespective of the pathogen studied, the risk of infection for consumers exceeded the WHO tolerable risk for consumption of vegetables irrigated with wastewater. This was mainly because the concentration of these in the irrigation water far exceeded the recommended guidelines for unrestricted agriculture. However, the high risk of infection cannot only be attributed to irrigation with the wastewater, as the control vegetables also recorded contamination albeit at a lower level. Contaminated soil could also lead to increase in contamination of vegetables especially during rain when splashing occurs or during irrigation practices, such as sprinkler or the use of a watering can. However, in this study drip irrigation was applied therefore eliminating the effect of the irrigation method. Therefore, to protect consumers of the vegetables there is a need to incorporate the multiple barrier approach where post-harvest treatment of the vegetables is needed to reduce the contamination levels. One such approach is the cessation of irrigation before harvest as the WHO guidelines estimate a 0.5 day^{-1} die-off for bacterial pathogens (WHO, 2006), as well as washing and cooking of the vegetables (Oie et al., 2008). Therefore further reduction in concentrations would be achieved with this approach which would provide a further barrier to infection.

Table 7.5 Risk of infection with selected pathogens

Pathogen	Onetime probability of infection			Annual probability of infection*		
	Irrigation water (Farmers only)	Spinach	Beetroot	Irrigation water (Farmers only)	Spinach	Beetroot
E. coli	2.89×10^{-2}	6.0×10^{-2}	3.33×10^{-2}	3.52×10^{-1}	9.9×10^{-1}	9.9×10^{-1}
Campylobacter spp	5.17×10^{-1}	5.45×10^{-1}	3.19×10^{-1}	1	1	1
Somatic coliphages	1.64×10^{-2}	5.15×10^{-2}	4.55×10^{-2}	9.16×10^{-1}	9.57×10^{-1}	9.9×10^{-1}
Cryptosporidium	na$	3.85×10^{-1}	4.29×10^{-1}	na	1	1
STHS**	Na	4.17×10^{-1}	4.80×10^{-1}	na	1	1

*Annual risk was estimated for farmers was based on 150 days of exposure. For consumers annual risk was estimated based on consumption of 10 g of vegetables for 208 days per year.

$ na – not applicable

** STHs – soil transmitted helminths

7.9 CONCLUSION

Irrigation of vegetables with effluents from the ABR would lead to an increased risk of infection with bacterial, viral and parasite pathogens. Therefore, the multiple barrier approach as suggested by the WHO needs to be adopted to reduce the risk of infections. Measures such as the type of irrigation method, washing with salt or chlorine-based disinfectants, etc. will need to be used in order to reduce the risk of infections and maximise the benefits that would accrue from the use of these effluents.

It is worth noting that the high concentration of pathogens in the vegetables could not be attributed only to the effluents used for irrigation, due to the contamination levels recorded in the control vegetables as well.

Also the use of spinach and beetroot are indicative of worst case scenarios where the effluent is applied directly to the crops. In the present study, banana and taro were selected because the edible parts are enclosed in a protective cover. The banana fruit is raised above the ground and the probability of contact with the effluent is low. The taro corm also grows underground. Sub-surface irrigation was also used to minimize contact between the effluent and the growing plants. The harvested crops are generally cooked for consumption. There were no colonies present on the banana fruit and only a few colonies were found on the banana peel.

8 STAKEHOLDER ANALYSIS OF THE SOCIAL ACCEPTABILITY OF THE DECENTRALISED WASTEWATER TREATMENT EFFLUENT AND HUMAN EXCRETA-DERIVED MATERIALS FOR USE IN AGRICULTURE

8.1 Introduction

Despite the increased supply of urine diversion (UD) toilets as basic sanitation facilities in peri-urban and rural areas in South Africa, the use of human excreta especially for food production has not gained ground. The perceptions and beliefs of the users represent a major stumbling block to the use of the products from dry toilets and this has been strengthened by hygiene awareness programmes. The mind-set is that of an ‘unhygienic’, ‘smelly’, ‘unacceptable’ and ‘repulsive’ material. With the advent of the decentralised wastewater treatment system (DEWATS) in which the effluent has undergone some level of treatment as well as giving an additional advantage of supplying not only nutrients but water, there was a need to acquire knowledge of the perceptions of all stakeholders.

