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EFFECTS OF IRRIGATING *EUCALYPTUS GRANDIS* PLANTATIONS WITH A MIXTURE OF DOMESTIC AND PULP AND PAPER MILL EFFLUENT ON SOIL QUALITY AT A SITE IN NORTHERN ZIMBABWE

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ABSTRACT

Eucalyptus grandis plantations established in 1993 and 1996 at Greenacres farm in northern Zimbabwe were irrigated with a mixture of domestic and pulp and paper mill effluent. Changes in soil pH, electrical conductivity (EC_e), soil organic carbon (SOC), available P (AP), total N (TN), available K (AK), CEC and exchangeable sodium percentage (ESP) were investigated in the 0-20 and 20-40 cm soil layers of the non-irrigated and irrigated plantations. Irrigation for 12 and 15 years with hazardous (EC_w 2.029 dSm^{-1}, SAR=15.54) effluent mixture significantly ($p<0.05$) limed ($0.95<\Delta pH<1.8$ units), sodified ($9.3<ESP<17.4$) and salinised ($5.4<EC_e<7.8$ dSm^{-1}) the Chromic Luvisol. The parameters were increased ($p<0.05$) by between 8% and 500% in the order: $CEC<pH<TN<AK<AP<EC_e<SOC<ESP$. Irrigated soils had lower ($p<0.05$) EC_e and CEC in the 0-20 cm layer than in the 20-40 cm layer and the opposite was observed for SOC and AK. The soil differences were attributed to processes induced by effluent irrigation.

Keywords: effluent, *Eucalyptus grandis,* irrigation, salinity, sodicity, soil quality

INTRODUCTION

The growing competition for water and declining freshwater resources has led to the utilization of marginal quality water (wastewater) for irrigating productive agricultural or forest crops. Wastewater irrigation as a land based treatment option is an environmentally safer disposal option than direct discharge into surface water bodies (Khouri, Kalbermatten & Bartone, 1994). Compared to conventional wastewater treatment methods, land treatment systems have lower energy, construction and maintenance costs. In addition, wastewater is a valuable source of plant macronutrients (N, P, K), micronutrients as well as organic matter (OM) needed for maintaining fertility and productivity levels of the soil (Bhatia, 1998; Rusan, Hinnawi, & Rousan, 2007; Weber, Avnimelech, & Juanico, 1996). Tree plantations have been reported by Livesley, Adams & Grierson (2007) to be effective land-based systems for effluent treatment due to their capacity to transpire large amounts of waste water while retaining or transforming the nutrients contained within, thereby reducing surface and ground water pollution. Plant uptake of wastewater nutrients therefore reduces the risk of eutrophication and the attendant problems of oxygen depletion, fish kills and foaming odours (Pescod, 1992).

Papadopolous (1995) reported that wastewater contains physical, chemical and biological constituents that affect its suitability for reuse in agriculture. The pulp and paper (PP) industries were reported by Kumar, Pathak & Pathak (2010) to be high consumers of raw water and discharge huge quantities of effluent per tonne of paper produced. These industries are also leading generators of organic matter rich effluent in the world (Palaniswami & Sree, 1994). Thompson, Swain, Key & Foster (2001) reported that the raw effluent from PP mills can, thus potentially be very polluting and most compounds that make up the effluents are known to be toxic, mutagenic, persistent and bio-accumulating.

The effects of long term wastewater irrigation on soil chemical properties were reported by Gwenzi & Munondo (2008) to vary depending on soil type, elemental consideration, wastewater quality, crop species and climatic conditions. Gwenzi & Munondo (2008) also reported that 26 years of continuous effluent irrigation significantly enriched the 0-30 cm soil layer with essential plant nutrients, commonly deficient in most Zimbabwean soils. However, continuous application of hazardous wastewater can also increase chemical degradation processes of farmland soils (Mukherjee &Nelliyat, 2006). In Zimbabwe, excessive irrigation of pastures with hazardous tannery effluent was reported by Gotosa (1996) to induce salinisation and sodification of otherwise well drained sandy soils and also contaminated water resources.

