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Soil Quality after Six Years of Paper Mill Industrial Wastewater Application

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ABSTRACT: The application of wastewater to irrigate soils may be an attractive option for paper mills, especially when the effluents can also provide nutrients to plants. Since there could be negative environmental effects, such activity must be preceded by a thorough evaluation of the consequences. The changes in soil quality of a *Neossolo Flúvico Distrófico* (Typic Udifluvent) were evaluated over a period of six years of irrigation with treated effluent from a wood pulp company. Although effluent application for six years did not affect soil resistance to penetration and soil hydraulic conductivity, it promoted a decrease in the mean size of aggregates and an increase in clay dispersion. Effluent application increased soil pH but did not change exchangeable Ca and Mg contents and organic carbon. After a full rotation of eucalyptus cultivation common in Brazil (six years), no negative effects in tree growth were found due to effluent irrigation. However, effluent addition caused higher values of Na adsorption ratio and intermediate electrical conductivity in the soil, which indicates a possible negative effect on soil quality if the application continues over a longer period. Therefore, a monitoring program should be carried out during subsequent crop rotations, and alternatives must be studied to obtain better effluent quality, such as adding Ca and Mg to the wastewater and using gypsum in the soil.

Keywords: industrial effluent, water reuse, clay dispersion, wastewater disposal, salinity.

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INTRODUCTION

Brazilian paper mill industries have increased their activities to increase production levels to compete in supplying world paper demand. This process has increased the demand for raw material, which consists essentially of wood from eucalyptus and pine (*Pinus*) species. This higher demand for wood has led to the need for better management to increase forest productivity. In Brazil, irrigation of forests is under investigation because water availability for planted forests is considered the most limiting factor in a tropical climate, while solar radiation and temperature are not limiting.

The paper production process generates a considerable volume of effluents, which must be treated before they can be disposed of in order to meet environmental standards. Therefore, disposal of these wastewater products through irrigation can be an attractive alternative (environmentally as well as economically) for the final destination of these effluents, which currently are drained into surface waters. In addition to eliminating an additional treatment process, the wastewater can be considered a source not only of water but also of supplementary nutrients (Rezende et al., 2010).

Studies on the use of different kinds of wastewater for irrigation have been reported by various authors (Santos, 2004; Lado et al., 2005; Cavallet et al., 2006; Sousa et al., 2006; Fonseca et al., 2007; Gloaguen et al., 2007; Heidarpour et al., 2007). These studies focused on effluent reuse for agriculture, mainly water from treated urban and industrial sewage. A few studies assessing the use of waste from paper mill industries in soils are reported in the literature (Chhonkar et al., 2000; Singh et al., 2002; Singh, 2007; Roy et al., 2008; Boruah and Hazarika, 2010; Rezende et al., 2010; Morris et al., 2012; Singh et al., 2013). However, studies on the reuse of paper mill industry effluents and their potential use in forest soils are scarce, especially for tropical soils and for effluents resulting from the industrial Kraft bleaching process. This wastewater generally has a high concentration of Na and a high Na adsorption ratio. This can lead to increased Na content in the soil, thus degrading the soil physical and chemical properties, and directly or indirectly affecting plant growth in a negative way. In clay soils, there is a risk of dispersion, decreasing aggregate stability, resulting in poorer structure and lower soil porosity. Surface sealing and lower hydraulic conductivity will increase soil susceptibility to erosion.

The reuse of wastewater in forest soils is an interesting option considering the following aspects: forest trees are not a component of the human food chain; reuse of industrial water will improve the image of the company in regard to environmental conservation; trees demand more water as compared to other crops, so larger volumes of water can be applied to smaller areas; and trees have high C and N retention in their biomass (mainly in the trunk), which represents an important long-term mechanism for storing these elements in the ecosystem (Smith and Bond, 1999). These advantages of the reuse of wastewater from paper mill production on forest soil are strengthened by the generally short distance between factory facilities and forested areas.

The study reported here evaluates the use of effluents from the wood pulp industry that uses the Kraft process for paper production. We hypothesized that prolonged wastewater irrigation affects soil quality, changing soil physical and chemical properties. Specifically, the effects on the physical and chemical qualities of an Entisol soil planted to eucalyptus over the full eucalyptus production rotation were assessed.

