forests

MDPI

Article

Fertilization Response, Light Use, and Growth Efficiency in *Eucalyptus* Plantations across Soil and Climate Gradients in Brazil

Renato Meulman Leite da Silva [1], Rodrigo Eiji Hakamada [2], José Henrique Bazani [3], Marina Shinkai Gentil Otto [3,4,*] and José Luiz Stape [5]

1 International Paper of Brasil-Rod. SP340, km171, Mogi Guaçu 13.840-970, São Paulo, Brazil; renato.meulman@ipaper.com
2 Department of Forest Sciences, University of São Paulo, Av. Padua Dias, 11, Piracicaba 13.418-970, São Paulo, Brazil; rodrigo_hakamada@yahoo.com.br
3 4tree Agroflorestal, R. Tiradentes, 435, Piracicaba 13.400-760, São Paulo, Brazil; bazani@4tree.com.br
4 Department of Plant Physiology and Biochemistry, University of São Paulo, P.O. Box 9, Piracicaba 13418-970, Sao Paulo, Brazil
5 Suzano Papel e Celulose, Rod. Br 101, Km 945,5, *s/n*, Mucuri 45930-000, Bahia, Brazil; stape@suzano.com.br
* Correspondence: msgentil@usp.br; Tel.: +55-19-98287-3806

Academic Editors: Reynaldo Campos Santana and Timothy A. Martin
Received: 25 January 2016; Accepted: 19 April 2016; Published: 31 May 2016

Abstract: Fertilization increases productivity in *Eucalyptus* plantations, but losses in productivity associated with soil fertility continue at operational scales. In this study, we evaluated the fertilization response (FR), light use efficiency (LUE) and growth efficiency (GE), *i.e.*, the amount of wood biomass accumulated per unit of light absorbed (LUE) and per unit of leaf area index of *Eucalyptus* plantations. We used a "twin plot" approach, with 161 blocks representing 52,700 ha of planted forests that spanned a broad range of edaphoclimatic conditions in southeastern Brazil. The normal plots (NP) were part of a permanent inventory network, whereas the twin plots (TP) received extra high levels of fertilization and extra weed control after fertilization. The intensive management (twin plots) led to a large increase of 5.3 $Mg \cdot ha^{-1} \cdot year^{-1}$ of wood increment. The region without dry periods and with soils with high clay content was most responsive to fertilization, with a 15% increment in the LUE and 10% increase in the GE of the TPs compared with those of the NPs. Our results suggested that water availability was the primary element affecting productivity and potential response to fertilization. With this information, decisions can be made on which regions should receive priority fertilization investments. However, more research is required to determine the most limiting nutrient in each type of environment.

Keywords: twin plots; intensive management; attainable productivity; water availability

1. Introduction

In recent decades, the global planted area of *Eucalyptus* has increased significantly, covering approximately 10% of the planted forest area worldwide (approximately 12 million ha) [1]. In Brazil, *Eucalyptus* forests occupy 5.1 million ha, of which over 1.1 million are in São Paulo [2]. The supply chain activities of the wood industry, including production, harvesting, and transportation, contribute to the social, economic, and environmental well-being of society. For example, approximately 0.97 ha of native forest is preserved per 1.0 ha of *Eucalyptus* plantation in Brazil [2]; thus, millions of hectares of native forests are preserved. *Eucalyptus* is the most productive planted forest in Brazil, with an average productivity of 40 $m^3 \cdot ha^{-1} \cdot year^{-1}$ [3]. This high productivity is linked to the availability of natural resources, genetic characteristics, and silvicultural management [4]. Productivity in São Paulo State is limited by nutrient deficiencies in soils of low fertility, high nutrient export at harvest, and inefficient nutrient use. The lack of nutrients such as nitrogen, phosphorus, boron, potassium, and magnesium or the excess of nutrients such as calcium, magnesium, and copper limits productivity [5].

Among the natural resources required for plant growth (*i.e.*, water, light, and nutrients), nutrient availability is the resource most easily manipulated by foresters, throughout practices of soil preparation and conservation and applications of fertilizers. The efficiency of this management approach is site-specific for each type of nutrient applied [5–8].

Although knowledge on tree nutrition has advanced, losses in timber productivity associated with nutritional problems continue at operational scales [6]. Trees without equilibrated nutrition may lead to a heterogeneous population, compromising the site productivity [9]. For industrial forests, understanding the value and spatial distribution of the fertilization response is essential for optimal investments in silviculture. A twin plots (TP) design is one approach to quantify the potential response to fertilization. This method establishes paired plots (control and treated plots) across a number of selected sites that represent the landscape [8]. This approach differs from that of the classic experimental design of fertilization experiments because of a greater power of statistical inference across many stands, leading to a broader understanding of fertilization response by covering most of the environmental variability in a short period of time [6]. The control plot may be a normal plot of a permanent inventory network used to measure the actual productivity of a forest under the traditional fertilization regime of a particular owner. The treated plot receives an intensive treatment (high levels of fertilization and weed control) for quantitative insights into the factors that limit operational productivity.

The relationship between resource availability and productivity is expressed in the following equation: *Production = supply + resource capture efficiency + resource use efficiency*. Thus, productivity is strongly influenced by the resource supply and is dependent on the efficiency of the plant in capturing and using these resources [10,11]. Resource use efficiency is an indication of how plants use resources (e.g., biomass produced per unit of resource consumed) and is a determining factor in wood growth. Growth efficiency, e.g., the amount of wood growth per unit of leaf area, also express how active are the leaves in converting carbon into biomass; this process is strongly influenced by leaf nutritional status [12].

The use efficiency of different natural resources has been examined in several studies (*i.e.*, water use efficiency-WUE; light use efficiency-LUE; and nutrient use efficiency-NUE; [10,13]. With increases in the resource supply, e.g., through fertilization, plants use not only nutrients but also other resources more efficiently [10]. For example, an increase in the availability of water can increase LUE, WUE, and nitrogen use efficiency [11]. Soil fertility influences LUE by increasing the amount of light absorbed with an increase in leaf area index (LAI) or by increasing plant efficiency in using radiation absorbed with an increase in leaf retention, as occurs in response to potassium fertilization [14].

