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Effluent application to the land: Changes in soil properties and treatment potential

V.A. Tzanakakis[a,*], N.V. Paranychianakis[b], P.A. Londra[c], A.N. Angelakis[a]

[a] NAGREF, Institute for Agricultural Research, 71307 Iraklio, Greece
[b] Dept. Environmental Engineering, Technical Univ. Crete, Chania 73100, Greece
[c] Dept Natural Resources Management and Agricultural Engineering, Agricultural University of Athens, Iera Odos 75, 11855 Athens, Greece

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ABSTRACT

Four pilot land treatment systems (LTS) planted with different plant species were investigated as a means of managing wastewater in small communities. The effects of effluent application on soil properties during three years of operation are presented. LTS were planted with *Eucalyptus camaldulensis*, *Acacia cyanophylla*, *Populus nigra* and *Arundo donax*. Wastewater was pre-treated in a septic tank and applied to LTS at suitable rates to meet crop water requirements. Effluent application was found to increase soil organic matter, P and TKN content, particularly, in the topsoil but plant species had no effect on these parameters. Increases were also observed for salinity and sodium adsorption ratio which were found to depend on hydraulic loading. Winter precipitation leached the majority of the salts accumulated during the application period. Nitrates accumulated in the soil profile throughout the application period and this increase was dependent on plant species. LTS planted with *A. donax* showed the lowest NO_3-N concentration in soil pore water, an effect which cannot be explained by differences in application rates or plant uptake. This may imply stimulated denitrification rates induced by the rhizosphere of reeds. Effluent application also increased total and macro porosity compared to their initial values and bulk density.

1. Introduction

Land-based wastewater treatment systems have evolved significantly during their long history (Paranychianakis et al., 2006). Initially, emphasis was placed on the maximization of application rate per unit of land rather than optimization of water and nutrient use, and they were operated as “disposal” sites. With the passage of time, an understanding of the basic processes determining the removal, transport and fate of pollutants provided valuable information for the development of the basic principles of planning, operation and maintenance. Currently, land treatment systems (LTS) are planned and operated as reuse systems aiming to optimize water and nutrient use (US.EPA, 2006).

Wastewater contains increased concentrations of nutrients and application at rates to meet crop evapotranspiration (ET) often results in the overloading of LTS with nutrients (Paranychianakis et al., 2006). The accumulation rate depends on effluent nutrient concentration, hydraulic loading rate, crop uptake and environmental conditions (Degens et al., 2000; Falkiner and Polglase, 1999). Although the potential risks associated with nutrient accumulation in the soil differ greatly depending on soil properties, topography and geomorphology (Barton et al., 2005), it has become clear that appropriate measures must be adopted to eliminate these risks in order to ensure environmental sustainability and to avoid soil degradation.

Potential solutions for eliminating nutrient overloading include the adoption of appropriate pre-application treatment schemes and the selection of vegetation with a high potential of nutrient uptake. On the other hand, adjustment of effluent application rates to satisfy crop N or P requirements, a common practice for biosolids, has some important drawbacks. These include uncertainties regarding nutrient availability, the amount of N lost through volatilization, denitrification or leaching, and the accurate estimation of crop nutrient requirements. Additionally, taking into account that LTS are currently operated as reuse systems aiming to maximize yield (US.EPA, 2006), the interruption of irrigation may result in decreased yields, especially in regions with hot climates. However, the selection of plant species with a high potential for nutrient uptake and/or high values of water use efficiency (WUE) could alleviate this problem (Tzanakakis et al., 2009; Paranychianakis et al., 2006).

The long-term application of effluent induces changes in soil properties, including physical changes, and changes in organic matter, nutrients and salts (Walker and Lin, 2008; Lado and Ben-Hur,

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* Corresponding author.
E-mail address: vetzanakakis@cyta.gr (V.A. Tzanakakis).

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Table 1
Soil physical and chemical properties in the study area at the beginning of the study.

Parameters	Soil depth (cm)				
	0–7.5	7.5–15	15–25	25–35	55–65
pH	7.59	7.75	7.56	7.52	7.48
EC (dS/m)	0.35	0.35	0.51	0.65	0.88
Organic matter (%)	1.14	0.91	0.84	0.70	0.61
TKN (%)	0.057	0.046	0.048	0.042	0.037
NH_4^+-N (%)	–	–	0.0040	0.0043	0.0042
Olsen-P (ppm)	14.77	13.46	13.02	13.52	13.34
NO_3^--N (ppm)	–	–	5.42	8.17	5.99
Sand (%)	–	–	28.50	28.48	30.48
Clay (%)	–	–	35.50	35.52	35.52
Silt (%)	–		36.00	36.00	34.00
Soil texture	–	–	CL	CL	CL
$CaCO_3$ (%)	–	–	55.00	56.32	55.44
Bulk density (gr/cm^3)	1.41		1.49	1.46	1.49
Total porosity (cm^3 cm^{-3})	0.432		0.420	0.416	0.432

2009; Truu et al., 2009), which in turn may affect key treatment processes, crop yield, land sustainability and environmental risks. Of particular importance is the accumulation of salts, sodicity, and changes in soil structure (Lado and Ben-Hur, 2009; Leal et al., 2009) which may impose limitations on system performance.

