ABSTRACT

CARRERO, OMAR ERNESTO. Effects of Intensive Silviculture on the Productivity of Eucalyptus in Venezuelan Llanos and a Probabilistic Analysis of its Profitability. (Under the direction of Dr. Jose Stape and Dr. Frederick Cubbage).

The demand for forest products has been increasing in Latin America due to population and economic growth during the last two decades. To satisfy this regional and worldwide demand, a new forest plantation area has been established using fast growth species like eucalypt and pine. To reach this goal, a larger planted area is not the only necessity. The forests also need to have high productivity to allow developers to concentrate forest plantations in a smaller area, thereby enhancing the company profitability. To increase forest productivity, it is necessary to understand what the main growth limiting factors are, and to estimate how large the gap is between current and attainable productivity in order to determine where silvicultural treatments should be applied economically. In Venezuela, industrial forest plantations have been established during the last 40 years, mainly with caribbean pine; as a result, there is a lack of information regarding the more productive clonal Eucalyptus forests. We used a large permanent inventory plot network to characterize Eucalyptus plantations' growth patterns in Venezuela's western llanos, based on the Sullivan Clutter growth and yield model. The inclusion of rainfall in the model increased its accuracy, highlighting the effect of water supply on Eucalyptus growth. A simulation was performed to assess the impact of annual rainfall variability on yield, indicating that the risk of drought can be incorporated into forest planning decisions. To estimate the gap between current and attainable productivity of clonal Eucalyptus forest in Venezuela, we established 53 pairs of inventory plots covering different site and forest conditions. In each pair. a control plot received the regular management applied by the company, and the paired plot (twin plot) received extra fertilization plus extra weed control. The intensive silviculture management response was estimated as 2.6 Mg ha^{-1} yr^{-1} after two years, representing 20% over the current productivity (12.4 Mg ha^{-1} yr^{-1}). In 25% of the sites, where 75% of the surface was covered by weeds, a third plot (triplet) was established receiving only extra weed control besides the operational management applied traditionally. Stem biomass gain was 1.7 and 3.9 Mg ha^{-1} yr^{-1} (13% and 28% over the control) after 2 years for the extra weed control and extra weed control plus extra fertilization treatments respectively, showing that both fertilization and

weed control are needed to increase yield. We estimated the intensive silviculture profitability, using the average response and the Venezuelan prices, which showed a Net Present Value (NPV) of 402 USD ha-1. A linear model was fitted to identify the profitable responsive stands through their soil and stand attributes. Biomass growth of the control plot and landscape position were identified as the main explanatory variables for this tool. The NPV considering the probability of misclassifying responsive and no responsive stands was estimated in 224 USD ha-1. Two strategies were tested to eliminate classification uncertainty: 1) long term strategy: reducing the model error by fitting a better predictive model, and 2) short term strategy: applying the treatment in the most responsive sites, shifting the median response to the right, but at the same time reducing the proportion of treated stands. The NPV turned to be 568 and 364 USD ha-1 respectively, which represents an increase of 344 and 140 USD ha-1 over the case where all the area was treated. These long term strategies' increased NPV represents be maximum amount of money that could be invested in research to reduce uncertainty by identifying where and when silvicultural treatments should be applied to obtain a higher profitability.

Effects of Intensive Silviculture on the Productivity of Eucalyptus in Venezuelan Llanos and a Probabilistic Analysis of its Profitability

by
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DEDICATION

To Carmen Aurora, the other half of myself, the best one.

To Fanny, Omar, and Tata.

BIOGRAPHY

Omar Carrero was born in Merida, Venezuela, in 1975. From his parents, Omar and Fanny, he learned to be a hard worker and a dreamer. He graduated with a Magna Cum Laude distinction and a Bachelor of Science degree in Forestry at the Universidad de Los Andes in 2000. In 2001, he married Carmen Aurora Soto. Also in 2001, he started working as a professor at the Forest School, Universidad de Los Andes where he taught for 7 years. He has had the opportunity of been working in different research projects with foreign universities and as a consultant for Venezuelan forest companies and government agencies. In 2006 he got a Master of Science degree in Economics at the same University. In 2008 he started his PhD at North Carolina State University. He is planning to enjoy life the rest of his days, since he understood that the best human invention ever is friendship.

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INTRODUCTION

Latin America's economy has been growing fast during the last decades, helping decrease poverty and increase the middle class. The growing population with more income creates a higher demand for products and services (CEPAL, 2011, IFM, 2011). Forest products are among them, and to supply the demand both locally and abroad, a larger area of forest plantations are a need. In South America, the total roundwood production grew from 20 million m^3 in 1963 to 175 million m^3 in 2003. In 2005, the plantation forest area reached 12 million hectares (Gonzalez et al., 2008). Venezuela has followed the same process, and now has approximately 600.000 ha of planted forest, 25.000 ha of which is *Eucalyptus*, used mainly for paper and paperboard production. The most attractive forest plantations are the ones with higher productivity, which are well represented by the clonal Eucalyptus plantations that reach twice the Caribbean pine productivity. However, in Venezuelan Western Llanos, where most of the Eucalyptus plantations are located, there is a large variability within site quality and on inter-annual rainfall, which both affect forest productivity. Understanding the main factors limiting growth is essential for an adequate timber supply.

In Western Venezuela, it was identified that *Eucalyptus* plantations grew better in well drained soils with clay loam textures (Henri, 2001). Acosta et al. (2005) also found that productivity in Eucalyptus in western Venezuela correlated with physical soil properties, which suggests that water supply is an important factor influencing the productivity. Rojas (2000), studying the relationship between soil factors, foliar nutrients and growth for *Eucalyptus* clones in western Venezuela, found that yields at all ages were positively correlated to soil extractable phosphorus and sand content, but not to soil total nitrogen. However, we do not know what could be the effect of rainfall and its variability on growth and yield; neither do we know what could be the attainable forest productivity and the treatment response probability density function. Both are needed for financial analysis of silvicultural treatments and decision making.

To increase forest site productivity, it is necessary to understand what are the main growth limiting factors in the system, and how responsive the stands are to silvicultural treatments. To approach that, we first characterized the Eucalyptus plantation growth pattern in the western llanos in Venezuela using an inventory plot network with 900 plots, which led us to incorporate rainfall into a growth and yield model. We estimated the effect of this variable on forest stand growth, and we simulated different rainfall patterns during a rotation to assess the impact of inter annual rainfall variability in volume yield, which could be useful for forest planning. Next, we manipulated the forest to determine the gap between the current productivity and the attainable productivity to identify those sites where gains due to silviculture are higher using a set of 53 paired plots covering all site quality and forest conditions (Stape et al., 2006). We assessed the effect of fertilization and weed control on light use and light use efficiency to understand what process is more affected by those practices in the particular system studied. Finally, we evaluated the profitability of the silvicultural practices on yield at the plot level, incorporating its treatment response variability into the financial analysis, which permitted us to assess short term and long term strategies to increase forest site productivity and profitability.

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CHAPTER 1: Growth Patterns of Eucalyptus Clonal Plantations in the Venezuelan Western Llanos and the Incorporation of Rainfall Effect on Growth and Yield Models

ABSTRACT

The area of *Eucalyptus* plantations in Latin America has been expanded rapidly during the last decades to satisfy the increasing demand for timber-derived products due to a larger population which has a higher income. In Venezuela, the Eucalyptus plantations area is incipient, but has been increasing since the 1980's, and most of the planted area is located on the Western Llanos. Forest production varies a lot due to site variability and on interannual rainfall which could affect forest site productivity and in consequence timber supply, but its magnitude is still unknown. Site conditions and rainfall amount could have different spatial and temporal effects, which could affect the stumpage inventories, ultimately having an effect on forest planning, optimal rotation, and forest operations. Forest managers can better plan wood supply by characterizing growth patterns, understanding whether rainfall has an influence on growth in a particular area, and estimating how yield varies due to rainfall in different sites. The objectives of this research were: 1) To characterize the growth patterns of Eucalyptus plantations in western Venezuela, 2) To estimate the influence of yearly rainfall on forest growth and yield, and 3) To estimate the impact of rainfall variability on timber yield distributions based on historical rainfall distributions. We characterized the growth pattern for clonal *Eucalyptus* plantations in the Venezuelan Western Llanos by fitting the Sullivan-Clutter model. We fitted a second model where we included rainfall as an explanatory variable to identify a relationship between yield and rainfall. We found that rainfall has a significant relationship with stand growth and yield. As rainfall increases, growth also increases but at decreasing rates, up to it reaches an asymptote. The growth rates and the asymptote vary depending on stand age and S. Simulation revealed that higher Sstands will have a higher yield, but at the same time the yield variability is higher when account rainfall variability is taken into account. Yield at rotation age was: 125, 170, 231, and 291 m^3 ha^{-1} for SI: 19, 23, 27 and 30 m. The values ranges for the same Swere: 116-129, 158-175, 215-239, and 270-300 m^3 ha^{-1}. For all Sthe probability density function simulated is skewed to the left, but becomes flatter as the Sincreases.

Keywords: yield model, rainfall variability, productivity, site

1. Introduction

The area of *Eucalyptus* plantations in Latin America has been expanded rapidly during the last decades to satisfy the increasing demand for timber-derived products due to a larger population which has a higher income. In Venezuela, the Eucalyptus plantations area has been expanded since the 1980's, and most of the planted area is located on the Western Llanos (Ministerio del Ambiente, 2006); however, Venezuela still imports large numbers of wood-based products (Gonzalez and Carrero, 2007, Carrero, et al. 2008). Forest plantation development in Venezuela occurs mainly with *Pinus caribaea* in the East, where around 0.6 million hectares have been established since the late 1960's. In the last four decades, the Eucalyptus plantations areas have been increasing in the tropics, and through breeding and silviculture, it has been possible to reach productivity levels that permit companies to produce wood products in short rotations and lower costs. In Venezuela, Eucalyptus plantations have been used in mono-specific plantations or in agroforestry systems for pulp for paper and paperboard production.

