Open Journal of Forestry
2012. Vol.2, No.4, 225-231
Published Online October 2012 in SciRes (http://www.SciRP.org/journal/ojf)

Scientific Research
DOI:10.4236/ojf.2012.24028

Site Productivity of Clone and Seed Raised Plantations of *Eucalyptus urophylla* and *Eucalyptus grandis* in Southeast Mexico

Reyna Pérez-Sandoval[1], Armando Gómez-Guerrero[1], Aurelio Fierros-González[1], William R. Horwath[2]
[1]Forestry Program, Postgraduate College, Montecillo, Mexico
[2]Department of Land, Air and Water Resources, University of California-Davis, Davis, USA
Email: agomezg@colpos.mx

Received June 27th, 2012; revised August 1st, 2012; accepted August 15th, 2012

The relationship between soil variables and forest productivity of *Eucalyptus urophylla* (Eu) and *E. grandis* (Eg) was studied in commercial forest plantations (CFP) in Huimanguillo, Tabasco, Mexico. The group of Eu included seed and clone raised plantations and the Eg group included only seed raised plantations. Tree measurements and soil sampling were carried out at 56,500-m^2 plots. Two soil depths (0 - 20 and 20 - 40 cm) were sampled and analyzed for physical and chemical properties. Site Index (SI), calculated at year 14 was used as indicator of forest productivity. Simple correlation, multiple and second order regressions were used to test the effect of soil variables on productivity. Results showed that mean annual increments (MAI) of Eu and Eg were comparable to other regions of the world reaching 49 $m^3 \cdot ha^{-1} \cdot y^{-1}$ across a range of low to high soil fertility gradient (15 to 80 $m^3 \cdot ha^{-1} \cdot y^{-1}$). For both species, regardless of the production method (seed or clone), soil texture was the most relevant variable to explain variation in productivity. Eu productivity was correlated to exchangeable Mg (0.3) and Al (0.3) in the 0 - 20 cm soil depth and CEC (0.4) and exchangeable Al (0.6) in the 20 - 40 cm soil depth. Compared to clone plantations, seed plantations showed higher correlations between soils properties and productivity. Aluminum saturation was negatively related to Eg productivity. The highest correlation between soil and productivity were found for Eg, with soil P-availability and aluminum saturation explaining 82% and 85% of the variation, respectively. This works shows that low fertility soils, previously used as pasturelands can be productive for forest plantation purposes and contribute to carbon sequestration.

Keywords: Forest Plantations; Forest Soils; Site Index; Fast Growing Species

Introduction

Commercial tropical forest plantations (CFP) can relieve pressure on primary forests and meet timber supply needs, support local economies and stimulate biomass and soil carbon sequestration (Diaz-Balteiro & Rodriguez, 2006; Lima et al., 2006). The increasing demand for wood products and the benefits of sequestering carbon dioxide are important aspects of forests plantation, however, more information is needed on soil resource demands and environmental impacts from fast-growing forest species (Laclau, 2009). This information is especially needed to plant trees on marginal lands such as degraded agricultural and pasture and to ensure sustainable forest production practices.

Eucalyptus is the most important genus planted in CFP worldwide and shows a broad productivity response depending on species, clones and soils factors (Onyekwelu et al., 2011). *Eucalyptus sp*. have some of the highest net primary productivity rates up to 49 $m^3 \cdot ha^{-1} \cdot y^{-1}$ (Hubbard et al., 2010). Mean annual increments of clone plantations of *Eucalyptus sp*. with no fertilization, with fertilization and fertilization combined with irrigation are 33, 46 and 62 $m^3 \cdot ha^{-1} \cdot y^{-1}$, respectively (Stape et al., 2010). The high biomass accumulation potential makes *Eucalyptus* sp. a good prospect for timber, wood products and carbon sequestration projects. Afforestation with fast growing species has been proposed as a strategy for mitigating carbon dioxide emissions but there is a dearth of information on the sustainability of these plantations and more information is needed to broadly implement carbon sequestration projects, especially on low productivity sites.

Some tropical areas of the world have the highest potential to support CFP with fast-growing species due to adequate soil moisture and favorable climatic conditions; however, soil nutrient availability negatively impact net primary productivity and sustainable tree growth (Ryan et al., 2010). These areas also often contain highly weathered soils, which may affect nutrient availability and present other issues such as high exchangeable Al (Van Wambeke, 1992). Information on the productivity of forest systems around the world is important to project future trends in carbon cycle and timber products. The Southeast region of Mexico has a high potential for CFP and since the 90's specific government programs have supported the establishment of CFP with *Eucalyptus* sp. (Ceccon & Martinez-Ramos, 1999). However, few studies on productivity and soil factors in tropical Southeast Mexico have been done to support implementation of CFP.

Results from previous studies of world forest systems show that the principal abiotic factors influencing tree growth are related to water supply and soil physical properties (Gonçalves et al., 1997; Fisher & Binkley, 2000; Stape et al., 2004). The effects of soil chemical and biological properties on soil productivity are more difficult to demonstrate, because the duration of their changes as a result of forest activities is less predictable (Grigal, 2000). Soil-plant relationship studies are also important to make accurate forest productivity assessments and optimize carbon sequestration efficiency in climate change mitigation projects (Laffan, 1994; Coops et al., 1998; Stape et al., 2004).