Even though nutritional management of *Eucalyptus* leads to significant increases in the productivity and sustainability of forest plantations in Brazil [15–17], few studies have quantified light use and growth efficiency in response to fertilization. The objective of our study was to gain insight into fertilization response, light use efficiency, and growth efficiency of *Eucalyptus* plantations along an edaphoclimatic gradient in southeastern Brazil. Moreover, this study addressed the following questions: What is the difference between actual and potential productivity of *Eucalyptus* forests in southern Brazil? Is there variability in wood productivity on a temporal and spatial scale that can be adjusted by forestry management? Can the increases in productivity correlated with fertilization be explained by increases in light use and growth efficiencies?

2. Materials and Methods

2.1. Site Description and Location

A total of 161 plots (400 m^2, containing 66 trees per plot) were installed in *Eucalyptus* plantations at Suzano Pulp and Paper Company in São Paulo State. The plots were selected based on a random sample of 1832 inventory plots (ranging between 2 and 4 years of age) that spanned a broad range of soil and climatic conditions separated into three regions (Table 1). The selected plots represented a 52,700-ha area of planted forests in three regions in the state of São Paulo (Figure 1).

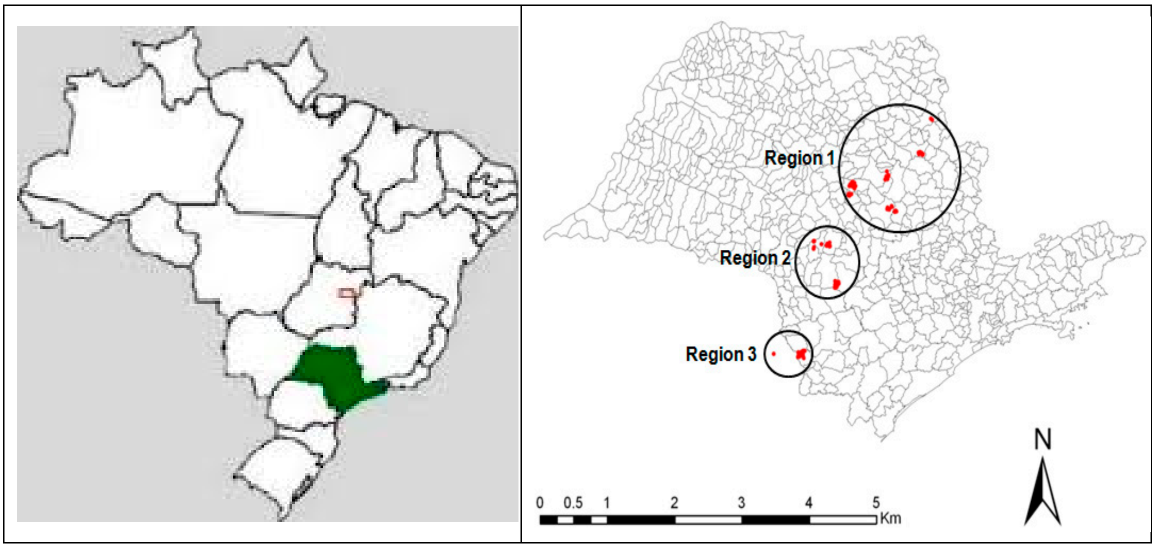


Figure 1. Geographical location of plots in three regions of São Paulo state, Brazil. The circles represent the regions and the red areas the experimental blocks.

Each inventory plot (normal plot–NP) was paired with a second plot (twin plot-TP) of identical dimensions separated by approximately 20 m. A paired t-test was used to test for initial differences in wood biomass between normal and twin plots.

Following plot establishment, soils were sampled at 0–15 and 15–30 cm depths at four locations inside each plot. The soils were analyzed using the methodology described by Raij *et al.* [18] for the following chemical variables: pH ($CaCl_2$), organic matter (OM), P, Ca, K, Mg, and micronutrients. Nitrogen was not directly included in the original analysis, but we used organic matter amount as an indicator of nitrogen soil content [19–21]. Brazilian *Eucalyptus* plantations typically do not respond to nitrogen fertilization [21].

Table 1. Climatic characteristics and classification (Köppen) of the three study regions.

Region	Temperature (°C)			Annual Rainfall (mm)	Annual Soil Water Deficit (mm)	Köppen Classification
	Minimum	Average	Maximum			
1	16.9	22.0	24.2	1461	47 to 110	Aw and Cwa
2	16.5	21.0	23.8	1369	3 to 17	Cfa
3	13.5	17.0	20.1	1549	0	Cfb

Source: Sentelhas *et al.* [22].

All stands received maintenance fertilization with N, P, K, Ca, and Mg according to the conventional prescriptions of the company (Table 2). Twin plots received an additional fertilization that contained 4 t· ha^{-1} of lime, 2.5 t· ha^{-1} of NPK 18:08:18, 800 kg· ha^{-1} of Single Superphosphate, and 300 kg·ha^{-1} of FTE (*Fritted Traced Elements*: 1.8% B, 0.8% Cu, 3% Fe, 2% Mn, 9% Zn, and 0.1% Mo); the fertilizer was applied four times from January 2004 to April 2005. To eliminate the effects of other factors on tree growth, pests, diseases, and weeds were effectively controlled in the plot areas. Both treatments were weed-controlled, but the twin plot received an extra weed control when necessary to avoid weed effects after the extra fertilization (three times during the study period).

Table 2. Total amount of macronutrients (kg·ha^{-1}) applied to the conventional fertilization plots and the extra fertilization twin plots.

Region	N	P	K	Ca	Mg
Region 1	85	35	180	160	40
Region 2	90	22	140	50	25
Region 3	85	25	130	140	60
Extra [1]	270	115	224	942	408

[1] Fertilization split in four applications during the period from January 2004 to April 2005. Additionally, the twin plots received 300 kg·ha^{-1} of FTE-BR12 (5.4 kg·ha^{-1} B; 2.4 kg·ha^{-1} Cu; 9 kg·ha^{-1} Fe; 6 kg·ha^{-1} Mn; 27 kg·ha^{-1} Zn; 0.3 kg·ha^{-1} Mo).