MATERIALS AND METHODS

Site location and treatments

The experimental site is located at 19° 18′ 23″ S and 42° 22′ 46″ W, 220 m above sea level in the municipality of Santana do Paraíso in the east central region of the state of Minas Gerais, Brazil. The regional climate is Aw, according to the Köppen climate classification system. Mean annual precipitation is 1,163 mm, the average annual temperature is 25.2 °C (maximum and minimum temperatures are, on average, 31.5 and 19.1 °C), and mean relative humidity is 65.2 %.

The soil of the lowland experimental area was classified as a Typic Udifluvent (Haplic Fluvisol Dystric by the FAO Soil Classification System) or *Neossolo Flúvico Distrófico* according to the Brazilian Soil Classification System (Embrapa, 2006). A nearby area with forest vegetation was considered as a control (T1), and experimental treatments were eucalyptus clones grown with no irrigation (T2), with irrigation from a regional stream (T3), with fertigation (T4), and with application of the treated effluent (T5). Lime was applied in treatments with eucalyptus as recommended (Ribeiro et al., 1999). The water used in T5 was from an effluent treatment station with average composition, as shown in table 1.

Water (T3, T4, and T5) was applied through a drip irrigation system after prior filtering of the water to preserve the dripper (and to prevent clogging). Irrigation rates were based on the potential evapotranspiration (ET_0) of the trees, estimated from the Penman-Monteith equation based on local climate data.

The total study area was 4.92 ha. The experiment covered the full productivity rotation. All evaluations were carried out after six years of application of the treatments, representing a full productivity rotation of 26 different clones of eucalyptus in Brazil.

Soil sampling

Soil samples were taken from the rows where the eucalyptus was planted, along the irrigation lines. For the soil physical quality evaluation, disturbed and undisturbed soil samples were collected in all treatments from the 0.00 to 0.10 m depth (depths where the greatest effects from effluent application are expected): four disturbed and compound samples (each one from 20 simple samples) and forty undisturbed samples with cores of 98.17 cm^3.

Laboratory and field assessment

The following properties of the soil samples were determined in the laboratory: texture by the pipette and sieving method (Ruiz, 2005); routine chemical soil analysis (pH in water, Ca^{2+}, Mg^{2+}, K^+, Na^+, CEC, organic carbon, and exchangeable sodium percentage); chemical characterization of soil saturated paste extract (SPE), with determinations of electrical conductivity (EC), pH, Ca^{2+}, Mg^{2+}, Na^+, K^+, and calculation of sodium adsorption ratio (SAR) (Richards, 1954); percent sodium saturation (PSS); organic carbon (Yeomans and Bremner, 1988); water-dispersible clay (WDC); clay dispersion index (CDI), i.e. the ratio of WDC to clay content; aggregate size distribution as estimated by the geometric mean diameter (GMD) and mean weight diameter (MWD) (Nimmo and Perkins, 2002); particle density (Pd); bulk density (Bd); total porosity (TP=1-Bd/Pd); microporosity (Mi)

Table 1. Chemical composition of the treated effluent from the paper mill industry

	pH	EC	N	P	K	Na	Ca	Mg	Zn	Cu	Fe	Mn
		dS m^{-1}	mg L^{-1}									
A(1)	7.88	1.91	3.5	2.6	45.5	1030	34.0	3.6	0.3	0.2	1.4	0.2
Sd(2)	0.25	1.74	3.1	1.8	66.1	1467	45.3	4.9	0.4	0.3	2.5	0.2
	T	TS	CL	OC	PHE	O+G	AOX	SS	COL	BOD	CODs	CODt
	°C	mL L^{-1} h^{-1}	mg L^{-1}									
A(3)	35.7	28.8	202.1	99.7	0.02	2.4	1.9	0.1	410.1	26.0	175.9	201.9
Sd	1.1	7.4	33.6	13.0	0.05	0.5	0.2	0.1	76.8	7.7	23.7	25.3

EC: electrical conductivity; T: temperature; TS: total suspended solids; CL: chloride; OC: organic carbon; PHE: phenols; O+G: oils and grease; AOX: adsorbable organic halogens; SS: suspended solids; COL: color; BOD: biochemical oxygen demand (five days, 20 °C); CODs: chemical oxygen demand (soluble); CODt: chemical oxygen demand (total). (1) Average of 2003 to 2007 values; (2) Sd: standard deviation; (3) A: average of 2007 values.

from water retained in soil samples subjected to a potential of -0,006 kPa; macroporosity (Ma), as the difference between TP and Mi; and soil hydraulic conductivity (K_0). The methods of analysis, where not indicated, were according to standardized methods (Donagema et al., 2011).