The effect of wastewater on soil pH has been reported to be inconsistent depending on the quality of the wastewater (Mapanda, Mangwayana, Nyamangara & Giller 2005; Rusan et al., 2007). Nyamangara & Mzezewa (2001) reported a pH rise following application of a mixture of sewage effluent and sludge on soils under pastures for a period of 30 years due to high levels of basic elements. On the contrary, lowered soil pH from wastewater irrigation of forage was reported in Jordan due to high NH_4^+ levels in the wastewater (Hayes, Manciano, & Pepper 1990; Mohammad and Mazahreh, 2003). Feizi, Hayes & Pepper (2001) reported a decrease in soil salinity of between 61 and 68% in the top 40 cm of the soil following treated wastewater irrigation due to low levels of Ca^{2+} and Mg^{2+} in the wastewater. Feizi et al. (2001) further reported a 4% increase in soil organic carbon (SOC) in top soil (0-20 cm) under forage crops irrigated with treated wastewater, while a decrease of 31% was reported in the 20 – 40 cm soil layer. In Jordan, 10 years of wastewater irrigation of forage increased soil available K by 32.5% in the 0 – 20 cm layer (Rusan et al., 2007). On the contrary, in Zimbabwe, Nyamangara & Mzezewa (2001) reported a decrease in K with soil depth in pasture soils that were irrigated with sewage effluent for a period of 30 years, invariably due to plant uptake.

The PP mill effluent has had rapid influence on soils and Kumar et al. (2010) found significant increases in EC, Na, $PO_4{}^{3-}$, SO_4^{2-}, Cl^-, K^+ and Ca^{2+} content after 90 days of irrigation. Kannan & Oblisami (1990) reported doubled total soil N after 15 years of continuous PP mill effluent irrigation in the (0 – 15) cm soil layer whilst available soil P also increased.

Effluent irrigation could strain the environment through contamination of land and water resources which in turn affect their sustainable utilization due to continued loading of nutrients. Expensive ameliorative measures (such as addition of gypsum, drainage provisions, leaching etc) maybe required for sustainable effluent irrigation (Hillel & Feinerman, 2000). This scenario could curtail the sustainability of economic developmental projects producing large volumes of effluent such as the paper and pulp.

In Zimbabwe, research work on the effect of PP mill effluent irrigation on soils has not been comprehensive. Previous research work conducted at Green acres farm focused on short term (<6 years) effects of wastewater irrigation on plant development without paying attention to changes induced on levels of soil quality parameters due to long term irrigation except for work done by Hungwe (1999). This trend has been the global norm for research conducted on wastewater reuse in agriculture resulting in inadequate information on long term effects of wastewater reuse on soil chemistry and fertility (Rusan et al., 2007). Soil quality and its deterioration or improvement at the Green acres farm influences the sustainability and quality of eucalyptus produced for use at the PP mill. This study sought to assess the long-term effects of wastewater irrigation on selected soil quality parameters namely: pH, ESP, salinity, available nutrients and organic carbon.

MATERIALS AND METHODS

Description of the study site

Effluent irrigated *E.grandis* plantations were established between 1993 and 1996 at Green Acres Farm near Norton town, Zimbabwe on latitude $17^0 55^/$S, longitude 30^0 $43^/$E and at an altitude of 1000 m a.s.l (Fig. 1). The plantations, which are 2 660 ha in extent provided full disposal for secondary treated domestic effluent for Norton town which accommodates approximately 67,000 people, and secondary treated PP mill effluent. The PP mill effluent underwent mechanical separation (screening and clarification), flowed overland into a temporary storage water lagoon (dam) where it was mixed with municipal effluent. The approximate ratio of effluent mixture was 2:1 (2 parts PP mill effluent: 1 part treated domestic wastewater). The mixture was then pumped to *E.grandis* plantations for weekly furrow irrigation. There was however no proper irrigation scheduling as effluent was sometimes reportedly disposed even without maturation in the lagoon. The irrigated land is generally flat with slopes of up to 2%.

Norton has a semi-humid tropical climate, receiving between 750 and 1000 mm yr^{-1} rainfall unimodally spread between October and March (DMS, 1977). The soil type at the site is *Fersialitic (Norton 5E.2)* according to the Zimbabwe soil classification system or *Chromic luvisol* (FAO-system) or *Rhodic Paleustalf* (USDA soil taxonomy) (Nyamapfene, 1991). The soils are deep (>150m), moderately to strongly leached and derived from crystalline mafic rocks which give rise to reddish brown to dark red acidic (pH_{CaCl2}=4.4) clays (>64% clay and dominated by inert clay fraction) with moderately developed sub angular blocky structure (Nyamapfene, 1991).

