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Evaluation of the Productivity of Irrigated *Eucalyptus grandis* with Reclaimed Wastewater and Effects on Soil

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Abstract The growing demand for new sources of water for irrigation has led to an increase in the practice of using treated wastewater in agricultural processes. Thus, in the present research, we have assessed the irrigation of a culture of eucalyptus with reclaimed wastewater. The sewage comes from domestic sources and was treated in a facultative lagoon. The culture of eucalyptus was assessed through plant diameter at breast height and total volume of wood produced. Soil contamination was determined through its salinization and the values of sodium adsorption ratio (SAR). The use of wastewater in irrigation has brought an increase of 82.9 % in productivity compared to traditional cultivation. This shows that in a same area of cultivation, practically double of the eucalyptus wood could be obtained and used in the most different industrial activities. In addition, it would prevent the entering of a large amount of nutrients in water bodies due to their recycling in the agricultural culture. In the period of 4 years of studies, SAR has always been below the values pointed by the literature as indicators of problems for the soil.

Keywords Effluent · *E. grandis* · Nutrients · SAR · Reuse

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1 Introduction

For regions where there is a scarcity of water or low rainfall regime, the use of reclaimed wastewater may be a solution, as, in addition to meeting the water demand of the planting, it also allows the recycling of nutrients (Monnet et al. 2002). Domestic effluents have large amounts of nitrogen and phosphorus, which can replace synthetic fertilizers in vegetable culture. Moreover, they are a water resource that is constantly available (Toze 2006) and their use eliminates the need for expensive tertiary treatments (Angelakis et al. 1999).

Many developing countries have little scientific knowledge on the viability of this reuse (Batarseh et al. 2011). Typically, they throw a large portion of wastewater directly into water bodies (rivers, seas, and lakes), causing serious damage to the environment (Salameh et al. 2002; Jiries et al. 2000; Shahalam et al. 1998).

Studies have demonstrated the potential of treated effluent in the cultivation of trees with high biomass content as a form of tertiary treatment of effluent. These trees feature high evapotranspiration and absorb the nutrients present in the effluent (Minogue et al. 2012; Rockwood et al. 2004). Falkiner and Smith (1997) promoted a research using treated effluent for irrigation of eucalyptus and pinus and concluded that the reuse did not cause negative effects to the trees.

In the State of São Paulo, located in the southeastern region of Brazil, there is a great shortage of water resources due to the high concentration of population and the diversity of industrial and agricultural activities. Among the cultures that have been developed in the last years, the planting of eucalyptus has been highlighted, as it occupies an area of 1.044.813 ha.

The use of reclaimed wastewater in the irrigation of eucalyptus could accelerate its growth, which represents an alternative for the supply of wood for industrial activities, such as power generation, civil works, and paper production. Smethurst et al. (2003) state that eucalyptus tends to have increased leaf area, and stem volume as the nutrients are present in cultivation.

Although this practice is a way to save water and to recycle nutrients, it cannot be carried out indiscriminately. A link between Sanitary Engineering and Irrigation Engineering is needed to ensure that sewage is treated in the soil and to prevent the contamination of any aquifer.

Siebe (1998) and Angin et al. (2005) state that irrigation with untreated wastewater increases the concentration of organic matter and nutrients into the soil, besides increasing the concentration of the main cations. Soils with high sodium values will have their permeability reduced. This decreases the rate of infiltration and causes the formation of crusts on the surface due to the dispersion of particles (Pearson 2003; Qian and Mecham 2005).

High salinity can inhibit plant germination, which negatively influences the growth rate. This will produce a decrease in productivity and the impairment of the crop (Rhoades 1982).

The sodium adsorption ratio (SAR) is employed to generate information on the comparative concentrations of Na^+, Ca^{2+}, and Mg^{2+} in the soil solution. Qian and Mecham (2005) state that the SAR tends to increase as there is the application of wastewater in the soil. Sodium-related issues should begin to appear when the value is between 12 and 15 (Munshower 1994).

Sodium can be directly toxic to plants, because it unbalances the osmotic potential and affects the roots' ability to absorb water and nutrients (Tester and Davenport 2003). Irrigation with water with high concentrations of salts can cause a decrease in the diameter of canopy (Noshadi et al. 2013), in leaf area and height, and in the dry weight of the plants (Malash et al. 2008).

Often, there is not an increase in salinity when the wastewater is treated before use (Qian and Mecham 2005). For example, in California, after 5 years of using treated effluent, there was no loss of productivity or quality in food crops (Barau et al. 1987).

Salinity in soil can be reduced by using a quantity of water that is higher than the difference between plant consumption and effective precipitation. The goal would be the expulsion of excess soluble salt introduced by wastewater, reducing or eliminating the risk of high soil salinity (Corwin et al. 2007). The increase in the concentration of magnesium and calcium can also reduce the load of sodium in the soil (Pearson 2003).