Further, the least limiting water range (LLWR) (Silva et al., 1994) of the soil was determined; for each treatment, forty undisturbed samples were obtained in metal rings of 0.05 m diameter and approximately 0.05 m height from the center of the 0.00 to 0.10 m depth layer. In the laboratory, the 40 cores were separated into 10 groups of four cores, and after saturation, each group was brought to equilibrium with one water potential using either a tension table (-0.004; -0.006; and -0.008 MPa) (Romano et al., 2002) or pressure chambers (-0.01, -0.03, -0.05, -0.07, -0.1, -0.5, and -1.5 MPa) (Dane and Hopmans, 2002). After equilibrium, soil resistance to penetration (SRP) was obtained in the center of each sample using an electronic cone penetrometer (Marconi, model MA-933, Brazil) - cone diameter was 1.27 cm, cone angle was 30°, and cone surface area was 1.27 cm^2. Samples were then weighed, dried in an oven, and weighed again to calculate soil moisture (θ) and Bd. The maximum SRP values obtained in each soil core were adjusted in relation to Bd and θ using a nonlinear regression model: $SRP = a \times \theta^b \times Bd^c$, according to Busscher (1990). The θ values were adjusted in relation to Bd and to soil water potential (ψ) using a nonlinear regression model: $\theta = e^{(d+e\,Bd)} \times \psi \times f$ (Tormena et al., 1998). Adjusted constants (a, b, c, d, e, and f) for these equations were obtained using the software Statistica®. The final LLWR graph was obtained using an Excel® algorithm (Leão and Silva, 2004).

In the field, hydraulic conductivity (K_0) was estimated with a Guelph permeameter (Reynolds et al., 1992), with four replicates, and the field SRP was verified with an impact penetrometer up to a depth of 0.50 m, with 40 replicates.

Statistical analysis

The dataset was analyzed by four orthogonal contrasts (C) after the F test in order to compare C1: no cultivation (T1) *vs.* cultivation (T2+T3+T4+T5); C2: no irrigation (T2) *vs.* irrigation (T3+T4+T5); C3: irrigation with water (T3) *vs.* other irrigations (T4+T5); and C4: fertigation (T4) *vs.* effluent application (T5). Statistica® was used in all statistical analyses.

RESULTS AND DISCUSSION

Replacing the vegetation of the native forest with eucalyptus trees increased clay dispersion (WDC and CDI), increased Bd, and decreased aggregate size (GMD and MWD), causing a reduction in total porosity (Table 2). These results, indicated by the C1 contrast, are common and frequently observed when anthropic activities are implemented in soils, a result of forest management practices.

Although no changes were expected in texture, effluent application for six years (T5) caused a decrease in soil clay and silt contents, as indicated by the C4 contrast. This may be explained by the effect of the effluent on clay dispersion, causing this fraction to move deeper into the soil profile, considering the higher CDI and lower GMD and MWD values for T5.

The flocculation effect of the effluent as a result of a higher soil saline concentration could negatively affect the degree of dispersion of the aggregates in laboratory analysis, thus decreasing the clay content obtained; however, this is not supported by the WDC values (Table 2). Increases of fine and coarse sands in the treatment with the effluent (T5) are directly associated with the decrease of the fine fractions clay and silt.