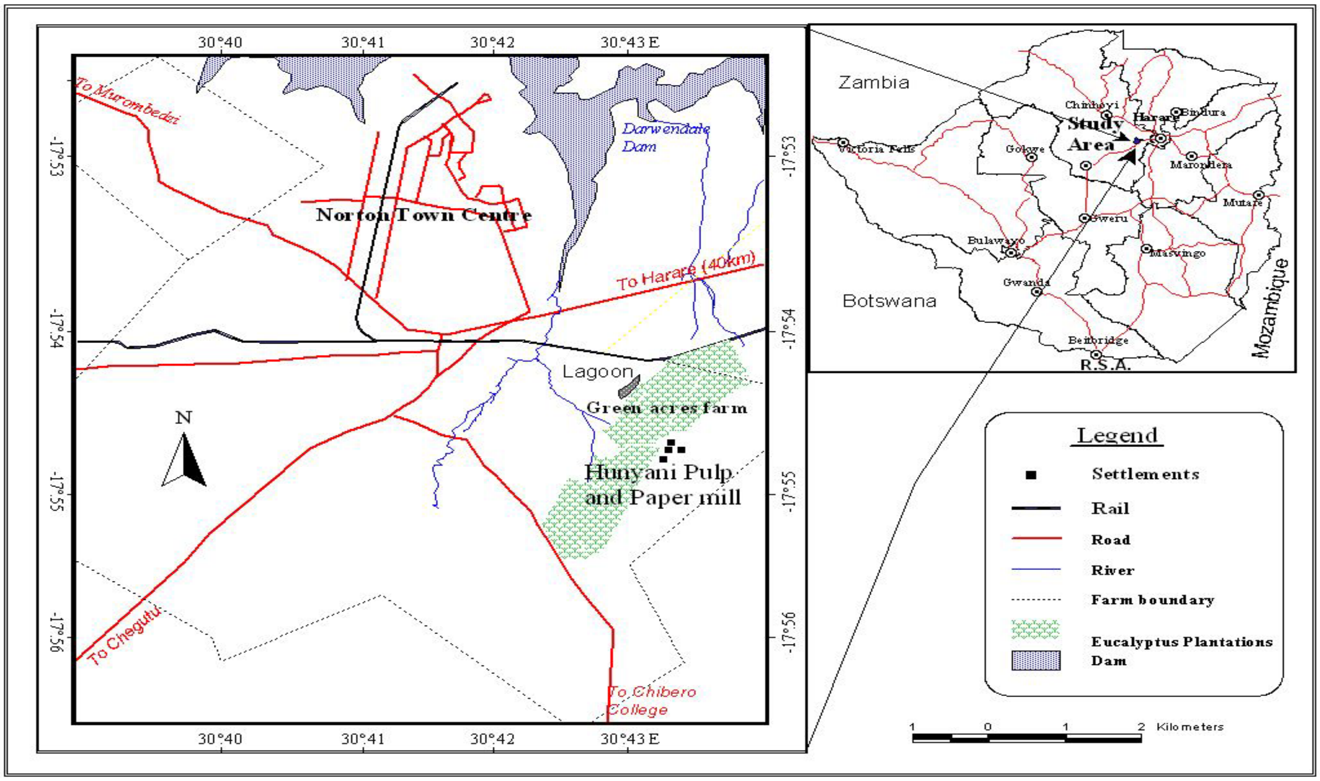

Fig 1: Location of the study area

Experimental design

The experimental design was a 3x2 split plot comprising irrigation period as the main plot factor (treatment) and the sampling depths (0-20 cm; 20-40 cm) as the sub plot factor. Stratified sampling was adopted for soil quality assessment. The main plots constituted the sampling strata on which the replicate sampling plots were randomly located and these were:

Treatment 1: Compartment 130; 2.2 ha in extent and at head reach, soils under *E. grandis* and wastewater was continuously applied for the past 12 years.

Treatment 2: Compartment 123: 3.6 ha in extent, soils under *E. grandis* and wastewater was continuously applied for the past 15 years.

Treatment 3: Compartment 61 A: control, 5 ha in extent, non irrigated soils and *E. grandis* grown under rainfed conditions.

Wastewater sampling and analysis

Effluent samples were collected monthly in June, July and August 2008. Grab samples were collected in 1-litre polythene sterile bottles (rinsed with distilled water and own sample prior to collection) at the exit point of the conveyance pipe from the lagoon to the irrigation compartments during wastewater irrigation. The samples were stored in a refrigerator at 4^0C until analysis within 24 hours. The pH and electrical conductivity (EC_w) were determined in the field using portable pH meter (Model:Hanna H1 8314) and EC meter (Model:Orion 150). Determination of NO_3^-, PO_4^{3-} , K^+, Na^+, organic C and TDS was done using standard methods. Zimbabwean and FAO guidelines (Ayers & Westcot, 1985) for assessing suitability of water for irrigation were used to evaluate effluent analytical data.