The aim of this study was to find soil variables that show a relationship with the productivity of CFP of *Eucalyptus urophylla* and *Eucalyptus grandis* on Haplic Acrisols and Gleyic Cambisols (FAO, 1989) formerly occupied by extensive cattle ranching. The study performed in 56 sites provide a comprehensive analysis of soil effects on CFP productivity, encompassing an array of soil physical and chemical properties to investigate responses of seed and clone raised plantations in southern Mexico.

Materials and Methods

Site Location and Description

Fifty six 500-m^2 plots were randomly established on 21 areas. Larger areas had 2 - 3 plots with at least 400 m and with apparent contrast in productivity. plantation areas of commercial forestry operations located in the municipality of Huimangillo, Tabasco, in Mexico (17˚19’ North latitude and y 93˚23" West longitude) (**Figure 1**). The 56 sampling sites included two species, *Eucalyptus urophylla* (Eu) ($49/56$) and *E. grandis* (Eg) ($7/56$). Eg plantations included seed and clone raised ($9/49$), and ($19/49$) respectively. A set ($21/49$) of sites with a seed-clone mix of 50/50 was also analyzed. All Eg plantations were seed raised. Ages for Eu and Eg plantations ranged from 4 to13 years old. Mean annual temperature and precipitation at the study area are 2˚C and 2260 mm, respectively (**Figure 1**). Soils types are Haplic Acrisol and Gleyic Cambisol (FAO, 1989). Previous land use of the sites was pasturelands and conversion to forestry was done to explore systems with a higher return on investment compared to cattle ranching alone. The site preparation for the establishment of all plantations is the same and includes herbal stratus removal, sub-soiling (60 cm depth) and initial fertilization (18-46-00).

Soil Analysis

Soil samples were collected from each plot. Five sampling points on the plot were used to make a composite soil sample for two soil depths 0 - 20 and 20 - 40 cm. Soil analyses were performed according to the Mexican Norm (NOM-021- REC-NAT-2000, 2001), including, pH (KCl 1M, 1:2), organic matter (OM) (Walkley and Black), total N (TN) (Kjeldahl), available P (P) (Bray y Kurtz 1), cation exchange capacity (CEC), exchangeable cations (Ca, K, Mg), (ammonium acetate 1 N, pH 7), exchangeable Aluminum (E-Al) (Barnhissel and Bertsch), soil texture (Bouyoucos) and soil moisture at field capacity (FC) (–0.03 MPa) and soil bulk density (Paraffin method). Aluminum saturation (Al-Sat) was estimated as E-Al/(Ca, K, Mg) + E-Al) × 100 (Van Wambeke, 1992). Subscripts 1 and 2 will be associates to the abbreviations of soil variables for the two soil depths 0 - 20 and 20 - 40 cm, respectively.

Site Index (SI)

The height of five dominant trees from each plot was measured to estimate SI. The SI was estimated from an equation relating tree height and age using a base age of 14 years. The equation was developed from the measurements of 1192 500-m^2-circle plots located around the study area. The general SI equation describing the trend for all plant production methods, seed, clone, and the mix, was as follows.

$$SI = H_d \times \exp\left(1.702389 \times \left(1/A_i^{0.735836} - 1/A_b^{0.735836}\right)\right) \quad (1)$$

where SI = site index (m); H_d = average height of five dominant trees in the plot (m), A_i = age of the plantation and A_b = base age of 14 years. The analytical method for the SI equation is explained in Gómez-Tejero et al. (2009).

Individual tree volume was estimated from Equation (2) derived from the analysis of 635 trees, from which 459 and 176 were seed and clone raised, respectively. Both equations, for SI and individual tree volume were developed by De los Santos (2009, unpublished data) with measurements of trees growing in the same study area. Stand volume per hectare and potential productivity (m^{-3}·ha^{-1}·y^{-1}) was estimated using the average tree volume of each site and expanding the measurements to 1100 trees per ha. Depending on the plantation management and final

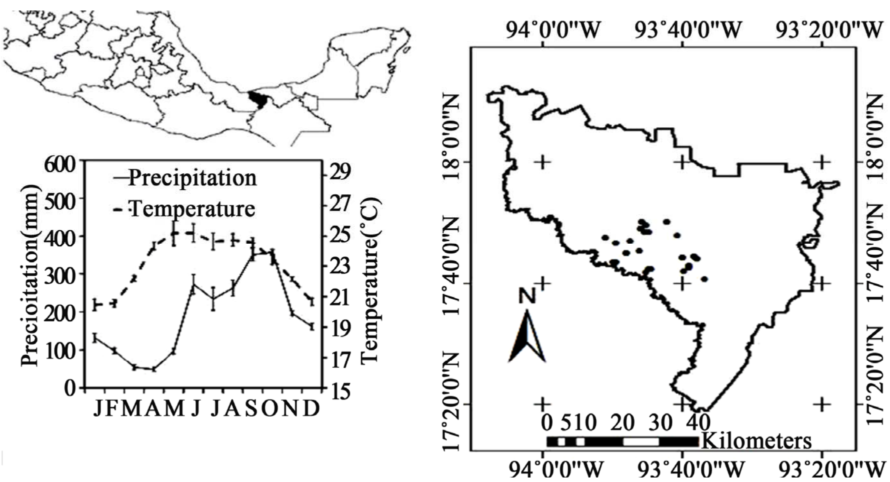

Figure 1.
Study sites locations and climate conditions.

timber products in the study area, the number of trees per ha varies from 800 to 1100. However, we estimated potential productivity with 1100 trees per hectare as this was the stock density for pulp production in the study plots used in this study. The stand volume divided by the age of the plantation gave an estimate of the mean annual increment of the plantations.

$$V = 0.000084 \times D^{1.731858} \times H^{0.955688} \times A^{0.018002} \quad (2)$$

where: V = Tree volume in m^3; D = diameter in cm; H = height in m; and A= age in years.