In the areas under eucalyptus, no difference was observed in soil structure, as represented by the values of Bd, TP, Mi, and Ma. However, effluent application led to a reduction in

Table 2. Soil physical quality in response to the treatments evaluated, and contrast analysis among treatments

Treatment	CS	FS	SIL	Clay	WDC	CDI	GMD	MWD	Bd	TP	Mi	Ma	K_0 field	K_0 lab
	%						mm		Mg m^{-3}	m^3 m^{-3}			cm h^{-1}	
Forest vegetation (T1)	50	11	12	27	11	39	2.60	2.31	1.33	0.49	0.30	0.19	2.30	21.92
No irrigation (T2)	42	14	15	29	16	53	2.21	1.75	1.39	0.47	0.29	0.18	6.83	7.76
Water irrigation (T3)	39	18	16	27	15	54	2.48	2.01	1.38	0.47	0.29	0.18	11.75	10.26
Fertigation (T4)	30	20	20	30	17	52	2.49	1.95	1.37	0.47	0.30	0.17	3.27	7.24
Treated effluent (T5)	46	16	14	24	14	59	2.03	1.52	1.39	0.47	0.29	0.18	2.81	17.06
C1$^{(1)}$		$(-)^{**}$	$(-)^{*}$		$(-)^{*}$	$(-)^{**}$	$(+)^{**}$	$(+)^{**}$	$(-)^{**}$	$(+)^{**}$				$(+)^{**}$
C2														
C3													$(+)^{*}$	
C4	$(-)^{**}$	$(+)^{*}$	$(+)^{*}$	$(+)^{*}$		$(-)^{**}$	$(+)^{**}$	$(+)^{*}$						$(-)^{*}$

CS: coarse sand; FS: fine sand; SIL: silt; WCD: water-dispersible clay; CDI: clay dispersion index; GMD: geometric mean diameter; MWD: mean weight diameter; Bd: soil bulk density; TP: total porosity; Ma: macroporosity; Mi: microporosity; K_0 field: soil hydraulic conductivity with Guelph permeameter; K_0 Lab: saturated soil hydraulic conductivity. $^{(1)}$ Contrasts: C1: native forest vs. eucalyptus; C2: non-irrigated vs. irrigated; C3: irrigated vs. fertigated; C4: fertigated vs. fertigated with effluent. ** and *: significant contrasts at 1 and 5 %, respectively. Signals (+) and (-) mean higher or lower averages in the same contrast, respectively, comparing the first term with the second one of the contrast.

aggregate size, as shown by the GMD and MWD indices (contrast C4), corroborating the dispersion tendency indicated by CDI values. Studies on the effect of effluent application on aggregate size and stability are usually restricted to WDC and CDI determination. On the other hand, Levy et al. (2003) and Bhardwaj et al. (2007) could not verify the supposed effect of effluent application on the aggregate stability of clay soils. The authors tested effluents from domestic sewage and concluded that the absence of any effect was a result of its lower SAR value and the input of organic matter combined with the wastewater application.

Soil hydraulic conductivity (K_0) data showed a discrepancy between laboratory and field determinations (Table 2). This can be explained because the K_0 estimation with a Guelph permeameter was performed considering a multidirectional flow of the whole soil at a 0.00-0.20 m depth, and the K_0 determination in the laboratory considered only the downflow through an undisturbed 0.05 m soil sample collected in a metal ring. Analyzing field data, the native forest (T1) exhibited lower K_0 values than the other treatments cultivated with eucalyptus (contrast C1, Table 2). This may be due to the subsoiling of the eucalyptus plantation, which improves soil water movement in these treatments, since the evaluation was made in the eucalyptus plant row. The high K_0 observed in the water-irrigated treatment (T3), as determined by the significance of the C3 contrast, is improbable and may be due to natural soil variability, commonly verified in this determination. When data from the K_0 determination in the laboratory was considered, the expected high values for the natural forest (T1) in relation to all eucalyptus treatments was confirmed (contrast C1). For this determination, soil sampling was done in all areas and not only in the plant row. In the laboratory, higher K_0 values were seen from the effluent treatment (T5) among treatments in which eucalyptus was planted, which was not verified in the field determination. This may suggest a positive effect of effluent application on soil structure, which is not confirmed by analyzing the other soil physical properties evaluated.