Although the total Eucalyptus area planted in Venezuela is small (less 25.000 hectares), a well-established permanent plot network exists. This network is useful not only to estimate wood stock, but it also to gain a better understanding of Eucalyptus plantation growth patterns and their relationship with climate and environmental variables. Future plantation expansion probably should occur in this region due to land availability, appropriate environmental and soil conditions to establish Eucalyptus plantations, and forest plantation management experience accumulated for more than three decades. Characterizing growth patterns, understanding whether rainfall has an influence on growth in a particular area, and estimating how yield varies due to rainfall in different sites could permit forest managers to make decisions to better plan timber supply. However, growth patterns in the Venezuelan Western Llanos are unknown because there exists a large variability among sites and on interannual rainfall. This variability could affect forest site productivity and in consequence timber supply, but its magnitude is still unknown. Site conditions and rainfall amount could have different spatial and temporal effects, which could thus affect the stumpage inventories and ultimately have an effect on forest planning, optimal rotation, and forest operations.

This area of the country is characterized by typically well-defined wet/dry seasons and extreme rainfall events that could affect forest productivity. It is well known that Eucalyptus is very sensitive to water availability. Water has been identified as one of the most important factors determining forest plantations productivity in many places around the world (Gholz, et al.,1990). Stape et al. (2004) found that water supply limited growth in Eucalyptus grandis x urophylla plantations in northeastern Brazil. They used data from a field trial with a control and an irrigated treatment, and they found that wood biomass increased from 36.6 Mg ha^{-1} to 107 and 141 Mg ha^{-1} respectively after two years. Ryan et al (2010), in clonal Eucalyptus plantations in Brazil, found that a higher water supply increases wood net primary productivity by 27%, due to increases of light interception, photosynthetic efficiency, gross primary productivity, and partitioning to wood. Rainfall distribution affects water availability and vapor pressure deficit; consequently, stomatal conductance is affected, restricting CO_2 fixation (de Castro et al, 2008; Almeida et al., 2007; McDowell et al., 2006; Gholz et al., 1990; Cannell, 1989). Almeida et al. (2007) studied the relationship between the growth and the water balance of *Eucalyptus grandis* hybrid plantations in Brazil, finding that forest growth is affected by water availability, mainly by drought. The same conclusions were found when the system was simulated using a process based model (3PG) for *Eucalyptus* plantations in Brazil, which permitted assessment of the effects of drought on productivity (Almeida et al, 2004). The evaluation of water supply is very important for selecting the best harvesting and silvicultural practices, especially for tropical conditions where rainfall and distribution is the main limiting factor to reach higher productivities (Gonçalves et al., 2008).

In Eucalyptus plantations in Venezuela, productivity was correlated with soil texture, which is associated with water holding capacity in a particular site. Studying the relationship between soil characteristics and productivity of *Eucalyptus urophylla* and *Eucalyptus grandis* plantations in Western Venezuela, Henri (2001) found that soil texture is a good predictor of tree growth. Trees grew better in soils with clay loam textures, and excessive soil moisture was inversely correlated with tree growth in *Eucalyptus grandis*.. Acosta et al. (2005) also found that productivity in Eucalyptus spp in western Venezuela is correlated with physical soil properties, which suggests that water supply is an important factor influencing the productivity. Rojas (2000), studying the relationship between soil factors, foliar nutrients and growth for *Eucalyptus grandis X urophylla* clones in western Venezuela, found that volume at all ages were positively correlated to soil extractable phosphorus and sand content.

Due to the importance of climatic variables on tree growth, several attempts have been made to include them in empirical growth and yield models. Smith (1999) pointed out that there was a common opinion regarding the need to integrate site factors, such as water supply and nutrition parameters, in order to reach full potentiality by the empirical growth and yield models. Following Whitehead and Beadle (2004), the adoption of hybrid models, those growth and yield models incorporating physiological and climatic variables, will become the standard if they desire to predict the effects of environment and silviculture on productivity. Soares and Leite (2000) modified the Sullivan-Clutter model to include rainfall as a predictor variable. They found the modified model allowed accurate estimates of volume and basal area. Their case study was in tropical Eucalyptus plantations in Brazil, where rainfall variability has a large effect on site productivity. Snowdon et al (1999) incorporated a simple index as rainfall into a growth and yield models reducing significantly the error mean squares. They suggested using the modified model in regions with high seasonal rainfall variability and with species sensitive to those changes. Woollons et al. (1997) included radiation and rainfall into a projection model, improving precision and accuracy when modeling basal area growth. Battaglia et al (1994) used environmental data on an empirical growth and yield model to enhanced predictions of volume. Temps (2005) included climatic variables into a yield model in Pinus taeda in Brazil. He used the Chapman Richards model, which was modified to include a modifier representing climatic variables, specifically the mean annual rainfall which modifies the asymptote in the model.

Another approach to link environmental variables with growth and yield is to use Process Based Models (PBM). Paul et al. (2003) linked Montecarlo simulation with a process based model called 3PG (Landsberg and Waring, 1997) to do a sensitivity analysis to predict change in soil carbon after afforestation. Through this approach they identified the parameters which influenced the system, which deserved more accurate values to be used in the model to reduce the uncertainty. Battaglia et al. (2002) used another PBM (PROMOD) to compare the sensitivity of financial returns to site survey cost, land cost, harvesting cost, and land productivity. They found that tree growth is the strongest factor determining the profit. They suggested the use of PBM to understand the effect of environmental variability on productivity and profitability. Using the same PBM, Mummery and Battaglia (2001) estimated spatial productivity risk associated with variations in soil depth, nutrient status, and drainage; whose results are very useful to decide where to plant and also to assess the risk associated with such decision. Using the CABALA method, Mummery and Battaglia (2004) assessed the importance of rainfall distribution in predicting eucalypt plantation growth, and risk. The model was applied in an Australian region where precipitation fluctuation around historical average is common. It was shown that using long term average rainfall for strategic planning for site selection and management fails because it does not take into account this variability.

Processes based models can be very useful, but they have the disadvantage of requiring much more data to parameterize and validate the model. Empirical models, on the other hand, have been used for a long time and are well accepted as tools for decision making. However, empirical models have been fitted commonly using the general linear model, which has rigid assumptions. This model assumes the errors follow a normal distribution and are independent and with homogenous variance $N \sim (0, \sigma^2 I)$ (Gujarati and Porter, 2009). But when dealing with permanent plots data, it is common to find autocorrelation and heterocedasticity because measurements from the same plots will have correlation, and also because as stands grow, the variability around the mean increases (West, 1995; Gregoire et al., 1995; Fortin et al., 2007; Carrero et al., 2008). Sullivan and Clutter (1972) recognized the consequences of using the general linear model and its rigid assumptions when dealing with repeated measurements in forestry. On this model, the parameters estimated are unbiased but the variance is, which make its significance tests usefulness. Mixed models could be useful to deal with these issues because it is possible to model the structure of the variance-covariance matrix. Some cases related with trees and stand growth have been treated using mixed models. Gregoire et al. (1995) used mixed models for modeling basal area. Several researchers used them for modeling dominant height (Fang and Bailey, 2001; Wang et al, 2007; Carrero et al., 2008; Jerez, et al. 2011). Stem taper was modeled by Garber and Maguire (2003) and Leites and Robinson (2004). Also they were used to model individual tree increment (Calegario et al., 2005; Weiskittel et al., 2007), and cumulative bole volume (Gregoire and Schabenberger, 1996).

Although the importance of growth and yield models and hybrid models have been recognized for planning and decision making, there does not exist a recent growth and yield model for Eucalyptus plantations in Venezuela; neither is there a growth and yield model which incorporates rainfall as explanatory variable. Such a model could be of the main importance for planning, decision making and rainfall variability risk assessment.

The objectives of this research were: 1) To characterize the growth patterns of Eucalyptus plantations in western Venezuela, 2) To estimate the influence of rainfall on growth and yield, and 3) To estimate the long term expected productivity distributions based on historical rainfall distributions.

2. Methods

2.1. Area Description.

The study area is located in Venezuela, between 9° 50’ N and 9° 21’ N and 69° 26’ W and 68° 15’ W. This area corresponds to the Venezuelan States of: Lara, Portuguesa and Cojedes (Figure 1). Eucalyptus plantations in this area belong to two forest companies: Papeles Venezolanos C.A (PAVECA) and Smurfit Kappa Carton de Venezuela (SKCV). PAVECA produces paper products and have established since the early 90’s around 6.000 hectares of clonal *Eucalyptus urophylla* and its hybrids in Cojedes state. SKCV has established around 15.000 hectares since the early 80's, using *Eucalyptus urophylla,* and hybrids in Lara, Portuguesa and Cojedes states. In this area we selected three regions for our case study, because they represent most of the conditions characteristics of the area where plantations are located.