Two primary soil types were included in the study areas. In regions 1 and 2, the typical soil is an Entisol-Psamment, which has a sandy texture, low clay content, low cation exchange capacity, and low base saturation. In region 3, the typical soil is an Ultisol, which has a clay texture (clay content > 40% in the 0–30 cm layer), with twice the organic matter content and higher K content than in regions 1 and 2 (Table 3). The differences in physical and chemical properties between the two soil layers (0–15 and 15–30 cm) were small. The nutrient content of the surface layer (0–15 cm) was higher than that in the deeper layer.

Table 3. Soil physical and chemical properties at the three sites.

Region	Clay [1]	Silt [1]	Sand [1]	pH [2]	OM [3]	P-res [4]	K [4]	Ca [4]	Mg [4]	H+Al [5]	SB [6]	CEC [7]	BS [8]
#		%			g·kg^{-1}	mg·kg^{-1}				mmol$_c$·kg^{-1}			%
						Soil depth 0–15 cm							
1	9	2	90	4	17	9	0.4	9	1	44	10	55	16
2	11	3	86	4	17	9	0.4	5	1	54	6	60	11
3	41	7	52	4	37	11	0.7	2	2	103	4	107	5
						Soil depth 15–30 cm							
1	9	2	89	4	14	10	0.4	6	1	43	7	50	13
2	11	3	86	4	15	10	0.3	4	1	49	5	54	9
3	42	8	50	4	34	10	0.6	2	1	101	3	104	4

[1] Pipette method [23]; [2] $CaCl_2$ 0.01 mol·L^{-1} with soil solution ratio 1:2.5; [3] Organic matter determined by potassium dichromate and sulfuric acid extraction; [4] Ion exchange resin [18]; [5] Potential acidity estimated by pH SMP method [18]; [6] SB-Sum of bases; [7] CEC-Cation exchange capacity; [8] BS-Base saturation.

2.2. Growth Determination and Fertilization Response

We measured all tree diameters (D) and 20% of tree heights: heights of the other trees were estimated with a site-specific hypsometric regression ($H_{est} = \ln\beta_0 \times \ln(-\beta_1 \times (1/D))$, where H*est* is the estimated height and β_0 and β_1 are the coefficients estimated for each region.

Tree volume (Vol) was estimated from tree diameter (DBH, in cm). Tree height (H, in m) was estimated using a specific taper model developed through the Smalian method and then the *Schumacher-Hall* [24] model was used to determine the individual volume: $\mathrm{Vol} = e(-9.56170571390879 + 1.94813158669387 \times \mathrm{Ln(D)} + 0.868952145305574 \times \mathrm{Ln}(H_{est}))$ ($p = 274$; $R^2 = 0.98$). Basic wood density was determined after cubage of trees using the hydrostatic scale method [25], which was also used to calculate stem biomass.

The mean annual increment at 7 years of age for each plot was calculated to compare the paired plots and the fertilization response (FR) of each pair, in each period. The FR was determined using the equation proposed by Ferreira and Stape [6]: FR = $(CAW_T/BIOM_T - CAW_N/BIOM_N) \times ((BIOM_T + BIOM_N)/2)$, where *CAW* = current annual woody increment (Mg· ha^{-1}· year^{-1}); *BIOM* = stem initial biomass (Mg· ha^{-1}); and $_T$ = twin plot and $_N$ = normal plot.

2.3. Leaf Area Index, Light Use Efficiency, and Growth Efficiency

Leaf area index (LAI) was determined ($m^2{}_{leaf.}m^{-2}{}_{soil}$) using an indirect method of hemispherical photography. Photographs of the forest canopy were collected using an Opteka Fisheye hemispheric lens 0.22× (New York, USA) and a Fujifilm S5000 digital camera (Tokyo, Japan). A total of six photos were taken inside each plot (three photos within rows and three between rows). All photographs were taken using a tripod leveled and positioned centrally with the north axis (azimuth = 0°).

The photographs were analyzed with Hemisfer ® software [26] to calculate the vegetation area index (VAI) of the canopy. To estimate LAI, we used the calibration equation (LAI = $\ln((1.24285 \times \text{VAI})^{-0.82229})$ developed by Giunti Neto *et al.* [27].

Growth efficiency (GE) was calculated [28] using the relationship between current annual increment (CAI) and LAI for a determined period (*n*): GE = CAI_n/LAI_n.

LUE was estimated using the equation proposed by Landsberg and Gower [29] (LUE = $CAI_n \times 100/APAR_n$). Absorption of photosynthetically active radiation was calculated based on the Lambert-Beer law that relates LAI and the coefficient of forest light extinction with the incident radiation ($APAR_n = PAR - PAR^{-k.LAI}$), where *k* is the extinction coefficient of PAR for *Eucalyptus*, 0.45. We used this value based on some work performed for clonal *Eucalyptus* in Brazil [11,30].

Photosynthetically active radiation was approximately 50% of global radiation (Qg) [31]. Global radiation was calculated using the equation $Qg = Q_0 \times 0.16 \times (T_{max} - T_{min})^{-2}$, where Q_0 = extraterrestrial radiation (MJ· m^{-2}· day^{-1}) and T_{max} and T_{min} = maximum and minimum air temperature (°C), respectively. Extraterrestrial radiation was estimated with the equation (1):

$$Q_0 = 37.6 \times \left(10.033 \times cos\left(\frac{N \times 360}{365}\right)\right) \times \left(\frac{\pi}{180 \times hn \times sen\varnothing \times sen\delta + cos\varnothing \times cos\delta \times sen\ hn}\right) \quad (1)$$

where *N* = number of days in a year (1 to 365); *hn* = hour angle sunrise (radians); *Φ* = latitude (radians); and *δ* = solar declination (radians).