Statistical Analysis

A correlation analysis was used to explore how soil variables explain variations in productivity, as represented by SI across sites. Multiple regressions using the stepwise selection method were used to determine the combination of soil variables that explained the variation of forest productivity. Also, second order equations to explain SI were tested. Second order equations were used to determine if any of the soil variables showed a threshold at which the productivity of the plantations was reduced. Because no all combinations of plant production methods and species were established on each area, the analyses were carried out in three ways: 1) Analyzing all Eu sites regardless of production method, Seed, Clone or Mix; 2) Analyzing Eu by production method; and 3) Analyzing the group of Eg plantations that were all seed raised. All analyses were done using Statistical Analysis System (SAS) for Windows 9.0.

For presentation purposes, the subscripts, $_{\text{global}}$, is used for the analyses of Eu plantations regardless of the origin of the plants (Seed, Clone or Mix). The subscripts $_{\text{seed, clone,}}$ and $_{\text{mix}}$ are used for the analyses of Eu plantations raised from seed, clone and mix, respectively. In analogous way, the subscript $_{\text{grandis}}$ denotes the analysis for Eg plantations which were all seed raised plantations

Results

Soil Variables

The mean soil pH among the study sites in the 0 to 20 cm soil was 4.8 and ranged from 3.7 to 5.6. Clay content ranged from 9 to 45% in the 0 to 20 cm soil. The highest coefficient of variation of soil properties were seen for P-availability, exchangeable cations and base saturation with increased variation with soil depth. Cation exchange capacity decreased from 8.2 Cmol$_c$kg^{-1} in the first soil depth to 5.8 Cmol$_c$kg^{-1} in the second soil depth. Aluminum saturation ranged from 4.2% to 91% in all soil depths. Other soil parameters and basic statistics for the study sites are shown in **Table 1**.

Table 1.
Soil variables at the study sites.

	Soil Depth (cm)							
	0 - 20				20 - 40			
Variable	Mean	Min	Max	CV (%)	Mean	Min	Max	CV (%)
pH	4.8	3.7	5.6	6	4.8	3.9	6	6
OM (%)	5.8	1.6	11.6	38	3.5	1.4	7.4	40
P (mg·kg^{-1})	2.7	0.1	13.6	81	2.4	0.1	12.8	121
K (Cmol$_c$Kg^{-1})	0.1	0	0.4	100	0.1	0	0.4	100
Ca (Cmol$_c$Kg^{-1})	0.8	0	3.2	88	0.5	0	2.8	100
Mg (Cmol$_c$Kg^{-1})	0.2	0	0.6	100	0.2	0	0.6	100
CEC (Cmol$_c$Kg^{-1})	8.2	2.6	13.2	29	5.8	2.6	10.5	31
BS (%)	15.4	1	47.3	77	13.3	0.6	65.1	91
E-Al (Cmol$_c$Kg^{-1})	0.6	0.1	1.1	33	0.5	0.1	2.1	80
Al-Sat (%)	40.3	12	87.5	50	45.8	4.2	90.9	47
BD g/cm^3	0.6	0.4	1.6	50	0.6	0.4	1.4	33
TN (%)	0.2	0.1	0.3	50	0.1	0	0.4	100
FC (%)	23	10	34	25	22.2	13	35	22
Clay (%)	25.5	9	45	32	31.3	15	64	31
Silt (%)	15.7	2	60	54	14.5	7	26	30
Sand (%)	58.4	11	77	20	54.3	25	73	21

n = 56; CV = Coefficient of variation; OM = Organic matter; P = Phosphorus; K = Potassium; Ca = Calcium; CEC = Cation exchange capacity; BS = Base saturation; Al = Aluminum; E-Al = Exchangeable aluminum; BD = Bulk density; TN = Total nitrogen; FC = Field capacity.

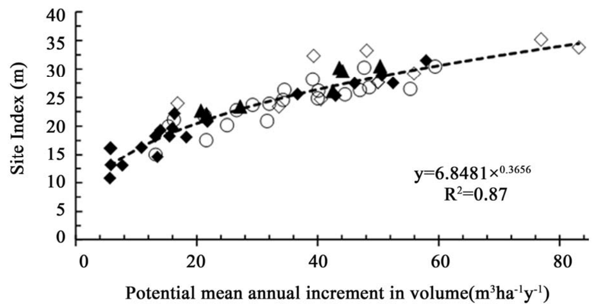

Figure 2.
Relationship between Site index and potential mean annual increments for seed and clone rised plantations of *Eucalyptus urophylla* (Eu) and *E. grandis* (Eg). White diamond = Eu-seed; black diamond = Eu-clone; Circle = Eu-mix; Triangle = eg-seed.

Tree Growth Parameters

SI varied from 10 to 35 m. Clone and seed plantations showed variation in potential mean annual increment in the range 7 - 80 m^3·ha^{-1}·y^{-1}. The highest productivity for Eg was 50 m^3·ha^{-1}·y^{-1} (**Figure 2**). The relationship between SI and mean annual increment correlated well (R^2 = 0.87). Other stand parameters are shown in **Table 2**.

