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Research Article

Applying Sewage Sludge to *Eucalyptus grandis* Plantations: Effects on Biomass Production and Nutrient Cycling through Litterfall

Paulo Henrique Müller da Silva,[1] Fabio Poggiani,[2] and Jean Paul Laclau[3]

[1] *Instituto de Pesquisas e Estudos Florestais, Avenida Pádua Dias, 11, Caixa Postal 530, 13400-970 Piracicaba, SP, Brazil*
[2] *ESALQ/USP, Av. Pádua Dias, no. 11-Agronomia, Caixa Postal 09, Piracicaba, SP, Brazil*
[3] *CIRAD, UMR Eco&Sols Ecologie Fonctionnelle & Biogéochimie des Sols & Agroécosystèmes, 2 place Viala, 34060 Montpellier, France*

Correspondence should be addressed to Paulo Henrique Müller da Silva, paulohenrique@ipef.br

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In most Brazilian cities sewage sludge is dumped into sanitary landfills, even though its use in forest plantations as a fertilizer and soil conditioner might be an interesting option. Sewage sludge applications might reduce the amounts of mineral fertilizers needed to sustain the productivity on infertile tropical soils. However, sewage sludge must be applied with care to crops to avoid soil and water pollution. The aim of our study was to assess the effects of dry and wet sewage sludges on the growth and nutrient cycling of *Eucalyptus grandis* plantations established on the most common soil type for Brazilian eucalypt plantations. Biomass production and nutrient cycling were studied over a 36-month period in a complete randomized block design. Four experimental treatments were compared: wet sewage sludge, dry sludge, mineral fertilizer, and no fertilizer applications. The two types of sludges as well as mineral fertilizer increased significantly the biomass of *Eucalyptus* trees. Wood biomass productions 36 months after planting were similar in the sewage sludge and mineral fertilization treatments (about 80 tons ha^{-1}) and 86% higher than in the control treatment. Sewage sludge application also affected positively leaf litter production and significantly increased nutrient transfer among the components of the ecosystem.

1. Introduction

Sewage sludge resulting from the treatment of urban liquid residue, channeled to treatment stations through the sewage system, is a residue rich in organic matter. This sludge corresponds to only 1% of the volume of sewage waste, but the treatment and final disposal represents 20 to 40% of the operational costs of a treatment station [1]. Several alternatives exist for disposing of the sludge produced in sewage treatment (solid fraction), such as dumping in sanitary landfills or incineration. The solid fraction of sewage sludge can also be applied as fertilizer in agroecosystems, although it must be used very carefully in order to reduce the risks of health-related problems for the population, damage to the environment, or financial loss to farmers [2].

Applying organic matter at the soil surface to improve its fertility is a traditional practice. Sewage sludge use in agricultural production systems has become an interesting alternative to discarding it, as it may increase overall crop production [3]. Risks associated with sludge application in forest plantations are lower than in agriculture, since tropical *Eucalyptus* plantations are usually managed to produce fire wood, charcoal, boards, or pulp and paper, and the final product (wood biomass) is not incorporated into the human food chain. Moreover, environmental impacts of sewage sludge applications in forest plantations are usually much lower than in agriculture since doses required to meet tree nutrient requirements are low [4]. Sludge applications are only required the first year of the rotation (every 6 to 7 years), whereas doses of the same order of magnitude may be applied annually for agricultural crops. Forest plantations are usually located on low fertile sandy soils and a fast development of *Eucalyptus* roots makes it possible to take up the nutrients released during sludge decomposition [5].

Studies have been carried out worldwide from the early 1970s to assess the effectiveness of applying organic waste residues to forest areas [6] and the effects on tree growth. In particular, early investigations in the state of Washington (USA) have shown positive effects of sewage sludge applications on the development of conifer plantations [7, 8]. Slow and continuous nutrient releases into soil solutions during sewage sludge decomposition may be an advantage in comparison with mineral fertilizations, fitting better nutrient availability with stand requirements [9]. De Lira et al. [10] observed a significant increase in eucalypt biomass production resulting from the application of sewage sludge, with a strong relationship between tree growth and the enhancement of nitrogen, phosphorus, and base cation contents within the upper soil layer. Sludge applications in fast growing plantation forests lead to a return within the ecosystem of nutrients exported at the harvest. The slow release of nutrients contained within the sludge makes it possible to restore soil nutrient stocks throughout the development cycle of forest plantations [11].

Previous research suggests that the application of sewage sludge might significantly improve the economic performance of forest plantations due to increases in wood production [12]. Furthermore, increases in net primary productivity associated with an increase in nutrient concentration in tree components (leaves, branches, wood, bark, and roots) lead to beneficial changes in ecosystem functioning, as a result of a higher nutrient transfers from the forest biomass to the litter and subsequently to the soil [13]. The application of sludge is likely to modify nutrient contents in the foliage and the retranslocation of nutrients in senescing leaves [14]. In particular, high concentrations of N and P in the sewage sludge may accelerate the decomposition rates of the litter in forest plantations [15].

Litterfall production is one of the main ways of nutrient transfer within the biogeochemical cycle in forest ecosystems and feeds the nutrient stocks in the litter layer accumulated in adult plantations [16]. Biogeochemical cycles of nutrients in forest plantations are largely influenced by tree species, soil fertility, fertilization regimes (type and doses), and silviculture [17, 18]. In the long term, litterfall production and chemical composition largely influence nutrient availability in forest ecosystems [19].