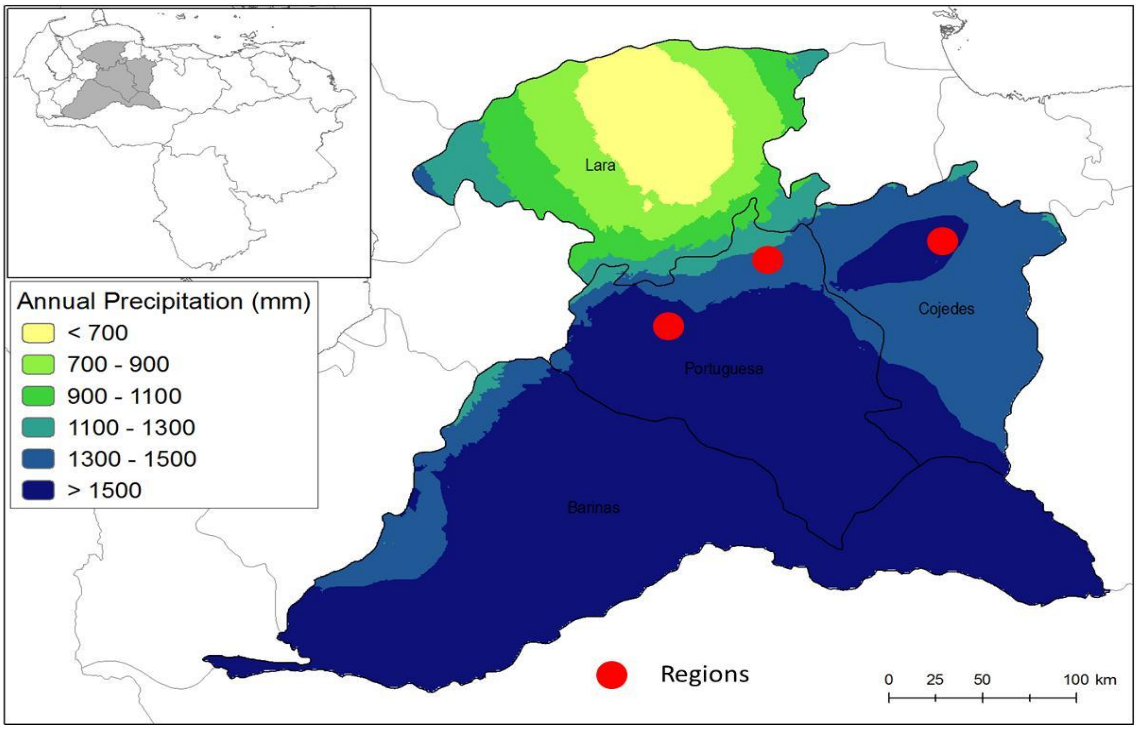

Figure 1. Study area and relative location in Western Venezuela. The three regions mean rainfall, and its variability are in table 1.

Soils at this region were formed during the quaternary by fluvial material sedimentation. Higher forest productivity (>30 m^3 ha^{-1} yr^{-1}) has been found in deep soils, with sandy loam to silty-clay-loam textures (Henri, 2011). In general those sites present good drainage and are slightly acidic. Lower productivity occurs on clay soils, which sometimes have abundant stones, poor drainage, or are strongly acid (Acosta, 2004).

The area where the plots were located is under the influence of Intertropical Convergence Zone (ITCZ), with two well defined seasons: the rainy season from April to September, and the dry season from October to March (Hetier et al., 2005). Climate data was gathered from weather stations, operated by the national government climate agency (INAMEH) located in a radius of 20 km of the plantations, and also from weather stations located in each farm operated by the companies. The mean temperature is 28.5 °C, and the yearly rainfall varies between 1300 and 1700 mm. Yearly annual rainfall variability is high in some locations, as indicated by the coefficient of variation and the difference between the maximum and the minimum which could be more than twice the minimum value (Table 1). Under Koeppen climatic zones, the area of interest is classified as Aw, because average temperature in the coldest month is higher than 18°C, typical of a tropical climate, the dry occurs in astronomic winter and it last more than 2 months, and the maximum average temperature occurs before summer solstice. Under Holdridge system it corresponds to Dry Tropical Forest (bs-T) (Paredes, 2009).

We observed maximum and minimum monthly temperatures, rainfall distribution, potential evapotranspiration, and real evapotranspiration assuming a water holding capacity of 165 mm. We used the methodology proposed by Thornwhite and Mather (1955), as shown in Table 2 for the first region.

Yearly rainfall time series (1943-2010) at San Carlos, Cojedes- Venezuela (Table 3), plotted in Figure 2, was used develop the growth and yield model and also to simulate a typical stand growth and yield. Sometimes the length of the cycle could be longer as occurs during the period 1948-1952, when the yearly rainfall was under the average, or in 2002-2007 when it was over the average. Another important characteristic to realize about the time series is that values are not independent, and there exists a serial correlation which should be taken into account for modeling the rainfall in a particular period.

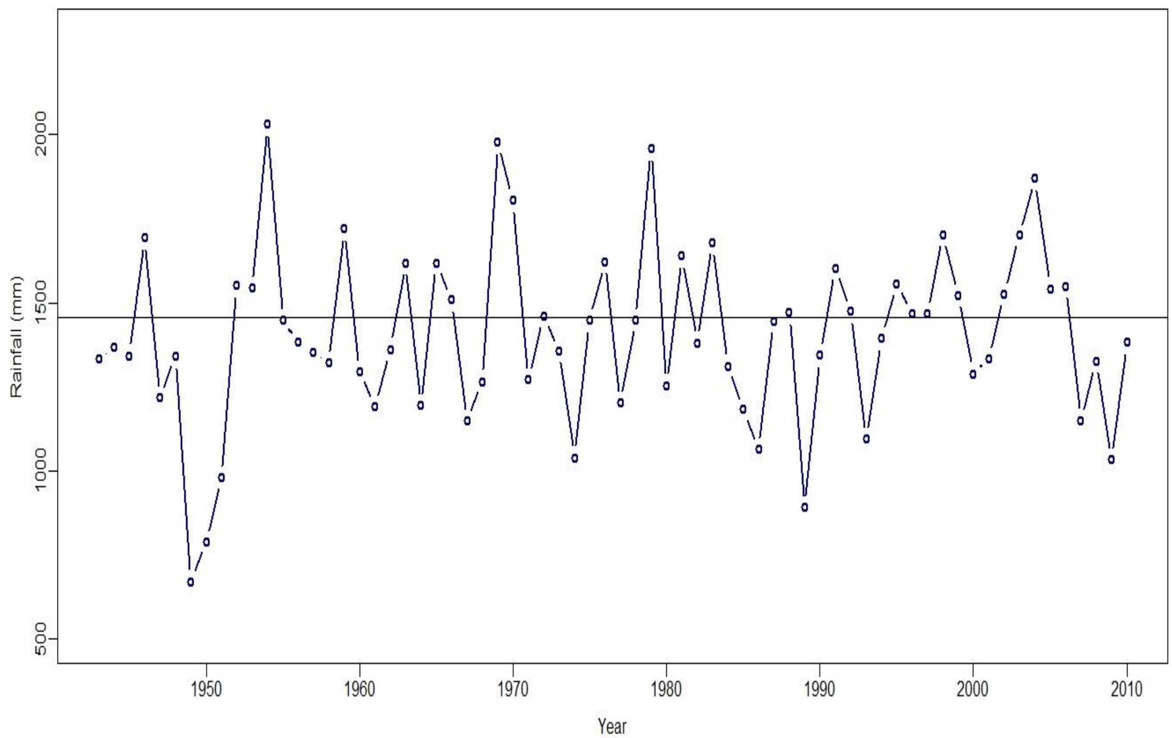

Figure 2. Annual rainfall time series from 1943 to 2010 at San Carlos, Cojedes. Average yearly rainfall is 1456 mm.

2.2. Plantation Management at the Permanent Plots

The network of permanent plots used included 950 plots measured yearly. From them we chose 320 to ensure spatial and temporal distribution. Plot size was generally 450 m^2, had a rectangular shape, and included 55-60 trees.

Plantation establishment occurred between May and June, using macro-cuttings produced in containers, originated from the company clonal garden. In PAVECA, subsoiling combined with disking (30 cm), and bedding in a 3x3 m, 4 x 2 m or 4 x 2.25 m (8 to 9 m^2/plant) are used. Pre and post establishment fertilization was used up to 2 years. Intensive weed control was applied in the first year, using pre and post establishment herbicides, which is applied manually (Stape, 2006). A combination of mechanical and manual weed control was applied every year up to the fifth year.

The network of permanent plots in SKCV included 44 plots, from which we selected 25, by the same reasons mentioned above. Plot size was 495 m^2 and, was composed by 55 trees, which were measured annually since they were two years old. Circumferences at breast height and height were measured for all the trees.

In SKCV, plantation management consisted of disking, subsoiling (80 cm), bedding when needed, and 3x3 m spacing (9 m^2/plant). Fertilization was applied between 3-5 weeks after plantations establishment. Pre and post establishment herbicides were applied up to the third year, during this period 3 chemical 2 mechanical control were applied.

The number of plots, their ages, the number of measurements, and dates are presented by region in table 4.

2.3. Stand Volume and Growth

Tree volume was calculated using equations developed locally for different clones (Appendix 5.2), and DBH and height measurements were done yearly since year 2.Volume per hectare, density and basal area were calculated adding the volume, number of trees alive and basal area of individual trees in each plot and scaling it to the hectare. Dominant height was calculated as the average of the 100 largest trees per hectare. Site index was (S) determined for every site by fitting a guide curve, relating dominant height and age using Schumacher model. A set of anamorfic curves were generated from it, representing S: 15,20, 25 and 30 m (Carrero et al., 2008). Site index (m) equivalency using different base ages (5, 6 and years old) are in table 5. Throughout this work S will be set as 5 years old.