8.2 Approach and methodology

This study was grounded on the qualitative interpretation model. Primary data were collected through in-depth interviews with relevant stakeholders. A stakeholder is defined as “any individual/organisation that could be affected or could influence the adoption of effluent in agriculture”. Some of these stakeholders were considered as experts in their respective fields while those in the focus groups were included because they represent the demography of those expected to benefit or buy into the technology. The identification of stakeholders was carried out through a mapping exercise and the stakeholders listed in Table 8.1 were identified for interviews. Although the initial intention was to interview all stakeholders to get the similarities and divergence of opinions, some stakeholders were not interviewed for this study due to their unavailability.

Table 8.1 Identification of different stakeholders in an analysis of the acceptability of DEWATS effluent and human excreta-derived materials for use in agriculture

Planned participants	Planned sample	Actual participants
eThekwini Water and Sanitation	3	3
Committee Chairperson, Health, Safety and Social Services (eThekwini)	1	0
Committee Chairperson, Human Settlements and Infrastructure (eThekwini)	1	0
KZN Department of Agriculture	1	1
Department of Agriculture (eThekwini)	1	1
Academic (Discipline of Housing), University of KwaZulu-Natal	1	1
KZN Department of Water and Sanitation	1	0
KZN Department of Human Settlement	1	0
Technocrat (an engineer)	1	1
Focus groups in rural and peri-urban areas	10	7

8.3 Focus group discussions with communities on the use of effluent for agricultural production

A total of seven focus group discussions were held over a period of three non-consecutive days. Two of these were in peri-urban areas while five were in rural areas. The choice of the locations was to understand whether perceptions about the use of effluent in agriculture are influenced by the rural-urban divide. Each focus group comprised a minimum of five participants while there were nine participants in the largest focus group. In total, there were 48 participants in all the focus groups. Participants in the focus groups were predominantly females. Only 9 of the 48 participants were males. The youngest participant in the focus group discussion was 19 years and the oldest 77 years.

Each focus group discussion was preceded by a comprehensive introduction which covered among other things, the purpose of the focus group and an overview of the DEWATS system at Newlands-Mashu and its linkage to agriculture. The explanation was carried out with the aid of pictures of the DEWATS, the wetlands and the agricultural site. After the introduction, participants were invited to ask questions on points that required clarification. Further discussions only commenced once all participants confirmed that they had a clear understanding of the project.

Furthermore, similar work done by Kanyisa Projects on the reuse of water from the Magabheni Pond was consulted.

All interviews and focus groups were recorded with the permission of research participants. Recorded interviews were transcribed and coded iteratively into themes with NVivo (a qualitative data analysis computer software package from QSR International) and analysed thematically.

This chapter presents the findings from the primary research grouped into key themes. Direct excerpts from quotes are italicised for easy identification.

8.3.1 Theme 1: Willingness to use the DEWATS effluent for agriculture

This study found a highly positive response towards the use of effluent in agriculture. Most respondents noted that it was a good idea to use effluent in agriculture even though none was aware of its potential benefit in agriculture prior to the focus groups. Participants drew parallels between recycling of water in urban centres and using effluent in agriculture. They noted that since recycled water is used in urban areas, there was no reason to be opposed to using effluent in agriculture. In addition, some participants had previous experience of using grey water to irrigate their farms. These respondents (from rural areas) were introduced to the use of grey water for irrigation by Zimele, a nongovernmental organisation, to address water scarcity.