The chemical composition of sewage sludge depends on the source from which it has been generated, such as industrial or residential facilities and the processes used in sewage treatment stations. The São Paulo Sanitation Company (Companhia de Saneamento Básico—SABESP, Brazil) started in 2002 an experimental process to thermally dry the sewage sludge produced in the São Paulo metropolitan area. Thermal drying is an expensive operation, but it significantly reduces the water content in the sludge, thus reducing transportation and field application costs. Furthermore, drying the sewage improves the quality of the sludge as it eliminates pathogenic microorganisms. Such aspects are important when the dried sludge is aimed at agro forest systems [20]. However, little is still known about the use and effect of thermal dried sewage sludge as fertilizer on growing eucalypts plantations. We studied the impact of the addition of wet (77% water content) and dried (7% water content) sewage sludges on tree growth and nutrient cycling in experimental plantations of *Eucalyptus grandis*, established on highly weathered soils (Ferrasol) in Brazil.

The objective of our study was to gain insight into the effects of the application of sewage sludge on the growth and nutrition of eucalypt plantations over the first half of the rotation. The effects of sludge applications (wet sewage sludge or dry sludge) on biomass production, leaf litterfall, and nutrient cycling were compared to mineral fertilizer applications (standard forestry practice of the region) and to a control treatment without nutrient addition.

2. Material and Methods

2.1. Study Area, Experimental Design, and Treatments. This study was conducted at the Itatinga Experimental Station, University of São Paulo, São Paulo State, Brazil (23°02′ S, 48°38′ W and 830 m altitude). The natural vegetation of the region is an arboreal savannah (Cerrado). The climate is Cfa according to the Köppen classification, the average annual precipitation is 1370 mm, and the average temperature is 19.2°C (1990 to 2004). The relief is typical of the São Paulo Western Plateau, with a topography ranging from flat to hilly.

The study area is characterized by very deep (>12 m) Ferralsols [21] developed on Cretaceous sandstone, Marília formation, Bauru group, with a clay content ranging from 14% in the A1 horizon to 23% in deep soil layers. The mineralogy is dominated by quartz, kaolonite, and oxyhydroxides, with acidic soil layers containing very small amounts of available nutrients (Table 1). Soil analyses down to a depth of 6 m at the study site were indicated by Laclau et al. [22]. This soil type is found in most of eucalypt plantations in the State of São Paulo, which is the state with the second largest planted area in Brazil.

The experiment was set up in a former *Eucalyptus saligna* plot managed as a coppice, without fertilizer application, from 1940 to 1998. The stumps were devitalized by glyphosate application and *E. grandis* seedlings were planted in 1998 with low fertilizer inputs (300 kg ha^{-1} NPK 10 : 20 : 10). High levels of nutrient exports with the boles, and the lack of fertilization from 1940 to 1998, made this a suitable area for expecting a eucalypt response to fertilizer inputs.

The previous 6-year-old *Eucalyptus grandis* plantation was harvested in February 2003, and then replanted with seedlings of *E. grandis*. A complete randomized block design was set up in April 2003, with 4 treatments and 3 blocks. Each plot had a total area of 384 m^2 (24 m × 16 m). The treatments were C (control), MF (mineral fertilization representative of the silviculture in commercial plantations), WS (10 Mg ha^{-1} on a dry basis of wet sludge applied), and DS (10 Mg ha^{-1} of dry sludge applied). Sewage sludge composition was poor in two essential nutrients for eucalypt growth: potassium and boron (Table 2). These nutrients were applied in the treatments with sludge in order to reach the total amount of potassium and boron added in the mineral fertilization treatment. Dolomite was broadcast on the soil surface

Table 1: Soil analysis of the experimental area before planting.

Depth (cm)	$P^{(1)}$	pH	K	Ca	Mg	CEC	$S\text{-}SO_4^{2-}$	$B^{(2)}$	$Cu^{(2)}$	$Fe^{(2)}$	$Mn^{(2)}$	$Zn^{(2)}$
			Exchangeable cations									
	$Mg\,g^{-1}$	$CaCl_2$	mmolc kg^{-1}					mg kg^{-1}				
0–5	3	4.0	0.2	1.7	1.3	27	24	0.08	0.27	35	0.9	0.27
5–10	2	4.0	0.2	1.0	0.7	21	30	0.07	0.20	25	0.4	0.13
10–20	2	4.0	0.2	0.8	0.7	17	34	0.06	0.23	18	0.2	0.10
20–50	2	3.8	0.0	0.8	0.4	14	9.6	0.05	0.22	14	0.2	0.12

(1) Resin extraction; (2) extractable amounts [23].

(1.2 kg $tree^{-1}$) in the MF treatment, as in most commercial eucalypt plantations in Brazil. Liming was an important point of difference between the mineral-fertilized and sludge plots and was likely to modify nutrient cycling within these fast-growing plantations. The amount of Ca applied to the mineral plots was approximately twice that applied to the sludge plots, and the amount of Mg was 4-5 times that applied to the sludge plots (Table 3). We did not apply exactly the same amounts of nutrients in the MF, WS, and DS treatments because we aimed at comparing fertilization regimes likely to be used at large scale in Brazil.

The seedlings were planted between the rows of the previous plantation after subsoiling (depth 45 cm). Mineral fertilizer and wet and dry sewage sludge were applied manually on a 1 m-wide strip in the planting row (at the soil surface without incorporation) some days after planting. Weed and ant control were undertaken before and after planting. High mortality rates occurred within the first days after sewage sludge application and all dead seedlings were replaced 15 days after treatment establishment.

Table 2: Chemical analysis of wet and dry sewage sludge applied in the experiment.