SI$_{\text{global}}$ and Soil Variables for *Eucalyptus urophylla*

Regardless of the plant production method, soil surface variables (0 - 20 cm depth) that were significantly correlated with SI were clay (0.6), sand (–0.4), and exchangeable Mg (0.3), Al (0.3). For the 20 - 40 cm soil depth, the soil variables that significantly correlated to SI were Clay (0.6), Sand (–0.6) exchangeable Al (0.6), CEC (0.4), and Silt (0.3) (Correlation matrix not shown). A seven-variable model explained 62% of the variation of SI$_{\text{global}}$ (**Table 3**, Equation (3)). Soil variables of the first depth included in the model were aluminum saturation, exchangeable calcium, and clay content. Second soil depth variables included in the model were sand, exchangeable alu minum, CEC, and field capacity. There were not second order

Table 2.
Stand Parameters and coefficient of variation (in parenthesis) for the plantations studied

Specie/Group	IS (m)	BDH (cm)	Basal Area ($m^2 \cdot ha^{-1}$)	Volume ($m^3 \cdot ha^{-1}$)	Mean Annual Increment ($m^3 \cdot ha^{-1} \cdot y^{-1}$)	Age (y)
Eu/Global	23.8 (24%)	18.7 (19%)	12.4 (40%)	236 (54%)	33.3 (56%)	7.8 (42%)
Eu/Seed	29.2 (16%)	21.8 (18%)	18.1 (30%)	361.7 (43%)	49.3 (42%)	7.6 (30%)
Eu/Clone	20.3 (29%)	16.9 (19%)	11.3 (41%)	171.7 (49%)	23.7 (74%)	9.0 (39%)
Eu/Mix	23.9 (16%)	17.7 (12%)	12.7 (34%)	188.1 (35%)	34.4 (38%)	5.8 (36%)
Eg/Seed	26.3 (14%)	22.9 (13%)	11.4 (36%)	392.9 (34%)	35.7 (34%)	11.0 (0%)

Eu = *Eucalyptus urophylla*; Eg = *Eucalyptus grandis*; Global = includes all plantations (seed, clone and mix).

Table 3.
Regression equations to explain the site index in the study sites.

Equation	Regression model	R^2	$P \leq$
3	IS_{global}=22.5 – 7.6 ($Sand_2$) + 7.6 (Al_2) – 0.16 (Al-Sat_1) + 0.38 (CEC_2) – 0.35 (FC_2) – 4.36 (Ca_1) + 0.30 + ($Clay_1$)	0.62	0.001
4	IS_{seed} = 26.86 – 2.21 (pH_1) + 1.2 (CEC_2) + 0.11 (Al-Sat_2)	0.96	0.001
5	IS_{clone} = 8.39 + 0.45 ($Clay_2$)	0.36	0.007
6	IS_{mix} = –14.99 +0.56 ($Clay_1$)+3.46 (OM_2)+ 0.61 (BS_2)+0.109 (Al-Sat_2)	0.58	0.054
7	$IS_{grandis}$ =42.41 – 0.31 (Al-Sat_1) + 0.32 ($Silt_2$)	0.94	0.003

IS_{global}=Site index, regardless the plant production method; Subscripts 1 and 2 are for the 0 - 20 and 20 - 40 cm soil depth, respectively. Soil variables abbreviations and subscripts as explained in **Table 1**.

equations that significantly explained SI_{global} (**Table 3**).

SI_{seed} and Soil Variables for *Eucalyptus Urophylla*

For the seed plantations, a three-variable equation with soil chemical variables explained 96% of the variability associated with SI_{seed} (**Table 3**, Equation (4)). Second order equations showed that 60 to 70% of the variation associated with SI_{seed} could be explained with clay or sand content in the second depth (20 to 40 cm) (**Figure 3**). The sum of silt plus clay was also significant with quadratic effects (not shown).

SI_{clone} and Soil Variables for *Eucalyptus urophylla*

Except for clay content in the 20 to 40 cm at the second soil depth the relationships between SI_{clone} and soil variables were not statistically significant. Clay content explained 36% ($P \leq 0.007$) of the variation of SI_{clone} (**Table 3**, Equation (5)). A second order equation with clay content significantly improved the relationship for SI_{clone} explaining 47% of the variation (**Figure 4**).

SI_{mix} and Soil Variables in *Eucalyptus urophylla*

A four-variable model explained 58% of the variation of SI_{mix} (**Table 3**, Equation (6)). Linear or second order equations did not help to improve the relationship in mixed plantations. None of the simple correlations between SI_{mix} and soil variables was significant.

SI_{seed} and Soil Variables in *Eucalyptus grandis*

For Eg a two-variable model explained 94% of the SI_{seed} variation ($P \leq 0.003$) (**Table 3**, Equation (7)). Aluminum saturation and *P* availability in the first and second soil depth respectively, explained more than 70% of the variation with single lineal relationships (**Figure 5**).

Discussion

Soil Variables and Tree Growth Parameters

Regardless of the production method (seed or clone), soil texture was the most relevant variable to explain variation in productivity for both species. According to the Mexican classification (NOM-021-RECNAT-2000) the soils at the study sites are acidic, with low P availability and low soil fertility inferred from low CEC, TN and OM. Results showed no correlation between TN and BD with tree growth. This finding was similar to that observed in Eu and Eg CFP growing in Alfisols and Ultisols in the states of Oaxaca and Veracruz (Delgado et al., 2009). The soil preparation practices and the humid environment in the study sites may have favored low soil strength. The average soil BD in the study sites was 0.6 $g \cdot cm^{-3}$ indicating that physical constraints for root growth are minimal, which likely explains the lack of relationship with forest productivity (Gomez et al., 2002). However, under pastureland use these soils can show soil strength as high as 9 MPa (Geissen et al., 2009).