2.4. Growth and Yield Model

2.4.1. The mean structure

We selected the Sullivan-Clutter (1972) growth and yield model because, when compared with other models, it has some advantages: 1) it is a stand model independent of tree size, 2) it permits different initial densities to estimate the volume per area unit, 3) it is compatible since it is possible to obtain the yield by integrating the growth or obtain the growth by derivation of the yield model, and 4) it is consistent since it is possible to project a future value year by year, or directly from the initial year to the final year obtaining the same results (Weiskittel, et al., 2011, Campos and Leite, 2009, Avery and Burkhart, 2001).

The yield model fitted was proposed by Sullivan and Clutter (1972) and can be expressed as:

$$\ln \boldsymbol{Vol_t} = \beta_0 + \beta_1 \boldsymbol{S} + \beta_2 \frac{1}{\boldsymbol{Age_t}} + \beta_3 \ln(\boldsymbol{BA_t}) + \varepsilon \tag{1}$$

Where:

$$\ln \boldsymbol{BA_t} = \beta_4 \left(\frac{\boldsymbol{Age_{t-1}}}{\boldsymbol{Age_t}}\right) \ln(\boldsymbol{BA_{t-1}}) + \beta_5 \left(1 - \frac{\boldsymbol{Age_{t-1}}}{\boldsymbol{Age_t}}\right) + \beta_6 \boldsymbol{S} \left(1 - \frac{\boldsymbol{Age_{t-1}}}{\boldsymbol{Age_t}}\right) + \varepsilon$$

Where: (2)

Vol_t= volume at age t (m^3 ha^{-1})
S= site index (m) for a base age of 5 years.
Age_t= stand age at age t (years)
BA_t= basal area at age t (m^2 ha^{-1})

To include the rainfall into the previous growth and yield model, we used the basal area projection model adjusted by Soares and Leite (2000):

$$\ln \boldsymbol{BA_t} = \beta_4 \left(\frac{\boldsymbol{Age_{t-1}}}{\boldsymbol{Age_t}} \right) \ln(\boldsymbol{BA_{t-1}}) + \beta_5 \left(1 - \frac{\boldsymbol{Age_{t-1}}}{\boldsymbol{Age_t}} \right) + \beta_6 \boldsymbol{S} \left(1 - \frac{\boldsymbol{Age_{t-1}}}{\boldsymbol{Age_t}} \right) + \beta_7 \ln(\boldsymbol{Rain_{t-1}}) \left(1 - \frac{\boldsymbol{Age_{t-1}}}{\boldsymbol{Age_t}} \right) + \varepsilon \qquad (3)$$

Where:

S= site index (m)
Age_t= stand age at age t (years)
BA_t= basal area at age t (m^2 ha^{-1})
$Rain_{t-1}$= yearly rainfall in the previous year (mm)

The model describes a logarithmic relationship between volume growth and rainfall as suggested by the data (Appendix 5.1), what can be expected because after attending the potential evapotranspiration additional rainfall will have a minor influence on growth.

2.4.2. The variance-covariance structure

Repeated measurements from permanent inventory plots have been used to fit the model, which is a reason to model the structure of variance covariance matrix. Measurements from the same plots are correlated, but at the same time errors around the mean also vary through time violating the assumptions of the general linear model. In our case, the fact that plots are clustered by regions introduces another source of correlation, since plots belonging to the same region share more similar soils, topography, temperature and rainfall, than plots belonging to different regions. Correlation could be modeled using two different strategies: 1) modeling directly the error matrix, or 2) inducing correlation by including into the model a random variable (Schabenberger and Pierce, 2002). The advantage of using a mixed model is its flexibility, permitting to model many different cases, including the one modeled using the general linear model (Schabenberger 2002, Calegario et al., 2005).

We modeled the structure of the variance-covariance matrix by assuming the region as a random effect, which also permitted us to do inference for the whole region of interest and not for just the locations selected. Using region as random effect allowed us to induce correlation between plots belonging to the same region. Serial correlation within plot was modeled using different variance-covariance matrix structures. Regions were assumed independent of each other. The variance covariance matrix generated as described is a block diagonal matrix, where each block represents a region (Appendix 5.3).

Models were fit by maximizing the likelihood using PROC MIXED in SAS 9.2. The variance covariance structure was modeled by using the statements random and repeated.

2.4.3. Goodness of fit

To evaluate the model fitting we evaluated: likelihood logarithm (- 2logL); Akaike information criterion (AIC); corrected Akaike (CAIC) and Schwartz Bayesian information criterion (SBIC) (Schabenberger and Pierce, 2002). The latter three compensate for the differences in degrees of freedom that arise from models with different structures (De los Santos-Posadas et al., 2006). In these criteria, the lower the value, the better the fit. We also used the residual sum of squares to compare models with different mean structures; however, when the mean structure was the same, we also used the other goodness of fit indicators.

2.4.4. Model validation

We used 427 observations (30% of the total) to compare observed and model predicted. We applied a t- test to estimate if any differences exist between the two groups, using a p-value of 0.05. We also generated a scatterplot with the observed and the predicted values to see if there were any differences at some particular level, since t-tests just compare averages.

2.5. Volume Projection Simulation

2.5.1. Rainfall sampling

We randomly sampled the yearly rainfall time series by choosing a random number corresponding to the starting year of the period, and we took the other six consecutive yearly rainfall values. We generated the random number by sampling over a uniform distribution having as extremes 1943 and 2004. In this way we generated rainfall values for a seven year period (rotation length), and also were able to keep the serial correlation between measurements. Rainfall pattern in Venezuela, as in most areas in South America, is influenced by El Niño Southern Oscillation (Ahrens, 2009); consequently, rainfall follows a cyclical pattern. For simulation purposes this serial correlation should be taken into account. Otherwise, assuming yearly rainfall as independent could generate wrong results since it is possible to get yearly rainfall period combinations that do not occur in reality.

2.5.2. Stand growth and yield simulation

We simulated stand growth for a whole rotation and for each S (15, 20, 25, and 30 m), using the rainfall generated for the whole rotation mentioned above. To start the simulation we used initial values for Basal Area (BA) depending on the site index: 3.6, 5.5, 7.5 and 9.5 m^2 ha^{-1} for 15, 20, 25 and 30 m respectively. To generate those values we fitted a linear regression between BA and S for 2 years old permanent plots.

Using this information we used equation (3) to project BA for one year, and to estimate volume we used equation (1). In this way we estimated stands BA and Volume for every year over the whole rotation. For each of the four site index, we simulated 1500 rotations, and we were able to generate a volume yield probability density function (PDF). This PDF permitted us to assess the effect of rainfall on yields' average and standard deviation.

3. Results

3.1. Eucalyptus plantation growth patterns in Western Llanos, Venezuela

At the western Llanos in Venezuela, we found site index for Eucalyptus plantations ranging from 14 to 35 m. Table 6 summarizes stand characteristics at 5 years old. Most of the permanent plots we used in our analysis belonged to site indexes between 15-25 m. Basal area ranged from 12 to 22 m^2 ha^{-1}, volume from 86 to 282 m^3 ha^{-1}, MAI from 17 to 57 m^3 ha^{-1} yr^{-1}, and stand density from 925 to 970 trees per hectare (TPH).

Dominant height (H_D) and age relationships were plotted (Figure 3) along the model fitted for different S(15, 20, 25, and 30 m). The linear model fitted and used as a curve guide to generate the anamorphic family curves is:

$$\ln(H_D) = 3.4952 - 1.9054 Age^{-1} + \varepsilon \qquad (4)$$

(0.0090) (0.0305)
p<0.0001 p<0.0001

R^2=0.70

Where:

H_D=Dominant height (m)

Age= stand age (years)

The intercept term and the inverse of age were statistically significant (Table 7). Dominant height at the base age (5 years) represents the S, and it ranges from 14 to 35m. Most of the plots are concentrated between 15 and 25. In proportion 1 % of the plots have a S < 15 m, 22 % between S 15-20 m, 58 % between S 20-25 m, 18% between S 25-30 m, and 1% >30 m.

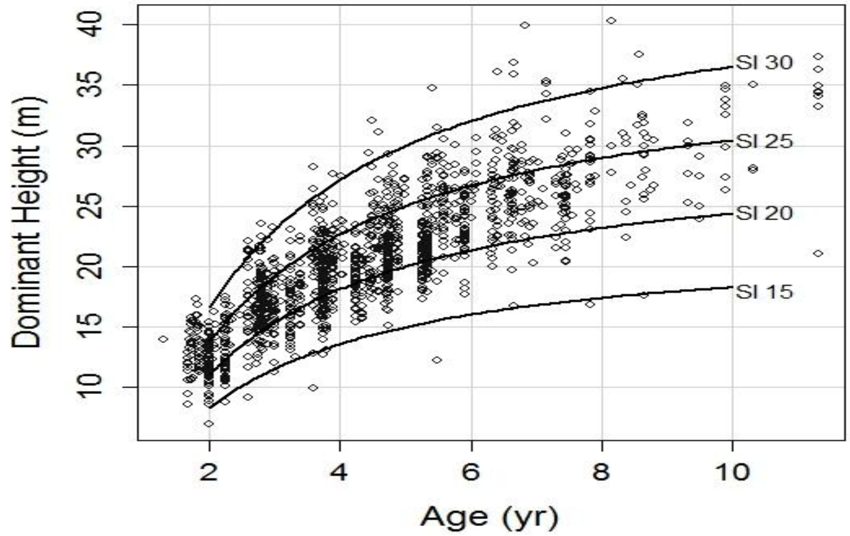

Figure 3. Dominant height and age relationship in *Eucalyptus urophylla* permanent plots in Western Llanos, Venezuela.