Given that water is a scarce resource in these communities, participants expressed willingness to accept options that will help address water shortage. The following excerpts from the focus groups further buttress participants' stance on the use of effluent in agriculture:

> ***"I will use it. This sounds like a good idea and I don't think it will present any problem. I am not sure how we can access the water though"***
>
> ***"In areas which are more urban, we have heard that they recycle domestic water for drinking water. So we would not be opposed to using the water"***
>
> ***"There are lots of things we see as being dirty or unhealthy whereas if you leave closer, you will continue to use them. The same thing works with cow dung that is used for fertilisation. It is used and as more as things are being exposed to us that these things can work, we need to learn that these things can help us with our farm"***
>
> ***"At the end of the day, we have to accept this kind of things. I have been taught that I can use grey water on my farm. I have used it and it works"***

Although all participants in the focus groups were open to using effluent in agriculture, analysis of interviews with some experts indicated that communities might be opposed to using effluent in agriculture. These experts cited traditional, social and religious issues as possible barriers. The following excerpt from the interview with the academic summarises this view:

> ***"African people, specifically the Zulu people, touching fecal matter whether dry or not, with pathogens or no pathogens, and touching urine whether there is some chemicals or not is something that they don't really do. So you got to have to navigate the cultural waters if you may call it. So culturally, the relationship touching faecal material is something taboo."***

Despite the expressed reservations about social acceptability of effluent in agriculture, all the experts expressed positive views about the potential of effluent in agriculture. One of the interviewees from EWS noted that using effluent in agriculture is the way we should go. To facilitate this, the interviewee noted that the EWS is in the process of modifying its facilities to accommodate the use of effluent in agriculture. The interviewee was of the view that the idea will be accepted by communities since EWS is already experiencing cases of people breaking sewage pipes to use the water to irrigate their farms. Similarly, the interview with the provincial DoA showed that the department was not opposed to the use of effluent in agriculture. The respondent noted that anything that we can reuse is good as long as we do not poison what grows. Furthermore, the respondent reported that the DoA will support this approach as long as it is economically viable and can contribute to improved crop yield. The counterpart from the eThekwini DoA reported that some farmers had noted yield increase in their fields from the use of faecal matter and have requested further supply. The interview with an MSc student at EWS indicated that participants in the study were ambiguous about using urine in agriculture, as they were totally opposed to being directly involved in the use of urine in agriculture or being responsible for collecting urine for agricultural purposes. The study also found that participants were totally opposed to the idea of using faecal matter in agriculture. For them, faecal matter should never be used in agriculture because it is repulsive, filthy and should not be touched or used for something that will be consumed.

8.3.2 Theme 2: Willingness to eat food grown using the DEWATS effluent

Besides the acceptability of growing food with treated effluent from wetlands, the study also examined the willingness to consume food grown using effluent. Analysis of focus group discussions showed that all participants were open to consuming food that had been cultivated using effluent. Some respondents alluded to the possibility that they could already be consuming food grown using effluent since they do not know how the food they buy is produced. In addition, other respondents referred to consuming food grown on sites where households' urine was disposed of. It was noted that since this was an acceptable practice, it was not inconceivable to consume food grown with effluent. The following excerpts further highlight the views of participants in terms of consuming foods grown using effluent:

> ***"Yes, I can eat it. For example, when I plant cabbage and it becomes infected, we take these TT chemicals and we spray. We don't know what these sprays contains but we still use it. I don't think this water is worse than those chemicals that I use"***
>
> ***"Yes, I can it. I have use grey water and I am eating the vegetable from that"***
>
> ***"I will eat the food grown in that way. Maybe we might be already eating this because the cabbage we buy from the shop, we do not know what they are grown from but we eat that food"***
>
> ***"The amaranth that we buy, those people that are selling it, where are they picking it? Those selling in Durban pick them at the dump site and people buy it from them. People won't go to pick these themselves but they will buy it knowing very well where it is picked from"***
>
> ***"Around the house, there is somewhere we the young boys throw the urine in the morning. Usually, that's a very fertile area around the house. We get imbuya from there to cook."***
>
> ***"As kids when we were young, we did not have toilets. We were sent to the field to do our number 2. We will farm the same place and we will eat food grown there"***