2.4. Statistical Analyses

Each pair of twin plots was treated as a repetition and the twin and normal plots were the treatments. Tree growth, CAW, biomass, tree density, LAI, GE, and LUE after treatment with fertilization were analyzed using paired *t*-tests. For comparisons of average growth rate and LAI among different regions, the data were submitted to analysis of variance, hypothesis testing, and Tukey's tests, with a significance level of 0.05. The analysis of variance was based on a completely randomized design.

3. Results

3.1. Productivity Plots

As expected, tree volume was not significantly different between the control and twin plots of each pair before the fertilization treatment (158 m^3· ha^{-1} (TP) *vs.* 157 m^3· ha^{-1} (NP), $p = 0.241$; Figure 2). With this equality, the correct interpretation of comparisons between plots after treatment application was assured.

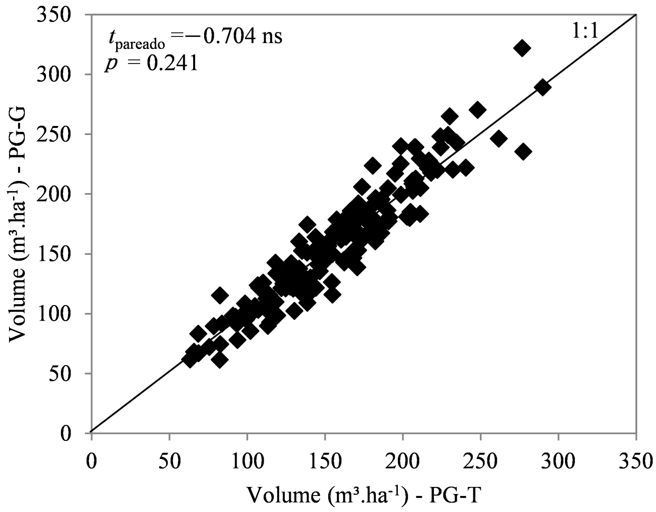


Figure 2. Correlation between initial volume of twin (TP) and normal (NP) plots.

Between 2003 and 2006, the average increase in the annual increment of TP plots was 24% compared with NP plots (Figure 3). In the first year (2003–2004), after the additional fertilization, a small increase was observed in the twin plots (6%). However, responses to fertilization were more evident in the second year of evaluation (2004–2005), and the approximate increases were 30% in region 1, 44% in region 2, and 70% in region 3, with an average of 45%. In the final period (2005–2006), the growth rate in the plantations decreased, and the relative difference between treatments was 30%.

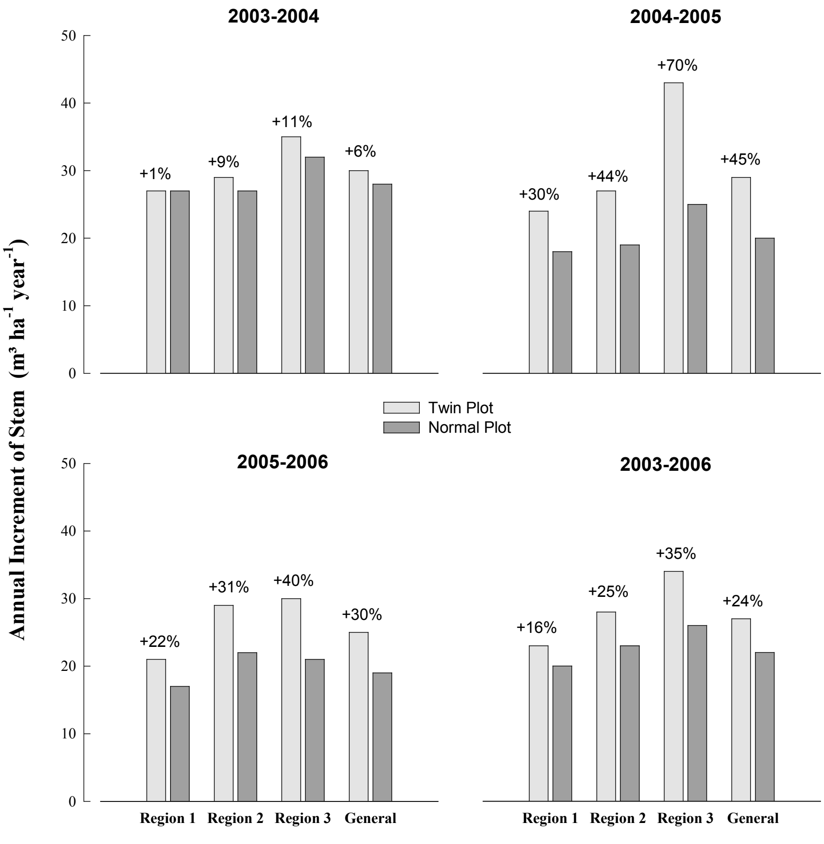


Figure 3. Current annual increment (CAI) for stems in the twin (TP) and normal plots (NP) for the periods between 2003 and 2006 in the three regions.

At 7 years of age, the average attainable productivity of the twin plots (TP) was 49 $m^3 \cdot ha^{-1} \cdot year^{-1}$ (22 $Mg \cdot ha^{-1} \cdot year^{-1}$), which was 11% higher than the productivity of the normal plots (NP), *i.e.*, 44 $m^3 \cdot ha^{-1} \cdot year^{-1}$ (20 $Mg \cdot ha^{-1} \cdot year^{-1}$).

The mean annual increment at 7 years of age (MAI7) in NPs (54 $m^3 \cdot ha^{-1} \cdot year^{-1}$) and TPs (62 $m^3 \cdot ha^{-1} \cdot year^{-1}$) was the highest in region 3. Region 1 had the lowest MAI7, of 38 $m^3 \cdot ha^{-1} \cdot year^{-1}$ (NP) and 41 $m^3 \cdot ha^{-1} \cdot year^{-1}$ (TP). The greatest difference between the actual and the attainable productivity was in region 3 (15%). The maximum productivity occurred in region 3, *i.e.*, 82 $m^3 \cdot ha^{-1} \cdot year^{-1}$, followed by regions 2 and 1 with maximum productivity of 78 and 57 $m^3 \cdot ha^{-1} \cdot year^{-1}$, respectively (Table 4).