The Sullivan-Clutter yield model fitted for the region was:

$$\ln \boldsymbol{Vol_t} = 3.1248 + 0.0782\boldsymbol{S} - 3.4643\frac{1}{\boldsymbol{Age_t}} + 0.2521\ln(\boldsymbol{BA_t})\left(\frac{\boldsymbol{Age_{t-1}}}{\boldsymbol{Age_t}}\right) + \varepsilon \quad (5)$$

(0.0887)	(0.0030)	(0.1828)	(0.0199)
$p<0.0001$	$p<0.0001$	$p<0.0001$	$p<0.0001$

$R^2=0.76$

Where:
Vol_t= volume at age t ($m^3\ ha^{-1}$)
S= site index (m) for a base age of 5 years.
Age_t= stand age at age t (years)
G_t= basal area at age t ($m^2\ ha^{-1}$)

All parameters were statistically significant (Table 8). Yield models for typical stands with S15, 20, 25 and 30 m., are represented for a whole rotation (Figure 4).

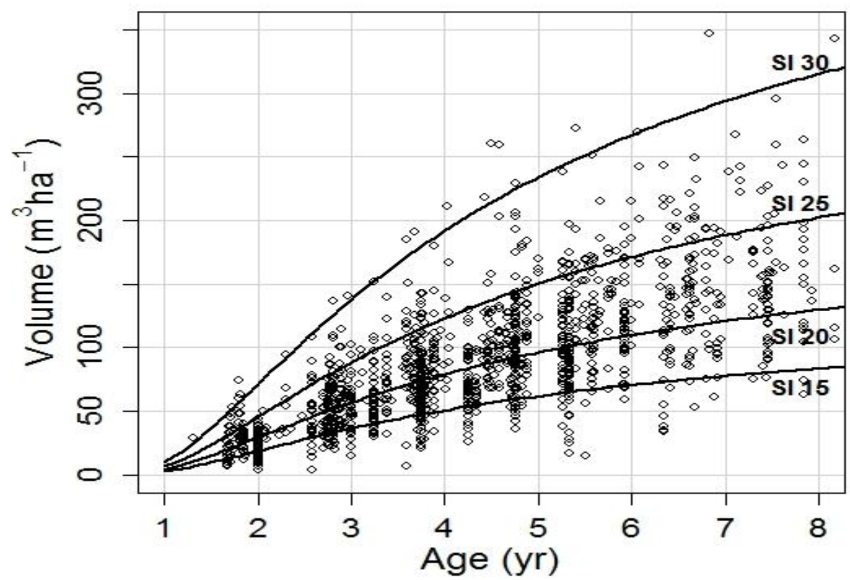

Figure 4. Projected stand volume by age for typical stands with S 15, 20, 25 and 30 m.

Typical stand volume at rotation age (7 years) were: 78, 121, 189 and 295 m^3 ha^{-1} for S: 15, 20, 25, and 30 respectively. The relationship between mean annual increment (MAI) and current annual increment (CAI) changes depending on S (Figure 5). The maximum MAI occurs at the same age (4 years); however, the MAI is 11, 17, 27 and 42 m^3 ha^{-1} yr^{-1} for S 15, 20, 25 and 30 m respectively. The maximum CAI occurs when stands are 2 years old, and reach values of 19, 29, 45, and 70 m^3 ha^{-1} yr^{-1} for the same S as previously indicated.

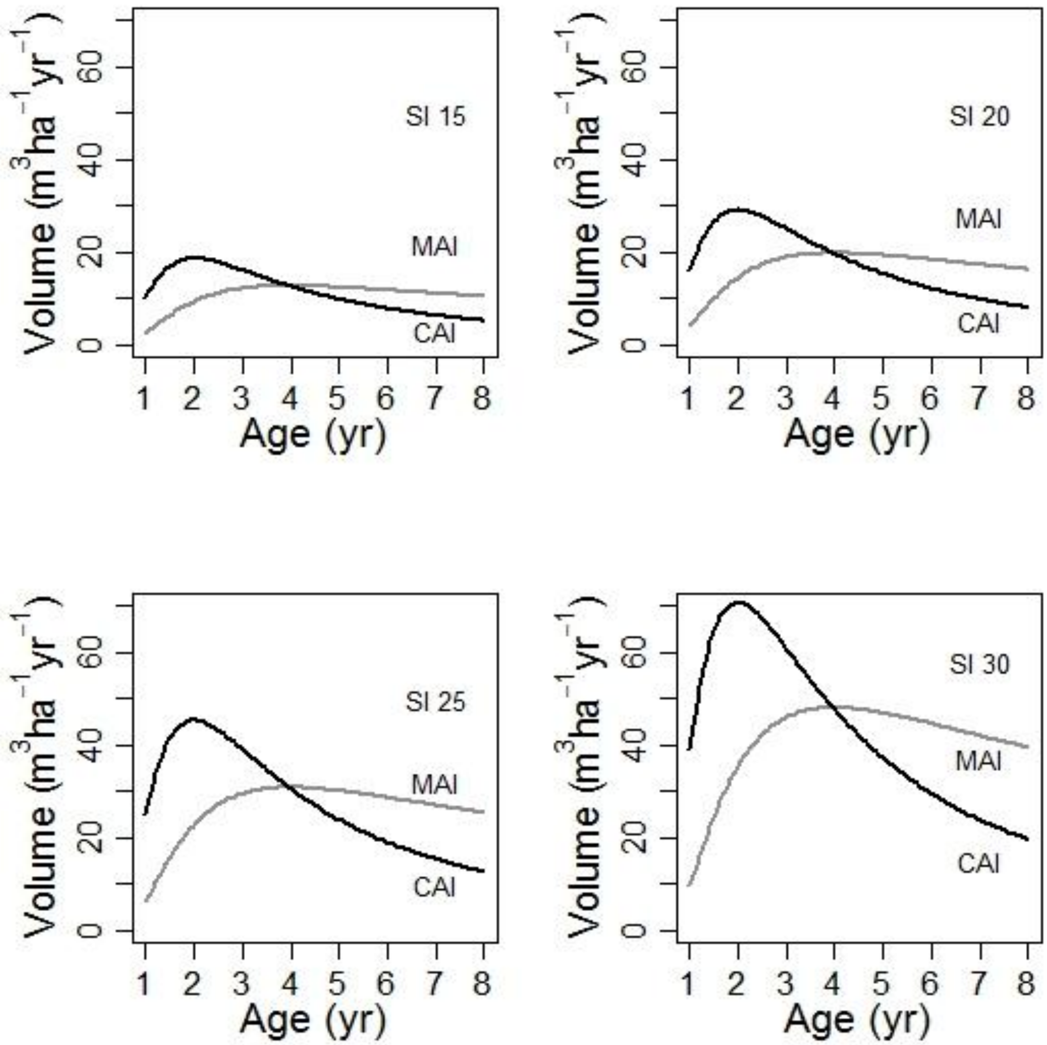

Figure 5. Mean annual increment and current annual increment for typical stands with S: 15, 20, 25 and 30 m. Maximum CAI at the maximum (2 years old) ranges from 19 to 70 m^3 ha^{-1} yr^{-1}, and maximum MAI (4 years old) ranges from 11 to 42 m^3 ha^{-1} yr^{-1}.

3.2. Rainfall influence on growth and yield

Rainfall had an influence on growth, which varied depending on stand age, and also on the amount of rainfall. Plotting stand volume growth against rainfall by age classes, it was possible to see a trend that stand volume growth increased as rainfall increased, but at a decreasing rate (Figure 6). This increase in growth occurs until it reaches a plateau which varies depending on initial growing period stand age. The plateau tends to be above 1400 mm.

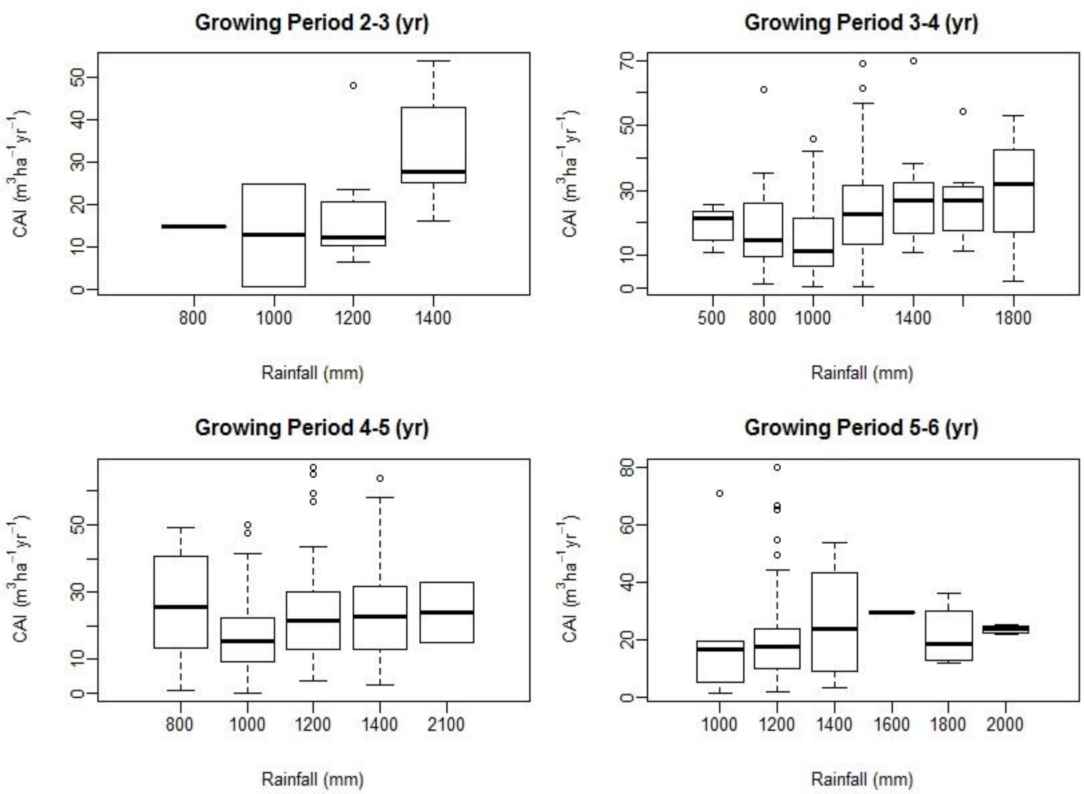

Figure 6. Stand volume growth and rainfall relationship by growing period and rainfall classes for Eucalyptus stands in western llanos, Venezuela.

