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Nitrogen and phosphorus leaching in a tropical Brazilian soil cropped with sugarcane and irrigated with treated sewage effluent

Julius Blum[a,b,*], Adolpho José Melfi[a,b], Célia Regina Montes[b,c], Tamara Maria Gomes[d]

[a] Departamento de Ciência do Solo, Escola Superior de Agricultura Luiz de Queiroz (ESALQ), Universidade de São Paulo (USP), P.O. Box 09, Piracicaba (SP), Brazil
[b] Núcleo de Pesquisa em Geoquímica e Geofísica da Litosfera (NUPEGEL), USP, Piracicaba (SP), Brazil
[c] Laboratório de analise ambiental e Geoprocessamento, Centro de Energia Nuclear na Agricultura (CENA), USP, Piracicaba (SP), Brazil
[d] Departamento de Engenharia de Alimentos, Faculdade de Zootecnia e Engenharia de Alimentos da USP, Pirassununga (SP), Brazil

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ABSTRACT

There are concerns about groundwater contamination with N and P from fertilizers and other anthropogenic wastes. Use of treated sewage effluent (TSE) for crop irrigation can reduce the use of mineral fertilizers; however, it may add more nutrients into the soil than are necessary for crops, increasing the possibility of leaching. Thus, knowledge of nutrient dynamics in TSE irrigated soils is important for the safe use of this resource. However, the reliability of studies regarding ion leaching is limited due the high propagated variance, as these studies involve independent measurements of variables related to soil and soil solution. The objective of this research was to quantify P and N leaching in a TSE-irrigated Brazilian soil and identify the main causes of variance of this quantification. The experiment consisted of a treatment without irrigation and treatments with TSE irrigation to meet 100% and 150% of the crop water demand (CWD). Soil physical properties and soil water potential gradient were used to calculate internal drainage, and nutrient concentration was measured in soil solution samples taken with ceramic suction cups at a depth of 1 m. Variance propagation was calculated by linearization, and the contribution of each variable to the total variance was isolated and quantified. Irrigation with TSE increased N leaching; however, when applied in dosages that met 100% of the CWD, it did not threaten the groundwater quality. P leaching was as low as 100 g ha^{-1} and was therefore not an environmental concern. N leaching can be estimated considering the total N input and the rainfall; however, long-term data are needed to improve the accuracy of this estimation. The variance propagation of the soil water potential measurements represented up to 70% of the nitrogen leaching variance.

1. Introduction

Waste produced in urban areas and agricultural fertilizers are the major contributors that raise the concentration of nitrogen (N) in the groundwater (Serhal et al., 2009). Crop irrigation with treated sewage effluent can replace commercial fertilizers, providing economic benefits; however, such treatment may add more N into the soil than is necessary for the crop (Leal et al., 2010). The over-applied N can easily be leached below the root zone due to fast nitrification in well-aerated soils and weak interactions between N-nitrate and soil colloids. The leached N is transported into bodies of water, causing eutrophication and making the water unfit for human consumption, as well as affecting marine species (Bond, 1998). However, special focus must be given to the phosphorus (P) input into water bodies because it is usually the limiting nutrient, and P control is of prime importance in reducing the accelerated eutrophication of fresh water (Sharpley et al., 1994). Thus, there are concerns regarding groundwater contamination with N and P from fertilizers and other anthropogenic wastes.

The magnitude of the nutrient losses by leaching in soil systems is proportional to the concentration of nutrients in the soil solution and the amount of drained solution (Ghiberto et al., 2009). Irrigation with wastewater can increase both the concentration of nutrients (Gloaguen et al., 2007) and the volume of drained solution (Barton et al., 2005), thus increasing the possibility of nutrient leaching into the groundwater. However, major fluxes in nutrient leaching are observed when the input or mineralization of nitrogen does not coincide with the nutrient uptake by plants (Oliveira et al., 2002; Sieling and Kage, 2006). Thus, we hypothesize that the higher evapotranspiration rates during the peak growth of the crop increases the necessity for irrigation, synchronizing nutrient input and nutrient uptake.