Stand parameters indicate that soils in the study area can potentially reach high levels of mean annual increment (MAI) with values from 23 to 49 $m^3 \cdot ha^{-1} \cdot y^{-1}$. This productivity falls in the range of that of some *eucalyptus* hybrids plantations (***E. urophylla*** × ***E. grandis***) in South America with MIA from 15 - 60 $m^3 \cdot ha^{-1} \cdot y^{-1}$ (Lugo et al., 1998; ITTO, 2009; Pagano et al., 2009; Almeida et al., 2010). Rodríguez et al. (2009) reported MAI in plantations of *Eucalyptus* nitens in Chile ranging from

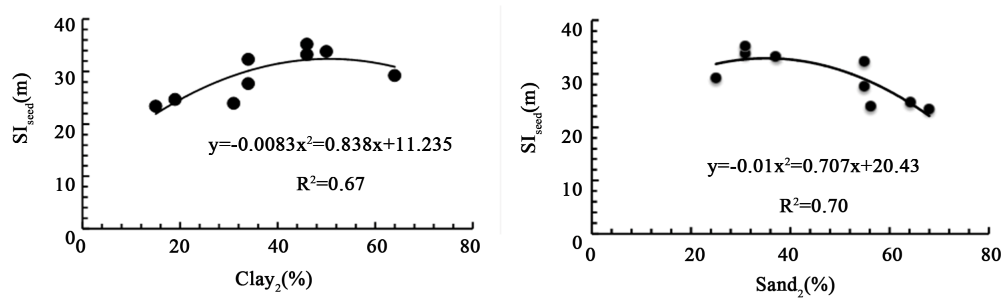

Figure 3.
Relationship between site Index and clay content (left) and sand content (right) at the 20 - 40 cm soil depth for seed raised plantations of *Eucalyptus urophylla*.

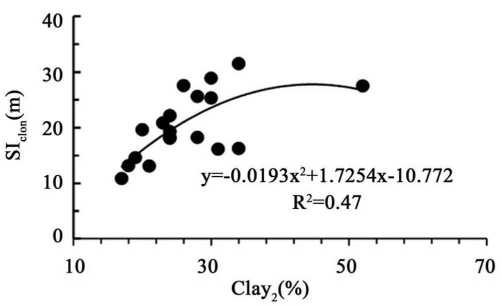

Figure 4.
Relationship between site Index and clay content in the 20 - 40 cm soil depth for clone raised plantations of *Eucalyptus urophylla*.

47 to 52 $m^3 \cdot ha^{-1} \cdot y^{-1}$. Under intensive management practices, genetic improvement and high productivity sites, *Eucalyptus* CFP produced 60 $m^3 \cdot ha^{-1} \cdot y^{-1}$ in MAI (Stape et al., 2006; Stape et al., 2010). With similar species used in this study, Eu, Eg and hybrids in low fertility soils (Dystrophyc Yellow Argisolsol) in Brazil showed similar productivity to our results with 1250 mm of annual precipitation (Almeida et al., 2004). Seppänen (2002) estimated that Eu and Eg can reach a productivity of 40 $m^3 \cdot ha^{-1} \cdot y^{-1}$ in tropical regions of Mexico in high-fertility soils, but the results indicate that higher productivity is likely possible.

SI_{global} and Soil Variables for *Eucalyptus urophylla*

Multiple regression equations with statistical significant parameters have the advantage of identifying the most relevant variables to explain productivity. However in our results the disadvantage of the seven-variable model is its contradicting outcomes, such as factors like exchangeable aluminum and field capacity that showed an opposite effect. However, the correlation analysis with single variables showed positive correlations with of $Clay_1$, $Clay_2$, $Silt_2$ and CEC_2, Mg_1, indicating that for all plantations of Eu, soil texture is the most important variable limiting its productivity. CEC is indirectly related to soil texture in that finer textured soils often have increased CEC. Other soil fertility variables like CEC_2, Mg_1 were also important but the transformation of these variables to test the quadratic effect did not improve the correlations with SI_{globa}.

The positive correlation between SIg_{lobal} and exchangeable aluminum (E-Al_1 and E-Al_2) is an unexpected result because E-Al is related to low pH. Exchangeable aluminum prevents fine root growth limiting the absorptive capacity of the root system. However, some reports point out that *Eucalyptus* sp. show some degree of tolerance to exchangeable aluminum (Silva et al., 2004). Negative relationships with Sand1 and Sand 2 confirm the importance of fine soil particles to increase water holding capacity of the surface soil. Soil texture indirectly influences productivity due to its influence on soil matrix potential and water storage, which directly effects soil water availability. *Eucalyptus* species respond rapidly to changes soil water availability increasing productivity (Hubbard et al., 2010). Acosta (2005) found similar results for Eu and Eg with lower productivity in sandy soils. When soil are prone to anoxic conditions due to high intensity rain events, coarse texture soil could be the best sites for Eu and Eg (Delgado et al., 2009).

The Equation (3) includes other chemical properties whose contribution in the model is not easy to explain. For example, Al and Ca have positive and negative effects, respectively, when the opposite relationship should have been expected. Although Equation (3) in **Table 3** explains 62% of the variation of SI_{global}, is a complex model for interpretation. Therefore, the explanations based on simple correlations are a result with more practical application. More importantly, when the relationship with soil variable describes a second order the trend is more useful as it shows a threshold for productivity.