Determinations	Wet sludge	Dry sludge
pH (0.01 M $CaCl_2$)	7.3	6.5
Bulk density	1.03 g cm^{-3}	0.97 g cm^{-3}
Moisture	77%	7.4%
Organic matter	546 g kg^{-1}	530.2 g kg^{-1}
Nitrogen (N)	32 g kg^{-1}	35 g kg^{-1}
C/N	9.4	8.5
Phosphorus (P)	14 g kg^{-1}	17 g kg^{-1}
Potassium (K)	2.2 g kg^{-1}	2.2 g kg^{-1}
Calcium (Ca)	25 g kg^{-1}	24 g kg^{-1}
Magnesium (Mg)	4.9 g kg^{-1}	3.9 g kg^{-1}
Sulfur (S)	6.6 g kg^{-1}	6.8 g kg^{-1}
Copper (Cu)	0.6 g kg^{-1}	0.7 g kg^{-1}
Manganese (Mn)	0.19 g kg^{-1}	0.3 g kg^{-1}
Zinc (Zn)	2.4 g kg^{-1}	3.2 g kg^{-1}
Iron (Fe)	39 g kg^{-1}	45 g kg^{-1}
Boron (B)	0.009 g kg^{-1}	0.002 g kg^{-1}
Sodium (Na)	0.6 g kg^{-1}	0.9 g kg^{-1}

2.2. Measurements and Sampling. Circumference at breast height and height of eucalypt trees were measured at ages 12, 24, and 36 months, excluding 1 buffer row in each plot. Allometric relationships between tree size and above ground biomass were established at each age by sampling 10 trees distributed throughout the circumference range in each of 3 adjacent plots with application of 10 Mg ha^{-1} of wet sewage sludge, commercial mineral fertilization, and a control treatment. The trees were separated into components: leaves, branches, stemwood, and stembark. The stem of each tree was sawn into 1 m sections at age 12 months and 3 m sections at 24 and 36 months. Diameters, lengths, and weight were measured in the field. The foliage was collected from three different sections of the crown of the trees at each age. Subsamples of each component were dried at 65°C to constant weight and ground for chemical analysis. Allometric relationships were established for each component at ages 12, 24, and 36 months and applied to the inventory in each plot of the experiment.

Foliar nutrient concentrations were measured every six months in fully expanded young leaves collected from the upper third of the crown in eight central trees within each plot. Leaf samples were dried (65°C), weighed, and the concentrations of N, P, K, Ca, Mg and S were determined [24].

Leaf fall production and nutrient returns to soil were assessed over the first 36 months after planting. Leaf litter was collected monthly in 12 plots (4 treatments in 3 blocks) from six litter traps (0.25 m^2 each one) systematically located in each plot to sample representative distances from the trees (a total of 18 traps per treatment). The samples were dried at 65°C and weighed. Composite samples were made for each season (summer, fall, winter, and spring) for chemical analysis to determine the concentrations of N, P, K, Ca, Mg, and S.

Leaf litter decomposition was measured using litter bags sprawled on the floor of the experimental areas. Nylon bags (20 cm × 20 cm) with a 5 mm mesh were filled with 10 g of air-dried leaf litter material. The mesh was chosen to interfere a minimum with the processes of leaf degradation by mesofauna, as well as to facilitate breakdown and leaching of nutrients from plant material. The collection of the remaining leaves contained in the sampled bags started when the trees were 18 months old, and the canopy of eucalypt stands was already closed, thus providing continuous shade in all the experimental plots. The litterbags were collected at 1.5, 3, 6, 9, and 12 months after set up in the plots. The leaves

Table 3: Nutrients added in the treatments through the sewage sludge and mineral fertilizer application to the soil of the experimental forest stands.

Treatment	Age (days by implantation)	Input (per tree)	N	P	K	Ca	Mg	S	B	Zn
			kg ha^{-1}							
(1) C (Control)		no fertilization	—	—	—	—	—	—	—	—
		TOTAL	—	—	—	—	—	—	—	—
(2) MF (Mineral fertilizer)	−45	1.2 kg dolomite*	—	—	—	440	160	—	—	—
	7	160 g NPK 6 : 30 : 6 + 2% S + 0.5% Zn	16	34	13	—	—	5	—	1.5
	90	70 g ammonium nitrate	39	—	—	—	—	—	—	—
	90	50 g potassium chloride	—	—	41	—	—	—	—	—
	90	8 g de Borax	—	—	—	—	—	—	1.5	—
	180	180 g NPK 20 : 0 : 20 + 0.5% B	60	—	50	—	—	—	1.5	—
		TOTAL	115	34	105	440	160	5	3	2
(3) WS (10 t ha^{-1} wet sewage)	7	26 kg wet sewage	320	140	21	248	48	66	0.1	24
	7	16 g potassium chloride	—	—	13	—	—	—	—	—
	90	50 g potassium chloride	—	—	41	—	—	—	—	—
	90	15 g de Borax	—	—	—	—	—	—	2.9	—
	180	34 g potassium chloride	—	—	28	—	—	—	—	—
		TOTAL	320	140	105	248	48	66	3	24
(4) DS (10 t ha^{-1} dry sewage)	7	6 kg dry sewage	322	154	21	228	36	63	0.1	32
	7	16 g potassium chloride	—	—	13	—	—	—	—	—
	90	50 g potassium chloride	—	—	41	—	—	—	—	—
	90	15 g de Borax	—	—	—	—	—	—	2.9	—
	180	35 g potassium chloride	—	—	29	—	—	—	—	—
		TOTAL	322	154	105	228	36	63	3	24

* Dolomite was broadcast on the soil surface 45 days before planting.

inside the bags were carefully removed, dried, separated from soil particles, weighed, and analyzed to determine the concentration of lignin.

Leaf-litter mass accumulated in the forest floor was collected every 3 months the third year after planting, from 6 collection points randomly located in each plot (18 positions per treatment). Square wooden frames with an area of 0.25 m^2 were used. The samples were dried at 65°C, weighed, and ground for chemical analysis.