Given the above, the objective of this work was to assess the productivity of a eucalyptus culture irrigated with treated sewage and to determine the changes caused to the soil by this practice.

2 Material and Methods

The project was installed in an agricultural area located in the city of Franca (State of São Paulo, Brazil). The coordinates are 249.764 m E, 7.735.225 m N, and altitude of 975 m. Near this area, there is a Facultative Lagoon Wastewater Treatment Plant. The volume of the facultative lagoon was 6.741 m^3, with hydraulic retention time of 25 days. The sewage was from domestic sources. Irrigation began in 2007 and lasted 5 years.

The local soil was classified as Quartzarenic Neosol according to Embrapa (2006), and the area was divided into 28 sectors. The dimensions of each of the sectors of the planting were 9.0 m in width and 12.0 m in length (Fig. 1). In each sector, there were a total of 18 plants of the *Eucalyptus grandis* species. This variety is one of the most used for pulp production in the State of São Paulo (Brazil).

2.1 Evaluation of the Tests

The tests used in the study are shown in Table 1.

For the fertilization performed before the planting, we used 200 kg ha^{-1} of synthetic fertilizer (NPK 6:30:6). Additional fertilization only occurred in the tests T3, T4, T5, and T6. This fertilization was made

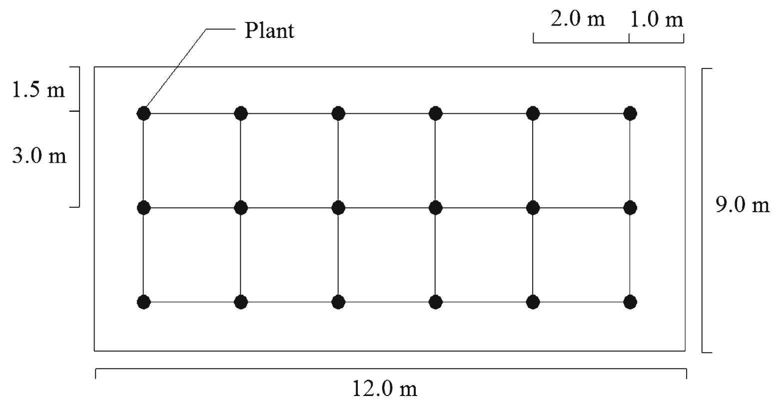

Fig. 1 Schematic representation of a planting sector

every 6 months with the use of 0.200 kg of synthetic fertilizer per plant, following the guidelines adopted for commercial planting.

Low throughput sprinkler was used for irrigation. The frequency of irrigation was controlled by the trees' water needs, measured by tensiometers installed in the irrigated sectors. Irrigation was performed in order to keep the tensiometer readings at −75 kPa, which corresponds to the water requirement of the culture.

The water used in tests T2 and T3 was obtained from a pond traditionally used for irrigation of several vegetable crops.

2.2 Evaluation of Productivity

After 4 years of experiment, we carried out measurements of diameter at breast height (DBH). This height was standardized at 1.30 m above ground for each plant. We used the "blume-leiss" hypsometer to measure the total height of the plants. From the DBH and height data, we determined the average wood volume per tree using Eq. 1 proposed by Guedes (2005), in which V is the volume, DBH is the diameter at breast height, and HT is the commercial height of the plant, adopted up to where the upper stem has a diameter greater than 0.05 m.

$$V = 1.7 \times 10^{-5} \times \mathrm{DBH}^{1.9117} \times \mathrm{HT}^{1.3065} \quad (1)$$

2.3 Soil Analysis

Twenty soil collections were carried out in each of the sectors (Fig. 1), between 0.00 and 0.20 m depth. Soil analyses were done according to Embrapa (2010). We carried out analyses of SAR

Table 1 Tests employed in the study

Tests	Water source	Number of planting sectors	Irrigation	Fertilization
T1	–	4	Without irrigation	Without fertilization
T2	Pond water	4	Eucalyptus water requirement	Without fertilization
T3	Pond water	4	Water requirement of the eucalyptus	NPK
T4	Effluent	4	1/3 of the water requirement of the eucalyptus	NPK
T5	Effluent	4	1/2 of the water requirement of the eucalyptus	NPK
T6	Effluent	4	Water requirement of the eucalyptus	NPK
T7	Effluent	4	Water requirement of the eucalyptus	Without fertilization

Table 2 Characteristics of the effluent from the facultative lagoon and pond water

Parameter	Unit	Effluent from the facultative lagoon	Pond water
Conductivity	$\mu S\ cm^{-1}$	1033.0±74.0	20.8±2.5
Phosphorus	$mg\ L^{-1}$	14.40±0.50	0.08±0.03
Ammoniacal nitrogen	$mg\ L^{-1}$	54.20±11.50	0.20±0.09
Sodium	$mg\ L^{-1}$	79.38±7.00	0.50±0.10
Calcium	$mg\ L^{-1}$	88.60±13.00	0.78±0.20
Magnesium	$mg\ L^{-1}$	4.02±0.80	0.08±0.03

and exchangeable sodium percentage (ESP) in the samples collected (Eqs 2 and 3).