8.3.3 Theme 3: Crops that can to be grown using the DEWATS effluent

In addition to eating food grown using effluent, the study also examined the type of crop that could be grown with effluent. Interviews with the experts showed preference for non-tuber crops. It was noted that tubers have direct contact with effluent and therefore carry the risks of pathogen contamination. In addition, they noted strongly that vegetables meant for salad should not be grown using effluent. The concern here is that pathogens might be present in the salad and will therefore pose health risks when consumed. In this regard, the participant from the DoA at the municipal level stated that the food could be cooked to kill the pathogens and not eaten raw. As a result, they recommended that only non-salad and non-tuber crops be grown using effluent. While the experts were selective with regard to crop choice, all participants in the focus group discussions did not have preferences for the kind of crop that should be grown using effluent. The choice of crop was informed by more practical considerations such as meeting water needs for growing vegetables. Some participants also noted that they will not want to grow sweet potato using effluent because of the possibility of exposure to high moisture which reduces the sweetness of the potato. The following excerpts from focus groups further highlight respondents' perceptions about the kind of crop that should be grown using effluent:

> ***"If you don't cook it then you have a problem. If you cook it you actually kill all the pathogens and you boil over the chemicals and stuff which will evaporate"***
>
> ***"I would have divided my crop based on the requirement of water that they need. I will concentrate on irrigated crops like vegetables. Beans and maize can be rain-fed. The important thing is about the availability of water and the requirement of water for crops"***
>
> ***"It is true, the kind of crop to grow should be about how much water is required to grow it. For instance, sweet potato does not like too much water. You grow it where there is too much water, it will not be sweet so growing something like 'amadumbe' will depend on how the water is used"***

8.3.4 Theme 4: Willingness to buy food grown using the DEWATS effluent for irrigation

The fourth point that emerged from the focus groups was the willingness to buy food grown with effluent. While no participant was opposed to buying food grown using effluent, two expressed reservations about being told that the food they buy was grown using effluent. For these respondents, it was better that they were unaware of how foods were grown rather than being informed of the details. The concern here is the fear of being looked down upon by others once they get to know that they consume food grown with effluent. Conversely, other respondents were insistent that they wanted to be informed of how what they buy was grown and were not opposed to buying food grown using effluent. For these respondents, their primary criterion in buying food is the quality not how it was grown. Views about buying food grown using effluent are further highlighted in the following excerpts:

"I will buy it. My interest is if it is big and attractive"

"We will buy it. When you buy you look at the crop, you don't think about how it was produced so we will buy it"

"We will buy it. Even the one we buy we don't know. The one we buy in the market, we buy the big ones but we don't know where it is produced"

"Yes, but I wouldn't like to be told, I wouldn't like it to be put in my face. It is better that we don't know because there might be lots of teasing and name calling. Some might be saying that you are eating food from there. We just want good quality food. We don't want to know how it is produced"

"We drink water from the tap and we are told the water is recycled but we still drink it. We leave our natural things and run to the tap water knowing that it is recycled"

Besides buying food grown using effluent, this study also examined whether food grown in this manner should be labelled as such. Interviews with participants from the DoA showed that food grown using effluent should be labelled. The participant from the DoA at the provincial level attributed the importance of food labelling to the growing interest in food traceability. Both respondents from the DoA and the participant from the Pollution Research Group were of the view that food grown using effluent can be labelled as organic. The participant at the provincial level noted that if the details are spelt out on the food label, such food will likely be acceptable to educated middle class families while less well educated people might find the idea repulsive and reject it. For the engineer interviewed for this study, it was sufficient to label the food as organic since effluent undergoes a series of treatments before being applied to crops. The participant further stated that organic materials used in other organic crops are not specified in detail and therefore saw no reason why food grown using effluent should be labelled differently. Similarly, the participant from the DoA at the municipal level cautioned against including all the details since people might find it offensive and therefore refuse to buy the food.