Nutrient retranslocations in senescent leaves were calculated multiplying the mass of leaves in litterfall by the difference in nutrient concentration in green leaves. A correction was made to take into account the decrease in leaf mass during senescence, from the ratio between the biomass of individual mature green leaves with the mass of the senescent fallen ones (approximately 18% in our experiment) [25].

2.3. Data Analysis. The measurement variables were submitted to variance analysis (ANOVA) at a 5% confidence level. The analyses that showed a significant F test were submitted to multiple-comparison tests through a Tukey range test.

3. Results and Discussion

3.1. Tree Growth. Treatment establishment led to significant differences in tree mortality the first days after planting. Whilst wet sewage sludge application led to a mortality of about 20%, tree mortality in the other treatments was <5%. Large losses of N by volatilization of ammonia have been reported by Robinson and Röper [26] after application of wet sewage sludge. Wet sludge application in our experiment led to large emissions of NH_3 (with a strong smell) and eucalypt leaves close to the sludge burnt the first days after application. Using ^{15}N-calibrated collectors in an adjacent experiment showed that 15–20% of total N within the same wet sludge was volatilized the first days after application [27]. Our experiment suggests that a minimum delay of 1 week should be respected between wet sewage sludge application and planting of eucalypt seedlings to avoid large mortality rates due to the volatilization of NH_3.

Wood biomass accumulation 12 months after planting was 9.2, 7.8, 7.0, and 3.2 Mg ha^{-1}in the dry sludge, wet sewage sludge, mineral fertilization, and control treatments, respectively, (Table 4). Wood biomass was significantly higher ($P < .05$) in the treatment with dry sewage application than in the treatment with mineral fertilizer inputs at 12 months after planting. However, wood biomass production was no longer significantly different at 36 months after planting, between the treatments with sewage sludge and mineral fertilization application (about 80 Mg ha^{-1}). The higher biomass production in the dry sludge treatment than in the wet sludge treatment (consistently in each year) may result from the initial seedling mortality generated by the ammonia volatilization. Even though dead seedlings were

Table 4: Aboveground tree biomass accumulated at 12, 24, and 36 months after planting.

Treatment	Biomass (Mg ha^{-1}) Leaf		Bark		Wood		Branch		Total	
12 months										
Control	1.1	b	0.6	b	3.2	C	1.5	b	6.5	c
Mineral fertilizer	1.4	b	1.1	a	7.0	b	2.3	a	11.8	b
Wet sewage	2.6	a	1.2	a	7.8	ab	2.3	a	13.9	ab
Dry sewage	2.9	a	1.3	a	9.2	a	2.6	a	15.9	a
24 months										
Control	4.1	b	2.4	b	13.2	b	4.3	b	24.0	b
Mineral fertilizer	7.2	a	4.8	a	34.5	a	8.0	a	54.6	a
Wet sewage	7.4	a	4.4	a	31.1	a	7.4	a	50.3	a
Dry sewage	8.6	a	5.3	a	37.6	a	8.8	a	60.3	a
36 months										
Control	2.1	c	4.2	c	41.4	C	4.0	c	51.7	C
Mineral fertilizer	3.9	a b	6.6	b	76.8	a b	6.0	a b	93.3	a b
Wet sewage	3.6	b	6.5	b	71.3	b	5.7	b	87.2	B
Dry sewage	4.4	a	8.0	a	87.5	a	6.6	a	106.5	A

Significant differences ($P < .05$) among treatments at a given age are indicated by different letters in the same column.

replanted 15 days after experiment establishment, large inter-tree competition led to a decrease in stand productivity in the treatment with wet sewage sludge application. A similar behavior has been demonstrated in other eucalypt plantations [28].

Biomass production of all above ground tree components was about twice as high in the 3 treatments with nutrient addition than in the control treatment at 36 months of age (Table 4). This strong response of eucalypt trees to nutrient availability at our study site might result from large exportations of nutrients from the plots over 60 years of short-rotation silviculture without any fertilization from 1940 to 1998. Biomass accumulation was comparable in the plots with mineral fertilizer and sludge applications at age 36 months, even though almost 3 times more N was added and 4 times as much P in the sludge treatments. This pattern was consistent with other field experiments in Brazilian eucalypt plantations showing that the amounts of nutrients applied in the MF treatment in our experiment were not limiting tree growth [29, 30]. *Eucalyptus grandis* trees do not respond to higher amounts of N, P, K, Ca, and Mg or micronutrient additions in this region [31]. Comparisons with other doses of sewage sludge at the same study site (up to 40 Mg ha^{-1} on a dry basis of sludge applied) showed that the dose of 10 Mg ha^{-1} in our study was sufficient to maximize the production of *Eucalyptus grandis* plantations [32]. The similar tree growth in the plots with mineral fertilizer and sludge applications showed that sludge mineralization led to a sufficiently fast release of nutrients to meet the high tree requirements (in N and P in particular) to establish the crown the first years after planting [33]. The total amounts of N and P supplied in the sludge were then in excess of requirements for these young trees. Contrarily to agricultural crops, *Eucalyptus grandis* trees are not affected by aluminium toxicity [34]. Many experiments in forest companies show that tree response to dolomite application is low in this area, and the higher amounts of Ca and Mg supplied in the MF plots than in WS and DS plots were unlikely to modify tree growth. By contrast, sap flow measurements and soil water content monitoring at this study site showed that tree transpiration is limited by the annual rainfall after canopy closure and that the main factor limiting tree growth is probably soil water supply (unpublished data). Biomass production in the MF, WS, and DS treatments was however very high in comparison with other commercial eucalypt plantations in Brazil and other forests worldwide [35, 36].