Soil sampling and analyses

Ten out of 40 established quadrants in each of the three studied plantation sites were systematically (every 4th) selected for soil sampling. Soil samples (200 g each) were collected from the 0-20 cm and 20 – 40 cm layers in August 2008 using a soil auger, at inter furrow positions within selected quadrants. The collected samples were air-dried, ground and passed through a 2 mm sieve and analysed at the SIRDC soil analytical laboratory, Harare.

Soil pH was determined in 0.01M$CaCl_2$ with a glass electrode (model 704 Mefrohm) (soil: $CaCl_2$ ratio 1:2) after calibration in pH buffers of 4 and 7 (Sparks, 1995). Soil electrical conductivity of the soil saturation extract (ECe) was determined in distilled water with a glass electrode (soil:H_2O ratio 1:5) (Anderson & Ingram,1993). Exchangeable cations were determined in 1M ammonium acetate extract, and the cation exchange capacity was determined through distillation following removal of ammonium ions and washing with 96% alcohol. Ca^{2+} and Mg^{2+} were determined in the extract by atomic absorption spectroscopy (Pye Unicom SP9) and Na^+ and K^+ by flame emission spectroscopy (Okalebo, Gathna & Woomer, 2002). Total N was determined by the Kjeldahlic oxidation method (Nelson & Sommers, 1998), available P by molybdenum blue method (Anderson & Ingram, 1993) and organic carbon content by the Modified Walkley Black method using acidified aqueous potassium dichromate (Anderson & Ingram, 1993).

Statistical analyses

Soil quality data obtained were subjected to analysis of variance procedure (ANOVA) to test for the effects of period of irrigation (main plot factor) and depth (sub-plot factor). The model used for ANOVA was:

$Y_{ijk} = \mu + P_i + D_j + (PxD)_{ij} + \square_{ijk}$

Where: Y_{ijk} = Response to the i^{th} period of irrigation in the j^{th} soil depth in the k^{th} replication

μ = overall mean (constant)

P_i = fixed effect of the i^{th} period of irrigation, i=1,2,3

D_j = fixed effect of j^{th} soil depth, j=1,2

k = replication index, k= 1,2,3….10

$\square_{ijk}$= random residual error associated with observation, $\square_{ijk}$-(N(0,σ^2)

Where necessary, the least significant differences (LSD) were used to separate treatment means at the 5% level of significance. The statistical package for social sciences (SPSS) version 15 (2006) was used for data analysis. The paired t-test was used to compare soil parameter means in the different soil depths of the treatments.

RESULTS AND DISCUSSION

Wastewater chemical characteristics

Table 1 shows the chemical characteristics of the effluent mixture used for irrigation at the site. The effluent values for pH, EC_w, SAR and [Na^+] are above acceptable ranges for water suitability for irrigation according to FAO and Zimbabwean guidelines. The effluent mixture was alkaline (pH=8.4 ± 0.06) and highly saline (EC_w =2.029 ± 0.116 dS m^{-1}). The alkalinity derived from the domestic effluent was attributable to the high pH of the effluent mixture. Patterson (2000) reported pH values of diluted detergents of between 8 and 11.5. The pH of detergents is purposefully high to facilitate easy removal of common dirt stains like soil and grease.

Basic cation concentration (mg l^{-1}) in the effluent decreased in the order: Na>>>K>Ca>Mg with average concentrations of 385 ± 3.2, 44 ± 1.2, 38.63 ± 0.410 and 9.34 ± 0.083, respectively. Although Gwenzi & Munondo (2008) reported a similar trend in effluent levels of basic cations, Na^+ was not as dominant as in the effluent under study. The effluent mixture had a very high sodium hazard, such that the mean SAR was 15.54 ± 0.187$(mel^{-1})^{1/2}$ and the mean $[Na^+]$ were more than five times the acceptable limit (Table 1).

The astronomical Na^+ levels in the effluent are attributed to sodium rich chemicals (notably Na_2SO_3, Na_2CO_3 and NaOH) used during the pulping process and from domestic detergent soaps in the municipal effluent. Furthermore, no chemical treatment to reduce sodium levels in the secondary effluent from the PP mill was done. The sources of K^+, Ca^{2+} and Mg^{2+} in effluent were other chemicals from pulping process and domestic inputs.

Table 1: The chemical characteristics of effluent applied at Green acres farm and FAO limits for long term wastewater irrigation.