As expected, the treatments with the effluent caused changes in soil chemical properties, especially when comparing soil from native forest and eucalyptus plantations (contrast C1, Table 3). Removal of native vegetation caused a decrease in organic carbon (OC) and cation exchange capacity (CEC) (Table 3). The decrease in CEC in eucalyptus growing areas can be linked to organic matter mineralization. The reduction in OC is also evident when comparing non-irrigated (T2) and irrigated areas (contrast C2), as better moisture conditions lead to higher microorganism activity, which will decrease the OC content. Although the effluent

Table 3. Soil chemical quality in response to the treatments evaluated, and contrast analysis among treatments

Treatment	pH	Ca^{2+}	Mg^{2+}	K	Na	ESP	CEC	OC
		—— $cmol_c\ dm^{-3}$ ——		—— $mg\ dm^{-3}$ ——		%	$cmol_c\ dm^{-3}$	$dag\ kg^{-1}$
Forest vegetation (T1)	5.05	2.10	0.41	81	4	0.18	8.03	2.32
No irrigation (T2)	5.77	2.63	0.80	118	14	0.91	6.79	1.80
Water irrigation (T3)	5.32	2.11	0.55	65	16	0.89	7.60	1.24
Fertigation (T4)	5.23	2.18	0.55	137	7	0.38	7.58	1.59
Treated effluent (T5)	6.02	2.16	0.70	130	170	11.68	6.33	1.28
C1$^{(1)}$			$(-)^{**}$	$(-)^{**}$	$(-)^{**}$	$(-)^{**}$	$(+)^{*}$	$(+)^{**}$
C2			$(+)^{*}$		$(-)^{**}$	$(-)^{**}$		$(+)^{*}$
C3				$(-)^{**}$	$(-)^{**}$	$(-)^{**}$		
C4	$(-)^{0}$				$(-)^{**}$	$(-)^{**}$	$(+)^{*}$	

ESP: exchangeable sodium percentage; CEC: cation exchange capacity; OC: organic carbon. $^{(1)}$ Contrasts: C1: native forest vs. eucalyptus forests; C2: non-irrigated vs. irrigated; C3: irrigated vs. fertigated; C4: fertigated vs. fertigated with effluent. **, * and ^{0}: significant contrasts at 1, 5, and 10 %, respectively. Signals (+) and (-) mean higher or lower averages in the same contrast, respectively, comparing the first term with the second one of the contrast.

contains considerable organic matter content, as indicated by the BOD values (Table 1), the filtering needed for irrigation reduces the organic matter input, and increases in OC were not found after wastewater application. Another study did not find any increases in soil OC after application of the paper mill effluent (Lin et al., 2008). In contrast, an increase in OC content in an experiment carried out in lysimeters filled with soil after the application of paper mill wastewater was associated with the dissolved lignin present in the residue (Singh et al., 2013).

No differences in soil Ca^{2+} contents were measured. This was an unexpected result because liming was previously applied, and the effluent used had a high concentration of this nutrient (Table 1). Naturally high contents of Ca^{2+} in the soil, as shown by the native forest treatment (T1), eucalyptus extraction, and the high concentration of Na^{+} in the effluents can be considered in possible explanations. Na^{+} can displace Ca^{2+} by mass effect, avoiding its sorption to soil sites.

Effluent application (T5) increased the soil Na^{+} content and soil pH, and decreased the exchangeable Al^{3+}. The higher Na^{+} content also increased the CEC, leading to an exchange sodium percentage (ESP) of 11.68 % (Table 3). This phenomenon was also observed in soil receiving urban sewage effluent (Santos, 2004). The higher ESP had an effect on clay dispersion. An ESP higher than 15 % is likely to affect soil structural and hydraulic properties (Richards, 1954), and, although this limit was not reached in this study, the results indicate a potential risk for structure deterioration. This supports the importance of a soil monitoring program in situations where effluent is applied, but this has to be considered only for particular soil-effluent combinations (Freire et al., 2003).

Effluent application changed the soil SPE composition (Table 4). The wastewater caused an increase in EC, pH, Na^{+}, and SAR values, which can be directly associated with effluent chemical properties (Table 1). The EC values did not change much, but high values of SAR were found in the effluent treatment (T5). This is reason for concern, because it indicates a low salt concentration combined with high Na^{+} contents in the soil solution. High Na^{+} activity can cause an expansion of the diffuse double layer in the soil, favoring soil dispersion. Furthermore, a possible effect on plants cannot be discarded, although no negative signs were found in the eucalyptus trees after six years; however, it is not known what the effect will be on the more susceptible seedlings of subsequent plantations.