3.2. Nutrient Cycling. Foliar concentrations showed large differences in tree nutrition between treatments (Figure 1). The concentrations of P in the foliage over 36 months after planting suggest that sludge application increased P availability and P nutrition. The lowest concentrations were observed in the treatment with application of mineral fertilizers, probably as a result of a dilution effect of P in a large biomass of leaves, and the lower overall rate of P applied compared to the sludge treatments. The concentrations of N and S were significantly higher in the plots with sludge application than in the control treatment only the first year after planting. Leaf concentrations of K were little affected by the treatments the first year after planting, but they remained significantly lower in the control than in the other treatments from 18 months after planting onwards. A great influence of K availability on the growth of *E. grandis* trees is commonly observed in Brazil [37] and foliar K concentrations show that K deficiency was strongly limiting tree growth in our control treatment. Whilst Ca concentrations were little affected by the treatments over the study, Mg concentrations were significantly higher in the MF treatment than in the other treatments, as a result of the large amount of Mg added with the dolomite.

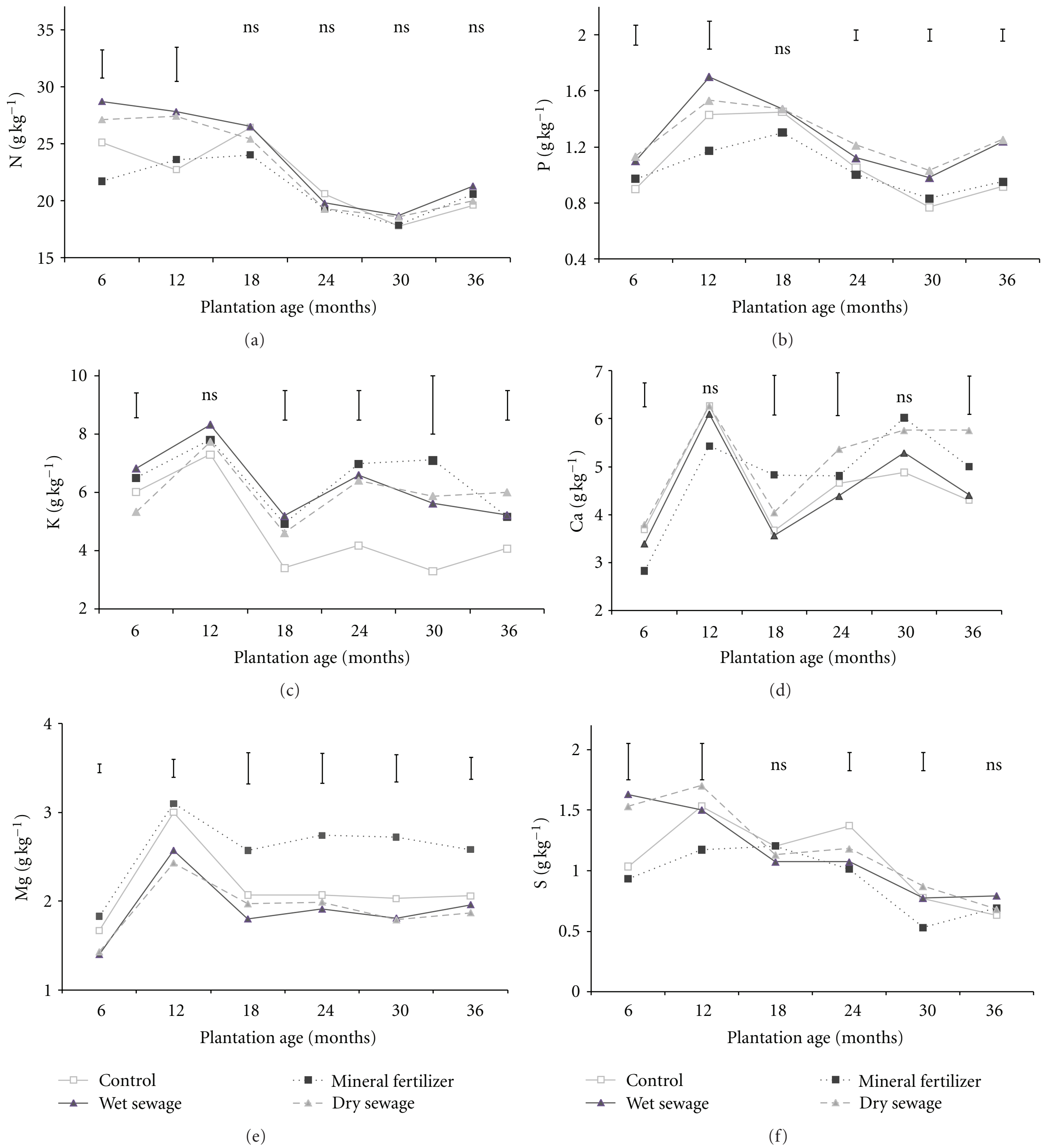

Figure 1: Nutrient concentrations within leaves sampled at 6, 12, 18, 24, 30 and 36 months after planting. Vertical bars represent the minimum significant value (Tukey—$P < .05$) and ns mean a not significant difference.

The application of sewage sludge affected not only tree nutrition but also nutrient cycling within the ecosystem. Leaf litterfall amounted to 5.2–5.4 $\mathrm{Mg\,ha^{-1}\,yr^{-1}}$ in the plots with wet sewage sludge, dry sludge, or fertilizer applications. However, leaf litterfall was 35% lower in the control treatment (Table 5). Only leaf litterfall was considered in our experiment because leaves are the main component of nutrient transfer from the crown to the soil within the first three years after planting *Eucalyptus grandis* in the Sao Paulo state [38]. The highest leaf fall amounts were found in all treatments during the driest months throughout the study period (Figure 2).