Parameter	**Mean ± SE**	**FAO Guideline limit for long term irrigation (Pescod, 1992)**
pH	8.4 ± 0.06	6.5 -8.4
TDS(mg l^{-1})	2300 ± 25.7	_
EC_w(dS $m^{-1})^b$	2.029 ± 0.116	2.0
NO_3^-(mg l^{-1})	1.4 ± 0.06	5
PO_4^{3-}(mg l^{-1})	4.3 ± 0.10	-
K^+(mg l^{-1})	44 ± 1.2	-
Na^+(mg l^{-1})	385 ± 3.2	72.0
Organic C (%)	0.50 ± 0.006	_
Mg^{2+} (mg l^{-1})	9.34 ± 0.083	-
Ca^{2+} (mg l^{-1})	38.63 ± 0.410	-
Ca : Mg ratio	4.97 ± 0.088	-
SAR $(mel^{-1})^{1/2\ a}$	15.54 ± 0.187	3.0

^{a} SAR = $[Na^+]/\sqrt{½ ([Ca^{2+}] + [Mg^{2+}])}$

Table 1 shows that the average concentration of NO_3^- was 1.4 ± 0.06 mg l^{-1} and fell within the acceptable FAO limit of <5 mg l^{-1}. The average PO_4^{3-}content was 4.3 ± 0.10 mg l^{-1} and the P also emanates from detergents. Patterson (2000) reported P levels of up to 55mg l^{-1} in diluted domestic detergents ready for use in Australia, which directly enriched the effluent after use. The average organic C content of effluent was 0.50 ± 0.006 % and the main source was the wood used in the PP mill. On the basis of high salinity and high sodium hazard, the effluent was unsuitable for irrigating the clayey soil at the study site (Pescod, 1992).

Effects of effluent irrigation on soil quality parameters

Soil pH

Mean soil pH ranged from 4.39 to 6.48 in soils of the non-irrigated and irrigated *E. grandis* plantations (Table 2). The soil pH values did not significantly differ ($p>0.05$) between the 0-20 cm and 20-40 cm soil layers, although it was slightly higher in the subsoil. The effluent was alkaline (mean pH=8.4±0.06; Table 1) and continuous effluent application raised soil pH (limed the soil). In the 0-20 cm layer, 12 years of effluent irrigation significantly increased ($p<0.05$) soil pH by 1.72 units or 39% compared to control site (pH= 4.39± 0.01) whilst the 15 year treatment site had 1.1 units or 25% higher ($p<0.05$). The liming effect of the effluent was also extended to the 20-40 cm layer, where 12 years of irrigation resulted in a significantly ($p<0.05$) higher increase in soil pH (+1.8 units) than 15 year irrigation site (+0.95 units) compared to control site (pH= 4.68± 0.057). The irrigation effluent had a liming effect on the soil whereby the contained basic cations (Na^+,K^+,Ca^{2+}, Mg^{2+} with a total concentration of 476.97mg l^{-1}: Table 1) in the effluent replaced acidic cations (H^+ and Al^{3+}) on soil exchange complex leading to reduced soil acidity and consequently higher soil pH. The added organic matter through effluent irrigation probably had a low level of decomposable fraction to significantly contribute towards acid generation which aid in pH buffering (Troeh & Thompson, 1993). The increase in pH was however not consistent with irrigation period as the increase in pH of soils irrigated for 12 years was higher than those irrigated for 15 years. Rusan et al. (2007) also reported an inconsistent increase in soil pH response to treated wastewater irrigation for 10 years.

Table 2: Mean pH, EC_e (dS m^{-1}), CEC (me%) ESP (%) in effluent irrigated and non-irrigated soils at Green acres farm (2008).

Site	**pH**	**EC_e (dS m^{-1})**	**CEC (me%)**	**ESP (%)**
0-20 cm				
Control (Rainfed)	4.39(0.010)^a	2.50(0.05)^a	5.30(0.09)^a	1.92(0.09)^a
Wastewater Irrigated (12 yrs)	6.11(0.041)^b	5.79(5.79)^b	8.00(0.18)^b	9.32(0.01)^b
Wastewater Irrigated (15 yrs)	5.49(0.200)^c	6.54(0.10)^c	6.32(0.09)^c	11.08(0.12)^c
20-40 cm				
Control (Rainfed)	4.68(0.06)^a	2.97(0.19)^a	6.91(0.10)^a	2.89(0.05)^a
Wastewater Irrigated (12 yrs)	6.48(0.04)^b	6.02(0.08)^b	8.80(0.12)^b	9.84(0.28)^b
Wastewater Irrigated (15 yrs)	5.63(0.15)^c	7.78(0.15)^c	7.36(0.07)^c	17.39(0.33)^c
Overal Sig. (p=0.05)^y	*NS*	*	*	*NS*