Table 4. The average and maximum annual increment at 7 years of age (MAI7) for twin and normal plots.

Region	*n* [1]	Average Increment				Maximum Increment			
		NP	TP	NP	TP	NP	TP	NP	TP
		$m^3 \cdot ha^{-1} \cdot year^{-1}$		$Mg \cdot ha^{-1} \cdot year^{-1}$		$m^3 \cdot ha^{-1} \cdot year^{-1}$		$Mg \cdot ha^{-1} \cdot year^{-1}$	
Region 1	75	38	41	18	19	52	57	24	26
Region 2	53	45	51	21	23	71	78	31	34
Region 3	33	54	62	25	28	70	82	31	36
General	161	44	49	20	22	71	82	31	36

[1] *n* = Total number of plots.

3.2. Fertilization Response (FR)

The average fertilization response (FR) between 2003 and 2006 was 5.3 $Mg \cdot ha^{-1} \cdot year^{-1}$. Region 3 was the most responsive region, followed by regions 2 and 1 (Table 5). The FR was normally distributed (Figure 4), with ~85% of the data showing a positive FR and 50% of the plots with an FR equal to or higher than the average (5.3 $Mg \cdot ha^{-1} \cdot year^{-1}$); similar proportions were found by Ferreira & Stape [6].

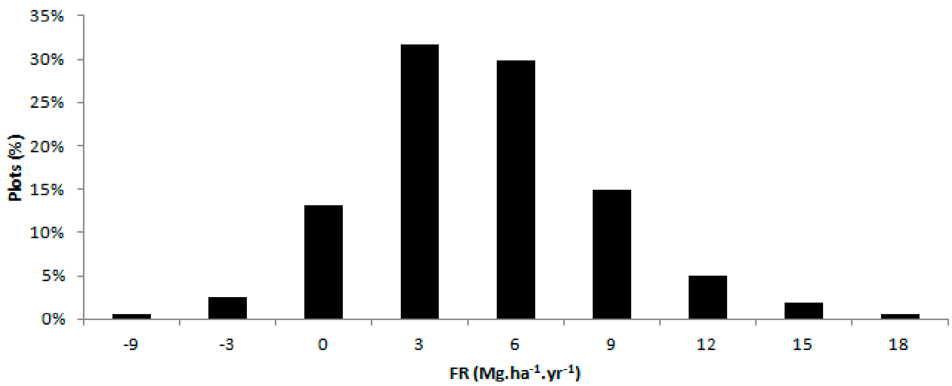


Figure 4. Distribution of fertilization response (FR) in 161 experimental plots.

Table 5. Response to fertilization in the three regions.

Region	Number of Plots	Fertilization Response *	
		$Mg \cdot ha^{-1} \cdot year^{-1}$	
Region 1	75	3.8	c
Region 2	53	5.6	b
Region 3	33	8.2	A

* Values with different letters are significantly different according to Tukey's test at 5% probability.

Fertilization response was also affected by soil characteristics (Table 6). Considering all regions together, organic matter and clay content were the most important variables. Region 1 was strongly affected by physical characteristics, such as clay and sand content. Chemical variables such as potassium and magnesium were more strongly related to FR in region 2. In region 3, the sum of bases and percentage of silt were the most strongly related soil variables influencing the FR.

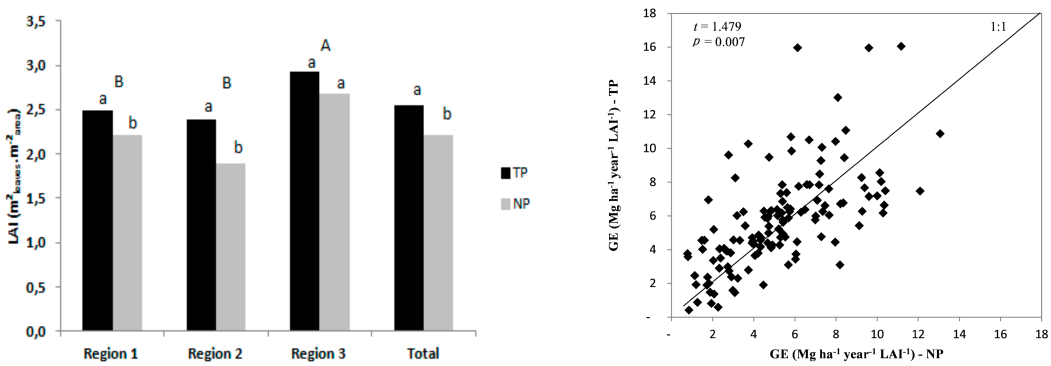
Table 6. Pearson's coefficient relating fertilization response and soil variables.

Variable	General	Region 1	Region 2	Region 3
OM	**0.31** **	−0.16 ns	0.02 ns	0.12 ns
P	−0.18 *	−0.21 *	−0.13 ns	−0.39 *
K	−0.09 ns	−0.32 **	−**0.48** **	−0.24 ns
Ca	−0.22 **	−0.06 ns	−0.08 ns	−0.29 ns
Mg	−0.14 ns	−0.35 **	−**0.42** **	−0.39 *
SB	−0.24 **	−0.11 ns	−0.16 ns	−**0.45** **
CEC	0.21 **	−0.36 **	0.20 ns	0.01 ns
BS	−0.26 **	−0.13 ns	−0.15 ns	−0.25 ns
% clay	**0.26** **	−**0.48** **	−0.19 ns	−0.02 ns
% silt	0.09 ns	−0.01 ns	−0.24 ns	−**0.59** **
% sand	−0.24 **	**0.48** **	0.25 ns	0.15 ns

OM—Organic matter; SB—Sum of bases; CEC—Cation exchange capacity; BS—base saturation. ** Significant at 1% probability; * Significant at 5% probability; ns: non-significant.

3.3. Leaf Area Index, Light Use Efficiency, and Growth Efficiency

In the absence of nutritional limitation, the LAI of the twin plots was 2.6 $m^2 \cdot m^{-2}$, compared with the LAI of 2.2 $m^2 \cdot m^{-2}$ in the normal plots, which was an increase of 15% in the LAI of the TPs. However, in region 3, with the highest productivity, the difference in LAI between NPs and TPs was not significant (Figure 5a).