SI_{seed} and Soil Variables for *Eucalyptus urophylla*

Only CEC_2 (**Table 3**, Equation (2)) shows the expected effect, indicating that for the same values of pH_1 and Al-Sat_2, SI_{seed} increases with higher values of CEC_2. Unexpectedly, higher SI_{seed} values correlate to low pH and higher saturation of Al. This result confirms that Eu performs well in acidic soils with high exchangeable aluminum (Henri, 2001). Results also indicate that, soil acidity in the study sites has not reached critical levels that prevent P availability for Eu. The levels of productivity found in this work are comparable with that of P-fertilized plots of Eu in China with 1800 mm of annual precipitation, where the productivity of Oxysols is limited by P availability (Xu et al., 2005).

Soil texture is very important for the productivity of *Eucalyptus* sp. plantations. The second order equation describing clay content in the 20 to 40 cm soil indicates that productivity will increase until clay content in the second soil depth reaches 50%. Forest productivity decreases when sand content exceeds 35% (**Figure 2**). Thresholds of soil properties are very important as they are useful to screen productive forest soils. The results of this work are in accordance to the findings of Almeida et al. (2004) who reported better productivity of *Eucalyptus* spp. plantations growing in clay loam soil textures than stands growing in clay soils.

SI_{clone} and Soil Variables for *Eucalyptus urophylla*

The productivity of the Eu clone group was not related to soil variables. The relationships between SI_{clone} and soil factors were poor. The productivity of clones of Eu was not negatively influenced by exchangeable aluminum or P availability. However, as in the rest of the groups, soil texture is the more relevant factor related to site productivity. The range where SI_{clone} increases is from 15 to 40% of clay content in the second depth, but higher clay content may lead to reduced productivity (**Figure 3**). Soil texture and available soil water capacity are the most important factors to explain productivity of Eu, Eg and hybrids of these species (Almeida et al., 2009).

SI_{mix} and Soil Variables for *Eucalyptus urophylla*

The variation of SI_{mix} could not be significantly explained with one soil variable. An equation with four soil variables accounted for 58% of the variation of SI_{mix}. The variability associated with the mixed plantations made it difficult to find equations to explain the SImix variation. The four soil variables included in the model (**Table 3**) showed positive relationship with tree growth. The positive effects of clay, organic matter and base saturation are expected results, but not that for aluminum saturation. However, taking into account that only four of the 56 plots showed pH values lower than 4.7, results suggest that the acidity of the study soil in the present is not critical for Eu, but negative effects may occur if the soil pH is lowered by soil management such as fertilization or shorter rotation intervals. Some tree species shows tolerance to soil acidity and moderate activities of soil aluminum are not harmful for some species of *Eucalyptus* (Silva et al., 2004).

$SI_{grandis}$ and Soil Variables for *Eucalyptus grandis*

Contrary to Eu, Eg plantations were negatively influenced by aluminum saturation and positively influenced by silt content. This result is in accordance to Silva et al. (2004) who reported that under controlled experiments Eg was less tolerant to soil aluminum than Eu. Indeed, low to moderate aluminum activities do not inhibit fine root elongation in some species and clones of Eu. This aluminum tolerance has been reported to be related to an internal detoxification process with malic acid (Silva et al., 2004). The results of this work suggest that Eg productivity is negatively influenced after aluminum saturation reaches 50% (Not shown).

This finding is also consistent to the availability of P, which is dependent on pH (**Figure 5**). Eg showed to be more sensible to P availability, this difference between species may be related to the capacity of internal P recycling. Many species of *Eucalyptus* grows in P-deficient soils recycle P internally efficiently P (Xu et al., 2005).

Eg productivity is also explained by silt content, which relates to water holding and soil fertility characteristics of the surface soil. The importance of surface soil texture for forest species has been demonstrated in other works and is related to the ability of the soil to provide water to plants in drought season (Gomez et al., 2002; Garcia-G et al., 2004). The Eg group showed the highest correlation between SI_{seed} and soil variables

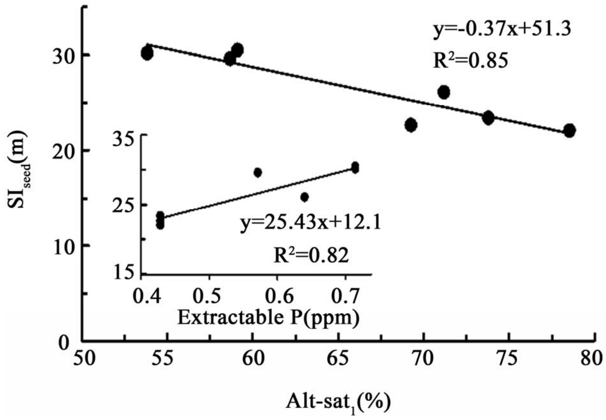

Figure 5.
Relationship between Aluminum saturation in the 0 - 20 cm soil depth and extractable-P in the 20 - 40 cm soil depth for seed raised plantations of *Eucalyptus grandis*.

with a lower number of variables, which indicates a high potential for developing accurate prediction of productivity from soil variables.