N.S.: not significant at P=0.05

Means in the same column followed by different letters are significantly different at P=0.05

^{y} Overall significance when depth means are compared

Electrical conductivity

The mean EC_e values observed ranged from 2.5 to 6.54 dSm^{-1} in 0-20cm soil layer and 2.97 to 7.78 dSm^{-1} in the 20-40cm layers of the studied sites. The 0-20cm layer of the non-irrigated site had an average EC_e value of 2.5 dSm^{-1}. Irrigating with effluent for 12 years significantly increased ($p<0.05$) the salinity by 3.29 dSm^{-1} (132%) whilst 15 years of irrigation resulted in a significant increase ($p<0.05$) by 4.04 dSm^{-1}(162%) when compared to the control. In the 20-40cm layer, both the 12 and 15 year effluent irrigated sites had significantly raised EC_e values by 3.05 dSm^{-1} (103%) and 4.81dSm^{-1} (162%) respectively. The higher values of EC_e indicate soil enrichment with soluble ions through continuous effluent application. Similar findings were reported by Mohammad & Mazahreh (2003), Rusan et al. (2007) and Singh (2007). The high salinity effluent (Table 1) degraded the soil and qualifies to be classified as saline ($EC_e>4$ dSm^{-1}) according to the Zimbabwean classification system (Nyamapfene, 1991) or Solonchak group of the FAO system (IUSS Working Group WRB, 2007). Salinisation was exacerbated by the flat terrain (<2% slopes) at the farm which promoted salt accumulation from evaporating stagnant water and lack of salt leaching provisions in the irrigation schedules. High soil salinity is likely to have affected carbon sequestration potential of the irrigated *E. grandis* plantations and yield. Myers et al. (1998) reported reduced performance of *E. grandis* (60-70% reduction in leaf and stem growth due to salt treatment and 50% reduction in the efficiency of conversion of carbon into biomass). The consumptive use would also be curtailed in the process thereby threatening water resources with contamination from the excess effluent.

Exchangeable Sodium Percentage

The ESP of the soil gives an indication of the soil structural stability and permeability. The average ESP values (%) of the soil across the treatments and depths varied from 1.92 to 17.39 as shown in Table 2. In the 0-20cm layer, effluent-irrigation of *E.grandis* significantly ($p<0.05$) increased the soil ESP by 385% (after 12 years) and 477% (after 15 years) from an average ESP value of 1.92 for the control site. In the 20-40cm layer, the average ESP value for the control site was 2.89 and effluent irrigation significantly ($p<0.05$) increased the ESP by 240% (after 12 years) and 500% (after 15 years). The increase in the soil ESP was caused by high levels of Na^+ in the effluent used for irrigating *E. grandis* at Greenacres farm (Table 1). The results of the study agree with preliminary research findings by Hungwe (1999) at the farm that established a significant increase in soil ESP after 6 years of wastewater application on the sites. Palaniswami & Sree (2003) also found a 127% increase in ESP of top soils irrigated with PP mill effluent for 4 years due to high Na^+ loading. A 4.5-fold increase in ESP was similarly reported by Kannan & Oblisami (1990) from 15 years of PP mill effluent irrigation.

The levels of soil ESP after 12 and 15 years of effluent irrigation (Table 2) indicate the occurrence of soil sodification. The soils at the effluent irrigated sites classify into the sodic group (ESP>9) according to the Zimbabwean soil classification system or Solonetz group of the FAO classification system for the 20-40cm layer of the 15 year site where the ESP>15 (IUSS Working Group WRB, 2007). However, the effluent irrigated sites had EC_e > 4 dS/m, ESP > 9 and pH < 8.5. The soils would overally be classified as saline-sodic group according to Zimbabwean system (Nyamapfene, 1991) or sodic solonchak unit of the FAO system. Such soils have adverse effects on plant growth and are difficult to manage under irrigated conditions.

Cation exchange capacity

The soil CEC gives a measure of the strength to which exchangeable cations are held by the soil. Across the treatments, the average CEC values (me%) ranged between 5.3 and 8.8. The 0-20 cm layer had significantly lower ($p<0.05$) CEC values than those for 20-40 cm layer. Compared to the control, 12 years of effluent irrigation increased ($p<0.05$) CEC in the 0-20 cm layer by 2.7 me% from 5.3 me%, whilst 1.02 me% was the raise after 15 years of irrigation. Similar trends were obtained in the 20-40 cm layer where effluent irrigation significantly ($p<0.05$) increased CEC by 1.89 me% (after 12 years) and 0.55 me 8% (after 15 years) compared to the mean CEC value of 6.91 ± 0.104 me% for the control site.