The forested control area (T1) had higher Ca^{2+} and Mg^{2+} contents in the SPE than the other treatments (Table 4), which is contrary to what was observed in the soil (Table 3). In the areas under eucalyptus, nutrient extraction was intense, decreasing the contents of the more readily available forms of both cations. The lower contents of Ca^{2+} and Mg^{2+} in the treatment that received the effluent (T5) are also explained by substitution by Na^{+} added in the effluent (mass effect).

The potential risk of the effluent of causing soil salinity problems is clearly shown by the EC, Na^+, and SAR values in the SPE of T5. The contents of Na^+ in the extract are extremely high and determine the high EC and SAR values. Whereas the EC of T5 shows a two-fold increase compared to the fertigated treatment (T4), the SAR shows a 40-fold increase. This high SAR, associated with an intermediate EC value, is a serious threat to soil physical quality. Although the WDC values found were not yet a reason for alarm (Table 2), this risk is present, as shown by the SAR and CDI values.

Adding Ca^{2+} and Mg^{2+} to the wastewater before soil application, and the use of gypsum, can be advisable to avoid damages to soil structure in the longer term, as negative Na^+ effects would be minimized; that way, SAR values can be reduced and flocculation can be improved. This is supported by studies showing that the application of urban sewage effluent in soils of contrasting textures caused clay dispersion only in sandy soil (Lado et al., 2005), which was related to the higher exchangeable Ca content present in the clay soil, which was rich in $CaCO_3$ (10 %).

Soils under eucalyptus showed a lower resistance to penetration (SRP) than the reference area (T1) (Figure 1). The subsoiling practice, as mentioned before, can explain this data. The higher SRP obtained in soil under the native forest is directly related to the lower moisture verified in T1, and no subsoiling practice in this area. The lower SRP observed in the fertigated treatment is attributable to the higher moisture present in T4. The data obtained did not suggest effects from treatments on SRP. Indirect effects, however, can be associated with soil moisture as affected by the application of water or wastewater.

Table 4. Soil chemical composition of saturated paste extract in response to the treatments evaluated, and contrast analysis among treatments

Treatment	pH	Ca	Mg	K	Na	SAR	EC
		mg L^{-1}				$(mmol\ L^{-1})^{1/2}$	dS m^{-1}
Forest vegetation (T1)	4.2	149.9	32.3	35.0	10.7	0.21	0.9
No irrigation (T2)	5.1	56.8	18.2	17.7	8.3	0.25	0.4
Water irrigation (T3)	4.6	59.7	13.8	11.7	11.7	0.35	0.4
Fertigation (T4)	4.6	84.5	25.7	35.7	10.7	0.26	0.6
Treated effluent (T5)	6.5	37.5	13.8	23.0	300.0	10.60	1.2
C1$^{(1)}$	(-)**	(+)**	(+)**	(+)**	(-)**	(-)**	(+)*
C2				(-)**	(-)**	(-)**	(-)**
C3	(-)**			(-)**	(-)**	(-)**	(-)**
C4	(-)**	(+)*	(+)*	(+)**	(-)**	(-)**	(-)**

SAR: sodium adsorption ratio, given by SAR = $Na^+ \times [(Ca^{2+} + Mg^{2+})^{-1/2}]$; EC: electrical conductivity. $^{(1)}$ Contrasts: C1: native forest vs. eucalyptus forests; C2: non-irrigated vs. irrigated; C3: irrigated vs. fertigated; C4: fertigated vs. fertigated with effluent. ** and *: significant contrasts at 1 and 5 %, respectively. Signals (+) and (-) mean higher or lower averages in the same contrast, respectively, comparing the first term with the second one of the contrast.