(**a**) (**b**)

Figure 5. (**a**) Average LAI for each region and treatment. Bars with identical letters are not significantly different. Lowercase letters represent the comparisons of treatments and uppercase letters represent the differences between regions (p = 0.05); (**b**) Correlation between growth efficiency (GE) in twin plots (TP) and normal plots (NP).

In additional, the growth efficiency (GE) of the twin plots was higher (10%) than that of the normal plots, with values of 5.8 and 5.3 $Mg \cdot ha^{-1} \cdot year^{-1}$, respectively, the difference was significant ($p > 0.05$; Figure 5b).

The light use efficiency (LUE) in the twin plots, 0.65 $g \cdot MJ^{-1}$, was 15% higher than that in the normal plots, 0.56 $g \cdot MJ^{-1}$ ($p > 0.05$; Figure 6).

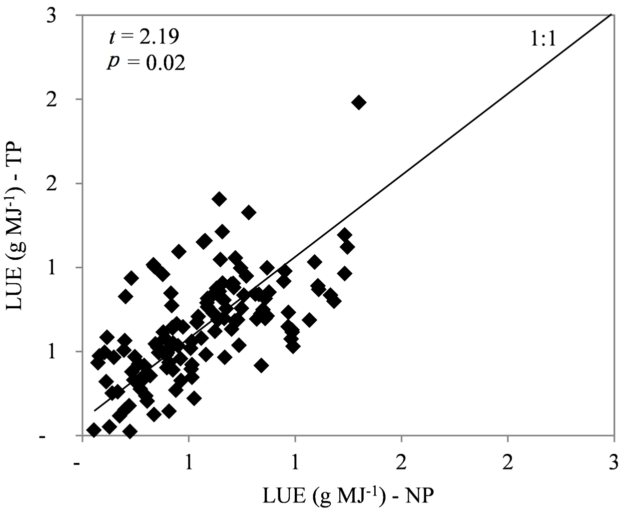


Figure 6. Correlation between light use efficiency (LUE) in twin plots (TP) and normal plots (NP).

4. Discussion

The additional fertilization led to large increases in wood increment, with an average response in the annual increment of 5.3 $Mg^3 \cdot ha^{-1} \cdot year^{-1}$. Similar results were found in other studies, with responses of 4.8 $Mg^3 \cdot ha^{-1} \cdot year^{-1}$ [8] and 4 $Mg^3 \cdot ha^{-1} \cdot year^{-1}$ [6] in *Eucalyptus* plantations in São Paulo State.

Region 3 was the most responsive to fertilization, which can be explained primarily by the climate, with no dry periods, and by the high clay content in the soils; consequently, the water retention capacity and organic matter content were high. Plant growth is controlled by the most limiting resource, according to Liebig's law of the minimum [32]. In tropical regions where water and light are not limiting resources, nutrition starts to be important and normally limits wood growth [29]. For region 3, the negative correlation of FR with the sum of bases and the silt content, which is an indicator of the primary source of nutrients [33], revealed nutritional aspects interfere more with FR than water availability.

In region 1, the climate has extended dry periods and the soils are sandy, which resulted in the lowest productivity (Table 4). Soil physical properties, particularly the clay content, are directly correlated with wood quality (lignin and holocellulose content) and the productive capacity of a site [34]. In this region, where water is a limiting factor, the extra addition of nutrients did not lead to an extra amount of wood, confirmed by the positive correlation between the FR and sand content.

The largest response to fertilization was in the region that also had the highest productivity (Region 3), which was different from the response observed by Ferreira and Stape [6]. Therefore, the area with the highest nutrient limitations on growth was also the most productive. Thus, water, the primary growth factor [11,17], was not limiting at this site, whereas in the other regions, particularly in region 1, the most limiting factor was water.

In the twin plots, LAI increased by 15% and GE increased by 10% compared with the normal plots. The increase in leaf area might explain the increase in productivity. Albaugh *et al.* [35] found much larger gains, an increase of 101% in the LAI, in response to fertilization in loblolly pine. In *Eucalyptus nitens* plantations, nitrogen fertilization increased the LAI by up to 3.1 units, *i.e.*, 56% increment [36].

Fertilization increased the LUE and the GE, which was also reported by Binkley *et al.* [37] for *Eucalyptus* and for other forest trees, including loblolly pine [38] and *Liquidambar styraciflua* [39]. These responses might be a result of higher photosynthetic rates with the addition of nutrients [40] or caused by less carbon partitioning to shoots [10,41].

Additional fertilization reduced nutrient limitations in the *Eucalyptus* plantations and increased wood productivity, LAI, and LUE. Thus, we can identify and quantify opportunities to improve the current fertility management of these plantation populations (high probability of response in 85% of the experimental blocks), particularly in region 3. Moreover, with nutrient limitations, wood production was reduced by 5.3 $Mg \cdot ha^{-1} \cdot year^{-1}$. We identified that for all sites, organic matter and clay content were related to FR. Additionally, for the intermediate and high fertility sites (region 2 and 3, respectively), potassium and magnesium, and the sum of bases and the silt content, respectively, were related to FR (Table 6). All of these responses together indicate these variables can be used as diagnostic tools for managers to decide where to invest in fertilization.

Water availability was the primary element affecting productivity and potential response to fertilization. When water resources are available, nutrient limitations become more apparent as the primary difference among the three regions. For practical applications, forest managers can use these results to determine which regions should receive priority in analyses of fertilization investment. For example, on a regional scale, fertilization investments would have a much higher return in region 3 compared with the other regions because of the greater potential for response and generation of economic returns from the plantation forests. Our findings do not provide exact information of where the responses would occur, but the main drivers are described in Table 6 (quantity of organic matter, clay content, potassium, magnesium, sum of bases and silt content). Fisher and Binkley [42] proposed a decision support method to minimize the risks. According to the authors, the risks are related to the average and variance of the response, being a high negative risk if the response is low and with a high variance. In our case, the high percentage of plots that had a positive FR (85%) could help managers to support a decision to apply fertilizer.