Conclusion

Soils at the study sites have low fertility, are acidic and show low availability of phosphorus. Nevertheless, forest productivity of *Eucalyptus urophylla* (Eu) and *E. grandis* (Eg) plantations in the study sites is high and comparable to that of other high productivity regions of the world. Regardless of the *Eucalyptus* species or the plant production method for the establishment, soil texture was the most relevant soil variable to explain changes in productivity. Soil texture also showed both, linear and quadratic relationships with productivity. The relationship between soil texture and soil water is key factor to consider in the establishment of forest plantations of *Eucalyptus* in Southeast Mexico. Aluminum saturation is not negatively related to the productivity of Eu but a negative relationship was seen for Eg. Soil phosphorus availability showed positive correlation with the productivity of Eg but not with that of Eu. This works shows that low fertility soils, previously used as pasturelands can be productive for plantation forestry purposes and could be considered for biomass carbon sequestration projects.

Acknowledgements

We thank the support of Forestaciones Operativas de México SA de CV (FOMEX). Authors and FOMEX declare no to have conflict of interests for publishing this work.

REFERENCES

Acosta, B., Márquez, O., Mora, E., García, V., & Hernández, R. (2005). Uso del método de análisis de componentes principales para la evaluación de la relación suelo productividad en *Eucalyptus* spp. *Forestal Latinoamericana, 37,* 17-44.

Almeida, A. C., Landsberg, J. J., Sands, P. J., Ambrogi, M. S., Fonseca, S., Barddal, S. M., & Bertolucci, F. L. (2004). Needs and opportunities for using a process based productivity model as a practical tool in *Eucalyptus* plantations. *Forest Ecology and Management, 193,* 167-177. doi:10.1016/j.foreco.2004.01.044

Almeida, A. C., Siggins, A., Batista, T. R., Beadle, C., Fonseca, S., &

Loos, R. (2009). Mapping the effect of spatial and temporal variation in climate and soils on *Eucalyptus* plantation production with 3-PG, a process-based growth model. *Forest Ecology and Management, 259,* 1730-1740. doi:10.1016/j.foreco.2009.10.008

Ceccon, E., & Martínez-Ramos, M. (1999). Aspectos ambientales referentes al establecimiento de plantaciones de eucalipto de gran escala en áreas tropicales: Aplicación al caso de México. *Interciencia, 24,* 352-359.

Coops, N. C., Waring, R. H., & Landsberg, J. J. (1998). Assessing forest productivity in Australia and New Zealand using a physiological-based model driven with average monthly weather data and satellite-derived estimates of canopy photosynthetic capacity. *Forest Ecology and Management, 104,* 113-127. doi:10.1016/S0378-1127(97)00248-X

Delgado, C. C. E., Gómez, G. A., Valdez, L. J. R., de los Santos, P. H., Fierros, G. A. M., & Horwath, R. W. (2009). Site index and soil properties in young plantations of *Eucalyptus grandis* and *Eucalyptus urophylla* in southeastern Mexico. *Agrociencia, 43,* 61-72.

Diaz-Balteiro, L., & Rodríguez, L. C. E. (2006). Optimal rotations on *Eucalyptus* plantations including carbon sequestration. A comparison of results in Brazil and Spain. *Forest Ecology and Management, 229,* 247-258. doi:10.1016/j.foreco.2006.04.005

FAO (1989). FAO-UNESCO soil map of the world (revised legend). Reprint of FAO World Soil Resources Report 60. *Technical Paper* No. 20.

Fisher, R. F., & Binkley, D., (2000). *Ecology and management of forest soils*. New York: Wiley.

García-G, R., Gómez, A., López, U. J., Vargas, H. J., & Horwath, W. R. (2004). Tree growth and $\delta^{13}C$ among populations of *Pinus greggii* Engelm at two contrasting sites in central Mexico. *Forest Ecology and Management, 198,* 237-247. doi:10.1016/j.foreco.2004.04.007

Geissen, V., Sánchez, H. R., Kampichler, C., Ramos, R. R., Sepulveda, L.A., Ochoa, G. S., de Jong, B. H. J., Huerta, L. E., & Hernández, D. S. (2009). Effects of land-use change on some properties of tropical soils- An example from Southeast Mexico. *Geoderma, 151,* 87-97. doi:10.1016/j.geoderma.2009.03.011

Gomez, A., Powers, R. F., Singer, M. J., & Horwath, W. R. (2002). Soil compaction effects on growth of young ponderosa pine following litter removal in California's Sierra Nevada. *Soil Science Society of America Journal, 66,* 1334-1343. doi:10.2136/sssaj2002.1334

Gómez-Tejero, J., De los Santos-Posadas, H., Fierros-González, A., & Valdez-Lazalde, R. (2009). Modelos de crecimiento en altura dominante para *Eucalyptus grandis* Hill *ex* Maiden *y E. urophylla* S. T. Blake en Oaxaca, México. *Revista Fitotecnia Mexicana, 32,* 161-169.

Gonçalves, J. L. M., Barros, N. F., Nambiar, E. K. S., & Novais, R. F. (1997). Soil and stand management for short-rotation plantations. In E. K. S. Nambiar, & A. G. Brown (Eds.), *Management of soil, nutrients and water in tropical plantations forests* (pp. 379-417). Canberra: ACIAR Monograph 43.

Grigal, D. F. (2000). Effects of extensive forest management on soil productivity. *Forest Ecology and Management, 138,* 167-185. doi:10.1016/S0378-1127(00)00395-9

Henri, C. J. (2001). Soil-site productivity of *Gmelina arborea*, *Eucalyptus urophylla* and *Eucalyptus grandis* forest plantations in western Venezuela. *Forest Ecology and Management, 144,* 255-264. doi:10.1016/S0378-1127(00)00390-X

Hubbard, R. M., Stape, J., Ryan, M. G., Almeida, A. C., & Rojas, J. (2010). Effects of irrigation on water use and water use efficiency in two fast growing *Eucalyptus* plantations. *Forest Ecology and Management, 259,* 1714-1721. doi:10.1016/j.foreco.2009.10.028

International Tropical Timber Organization (2009). Encouraging industrial forest plantations in the tropics. *Technical Series, 33,* 143.