On average, site index also changed as rainfall increased. When stands were 3 years old at the beginning of the period, S changed from 20 m to 25 m when rainfall changed from 500 to 1800 mm (Figure 7). Something similar was appreciated for other initial ages. However, when stands were 4 years old, S changed from 21 m to 24 m when rainfall increased from

1000 to more than 2100 mm . For the 5 year old stand, S changed from 24 to 27 when rainfall changed from 1000 mm to 2000 mm. As stands became older, changes in S due to changes in rainfall became smaller.

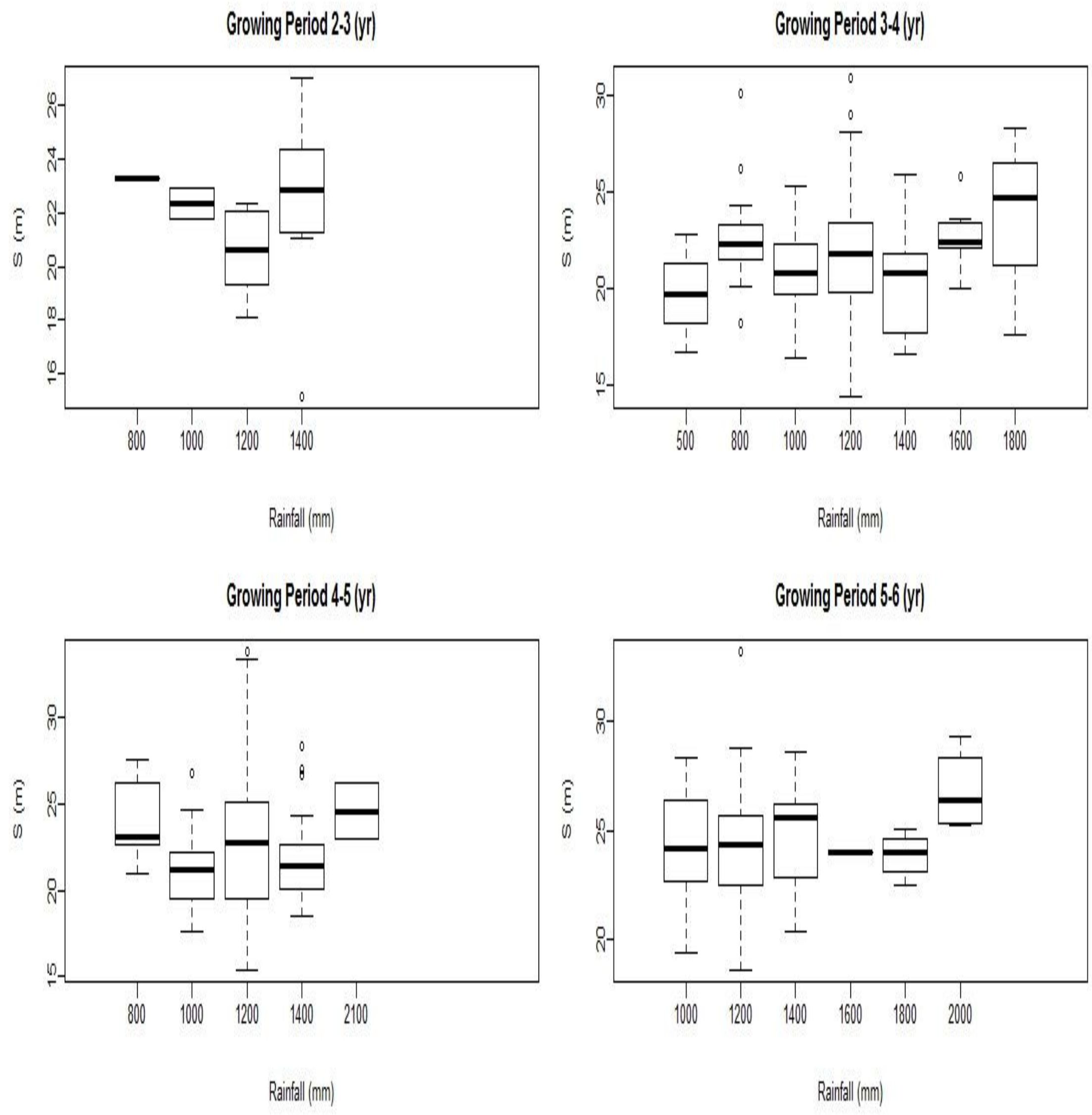

Figure 7. Site index and rainfall level relationship by growing period and rainfall classes for Eucalyptus stands in western llanos, Venezuela.

In order to take into account simultaneously the effect of different variables including the rainfall and assess its relationship with yield, we fitted different linear models using as a basis the Sullivan-Clutter model (Table 9).

We found that mixed models fit the data better than fixed models, as could be appreciated by the residual sum of squares, which are lower for the former models. The fixed model, which included rainfall, does not model the structure of the variance-covariance matrix, so it assumes normality, equal variance and independence of errors. All the mixed models consider the correlation between plots from the same region, and the serial correlation due to the presence of repeated measurements of the same subjects (AR(1) and CS). The variance components (VC) and the compound symmetry (CS) models fitted better the data than all the other models. The rank could change depending on the indicator used. As the goodness of fit for both models are almost the same, we choose the CS model since it also considers the correlation between repeated measurements from the same plot.

The Sullivan-Clutter yield model including rainfall, obtained by substituting eq (3) in eq (1):

$$\ln Vol_t = \underset{\substack{(0.0887)\\ p<0.0001}}{3.1248} + \underset{\substack{(0.0030)\\ p<0.0001}}{0.0782}S - \underset{\substack{(0.1828)\\ p<0.0001}}{3.4643}\frac{1}{Age_t} + \underset{\substack{(0.0199)\\ p<0.0001}}{0.2522}\ln\left(BA_t\right) + \varepsilon \qquad (6)$$

$R^2=0.76$

Where:

$$\ln BA_t = 0.0963\left(\frac{Age_{t-1}}{Age_t}\right)\ln\left(BA_{t-1}\right) + 0.4977\left(1-\frac{Age_{t-1}}{Age_t}\right) - 0.0089S\left(1-\frac{Age_{t-1}}{Age_t}\right) + 0.00004\ln\left(Rain_{t-1}\right)\left(1-\frac{Age_{t-1}}{Age_t}\right) \qquad (7)$$

Where:
Vol_t= volume at age t (m^3 ha^{-1})
S= site index (m) for a base age of 5 years.
Age_t= stand age at age t (years)
BA_t= basal area at age t (m^2 ha^{-1})
$Rain_{t-1}$= Rainfall in the previous period (mm)

Parameters estimates standard errors and p-values correspond to the CS model (Table 10). All the variables corresponding to the original model were statistically significant. The interaction between the term (1-age1/age2) and the rainfall was significant. This means that growth and yield has a relationship with the rainfall, but this relationship varies depending on stand age. Even when this interaction is statistically significant, its relative importance is lower when compared with the other variables included in the model. When rainfall was included into the Sullivan Clutter model it predicted the volume better when compared with the original model (Figure 8).

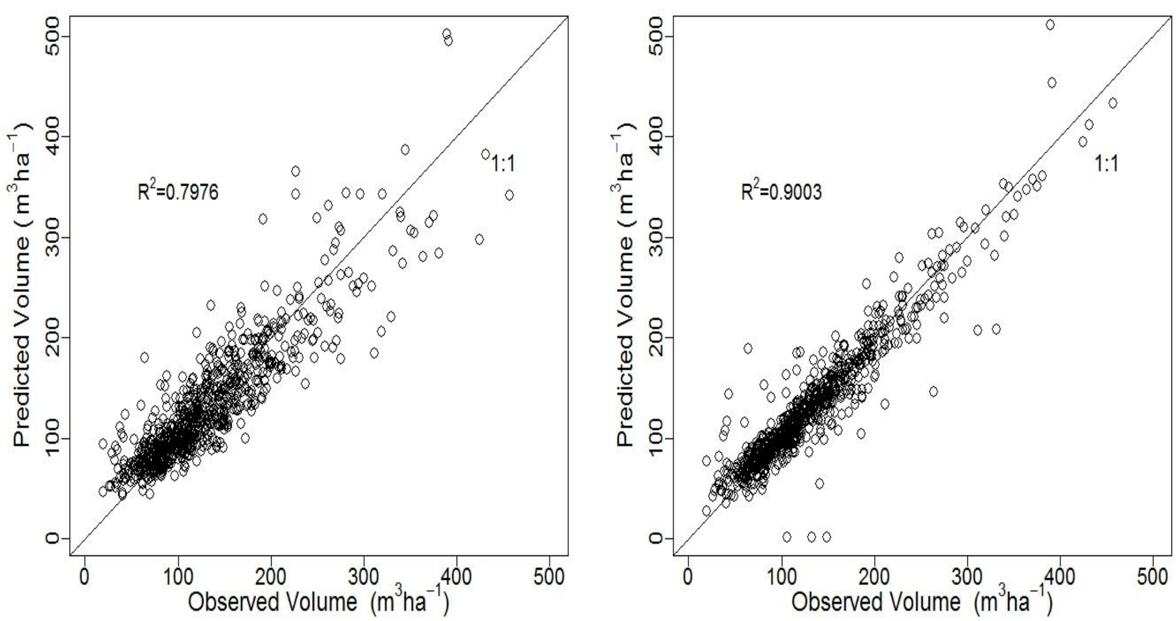

Figure 8. Predicted and observed stand volumes: original Sullivan Clutter model (left), and Sullivan Clutter model including rainfall (right) .