8.3.5 Theme 5: Willingness to take a job that requires working with DEWATS effluent or any other treated effluent

One of the benefits associated with recycling of human excreta is its potential to create income generation and employment opportunities. In this regard, participants in the focus groups were asked if they would take up a job that required using effluent to grow food. Analysis of the focus group discussions showed that all participants were open to accepting a job at such sites. Views of participants in this regard are presented in the following excerpts:

> ***"As long as I am not exposed to the waste because I am interested in the end product. At the end of the day, all I want is to be able to support myself through selling"***
>
> ***"Yes, I will take it. There is no problem with the produce"***
>
> ***"I have no concern. Before, when people are given work to collect waste, people will decline. They see it was working with death because it is not a very clean work to do but today, everyone wants to do that job. So if today we refuse to take this kind of idea, we will be left out. If we want to be clean, then we will be left out in food production"***

8.3.6 Theme 6: Barriers to the use of treated effluent in agriculture

One of the questions which this study aimed to answer was possible barriers to the adoption of effluent in agriculture. Participants in the focus groups were asked if there was anything in their culture or religion that could be a barrier to using effluent in agriculture. Findings of this study showed that all participants were of the view that there was nothing in their culture/religion that forbids them from using effluent in agriculture. These views are highlighted in the following excerpts:

> ***"I am not aware of any religious or cultural barrier"***
>
> ***"There is nothing that will prevent me from using it"***
>
> ***"There is nothing about the culture that prevents us from growing food from this treated waste water"***
>
> ***"There is no barrier but we need to be taught or trained that this water from the tap is recycled water."***

However, there were observations about possible health risks. A number of participants were concerned whether they could become sick if they had contact with effluent in the process of irrigating their farms. All respondents were open to using effluent in agriculture as long as there is a guarantee that there are no associated health risks. The interview with the engineer indicated that there are minimal health risks associated with using human excreta in agriculture. He noted that mathematical models have been developed to predict the health implications of urine use in agriculture. In addition, he noted that using human excreta is sometimes about making a trade-off between health and starvation. In his view, the nutrition benefits outweigh the health risks. However, he was of the view that there are technical challenges associated with extending this technology to communities. Such challenges include issues of theft of equipment and components of DEWAT systems. He also raised concerns about the possibility of political interest undermining the project.

Another possible constraint that was identified by participants in the focus group discussions was about the issue of communication. The concern here is that if the idea of using effluent in agriculture is not properly communicated to communities, there is a danger of multiple conflicting messages being circulated in communities. Against this backdrop, all participants were of the view that information must be properly communicated to community members. The concern was that lack of detailed information could undermine the adoption of the approach since false information might be circulated. It was also pointed out that since farmers are more familiar with farming practices, they will have better grasps of the strategy and should therefore be equipped to communicate the message to communities. According to this view, communities will accept food grown with effluent once farmers are able to demonstrate the benefits of growing food with effluent to community members. The following excerpts from focus group discussions present respondents' views about information sharing regarding the use of effluent in agriculture:

"We as farmers understand how it works but people buying it might be initially opposed to the consumption of the food. But once they see the result, they might be more open to the consumption of food grown in this way"

"If half information is given to people, that might jeopardize people using it but if everything is explained to people. If there is selective information highlighting the use of toilet without explaining how it works, then there will be problem".

"If it is explained to the community very well, they will accept. There shouldn't be problem"

"I don't agree with the issue of announcing to everyone. It will rather be announced to those who are concerned"

"There is no barrier but we need to be thought or trained that this water from the tap is recycled water. More information should be put forward"

A staff member from EWS confirmed the importance of proper communication of messages by stating that communities have had double messages about how to deal with the content of UD toilets in eThekwini. In recognition of the value of proper communication, all the participants from EWS emphasised the importance of educators from the municipality in communicating the message to communities.