The aim of this study was to quantify the potential wood productivity and the proportional response to fertilization with a complete nutrient supplement when plants were grown across a wide range of soil types and climatic conditions. Future studies should focus on the separate effects of different nutrients following fertilization to determine the most limiting elements in each environment.

Acknowledgments: This research was supported by Suzano Paper and Pulp Company, the University of São Paulo, Forestry Science and Research Institute (IPEF) and São Paulo Research Foundation (FAPESP).

Author Contributions: Main text.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lungo, A.D.; Ball, J.; Carle, J. *Global Planted Forests Thematic Study: Results and Analysis*; Planted Forests and Trees Working Paper; The Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2006.
2. Associação Brasileira Dos Produtores De Florestas Plantadas. *Anuário Estatístico ABRAF 2014: Base Year 2013*; Associação Brasileira Dos Produtores De Florestas Plantadas: Brasília, Brazil, 2014; p. 74.
3. IBÁ. Indústria Brasileira de Árvores. Available online: http://www.iba.org/shared/iba_2014_pt.pdf (accessed on 10 June 2015).
4. Zen, S. Influência da Matocompetição em Plantios de *Eucalyptus grandis*, Série técnica. *IPEF* **1987**, *4*, 25–35.
5. Sgarbi, F. Produtividade do *Eucalyptus* sp. em Função do Estado Nutricional e da Fertilidade do Solo em Diferentes Regiões do Estado de São Paulo. Ph.D. Thesis, Superior School of Agriculture Luiz de Queiroz, University of Sao Paulo, Piracicaba, Brazil, 2002; p. 101.
6. Ferreira, J.M.A.; Stape, J.L. Productivity gains by fertilization in *Eucalyptus urophylla* clonal plantations across gradients in site and stand conditions. *South. For.* **2009**, *71*, 253–258.
7. Laclau, J.P.; Ranger, J.; Gonçalves, J.L.M.; Maquère, V.; Krusche, A.V.; M'bou, A.T.; Nouvellon, Y.; Saint-Ándré, L.; Bouillet, J.-P.; de Cassia Piccolo, M.; *et al.* Biogeochemical cycles of nutrients in tropical Eucalyptus plantations Main features shown by intensive monitoring in Congo and Brazil. *For. Ecol. Manag.* **2010**, *259*, 1771–1785. [CrossRef]

8. Stape, J.L.; Binkley, D.; Jacob, W.S.; Takahashi, E.N. A twin-plot approach to determine nutrient limitation and potential productivity in *Eucalyptus* plantations as landscapes scales in Brazil. *For. Ecol. Manag.* **2006**, *223*, 358–362. [CrossRef]
9. Hakamada, R.E.; Stape, J.L.; Lemos, C.C.Z.; Almeida, A.A.; Silva, L.F. Uso do inventário florestal e da uniformidade entre árvores como ferramenta de monitoramento da qualidade silvicultural em plantios clonais de eucalipto. *Sci. For.* **2015**, *43*, 27–36.
10. Binkley, D.; Stape, J.L.; Ryan, M.G. Thinking about efficiency of resource use in forests. *For. Ecol. Manag.* **2004**, *193*, 5–16. [CrossRef]
11. Stape, J.L.; Binkley, D.; Ryan, M.G. *Eucalyptus* production and the supply, use and efficiency of use of water, light and nitrogen across a geographic gradient in Brazil. *For. Ecol. Manag.* **2004**, *193*, 17–31. [CrossRef]
12. Nilsson, U.; Allen, H.L. Short- and long-term effects of site preparation, fertilization and vegetation control on growth and stand development of planted loblolly pine. *For. Ecol. Manag.* **2003**, *175*, 367–377. [CrossRef]
13. Otto, M.S.G.; Hubbard, R.M.; Binkley, D.; Stape, J.L. Dominant clonal *Eucalyptus grandis x urophylla* trees use water more efficiently. *For. Ecol. Manag.* **2014**, *328*, 117–121. [CrossRef]
14. Laclau, J.P.; Almeida, J.C.R.; Gonçalves, J.L.M. Influence of nitrogen and potassium fertilization on leaf lifespan and allocation of above-ground growth in *Eucalyptus* plantation. *Tree Physiol.* **2009**, *29*, 111–124. [CrossRef] [PubMed]
15. Barros, N.F.; Novais, R.F.; Neves, J.C.L.; Leal, P.G.L. Fertilizing eucalypt plantations on the Brazilian savannah soils. *S. Afr. For. J.* **1992**, *160*, 7–12.
16. Gonçalves, J.L.M.; Barros, N.F.; Nambiar, E.K.S.; Novais, R.F. Soil and stand management for short-rotation plantations. In *Management of Soil, Water, and Nutrients in Tropical Plantation Forests*; Nambiar, E.K.S., Brown, A., Eds.; ACIAR Monograph 43; Australian Centre for International Agricultural Research: Canberra, Australia, 1997; pp. 379–418.
17. Gonçalves, J.L.M.; Stape, J.L.; Laclau, J.-P.; Bouillet, J.-P.; RANGER, J. Assessing the effects of early silvicultural managements on long-term site productivity of fast-growing Eucalypt plantations: The Brazilian experience. *South. For.* **2008**, *70*, 105–118. [CrossRef]
18. Van Raij, B.; Andrade, J.C.; Cantarella, H.; Quaggio, J.A. *Análise Química para Avaliação da Fertilidade de Solos Tropicais*; Instituto Agronômico de Campinas: Campinas, Brazil, 2001; p. 285.
19. Gonçalves, J.L.M.; Mendes, K.C.F.S.; Sasaki, C.M. Mineralização de nitrogênio em ecossistemas florestais naturais e implantados do estado de São Paulo. *Rev. Bras. Ciênci. Solo* **2001**, *25*, 601–616. [CrossRef]
20. Gonçalves, J.L.M.; Alvares, C.A.; Higa, A.R.; Silva, L.D.; Alfenas, A.C.; Stahl, J.; Ferraz, S.F.B.; Lima, W.P.; Brancalion, P.H.S.; Hubner, A.; *et al.* Integrating genetic and silvicultural strategies to minimize abiotic and biotic constraints in Brazilian Eucalypt plantations. *For. Ecol. Manag.* **2013**, *301*, 6–27. [CrossRef]
21. Pulito, A.P.; Leonardo de Moraes Gonçalves, J.; Smethurst, P.J.; Junior, J.C.A.; Alcarde Alvares, C.; Rocha, J.H.T.; Hübner, A.; de Moraes, L.F.; Miranda, A.C.; Kamogawa, M.Y.; *et al.* Available Nitrogen and Responses to Nitrogen Fertilizer in Brazilian Eucalypt Plantations on Soils of Contrasting Texture. *Forests* **2015**, *6*, 973–991. [CrossRef]
22. Sentelhas, P.C.; Pereira, A.R.; Marin, F.R.; Angelocci, L.R.; Alfonsi, R.R.; Caramori, P.H.; Swart, S. Balanços Hídricos Climatológicos de 500 Localidades Brasileiras. Piracicaba: Núcleo de Monitoramento Agroclimático. Disponível em. 2001. Available online: http://www.esalq.usp.br/departamentos/lce/nurma.htm (accessed on 20 May 2008).
23. Donagemma, G.K.; de Campos, D.V.B.; Calderano, S.B.; Teixeira, W.G.; Viana, J.H.M. *Manual de Métodos de Análise de Solo*, 2nd ed.; Centro Nacional de Pesquisa de Solos: Rio de Janeiro, Brazil, 1997; p. 212.
24. Schumacher, F.X.; Hall, F.S. Logarithmic expression of timber-tree volume. *J. Agric. Res.* **1993**, *47*, 719–734.
25. Barrichelo, L.E.G.; Foelkel, C.E.B.; Brasil, M.A.M. Métodos para determinação da densidade básica de coníferas e folhosas. *IPEF* **1971**, *2*, 65–74.
26. Schleppi, P.; Conedera, M.; Sedivy, I.; Thimonier, A. Correcting non-linearity and slope effects in the estimation of the leaf area index of forests from hemispherical photographs. *Agric. For. Meteorol.* **2007**, *144*, 236–242. [CrossRef]
27. Giunti Neto, C.J.; Stape, J.L.; Silva, S.R.; Hakamada, R.E. *Calibração do Uso de Fotos Hemisféricas, Do LAI—2000 e Do Ceptômetro para Estimativas de Índice de Área Foliar em Plantações de Eucalyptus*; Technical Report; Superior School of Agriculture "Luiz de Queiroz", University of Sao Paulo: Piracicaba, Brazil, 2007; p. 61.