The model was validated using independent data. Observed values and predicted values were plotted (Figure 9), and no statistical differences were found when the t test was applied (p-value=0.64). Every point in the plot represents the observed and the predicted value; if a point is located over the 1:1 line, it represents that the observed and the predicted value are equal. Points over/under the line indicate that the predicted/observed plot has a higher value than the observed/predicted plot.

In general the model predicts accurately the observed values for volume, which suggest enough confidence to be used for planning and simulation.

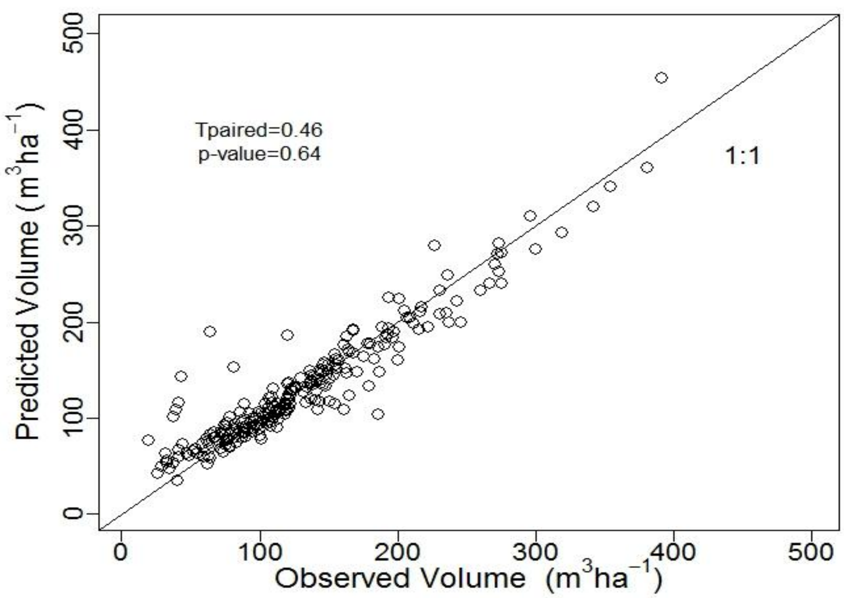

Figure 9. Predicted and observed stand volumes comparison of Eucalyptus stand volumes, to validate the fitted model, where can be observed that model predicts accurately stand volume values.

The relationship modeled between volume growth and rainfall changes depending on the level of rainfall and also on stand initial growing period age (Figure 10). The relationship modeled is similar to the relationship shown previously using the observed data (Figure 10).
To assess the effect of rainfall on stand volume growth, we plot the first derivative of the fitted Sullivan Clutter model, using different ages and selecting the same S (30 m) for all the cases. Volume growth in younger stands is more sensitive to rainfall level than in older stands. Stands 3 and 4 year old are especially sensitive to rainfall levels, which can be appreciated by the curve slope. Older stands follow the same trend but are much less sensitive to rainfall level changes as younger stands. Volume growth and rainfall relationship in older stands (5, 6 and 7 years old) are similar, and in practical terms, their difference is marginal at the stand level. Stand growth is more affected when the rainfall level is low as could be seen by the curve slope at low rainfall levels for all age classes.

Another interesting issue to point out is that the increase in rainfall level does not represent an important gain in older stands as occurs in younger stands for the same rainfall level, this is an important fact to take into account at the moment to decide where and in what kind of stands silvicultural treatments should be applied.

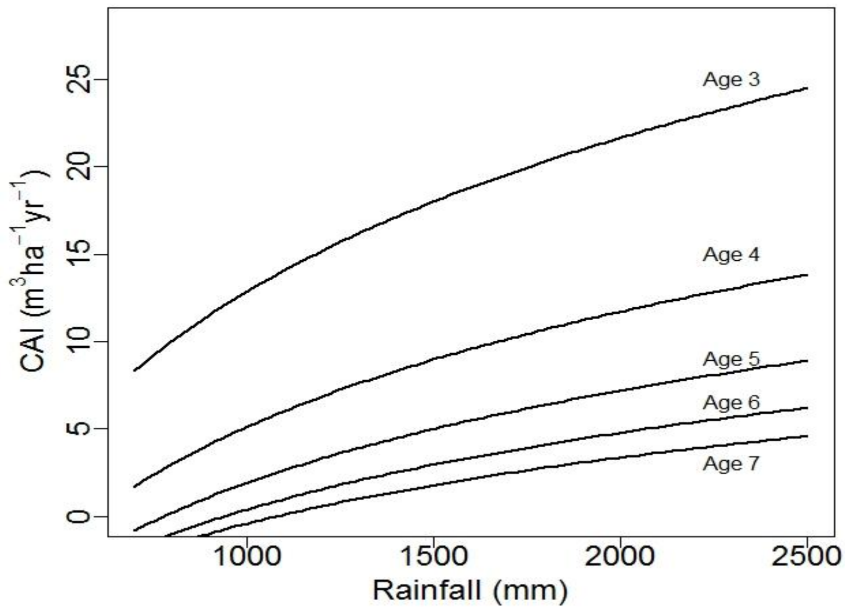

Figure 10. Volume growth at different rainfall and age levels for Eucalyptus stands in western llanos Venezuela, showing that younger stands and at lower rainfall levels sensitivity to rainfall changes is higher.

As we have seen previously, rainfall is an explanatory variable related with stand volume yield, and in consequence with stand volume growth. Lower volume growth is expected in periods when rainfall is under the average than in periods where is over the average, as suggested by the fitted model. But also the rainfall effect on volume stand growth depends on the stand's age.

3.3. Rainfall and Yield variability

To start the simulation, it was necessary to use as input the two year old stand's basal area (BA) for each S considered. Initial basal area was 3.58, 5.54, 7.51, and 9.47 m^2 ha^{-1} for S 15, 20, 25, and 30 m. The model fitted is in Figure 11, which shows the relationship between BA and S for the S range at the area of interest.

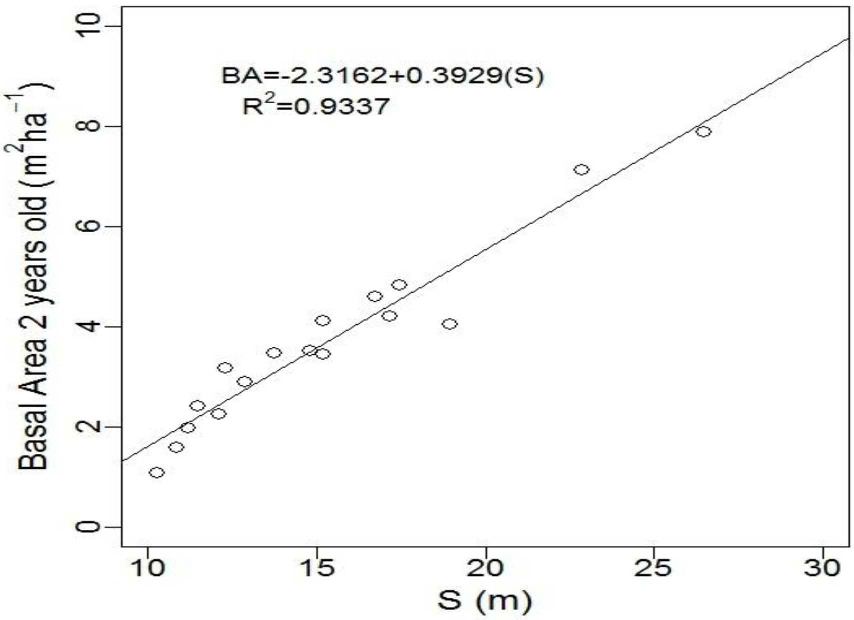

Figure 11. Basal area and S model fitted using information from two years old stands of Eucalyptus stands in western llanos, Venezuela.

The results of the simulations for typical stands with S of 15, 20 25 and 30 m are in Figure 12. As expected, average volume yield increased as S increased. In other words, a higher S related with a higher yield, but also increased the risk of getting lower values than the average during dry periods. Predicted yields averaged: 125, 170, 231, and 291 m^3 ha^{-1}, and standard deviations were: 3, 4, 5.6, and 7 m^3 ha^{-1} for S 15,20,25 and 30 m respectively. The values ranges for the same S were: 116-129, 158-175, 215-239, and 270-300 m^3 ha^{-1} (Figure 12). For all S plotted, the probability density function simulated was skewed to the left, but became flatter as the S increased. With this simulation we were able to generate any combination of rainfall sequences could occur during the rotation: wet period, dry period, dry period followed by a wet period, or a wet period followed by a dry period, with different length and intensity. Another useful use of this growth and yield model including rainfall, is to infer about the effect of extreme events, like drought periods and drought periods.