Policy constraint was also identified as a key barrier to the use of effluent in agriculture by all the experts interviewed for this study. The participant from the DoA at the municipality level stated unequivocally that the lack of a clear policy stance is a major barrier to the adoption of use of human waste in agriculture. According to the participant, the government is wary of the health implications of human excreta and therefore has refused to make a clear commitment to directing the department to encourage its use in agriculture. Such a stance, the participant noted, has resulted in a situation whereby the DoA could not give clear directives to communities to use human excreta in their fields. The participant noted that there is an urgent need for a policy change in order to address the current gap. In his view, policy change can be effected if there is scientific evidence documenting the health risks or the lack thereof associated with using effluent in agriculture. The engineer interviewed for this study expressed a similar view.

8.4 Stakeholder participation analysis

Stakeholder participation was considered an important factor in improving acceptability of effluent in agriculture. The participant from the discipline of housing at the University of KwaZulu-Natal was of the view that if community members are not properly engaged in the process, they could view it as an imposition from outside and reject it. In his view, a weakness of this kind of project is the undue emphasis on technical feasibility without considering the perspectives of beneficiaries of the projects. The concern here is that beneficiaries are considered as passive recipients of development projects and must therefore be grateful to technocrats who have put in much effort in making the project a reality. He further noted that lack of involvement of community members was premised on the view that they are ignorant and lacked the capacity to grasp the technical intricacies of projects. He also noted that while it is true that community members might not be able to grasp all technical details, involving them in all phases of projects is central to acceptance. Interviewees from the EWS emphasised the importance of community participation throughout the life cycle of the project. Similarly, the EWS MSc student highlighted how lack of community involvement in the rollout of UD toilets has resulted in nearly 80% of communities rejecting this sanitation option.

8.5 Emerging issues from the focused group discussions

One of the key questions that emerged from the focus groups was how communities will benefit from the current project. Some participants expressed willingness to have pilot sites for future similar projects located in their communities. There were also questions about the relevance of the projects in rural areas where wet sanitation options are not available and where homesteads are dispersed. Furthermore, participants expressed interest in learning more about the use of effluent in agriculture. Some of the participants requested that a site visit be organised to Newlands-Mashu.

8.6 Conclusions

The primary purpose was to examine the perspectives of stakeholders on their perceptions about the use of effluent in agriculture. In doing this, the study has provided the global picture in terms of sanitation backlogs, food insecurity and the link between sanitation and food security. In similar sanitation projects that have been carried out it was noted that there were generally negative perceptions on the use of human excreta in agriculture. Barriers such as religion, culture, smell, lack of knowledge and attitudes towards excreta were identified. In linking these to the present study, it was noted that using effluent was considered acceptable to all the stakeholders that participated in the study. Although barriers such as theft of equipment, health risks, and social stigma were identified in this study, they were not prevalent among the study participants.

The high level of acceptability of effluent could be attributed to two factors. Firstly, effluent is treated (anaerobic digestion) and the end product which is a clear liquid is appealing compared to handling raw faecal matter and urine. In addition, the detailed explanation of the DEWATS also gave participants a clear understanding of how the system works thus clarifying their doubts and concerns. With regard to the acceptability of effluent in agriculture, this study found highly positive attitude as respondents noted that it was a good idea to use effluent in agriculture even though none was aware of the potential benefit of effluent in agriculture prior to the focus groups.

Although the literature reviewed and interviews with experts all pointed to tradition, culture, lack of knowledge and religion as barriers to using human waste in agriculture, findings of this study has demonstrated that this is not the case for participants in the focus groups.

This study has provided useful insights about the social acceptability of effluent in agriculture. Although various studies have examined social acceptability of human excreta in agriculture, these studies have focused largely on either urine or faecal matter with little attention given to effluent. In this regard, this report has provided a useful contribution to knowledge and opportunity for further explorations of the social acceptability of effluent in agriculture in other contexts. However, concerns were raised by several experts with regard to effluent use in agriculture. There is need for continued engagement and consultations between regulators, policy makers, technicians and communities with regard to the use of DEWATS effluent for agriculture in South Africa.