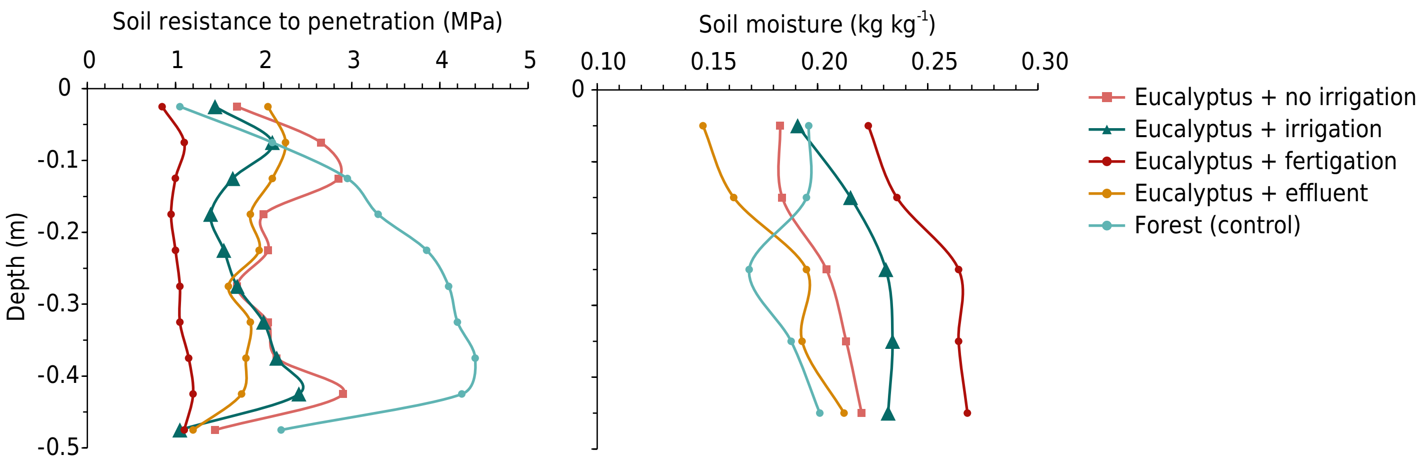

Figure 1. Soil resistance to penetration and soil moisture at the time of penetration evaluation in response to the treatments evaluated.

The LLWR is considered by some authors as the most appropriate for evaluating changes in soil physical properties because it combines soil parameters affecting plant and root growth development: Bd, aeration, SRP, and soil water retention (Tormena et al., 1998; Leão and Silva, 2004; Calonego and Rosolem, 2011), but not without criticism (de Jong van Lier and Gubiani, 2015). The shaded areas in the graphs of figure 2 show the range of moisture content where there are no limitations for the above parameters. The LLWR decreased under eucalyptus cultivation compared to the native forest (T1), particularly in the treatments with no water or effluent irrigation. The decrease was smallest in the fertigation treatment (T4). Considering the critical soil bulk density (Bdc), i.e., the Bd value