The CEC of the weathered soil at the site was mostly affected by clay mineralogy and organic matter content. According to Nyamapfene (1991), the clay fraction had high levels of sesquioxides (27% Al_2O_3 and 17% Fe_2O_3) whose CEC is pH dependent as well as organic carbon contributed CEC. The increase in CEC was also inconsistent with irrigation period length as the increase in CEC of soils irrigated for 12 years was higher than those irrigated for 15 years in both soil layers (Table 2).

Soil organic carbon

The average soil organic carbon content (g kg^{-1}) of the irrigated and non-irrigated sites varied from 3.21 to 12.85 (Table 3). The top soil (0-20) cm had significantly ($p<0.05$) higher SOC than the (20 – 40) cm soil depth. This was due to higher levels of humus and decomposable organic materials from leaf litter found in the surface soil layers than the lower depth. Compared to the control site, effluent irrigation increased ($p<0.05$) the SOC by 6.22 g kg^{-1} (194%) after 12 years and 9.65 g kg^{-1} (300%) after 15years in the 0-20cm layer. Significant ($p<0.05$) increases were also observed in the 20-40cm depth: +5.39 g kg^{-1} or 209% (after 12years) and +6.63 mg kg^{-1} or 257% after 15 years. The SOC increases obtained from this study were much higher than the 59% increase reported by Rattan et al. (2005) after 20 years of sewage effluent irrigation. In this study, SOC levels were a function of inputs, dominated by effluent application, plant litter contributions and heterotrophic respiration.The SOC content increases were thus, attributed to continued application of carbon rich effluent despite the high decomposition rates experienced in the tropical conditions which usually combat significant accumulation in the soil (Gwenzi, Gotosa, Chakanetsa & Mutema, 2009). The *E. grandis* trees grown sequestered carbon into the soil through leaf litter which also contributed to the significant ($p<0.05$) increase in SOC over time at the effluent irrigated sites. Higher SOC in irrigated soils was also ascribed to lowered carbon decomposition rates by the salinity inhibited (less metabolically efficient) microbial community as reported by Rietz & Haynes (2003**).** On the contrary, Wong et al. (2006) reported decreases in soil carbon as a result of declines in vegetation health resulting from increased salinity and sodicity where plant litter was the sole carbon input. The SOC influenced the NPK at the effluent irrigated sites.

Total Nitrogen (TN)

The mean values of total nitrogen (mg kg^{-1}) varied between 115 and 214 across the treatments and soil depths in the plantations (Table 3).

Table 3. Mean total N (mg kg^{-1}), SOC (g kg^{-1}), available K and available P (mg kg^{-1}) in effluent irrigated and non-irrigated rainfed soils at Greenacres farm (2008).

Site	**TN (mg kg^{-1})**	**SOC (g kg^{-1})**	**AK (mg kg^{-1})**	**AP (mg kg^{-1})**
0-20 cm				
Control (Rainfed)	115.1(0.9)^{a}	3.21(0.14)^{a}	101.2(1.55)^{a}	12.03(0.16)^{a}
Irrigated (12 yrs)	172.3(1.5)^{b}	9.43(0.25)^{b}	171.2(0.66)^{b}	21.95(0.71)^{b}
Irrigated (15 yrs)	208.2(1.4)^{c}	12.86(0.22)^{c}	179.5(1.25)^{c}	29.79(1.21)^{c}
20-40 cm				
Control (Rainfed)	118.2(0.85)^{a}	2.58(0.14)^{a}	101.1(1.18)^{a}	11.74(0.16)^{a}
Irrigated (12 yrs)	179.8(1.53)^{b}	7.97(0.27)^{b}	161.8(1.37)^{b}	18.67(0.44)^{b}
Irrigated (15 yrs)	214.2(2.17)^{c}	9.21(0.21)^{c}	165.1(2.24)^{c}	23.44(0.64)^{c}
Overal Sig. (p=0.05)^{y}	*NS*	*	*	*NS*

^{w}N.S.: not significant and * significant at P=0.05

Means in the same column followed by different letters are significantly different at P=0.05