Soil variability is the main problem related to the assessment of N leaching (Addiscott, 1996). The extent of all biological, chemical and physical processes responsible for N leaching vary due to soil

* Corresponding author at: Avenida Mister Hull 2977, 60021-970 Fortaleza, CE, Brazil. Tel.: +55 8533669452; fax: +55 8533669690.
E-mail addresses: jblum@ufc.br, juliusblum@yahoo.com.br (J. Blum).

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type (Barton et al., 2005), and different soil structures can accelerate the movement of solution to depths where the roots are unable to reach (McLeod et al., 1998). Therefore, spatial variations in the concentration of nutrients or in physical properties of the soil increase the variance of nutrients leaching, diminishing the reliability of the results. Ceramic cups have being commonly used to extract the soil solution in field experiments (Sieling and Kage, 2006; Ghiberto et al., 2009); however, Addiscott (1996) advised that this method is more reliable in sandy soils, because the soil space variability increases with the clay content. Clayey soils have higher range of water availability categories than sandy soils, and the soil matrix is by-passed by cracks and other channels. Besides, the volume of the soil from which the cups extract water is larger in sandy soils, resulting in a better space representativeness.

The use of the suction cup method to extract the soil solution and the soil water potential gradient to estimate soil drainage require measurement of the following: (i) ion concentrations in the soil solution; (ii) soil physical properties; and (iii) the soil water potential at different layers. These measurements contain independent errors that must be propagated to calculate the ion leaching variance. The variability of the physical properties of the soil and the ion concentrations in the soil solution are widely described in the literature; however, the influence of the error of each measure on the composition of the ion leaching variance is not well known. The knowledge of the main source of variation will be useful for controlling the error.

Because the knowledge of the N and P dynamics in wastewater irrigated systems is important for the safe use of this resource and because insufficient data regarding these issues have been produced (Duan et al., 2010; Sharpley et al., 1994), the objective of the present study was to quantify N and P leaching and identify the main cause of its variance during two years of sugarcane cultivation irrigated with treated sewage effluent (TSE) on an Oxisol soil located in southeastern Brazil.

2. Materials and methods

The experiment was carried out in Lins County, São Paulo State, Brazil (latitude: 21°38′56″S, longitude: 49°44′43″W, altitude 422 m). The soil of the experimental plots was classified as Typic Haplustox (Soil Survey Staff, 1999), sandy clay loam (770 g kg^{-1} of sand and 140 g kg^{-1} of clay at the 0–0.2 m layer and 710 g kg^{-1} of sand and 210 g kg^{-1} of clay at the 0.2–0.8 m layer); the mineralogy was predominantly composed of quartz and kaolinite and subordinately of hematite, magnetite and maghemite (59 g kg^{-1} Al_2O_3 and 23 g kg^{-1} of Fe_2O_3 at a depth of 0–1 m). The *F* test showed no significant difference between treatments for sand and clay content, assuming homogeneity between experimental plots.

A sugarcane crop (cultivar RB 72454) was planted in March 2005 and harvested every September from 2006 to 2010. N, P and potassium (K) fertilization was carried out every year after the harvest, following the regional recommendation (Raij and Cantarella, 1996). Because TSE irrigation is a source of N (Da Fonseca et al., 2007), during the studied period (2009–2010), half of the mineral nitrogen dosage suggested, 50 kg ha^{-1} year^{-1} of N, was applied as ammonium nitrate. In addition, 60 kg ha^{-1} year^{-1} of K was applied as potassium chloride, and 13 kg ha^{-1} of phosphorus was applied only in 2010 as triple superphosphate.