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\sqrt{\frac{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}}{2}}} \quad (2)$$

$$\mathrm{ESP} = \frac{\mathrm{Na}}{\mathrm{CEC}} \times 100 \quad (3)$$

where CEC is the cation exchange capacity. The concentrations of Na^{+}, Ca^{2+}, and Mg^{2+} are represented in $mmol_c\ dm^{-3}$, which were obtained following the guidance from the Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, WEF 2012).

3 Results and Discussion

In Table 2, we present the data related to the facultative lagoon effluent used as a source of water for irrigation. The result obtained for the nitrogen concentration was compatible with the data found by Fine et al. (2006), who used raw sewage effluent in the irrigation of eucalyptus from the *Eucalyptus camaldulensis* species.

The SAR value was 2.24, and when we apply this result in the diagram for the classification of irrigation waters (Ayres and Westcot 2008), we can see that the effluent would be classified as having high salinity and low risk of sodification. Due to the salinity of the effluent used, its use is not recommended for soils with poor drainage. Plants fertigated with the treated effluent must also have good salt tolerance.

Studies performed by Sun and Dickinson (1993) and Dun et al. (1994) showed that the *E. grandis* species has moderate salinity tolerance. Niknam and McComb (2000) state that this is the eucalyptus species most tolerant to salinity, which has a system of salt exclusion. By analyzing Table 3 and Fig. 2, we can note that, after 4 years of growing, the culture has not shown any signs of feeling the effects of the increased salinity. Tests T4 to T6, where effluent was used for irrigation, have significantly higher productivity values than those obtained in the tests in which only pond water irrigation was used (T2 and T3). We can observe that as there is an increase in the amount of effluent used in irrigation (T4-1/3, T5-1/2, and T6-water requirement); there is a trend of increased productivity. The value found for T6, where irrigation was used to satisfy all of the water requirements of the plant, was significantly greater than for T4 and T5.

Table 3 Productivity of the eucalyptus

Test	DBH (cm)	HT (m)	Volume ($m^3\ plant^{-1}$)	Productivity ($m^3\ ha^{-1}$)
T1	16.30±1.70 a	24.85±1.20 ac	0.24±0.06 a	395.81±102.77 a
T2	17.40±0.85 a	23.45±0.21 a	0.25±0.02 a	411.30±33.46 a
T3	16.60±0.99 a	23.80±0.42 a	0.23±0.03 a	384.18±52.61 a
T4	19.80±0.14 bc	25.60±3.25 bc	0.36±0.06 b	591.83±106.02 b
T5	19.80±0.85 bc	27.10±0.28 bd	0.38±0.04 b	636.65±60.76 b
T6	20.80±1.41 c	28.00±0.57 d	0.44±0.07 c	731.79±114.04 c
T7	21.15±0.78 bc	28.00±0.71 d	0.45±0.02 c	752.29±29.07 c

DBH diameter at breast height, *HT* commercial height of the plant

Statistical analysis between values with different superscript letters is statistically significant ($p<0.05$)

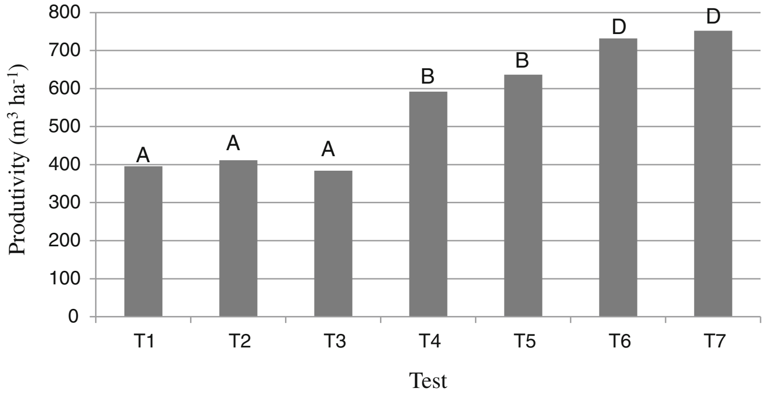

Fig. 2 Eucalyptus productivity graphic. Statistical analysis between values with different letters is statistically significant ($p<0.05$)

Tests T6 and T7 had the highest productivity. In both, irrigation was performed with a volume of effluent that met the water requirement of the culture. The only difference was related to the use of fertilization: T6 received NPK and T7 did not have any amount of synthetic fertilizer. The results showed that productivity was not affected by the use of fertilizer, which points to the possibility of complete replacement of conventional fertilizer by the use of reclaimed wastewater.