Laclau, J. P., Almeida, J. C. R., Gonçalves, J. L. M., Saint-André, L., Ventura, M., Ranger, J., Moreira, R. M., & Nouvellon, Y. (2009). Influence of nitrogen and potassium fertilization on leaf life span and allocation of above-ground growth in *Eucalyptus* plantations. *Tree Physiology, 29,* 111-124. doi:10.1093/treephys/tpn010

Laffan, M. D. (1994). A methodology for assessing and classifying site productivity and land suitability for eucalypt plantations in Tasmania. *Tasforests, 6,* 61-67.

Lima, A. M. N., Silva, I. R., Neves, J. C. L., Novais, R. F., Barros, N. F., Mendonca, E. S., Smyth, T. J., Moreira, M. S., & Leite, F. P. (2006). Soil organic carbon dynamics following afforestation of degraded pastures with *Eucalyptus* in southeastern Brazil. *Forest Ecology and Management, 235,* 219-231. doi:10.1016/j.foreco.2006.08.331

Lugo, A. E., Brown, S., & Chapmanan, J. (1988). Analytical review of production rates and stemwood biomass of tropical forest plantations. *Forest Ecology and Management, 23,* 179-200. doi:10.1016/0378-1127(88)90081-3

Norma Oficial Mexicana (2001). Que establece las especificaciones de fertilidad, salinidad y clasificación de suelos. Estudios, muestreos y análisis. Diario Oficial de la Federación del 14 de febrero de 2001. URL (last checked 26 June 2012). http://www.profepa.gob.mx/innovaportal/file/3335/1/nom-021-semarnat-2000.pdf

Onyekwelu, J. C., Stimm, B., & Evans, J. (2011). Review Plantation Forestry. In Günter et al. (Ed.), *Tropical Forestry 8: Silviculture in the Tropics* (pp. 399-454). Berlin: Springer-Verlag.

Pagano, M. C., Bellote, A. F., & Scotti, M. R. (2009). Aboveground nutrient components of *Eucalyptus camaldulensis* and *E. grandis* in semiarid Brazil under the nature and the mycorrhizal inoculation conditions. *Journal of Forestry Research, 20,* 15-22. doi:10.1007/s11676-009-0003-5

Rodríguez, R., Real, P., Espinosa, M., & Perry, D. A. (2009). A process-based model to evaluate site quality for *Eucalyptus nitens* in the bio-bio region of Chile. *Forestry, 82,* 149-162. doi:10.1093/forestry/cpn045

Ryan, M. G., Stape, J. L., Binkley, D., Fonseca, S., Loos, R. A., Takahashi, E. N., Silva, C. R., Silva, S. R., Hakamada, R. E., Ferreira, J. M., Lima, A. M., Gava, J. L., Leite, F. P., Andrade, H. B., Alves, J. M., & Silva, G. G. C. (2010). Factors controlling *Eucalyptus* productivity: How water availability and stand structure alter production and carbon allocation. *Forest Ecology and Management, 259,* 1695-1703. doi:10.1016/j.foreco.2010.01.013

Seppänen, P. (2002). Secuestro de carbono a través de plantaciones de eucalipto en el trópico húmedo. *Foresta Veracruzana, 4,* 51-58.

Silva, I. R., Novais, R. F., Jham, G. N., Barros, N. F., Gebrim, F. O., Nunes, F. N., Neves, J. C. L., & Leite, F. P. (2004). Responses of eucalypt species to aluminum: The possible involvement of low molecular weight organic acids in the Al tolerance mechanism. *Tree Physiology, 24,* 1267-1277. doi:10.1093/treephys/24.11.1267

Stape, J. L., Binkley, D., Jacob, W. S., & Takahashi, E. N. (2006). A twin-plot approach to determine nutrient limitation and potential in *Eucalyptus* plantations al landscape scales in Brazil. *Forest Ecology and Management, 223,* 1358-1362. doi:10.1016/j.foreco.2005.11.015

Stape, J. L., Binkley, D., & Ryan, M. G. (2004). *Eucalyptus* production and the supply, use and efficiency of use of water, light and nitrogen across a geographic gradient in Brazil. *Forest Ecology and Management, 193,* 17-31. doi:10.1016/j.foreco.2004.01.020

Stape, J. L., Binkley, D., Ryan, M. G., Fonseca, S., Loos, R. A., Takahashi, E. N., Silva, C. R., Silva, S. R., Hakamada, R. E., de Ferreira, J. M. A., Lima, A. M. N., Gava, J. L., Leite, F. P., Andrade, H. B., Alves, J. M., Silva., G. G. C., & Azevedo, M. R. (2010). The Brazil *Eucalyptus* potential productivity project: Influence of water, nutrients and stand uniformity on wood production. *Forest Ecology and Management, 259,* 1684-1694. doi:10.1016/j.foreco.2010.01.012

Van Wambeke, A. (1992). *Soils of the tropics, properties and appraisal*. New York: McGraw-Hill, Inc.

Xu, D., Dell, B., Yang, Z., Malajczuk, N., & Gong, M. (2005). Effects of phosphorus application on productivity and nutrient accumulation of a *Eucalyptus urophylla* Plantation. *Journal of Tropical Forest Sciences, 17,* 447-461.