Treatments consisted of the following: (i) without irrigation (WI), (ii) irrigation at 100% of crop water demand (CWD) (T100) and (iii) irrigation at 150% of CWD (T150). Three replications of each treatment were performed. Irrigation management was based on critical soil water tension at the 0–0.6 m soil layer as monitored by tensiometers. The irrigation was performed every time the soil matrix potential reached −40 kPa and was carried out for sufficient time to raise the soil water potential to −10 kPa at T100, and the time of irrigation at T100 was multiplied by 1.5 at T150. The TSE used in the experiment resulted in the following analytical data in mg L^{-1}: dissolved organic carbon (33.7 ± 31.8), alkalinity as HCO_3^- (302 ± 28), Cl^- (57.7 ± 10.6), P (3.6 ± 2.9), N-NH_4^+ (21.0 ± 10.2), N-NO_3^- (0.03 ± 0.1), Al (0.02 ± 0.01), Fe (0.12 ± 0.05), K (18.7 ± 13.4), Ca (7.90 ± 1.32), Mg (1.96 ± 0.58), Na (112.3 ± 43.14), S (51.2 ± 30.0), B (0.1 ± 0.02), Mn (0.02 ± 0.01) and Zn (0.02 ± 0.01). Cadmium, Cr, Cu, Ni and Pb were not detected. The electric conductivity was 0.89 ± 0.12 dS m^{-1}, the pH was 7.7 ± 0.3 and the calculated sodium adsorption ratio was 9.3 ± 3.2 (Blum et al., 2012). Inputs of N and P at T100 were 249 and 33 kg ha^{-1}, respectively. More detailed information about the experiment implementation, climate, irrigation management and wastewater treatment are reported in Leal et al. (2009).

Measurements of saturated hydraulic conductivity, bulk density and soil water content at 0, −0.5, −2, −6, −10, −30, −100 and −1500 kPa soil water potentials were carried out using soil cores taken in triplicate at depths of 0.1, 0.3, 0.5, 0.7 and 0.9 m in all experimental plots. Residual and saturated volumetric water content, the α and n empiric parameters of van Genuchten equation (Eq. (1)) (Van Genuchten, 1980), were fitted using Nonlinear Least Squares (nls) function with R software (R Development Core Team, 2008). Tensiometer readings were performed every 2 or 3 days at depths of 0.1, 0.3, 0.5, 0.7, 0.9 and 1.1 m. Soil volumetric water content down to a depth of 1 m was calculated using the van Genuchten equation and soil water potential at depths of 0.1, 0.3, 0.5, 0.7 and 0.9 m.

$$\theta_i = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (\alpha \times \psi_i)^n]^{1-(1/n)}} \quad (1)$$

where θ_i is the volumetric soil water content at the depth i, θ_r is the residual water content, θ_s is the saturated water content, ψ_i is the soil water potential, and α and n are empiric parameters of the van Genuchten equation.

The soil solution flux density at a depth of 1 m was calculated using the Darcy–Buckingham equation (Eq. (2)), for which the hydraulic conductivity as a function of the volumetric water content was estimated with the Mualen–van Genuchten equation (Eq. (3)) (Van Genuchten, 1980), and the soil water potential gradient was calculated as the difference between the soil water potential measurements at depths of 0.9 (ψ_a) and 1.1 (ψ_b) m. The average between the soil water content at 0.9 and 1.1 m was considered to be the soil water content at 1 m (Eq. (4)).

$$q_w = \frac{-k(\theta_m) \times \Delta\psi}{L} \quad (2)$$

$$k\left(\theta_m\right) = k_s\left(\frac{\theta_m - \theta_r}{\theta_s - \theta_r}\right)^{0.5} \times \left\{1 - \left[1 - \left(\frac{\theta_m - \theta_r}{\theta_s - \theta_r}\right)^{1/(1-1/n)}\right]^{1-1/n}\right\}^2 \quad (3)$$

$$\theta_m = \left[\frac{\theta_a + \theta_b}{2}\right] \quad (4)$$

where q_w is the soil solution flux density, $k(\theta)$ is the hydraulic conductivity as a function of the volumetric water content, θ_m is the mean soil water content between depths a (0.9 m) and b (1.1 m), $\Delta\psi$ is the soil water potential gradient, L is the depth difference between the measurement depths, k_s is the saturated hydraulic conductivity, and θ_a and θ_b are the soil volumetric water content at depths of 0.9 m and 1.1 m, respectively.