Another important finding is the comparison of test T7 with test T2. In T2, we adopted the management that may be traditionally used in the production of eucalyptus in areas with low rainfall. The results demonstrate that there has been an increase of 82.9 % in productivity of eucalyptus in relation to the generation of wood volume per hectare planted. In a same area of cultivation, practically double of the plant material could be obtained and used in the most different industrial activities. This way, deforestation of virgin forests or the use of other areas for the cultivation of eucalyptus would be avoided.

The averages of the tests that used pond water for irrigation (T2 and T3) showed no significant difference, regardless of the use of synthetic fertilizer. These results found for T2 and T3 were also not significantly different from those obtained in test T1, where irrigation and fertilization was not used. This statistical similarity between the test irrigated and nonirrigated with pond water can be explained by the high incidence of rainfall where the experiment was carried out. The average rainfall in the city of Franca (Brazil) for the years in which the experiment was conducted reached 1668.7 ± 150.6 mm year^{-1}. According to Almeida et al. (2007), an annual rainfall of 1350 mm is enough to meet the water requirement of the culture.

Thus, it is proven that the use of treated effluent in the eucalyptus production can be extremely beneficial to the environment, as there would be its recycling in an

Table 4 Levels of sodium, magnesium, and calcium in the soil

Test	Na (meq dm^{-3})	Mg (meq dm^{-3})	Ca (meq dm^{-3})	SAR (meq$^{0.5}$ L$^{-0.5}$)	ESP (%)
C_0**	<0.10 a	4.00 a	11.80 a	n. d.***	n. d.***
T1	0.10 a	4.00 a	10.67 a	0.04 a	0.33 a
T2	0.10 a	4.25 a	15.00 a	0.03 a	0.23 a
T3	0.10 a	3.50 a	16.25 a	0.03 a	0.24 a
T4	0.53 b	2.00 a	11.00 a	0.21 b	1.47 b
T5	0.57 b	2.25 a	10.75 a	0.22 b	1.48 b
T6	0.60 b	1.40 a	11.00 a	0.24 b	1.52 b
T7	0.50 b	1.50 a	7.50 a	0.24 b	1.15 b

SAR sodium adsorption ratio, *ESP* exchangeable sodium percentage

Statistical analysis between values with different superscript letters is statistically significant ($p<0.05$). **Initial condition of the soil. ***Not determined. Sodium values was below the limit of detection economic activity (Salameh et al. 2002; Jiries et al. 2000; Shahalam et al. 1998).

3.1 SAR and ESP of the Soil

In Table 4, we presented the data for the concentrations of cations, SAR and ESP obtained for the soil employed in the cultivation. We can see that in tests with effluent irrigation, there was a tendency to increase the concentration of sodium and the values of SAR. However, in no case, we had a SAR that surpassed the limits found in the literature (Munshower 1994).

With respect to the ESP, the lowest values were found for the tests irrigated with pond water (T2 and T3) and for the one with no irrigation (T1). Tests irrigated with effluent showed significantly greater ESP values; however, they can still be considered as relatively low. Falkiner and Smith (1997) got an ESP near 25 % when growing *E. grandis* in Australia, indicating a highly sodium soil.

The behavior observed in this study may be related to high rainfall rate observed in the years in which the research was conducted. In this case, there would be the expulsion of excess soluble salt introduced by wastewater, reducing or eliminating the risk of high soil salinity (Corwin et al. 2007).

Mishra et al. (2003) found a reduction of the values of ESP when cultivating a culture of eucalyptus over 9 years in a sodium soil. According to the authors, this reduction happened because of the increase in Ca^{2+} ions in the soil during the cultivation of eucalyptus. Moreover, there was a reduction in the rate of evaporation from the soil in the surface layers, increasing the rate of leaching and causing the reduction of exchangeable Na^{+}.

In Brazil, the legislation of the State of São Paulo (CETESB 2006) considers that the soil will be unfit for irrigation with effluent when ESP values reach 6 %. Dias et al. (2004) state that when the ESP surpasses 15 %, the soil can be considered as a sodium soil. This way, we can see from Table 4 that in none of the situations evaluated, these limits have been surpassed.

4 Conclusions

1. The results demonstrate that when the treated effluent was utilized in irrigation of *E. grandis* the DBH, the commercial height of the plant (HT) and the wood volume were higher. There has been an increase of 82.9 % in the productivity of eucalyptus in relation to the generation of wood volume per hectare.
2. The value found for sodium has increase after effluent irrigation, but SAR and ESP of the soil did not exceed the limit values presented in the literature, demonstrating that there was no risk of salinization so far.

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