^{y}Overall significance when depth means are compared

Effluent irrigated sites had significantly ($p<0.05$) higher TN than the control site for the two soil depths, due to nitrogen loading. In the 0-20cm depth, effluent irrigation significantly ($p<0.05$) increased TN by 57.2 mg kg^{-1} (+57%) after 12 years and by 93.1 mg/kg (+81%) after 15 years. In the 20-40cm depth, the TN increases ($p<0.05$) were: 61.6mg/kg (+52% after 12 years of irrigation) and 96.0 mg kg^{-1} (+81% after 15 years) when compared to the control site. The irrigation effluent was rich in NO_3^-N which consequently led to an increase in the soil TN. Rusan et al. (2006)'s findings show a consistent increase in soil TN in the top soil (0-20) cm after irrigation of forage crops with wastewater for 10 years. Kannan & Oblisami (1990) also reported a 100% increase in soil TN after 15 years of irrigating crops with PP mill effluent.

Available Phosphorus (AP)

The available soil phosphorus values (mg kg^{-1}) across treatments ranged between 11.04 and 29.79 (Table 3). Effluent irrigation significantly ($p<0.05$) increased AP by 9.92 mg kg^{-1} (82%) and 17.76 mg kg^{-1} (148%) after 12 years and 15 years respectively in the 0-20cm depth from a deficient mean value of 12.03 mg kg^{-1}. The corresponding increases for the 20-40cm layer were by 6.93 mg kg^{-1} (59%) after 12 years and by 11.7 mg kg^{-1} (100%) after 15 years of effluent irrigation from 11.04 mg kg^{-1}. The P applied to the soil is either taken up by plants, incorporated in organic P or becomes adsorbed onto Al, Fe and Ca surfaces depending on soil pH (AGRIFACTS, 2003; Ryden & Pratt ,1980). The higher AP in irrigated treatments was due to partial saturation of P fixation sites of the weathered soil rich in sesquioxides of Al and Fe but low in native soil P (Tagwira, Piha & Mugwira 1991). Extended period of continuous irrigation would improve the levels of AP in addition to higher application rates (similar to banding in soil fertility management). The organic carbon rich effluent was the main source of soil P. Phosphorus is usually less available in acidic conditions and this was the reason why the control site (most acidic soil) had the least amount of AP. However, the P capital was only raised from deficiency levels (at control site) to marginally adequate levels (15-30 mg kg^{-1}) at irrigated treatments (CSRI, 2006). The higher ($p<0.05$) AP levels in irrigated treatments was attributed to high effluent PO_4^{3-} levels and induced higher soil pH conditions (Table 1). This agrees with studies by Tagwira et al. (1991) which showed that P availability increases with liming as the irrigation effluent acted as a P source and a liming agent. Feizi et al. (2001) reported similar increases in AP levels in the 0 – 20 cm and 20 -40 cm soil layers in response to wastewater irrigation.

Available potassium (AK)

Table 3 shows that the average AK values (mg kg^{-1}) ranged from 101 to 179 across the treatments and soil depths. The increase in AK is attributed to the high amounts of K in the wastewater used for irrigation at Greenacres farm. The top 20cm had significantly ($p<0.05$) higher AK than the 20-40 cm depth. Effluent irrigation increased ($p<0.05$) AK values by 69% after 12 years and 77% after 15 years in the 0-20 layer from 101.1 mg kg^{-1} level in control site. However the corresponding increases in AK were lower but significant in the 20-40cm layer where 12 years of effluent irrigation raised ($p<0.05$) AK by 60.0 mg kg^{-1} and 64.0 mg kg^{-1} after 15 years. These relatively depressed increases in AK were attributed to low inherent (native) K levels in the basic rock derived soil and luxurious uptake of K^+ by the *E.grandis* trees at the expense of accumulation in lower horizons (Nyamangara & Mzezewa, 2000). Feizi et al. (2001)'s findings also show a similar trend whereby continuous wastewater application to forage crops for 10 years significantly increased soil AK by 32.5% and 16.3% in the 0-20 cm and 20 – 40 cm soil depths, respectively.

CONCLUSIONS

The development of soil salinity and sodicity at the disposal site was due to the use of hazardous irrigation water, inappropriate irrigation schedules and the lack of artificial drainage in the plantations. The effluent altered the soil to exhibit properties typical of arid regions irrespective of the irrigation period. The studied soil has not yet reached the steady state with regards to nutrient accumulation, salinisation and sodification processes that affect soil quality. The degraded status of the soil at the disposal would compromise its ability to further renovate the effluent mixture thereby risking further pollution of water resources. We therefore recommend addition of a soluble Ca^{2+} salt like gypsum to the effluent mixture to lower the sodium hazard and development of good artificial drainage facilities combined with leaching provisions during irrigation.

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