9 CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The field experiment has enabled a considerable amount of information to be gathered that has allowed estimates for amounts of nutrient loading to be calculated and also the area of land that will be required in order to utilise the DEWATS effluent as a source of fertigation. The N and P loading from the second (horizontal flow) wetland could not supply the N and P requirements of a banana/taro crop which indicates that water directly from the ABR could be used with close monitoring of the pathogen load. More of the NH_4^+-N was held within the soil with more NO_3^--N in solution within the root zone. Incidences of high N and P were observed during high rainfall periods. The high orthophosphate-P in leachates from piezometers above the DEWATS plant indicates that the concentration found in the field could not be attributed to the irrigation. From a water supply point of view more of the effluent could have been irrigated onto the land. The DEWATS plant at Newlands has the capacity to produce 35 m^3 of effluent daily. Under the general authorisations for wastewater use in the Government Gazette No 36820 of September 6, 2013 on General Authorisations the variables of importance are pH, EC, COD and faecal coliforms. Following the present restrictions on permissible levels the ABR effluent could be used for irrigation directly without passing through the wetlands. This substantiates the findings that the ABR if used directly could impact positively on a banana/taro intercrop. The implications of this outcome lie in the area of land to be allocated for households and that to be used for agriculture, thus 83 households would require about 0.9 ha of land for agricultural activities. Using the effluent from the ABR directly would exclude wetlands as components of the system. From a managerial point of view, the wetlands require skilled persons for maintenance which might not be easy to obtain in communities where DEWATS are to be installed. In other investigations using effluent from the ABR to directly irrigate other crops such as maize, Swiss chard and potato, the effluent was able to supplement half of the fertiliser requirement of these crops. These observations were a function of the crop and the soil type. Whereas most of the growth responses are more evident in the sandy Cf soil for potato, in Swiss chard it was the case for the acidic Ia soil. Maize irrigated with effluent and not fertilised performed comparably to that at half fertiliser application and irrigated with tap water. The shortfall of N and P observed in the field trial could be supplemented with nutrients from the HEDMs as was investigated with the following outcomes;

(1) All the excreta-derived materials used, i.e. LaDePa pellets, urine, nitrified urine concentrate, struvite, ABR effluent, and struvite-effluent have the potential to be soil fertilisers that provide N and P across a wide variety of soil types.

(2) These materials vary in their effectiveness depending on soil type.

(3) In some combinations of soil/excreta-derived material they were as effective as commercial fertilisers due to their slower reaction rates (this applies especially to struvite).

(4) It is likely that under non-controlled conditions a combination of these materials and commercial fertilisers may prove most effective as the latter will rapidly release their nutrients while the HEDMs are slow release sources and by association could extend nutrient supply throughout the crops growing period.

(5) The ammonium in urine-based fertilisers may be mineralised easily in sandy soil but the nitrate may be lost by leaching. A low pH, clay soil may reduce the amount of mineralisation or at best its rate will be very slow. On the other hand the rapid decrease of ammonium in soil without a commensurate increase in nitrate may suggest losses due to volatilisation. This effect was further investigated by using different application methods and it was concluded that a split application optimises utilisation of N and prevents losses.

(6) Channel flow may be an important mechanism for loss of nutrients and may be especially problematic in more strongly structured soils.

(7) The ABR effluent was confirmed to have a clear liming effect in a strongly acid soil both in the field and in potted soybean plants. Improved nodulation in soybean is an aspect which is soil pH dependent. This is an important aspect of its use and if in combination with excreta-derived materials that require higher soil pH it will enable adequate functioning of microbes for mineralisation of the ammonium.

9.2 Recommendations

1. The present study has only considered the agricultural use of the effluent on a limited range of crops on only one soil type in the field and over a very short time period. More crops and a range of different over a longer time period are required to assess the full potential for using DEWATS effluent in order to monitor both positive and negative impacts. This will give more information on land area requirement estimations.