Environmental factors, such as climatic variations, are likely to largely modify leaf fall and thus the nutrient cycling processes. The highest leaf fall occuring at times of water deficits may be a result of the eucalypts' "strategy" to reduce water consumption through a sharp decrease in leaf area. Even though this behavior was observed in all the treatments

Table 5: Average nutrient concentrations in leaf litter and total amounts of dry matter and nutrients returning to the soil via litterfall from 12 to 36 months after planting.

Treatment	Dry matter		N		P		K		Ca		Mg		S	
			Concentrations ($g\,kg^{-1}$)											
Control			10.2	a	0.4	a	0.9	b	6.1	c	1.7	b	1.4	a
Mineral fertilizer			9.5	b	0.3	a	2.3	a	8.1	a	2.8	a	1.3	a
Wet sewage			9.8	a b	0.4	a	2.1	a	6.7	b c	1.7	b	1.3	a
Dry sewage			9.3	b	0.4	a	2.0	a	7.2	b	1.7	b	1.3	a
	Annual amounts of dry matter and nutrients in litterfall													
	$Mg\,ha^{-1}\,year^{-1}$		$kg\,ha^{-1}\,year^{-1}$											
Control	4.0	b	46	a	1.6	b	3	b	24	b	6	c	7	a
Mineral fertilizer	5.2	a	54	a	1.6	b	10	a	41	a	14	a	7	a
Wet sewage	5.3	a	56	a	2.2	a	10	a	35	a	9	b	7	a
Dry sewage	5.4	a	55	a	2.3	a	10	a	37	a	9	b	6	a

Significant differences ($P < .05$) among treatments indicated by different letters in the same column.
Nutrient concentration is an arithmetic average obtained in the analysis performed during the study (12–36 months), nutrient returned value is the sum of all periods.

Table 6: Nutrient retranslocation (%) in senescent leaves during 1 to 3 years after planting.

Treatment	N		P		K		Ca		Mg		S	
Control	56.9%	b	71.4%	a	81.3%	a	−17.5%	a	32.5%	a	31.1%	a
Mineral fertilizer	62.5%	a b	77.0%	a	69.7%	b	−27.0%	a	14.8%	b	33.6%	a
Wet sewage	62.0%	a b	70.1%	a	70.7%	b	−26.6%	a	29.7%	a	32.8%	a
Dry sewage	64.0%	a	70.2%	a	68.7%	b	−21.2%	a	31.4%	a	37.3%	a

Significant differences ($P < .05$) among treatments indicated by different letters in the same column.

the leaf fall was lower and occurred later in the control treatment, possibly due to less competition for water among the trees of the same stand and consequently less water stress. Tree foliage biomass in the control treatment was about half that in the other treatments for the first 3 years after planting (Table 4), and a lower evaporative demand in this treatment might have reduced intertree competition during dry periods.

Concentrations of N, K, Ca, and Mg in the leaf litterfall were affected by the treatments (Table 5). Nitrogen concentrations were significantly higher in the control treatment than in the treatments with application of mineral fertilizers and dry sewage sludge. A low resorption efficiency of N in the control treatment (Table 6) was consistent with the lack of differences between treatments in foliar N concentrations from age 1 year onwards, suggesting that nitrogen was not limiting eucalypt growth, which has been observed elsewhere in this region [39]. By contrast, the concentrations of K in leaf litterfall in the control treatment were half that of the other treatments and were a result of a resorption efficiency for this nutrient being significantly higher in the control treatment than in other treatments. The highest Ca and Mg concentrations were found in the plots with mineral fertilizer addition, probably as a result of the large availability in the soil after dolomite application. No statistical differences between the treatments were found for P and S concentrations within the leaf litterfall. This suggests that other nutrients were limiting tree growth in this area (probably K).

The highest retranslocation of K and Mg were found in the treatments with the lowest foliar concentrations. Other studies in eucalypt plantations have shown that the highest retranslocation of N and P occurs for the trees with the highest concentrations of these elements in fully expanded young leaves [40]. Low differences in N and P concentrations within the fully expanded young leaves sampled the second and the third years after planting in our study might explain the low differences in retranslocation between treatments for these elements. Retranslocation of nutrients during leaf senescence in our study were slightly higher than the values observed in *Eucalyptus globulus* and slightly lower than in *Pinus radiata* plantations in Australia [41]. Negative values of Ca retranslocation were most probably a result of an accumulation of Ca in senescent leaves, as already shown for other tree species [42, 43].

Mineral fertilizer and sludge applications led to large differences in returns to the soil by litterfall for P, K, Ca, and Mg (Table 5). They were probably partly explained by the large differences between the amounts of N, P, S, Ca, and Mg applied to the mineral-fertilized plots and the sludge plots (Table 3). Application of sewage sludge and mineral fertilizers led to significantly larger amounts of K and Ca returning to soil with leaf litterfall than in the control treatment. Application of $10\,Mg\,ha^{-1}$ of sludge led to an increase of about 35% in the amount of P returning to the soil through litterfall in comparison with the mineral fertilization and control treatments. However, the proportion of

Table 7: Mean dry matter and nutrient amounts in the leaf litter accumulated on the soil surface in each treatment (average for the four seasons, the third year after planting).

Treatment	Biomass Mg ha^{-1}		N kg ha^{-1}		P		K		Ca		Mg		S	
Control	2.9	a	37.4	a	1.3	a	1.5	B	18.9	b	5.7	B	2.5	a
Mineral fertilizer	3.9	a	46.7	a	1.6	a	2.5	A	26.2	a	7.9	A	2.9	a
Wet sewage	3.3	a	39.3	a	1.6	a	2.3	a b	19.6	b	4.6	B	2.2	a
Dry sewage	3.7	a	44.0	a	1.9	a	2.8	A	24.7	a	5.5	B	2.7	a

Significant differences ($P < .05$) among treatments indicated by different letters in the same column.