28. Waring, R.H.; Thies, W.G.; Muscato, D. Stem growth per unit of leaf area: A measure of tree vigor. *For. Sci.* **1980**, *26*, 112–117.
29. Landsberg, J.J.; Gower, S.T. *Applications of Physiological Ecology to Forest Management*; Academic Press: Waltham, MA, USA, 1997; p. 354.
30. Almeida, A.C.; Landsberg, J.J.; Sands, P.J. Parametrization of 3-PG model for fast growing Eucalyptus grandis plantations. *For. Ecol. Manag.* **2004**, *193*, 179–195. [CrossRef]
31. Larcher, W. *Ecofisiologia Vegetal*; RiMa: São Carlos, Brazil, 2000; p. 531.
32. Sinclair, T.R. Mineral nutrition and plant growth response to climate change. *J. Exp. Bot.* **1992**, *43*, 1141–1146. [CrossRef]
33. Lana, M.C.; Neves, J.C.L. Capacidade de suprimento de potássio em solos sob reflorestamento com eucalipto do estado de São Paulo. *Rev. Árvore* **1994**, *18*, 115–122.
34. Gava, J.L.; Gonçalves, J.L.M. Soil atributes and wood quality for pulp production in plantations of *Eucalyptus grandis* clone. *Sci. Agric.* **2008**, *63*, 306–313.
35. Albaugh, T.J.; Allen, H.L.; Dougherty, P.M.; Kress, L.W.; King, J.S. Leaf area and above- and belowground growth responses of loblolly pine to nutrient and water additions. *For. Sci.* **1998**, *44*, 1–12.
36. Smethurst, P.; Baillie, C.; Cherry, M.; Holz, G. Fertilizer effects on LAI and growth of four Eucalyptus nitens plantations. *For. Ecol. Manag.* **2003**, *176*, 531–542. [CrossRef]
37. Binkley, D.; Stape, J.L.; Bauerle, W.L.; Ryan, M.G. Explaining growth of individual trees: Light Interception and efficiency of light use by *Eucalyptus* at four sites in Brazil. *For. Ecol. Manag.* **2010**, *259*, 1695–1703. [CrossRef]
38. Campoe, O.C.; Stape, J.L.; Albaugh, T.J.; Allen, H.L.; Fox, T.R.; Rubilar, R.; Binkley, D. Fertilization and irrigation effects on tree level growth, light interception and light use efficiency in Pinus taeda. *For. Ecol. Manag.* **2013**, *288*, 43–48. [CrossRef]
39. Allen, C.B.; Will, R.E.; Jacobson, M.A. Production Efficiency and Radiation Use Efficiency of Four Tree Species Receiving Irrigation and Fertilization. *For. Sci.* **2005**, *51*, 556–569.
40. Clearwater, M.J.; Meinzer, F.C. Relationships between hydraulic architecture and leaf photosynthetic capacity in nitrogen-fertilized Eucalyptus grandis trees. *Tree Physiol.* **2001**, *21*, 683–690. [CrossRef]
41. Giardina, C.P.; Ryan, M.G.; Binkley, D.; Fownes, J.H. Primary production and carbon allocation in relation to nutrient supply in a tropical experimental forest. *Glob. Change Biol.* **2003**, *9*, 1438–1450. [CrossRef]
42. Fisher, R.F.; Binkley, D. *Ecology and Management of Forest Soils*, 3rd ed.; Wiley: New York, NY, USA, 2000.