2. The SWB proved to be most useful for irrigation scheduling which enable more extensive estimates of land area and effluent usage to be arrived at. Nutrient (N and P) dynamics in the soil were not predicted accurately by the model due to spatial variation hence nutrient monitoring is recommended.

Although the SWB can be used for irrigation management, further studies can focus on three dimensional nutrients (N and P) movements to predict effects of DEWATS effluent irrigation on water catchment pollution using 3D Hydrus model.

3. Further studies will be required on the behaviour of pathogens in the effluents and the potential risks associated with them when the effluents are used on agricultural land.

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APPENDICES

Appendix 1 Typical nutrient range levels for subtropical bananas from leaf analysis (Silva and Uchida, 2000)

Nutrient	Deficient	Low	Optimal	High	Toxic
Nitrogen (%)	<2.6	2.6-2.8	2.8-4.0	nr	nr
Phosphorus (%)	<0.13	0.13-0.19	0.2-0.25	>0.25	nr
Potassium (%)	<2.5	2.5-3.0	3.1-4.0	>4.0	nr
N: K ratio	nr	nr	1:1.0-1:1.2	nr	nr
Sulphur (%)	<0.1	0.1-0.2	0.23-0.27	>0.27	nr
Calcium (%)	<0.5	0.5-0.7	0.5-1.2	>1.25	nr
Magnesium (%)	<0.2	0.2-0.3	0.3-0.46	>0.46	nr
Sodium (%)	nr	nr	0.01-0.10	nr	nr
Chlorine (%)	0.8-0.9	nr	nr	nr	nr
Copper (mg kg^{-1})	nr	3-7	7-20	nr	nr
Zinc (mg kg^{-1})	<14	14-20	21-35	>35	nr
Manganese (mg kg^{-1})	<10	25	1000-2200	4000-6000	nr
Iron (mg kg^{-1})	nr	nr	70-200	nr	nr
Aluminium (mg kg^{-1})	nr	nr	50-240	nr	nr
Boron (mg kg^{-1})	<10	10-20	20-80	80-300	>300
Molybdenum (mg kg^{-1})	nr	nr	1.5-3.2	nr	nr

nr – not reported

Appendix 2 Typical nutrient range levels for taro from harvested corms

		Concentration per dry mass
N	%	0.6-1.43
P		0.17-0.47
K		1.08-1.77
Ca		0.04-0.13
Mg		0.07-0.38
S		0.03
Fe	mg kg-1	16-57
Mn		11-16
Cu		7-9
Zn		40-120
B		3

(from Bradbury and Holloway 1988 & modified by Blamey 1996).

Appendix 3 Selected characteristics of the Sepane, Inanda, Cartref and Shortlands soils used in the course of the project

Soil property	Sepane	Inanda	Cartref (Kwadinabakubo)	Cartref (Ottos Bluff)	Shortlands
P (mg kg^{-1})	33	12	0.7	2.1	19
K (cmol$_c$ kg^{-1})	0.18	0.08	0.02	0.10	0.48
Ca (cmol$_c$ kg^{-1})	10.8	3.23	0.51	1.11	6.36
Mg (cmol$_c$ kg^{-1})	7.22	0.87	0.32	0.45	3.06
Exchangeable acidity (cmol$_c$ kg^{-1})	0	1.75	0.33	0.06	0.09
Total cations (cmol$_c$ kg^{-1})	18.3	5.92	1.19	1.73	9.91
Acid saturation (%)	0	30	28	3.4	1.0
pH (KCl)	5.30	4.11	4.00	4.95	4.50
Zn (mg kg^{-1})	21.7	2.80	0.14	0.07	3.00
Mn (mg kg^{-1})	10.0	10.7	1.41	3.52	21.9
Cu (mg kg^{-1})	9.5	3.6	0.35	0.70	9.3
Organic C (%)	2.6	6.0	0.5	0.18	2.3
N (%)	0.30	0.56	0.08	0.03	0.30
Sand (%)	23	30	79	80	21
Silt (%)	42	48	16	13	43
Clay (%)	35	22	5	7	36

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