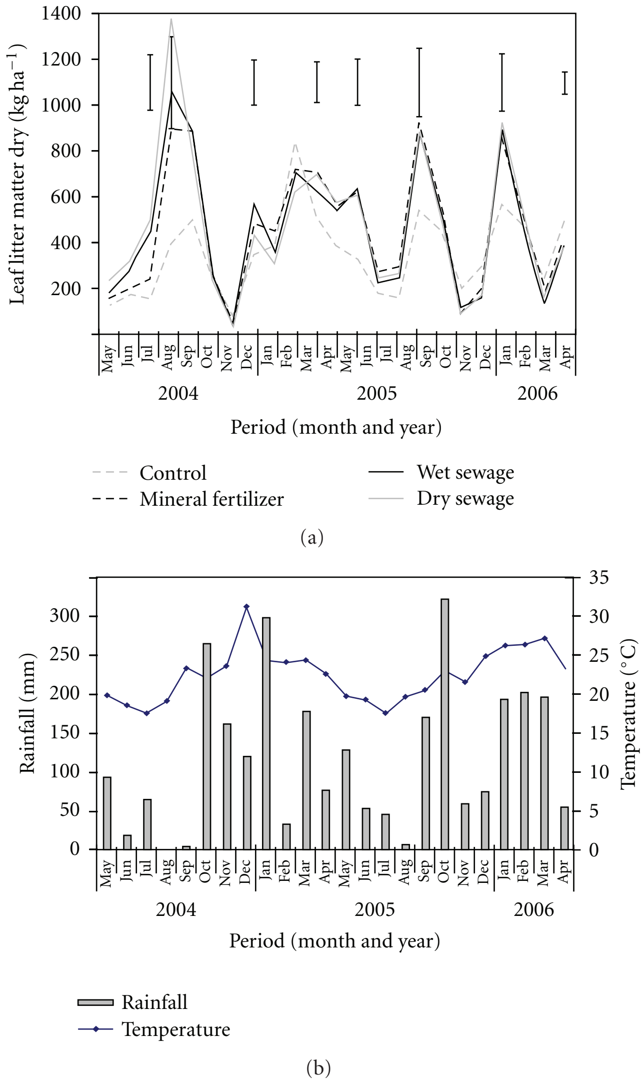

Figure 2: Monthly litterfall production (a), and rainfall and mean temperature (b), from May 2004 to March 2006. Vertical bars indicate least significant differences between treatments ($P < .05$). Differences were not significant when bars are not indicated.

P returned to the soil from 1 to 3 years after planting was very small (<1.5%) in comparison with the amounts applied. By contrast, N cycling through litterfall corresponded to a large proportion of the amount of N contained in wet and dry sludges (approximately 30%), with about 110 kg N ha^{-1} returning to the soil from 12 to 36 months after planting in the plots with application of wet and dry sludges. The amount of N commonly applied by Brazilian forest companies for the whole eucalypt rotation is of the same order of magnitude. The amount of Mg returning to the soil with litterfall was higher in the mineral fertilization treatment than in the treatments with sludge application and the control treatment, probably as a result of the large amount of Mg applied in the dolomite. The amounts of N and S in leaf litterfall were not significantly different between treatments, despite 3 times more N and 12 times more S applied in the MF than in the WS and DS treatments.

Leaf decomposition rates in the forest floor, assessed through litter bags, tended to decrease over time (Figure 3). Soluble compounds are commonly released during the initial stages of the process, followed by the most recalcitrant compounds such as lignin [44]. Litter bags in our study were installed in the field at the onset of the rainy season, so favorable climatic conditions contributed to the fast early decay observed (25% initial biomass decomposed within 90 days). The decomposition rate of leaf litter produced by eucalypt trees depended on the treatments. However, concentrations of lignin were not significantly different between treatments. An increase occurred in all the treatments throughout the degradation process, from 35% in the initial stage, to 42% at 90 days after litter bag installation, and 65% after 360 days of *in situ* decomposition. Leaf litter bags in the plots with sludge applications (wet and dry) exhibited 51% and 20% higher decomposition rates after 12 months of incubation than in the control and mineral fertilization treatments, respectively (Figure 3). A similar positive effect of nutrient availability on litter decomposition rates was reported by Kozovits et al. [45], after addition of N and P mineral fertilizers in a neotropical savanna. Higher decomposition rates in treatments with nutrient addition (with mineral fertilizer or sludge) were likely to result from a stimulation of micro-organisms by enhanced nutrient availability within leaf litter, and/or indirectly, through changes in microclimate under fertilized trees. Indeed, light, temperature, and soil moisture conditions were probably modified by the higher leaf biomass in the MF, WS, and DS plots than in the control plots.

Dry matter of leaf litter in the forest floor the third year after planting as well as N, P, and S contents were not significantly affected by mineral fertilizer and sludge additions (Table 7). By contrast, the amounts of K, Ca and Mg stored within leaves in the forest floor were lower in the

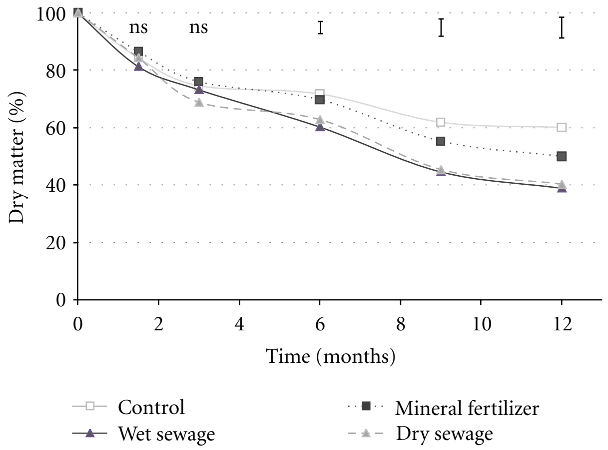

FIGURE 3: Dry matter (%) of leaf litter remaining after different times of decomposition within the litter bags distributed on the forest floor in the 4 treatments (time zero was October 2004). Vertical bars represent the minimum significant value ($P < .05$) and ns means not significant.