The objectives of this study were to investigate: (i) the treatment potential of LTS especially with regard to N, P and C assimilation, (ii) the changes in soil properties, and (iii) the effect of plant species. Results for a three-year period of operation are shown, including data from soil solution and soil samples taken at different depths. The knowledge provided is expected to contribute towards a better understanding of the capacity of LTS to assimilate domestic effluent, the optimization of their operation, the better management, and the elimination of the environmental risks.

2. Materials and methods

2.1. Site description

The study was carried out at the experimental station of NAGREF close to Skalani Village, located 10 km southern of Iraklio city in Crete, Greece (N 35°16.8′–E 25°11.2′). The climate is semi-arid with relatively humid winters and dry, warm summers. Meteorological data were obtained from a station next to the experimental field. The average precipitation in 2001, 2002, and 2003 was 495, 453, and 322 mm respectively, significantly lower than the long-term average (512 mm) (Chartzoulakis et al., 2001). Details on the climatic data and the values of reference evapotranspiration (ET_o) have been reported by Tzanakakis et al. (2009). The soil lies on tertiary marls and associated Holocene alluvium and it is classified as calcaric Regosol (RGca) according to FAO World Reference Base for Soil Resources. Its basic properties are shown in Table 1.

2.2. Experimental set up

One-year-old trees of eucalyptus (*Eucalyptus camaldulensis*), acacia (*Acacia cyanophylla*) and poplar (*Populus nigra*) were planted in October 2000 to form LTS. Each of the LTS included 16 trees planted in two double rows with four trees each. The planting distance was 1.00 m within and between double rows which were separated by a corridor 3.5 m. Plots were also separated from each other by a corridor 3.5 m wide. In addition, rhizomes of reeds (*Arundo donax*) were planted at distances of 0.50 m between and within rows. Further details on the experimental design and set up are reported in Tzanakakis et al. (2007, 2009).

Table 2
Hydraulic load applied at LTS as affected by plant species in 2001, 2002 and 2003 growing periods.

Plant species	Hydraulic load (mm)		
	2001	2002	2003
A. cyanophylla	637	1074	1852
E. camaldulensis	631	974	1822
P. nigra	724	725	1212
A. donax	736	1021	1515

2.3. Effluent application

Effluent was applied to the plots via micro tubes of 6 mm diameter established in the middle of double rows. Effluent composition was EC: 2.07 ± 0.06 dS/m, pH: 7.34 ± 0.07, TSS: 99.5 ± 21 mg/l, BOD: 348 ± 34 mg/l, TP: 9.43 ± 0.9 mg/l, TKN: 105 ± 14 mg/l, NH_4^+-N: 89 ± 11 mg/l, NO_3-N: 1.1 ± 0.3 mg/l, K^+: 29.5 ± 5 mg/l, Na^+: 129 ± 16, Mg^{2+}: 20.5 ± 4 mg/l, Ca^{2+}: 81 ± 6 mg/l, and SAR: 3.2 ± 0.2. Effluent was applied at rates to meet crop evapotranspiration (ET). ET was estimated by monitoring soil moisture depletion in the 0–60 cm layer through tensiometers installed at depths of 30 and 60 cm. The hydraulic loadings applied in LTS are shown in Table 2.

2.4. Sampling and chemical analyses

Samples of pre-treated effluent (septic tank) were collected weekly and analyzed according to the “Standard Methods for Examination of Water and Wastewater” (APHA, 1995) for pH, electrical conductivity (EC), BOD, TKN, NH_4^+-N, NO_3-N, total phosphorus (TP), orthophosphates, Na^+, Ca^{2+}, and Mg^{2+}. Soil solution samples were collected at approximately monthly intervals using soil water samplers (Soil Moisture Equipment Corp.) and analyzed for the parameters reported previously. Analysis of nitrates in soil water samples was carried out using the phenol-disulfonic acid method. The samplers were established in the middle of the doubled rows at depths of 15, 30 and 60 cm and were stabilized with a thin layer of betonite. Three soil solution samplers, one for each depth, were installed in each plot.

Soil samples were taken from 0 to 7.5, 7.5 to 15, 15 to 25, 25 to 35 and 55 to 65 cm depths, at the beginning and the end of each application period, prepared and analyzed according to methods referred to the Methods of Soil Analysis (1982). Four samples were taken from each depth in each plot. Particle size analysis of the soil samples was carried out by the Bouyoucos hydrometer method. pH, EC, soluble Na^+, Ca^{2+} and Mg^{2+} were assessed in saturation paste extracts with atomic absorption spectrometry (Ca^{2+} and Mg^{2+}) and flame photometer (Na^+). Soil organic matter (SOM) was assessed by the Walkley and Black wet-digestion method and available-P according to the Olsen method after extraction with $NaHCO_3$. Finally, total Kjeldahl nitrogen (TKN) was assessed by a macro-Kjeldahl device.

In October 2003, undisturbed soil cores were taken from experimental plots and control soil (not treated with effluent). Dry bulk density was determined by the core method after weighing the undisturbed soil samples (Blake and Hartge, 1986). Total soil porosity (TP) was calculated by bulk (BD) and particle density (PD) of the soil, TP = (1 − BD/PD), taking into account the particle density value as PD = 2.65 g cm^{-3} (Danielson and Sutherland, 1986). The pore size distribution was obtained by plotting the slope of soil water retention curves versus soil water potential. Penetration resistance of the soil was determined at the surface layer (0–15 cm) at various soil water contents with a portable penetrometer.