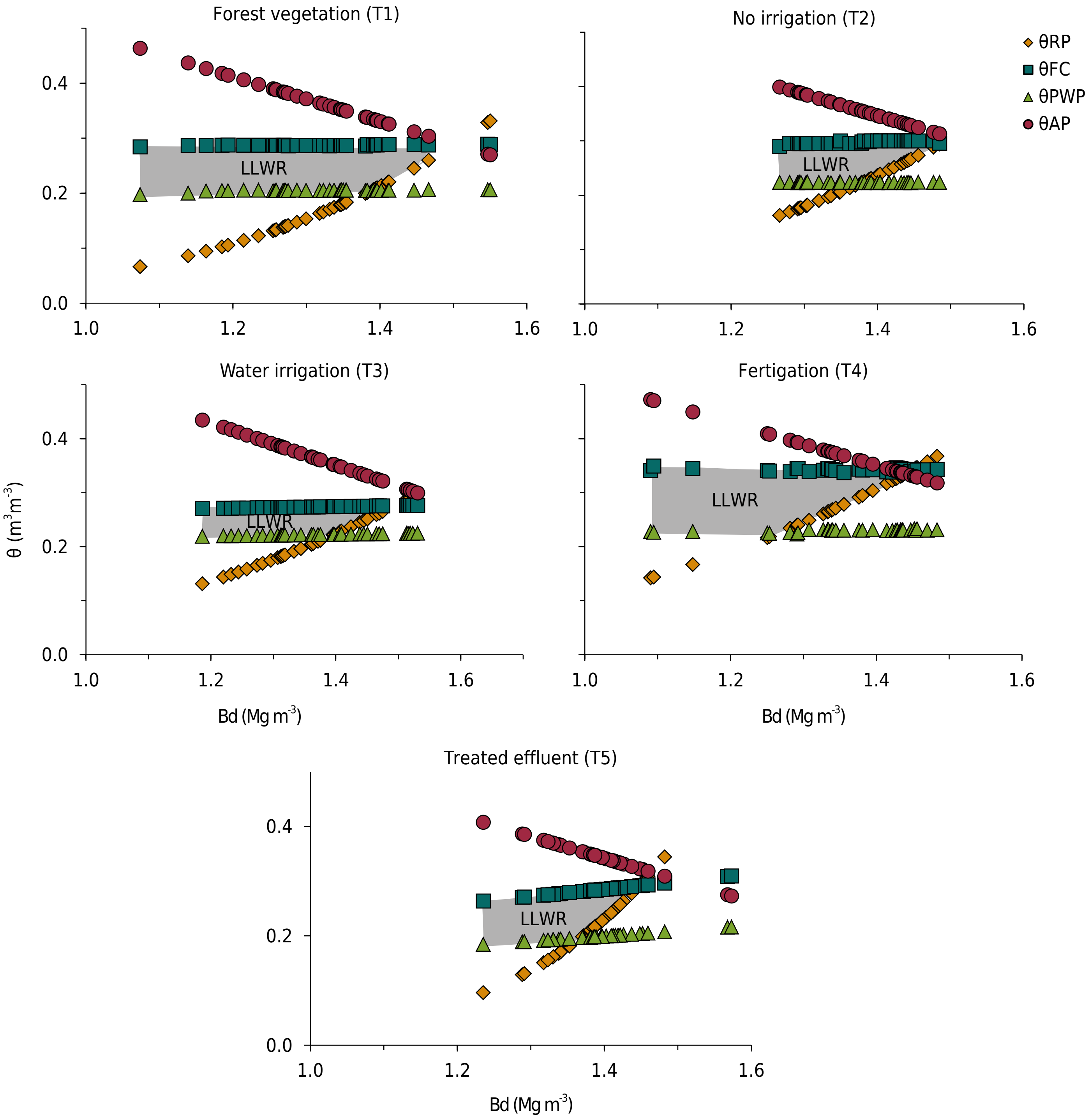

Figure 2. Least limiting water range (shaded area) of treatments evaluated with a variation of water content as a function of soil bulk density (Bd), related to critical levels of field capacity (θ_{FC}; ψ = -0.01 MPa), permanent wilting point (θ_{PWP}; ψ = -1.5 MPa), minimum air-filled porosity of 10 % (θ_{AP}), and soil resistance to penetration of 2 MPa (θ_{RP}).

where the LLWR reaches zero, and that adequate physical conditions for root development no longer exist (Leão et al., 2004), no expressive differences were verified considering all the treatments evaluated. The Bdc values obtained were 1.50, 1.50, 1.53, 1.44, and 1.46 Mg m^{-3} for the T1, T2, T3, T4, and T5 treatments, respectively. For all treatments, the main controller of the amplitude of the LLWR was available water - the difference in soil moisture between field capacity and the permanent wilting point. After Bd values of 1.3 to 1.4 Mg m^{-3}, soil resistance to penetration corresponding to 2 MPa defined the lower limit of LLWR. Air-filled porosity did not influence the range of the LLWR. Reduction in the amplitude of Bd values in the effluent treatment (T5), similar to no irrigation (T2), did not indicate any favorable conditions for root development.

All results obtained suggest that paper mill effluents can be used for soil irrigation under controlled conditions and through a continuous program for monitoring soil quality. However, it should be mentioned that not all possible contaminants of the wastewater used (e.g., organic compounds or heavy metals) were studied.

CONCLUSIONS

The reuse of treated wastewater from an industrial paper mill over a full eucalyptus tree rotation affects soil quality, especially increasing soil Na^+ content and soil pH. The increase in soil Na^+ concentration promoted by this effluent decreases aggregation indices and increases the clay dispersion index. Provided there is no contamination from heavy metals or pathogens, paper mill industry effluents can be used for eucalyptus trees under controlled irrigation management and a continuous program for monitoring soil quality.

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