control treatment than in the treatments with the highest inputs of each nutrient. The application of sludge led to large additions of N and P and enhanced nutrient recycling through an increase in leaf fall. However, sludge application did not result in significant changes in dry matter, and N and P contents of leaf litter accumulated in the forest floor. Nutrient storage within leaf litter at the soil surface results from a balance between the inputs through leaf fall and the outputs with litter decomposition. High litter decomposition rates after sludge application compensated for the increase in nutrient inputs in leaf fall and led to an unchanged storage of N, P, and S in the leaf component of the forest floor. A similar pattern was found in response to nutrient addition in Australian eucalypt forests [46].

4. Conclusions

In this experiment the application of wet and dry sludge (supplemented with K and B) in the planting rows was a large source of nutrients for eucalypt trees and significantly increased the wood biomass production in comparison with the control treatment. Moreover, the application of wet and dry sewage sludge enhanced the biological cycling of nutrients, which was reflected by higher foliar nutrient concentrations and nutrient returns to the soil through litterfall over the first half of the rotation. Wet or dry sludge applications did not have significantly different effects on nutrient cycling in *Eucalyptus grandis* stands. Our study shows that sewage sludge application in eucalypt plantations may be a valuable option for the final disposal of this residue, reducing considerably the requirements in mineral fertilizers. However, large amounts of ammonia volatilization may cause seedling mortality if planting occur the first days after wet sewage sludge application. Complementary studies are necessary to assess other important environmental impacts of sludge application, in particular, the fate of heavy metals in soils and surface waters.

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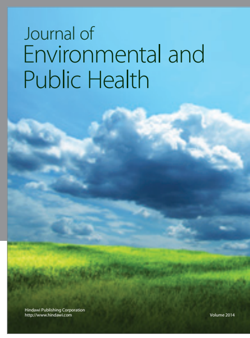
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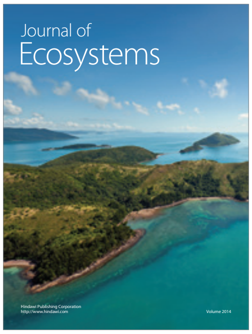
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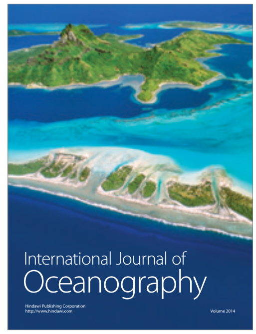
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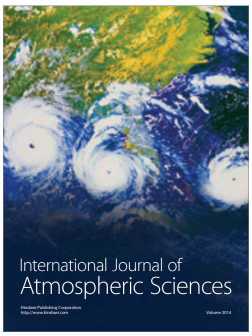
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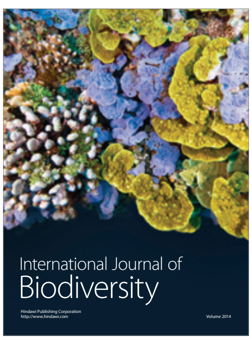
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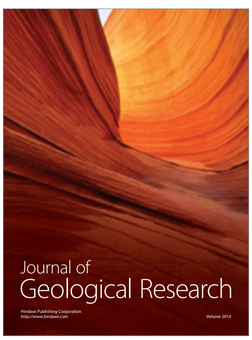
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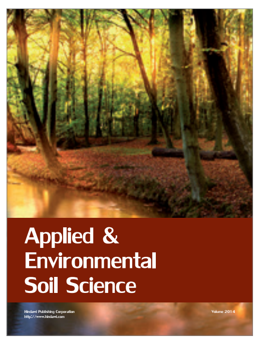
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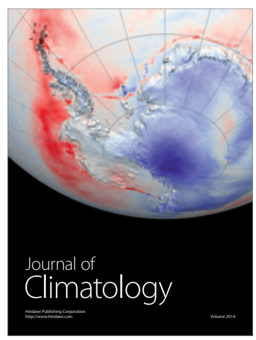
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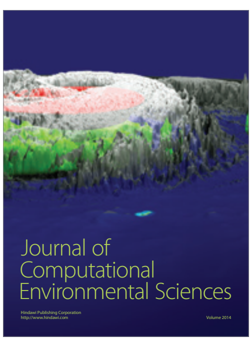
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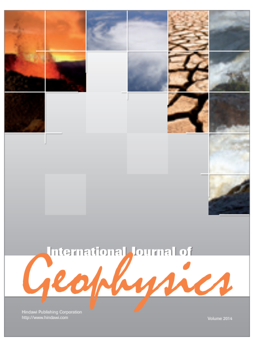
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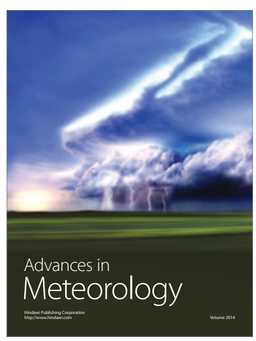
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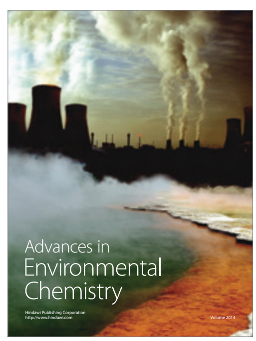
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