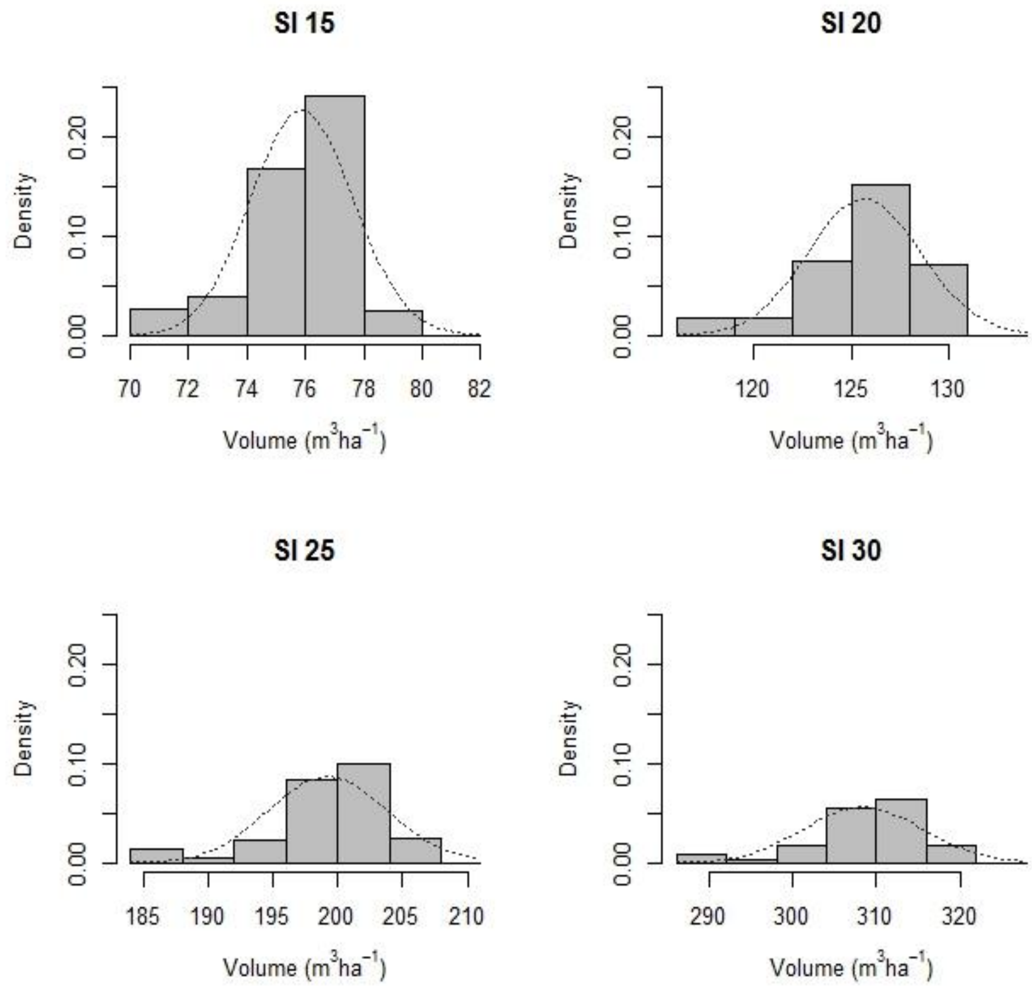

Figure 12. Simulated volume yield probability density function by S, showing an increase in average yield and variability as S increases as an effect of rainfall variability. Note the different volume value range.

Simulation results for extreme rainfall periods show the differences in basal area, volume, MAI and CAI for a typical stand with S 25 m (Table 11). Volume at rotation age reached 206 m^3 ha^{-1} during the wet period, and 185 m^3 ha^{-1} during the dry period. This range represents less than 10 % of total volume during average rainfall years. However, for an industrial plantation, this value could represent an important amount when considering large area extensions, which could affect timber supply to the mill.

4. Discussion

Eucalyptus plantations established in Venezuela's Western Llanos are located in areas where site index (base age 5 years) varies significantly (14 to 35 m), which is associated with a volume at rotation age between 88 and 294 m^3 ha^{-1}. This information should be taken into account for forest managers and policy makers to select areas for plantation establishment and also to satisfy the demand for domestic forest products. Currently there is a national discussion, in Venezuela, about the land quality that should be allocated for forest production, which is a topic common in many other countries in Latin America. To produce the same amount of timber as stands with S30 m, it is necessary to allocate 3 times more land in S19, 2 times more land in S 23, and 1.3 times more land if we just use S 27 stands. Those values correspond to the productivity levels reached with traditional management. Forest managers and policy makers should decide if they prefer to concentrate production in a smaller area affecting them intensively or use a broader area with all the operational problems associated to reach the same production levels.

Rainfall had a significant relationship with stand growth, as has been the case in other Eucalytus plantation studies (Stape et al., 2004; Landsberg and Sands, 2011) As rainfall increased, growth also increased but at decreasing rates, up until it reached an asymptote asymptote which depends on the difference between potential evapotranspiration and real evapotranspiration. Trees have some water demand amount, and any amount over the demand will be not useful; the stand growth will become limited by another factor. The growth rates and the asymptote varied depending on stand age and S. The asymptote in all cases was reached when rainfall level was between 1400 and 1600 mm. After reaching this asymptote, the extra rainfall did not significantly increase volume growth. Stape (2002) estimated the relationship between growth and rainfall, and he found the asymptote varied depending on the species, but in all cases it was between 1400 and 1600 mm. Better genetic material, deeper soils, a more homogeneous monthly rainfall distribution, and more intensive silviculture could explain this difference.

Growth rate as a function of rainfall levels were higher for young stands than for older stands, but at the same time they were more sensitive when drought periods occurs. A drop in rainfall levels, especially when it was low, represented a larger drop in productivity in younger stands than in older stands. Younger stands have a shorter root system that constraints the soil volume where trees could take the water from (Christina et al. 2011; Zani, 2012), but also because younger trees have a higher LAI and in consequence a higher transpirative surface (Xavier 2002; Zani, 2012). This is an interesting fact that should be taken into account when deciding what and where to apply silvicultural treatments. Applying silvicultural treatments to increase water availability seems that it should be done on younger stands and probably just on dry years, but this is something that needs a better understanding. Any increase in rainfall level will have a higher response in younger stands than in older stands. A deeper financial analysis should be done to assess the profitability of those treatments, and the stand characteristics where treatments should be applied.

Taking into account spatial and time correlation through the use of mixed model allowed us to model multilevel data structures. In our case, two different levels were considered: 1) the region level and 2) the plot level. Plots belonging to the same region shared the same weather information and similar environmental conditions: soils, temperature, wind speed, solar radiation. Measurements from the same plot were also correlated because we were measuring the same subject at different moments. The advantage of modeling the variance-covariance matrix structure with mixed models is that the standard error obtained to test the parameters significance is not biased; otherwise would arrive at the wrong conclusions and make incorrect decisions. So, mixed models could be used as a tool to incorporate weather information into growth and yield models without violating the basic assumptions of the general linear models.

Stand growth simulation over a rotation permitted us to test all rainfall combinations over seven year periods. We were able to simulate plantations established on dry or wet periods followed by wet or dry periods, or any other combination. For simulation we took into account rainfall serial correlation; otherwise, we would use independent rainfall for every year which would diminish the yield variability since a wet year (over the average) could be followed by a dry year (under the average). In reality, many years under/over the average could occur in a row.

Simulation revealed that higher S stands will have a higher yield as expected, but at the same time the yield variability is higher when taking into account rainfall variability. This conclusion is interesting take into account since yield is higher in better sites while at the same time it is more sensitive to rainfall variability. Then a drought period could affect more, in absolute terms, a high quality stand than a low quality stand. In any case, yield will be higher in high quality stands even when the drop in yield is also higher in those stands.

The yield variability as a consequence of rainfall variability during the rotation was not as high for this particular area. For every S considered, the lowest value in the distribution is around 10% lower than the average, and is lower than CAI for any year during the rotation. So even when rainfall has an effect on growth, it does impact strongly the rotation volume yield. The rainfall average in this area is around 1400 mm, which is also the threshold where extra rainfall does not increase growth. Then any variability over the average does represent an important increase in volume, but it represents more water in the system which could be accumulated and stored to be used in the next period which could be dry. An important thing to notice from the historical rainfall data, is that even when rainfall follow cycles, those are not too long or severe, and then the influence of extreme events does not seem to be significantly important, especially for older stands that are less sensitive than younger stands.

For planning purposes, the low yield variability we found represents an advantage since mill supply will not be affected strongly by rainfall variability, at least at the stand level.

However, at the forest level and depending on the age and S characteristic of the stands composing a particular forest, rainfall could an important effect. Incorporating this kind of information on harvest schedules models could give a better understanding of what could be the effect of rainfall variability and its effect on yield on the optimal harvest schedule at the forest level.

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APPENDICES

Appendix 1. Growth equations as the derivative of the yield equation

Volume

$$\ln V_2 = \beta_0 + \beta_1 A_2^{-1} + \beta_2 SI + \beta_3 \ln BA_2$$

Volume Growth

$$\frac{1}{V_2}\frac{\partial V_2}{\partial A_2} = -\beta_1 I_2^{-2} + \frac{1}{BA_2}\beta_3\frac{\partial BA_2}{\partial A} \quad (1)$$

Basal Area

$$\ln BA_2 = \alpha_0\left(1-\frac{A_1}{A_2}\right)\ln Rain + \alpha_1\left(1-\frac{A_1}{A_2}\right)SI + \alpha_2 \ln BA_1\left(\frac{A_1}{A_2}\right)$$

$$\ln BA_2 = \alpha_0 \ln Rain - \alpha_0 \ln Rain A_1 A_2^{-1} + \alpha_1 - \alpha_1 S A_1 A_2^{-1} + \alpha_2 \ln BA_1 A_1 A_2^{-1}$$

$$\frac{1}{BA_2}\frac{\partial BA_2}{\partial A_2} = +\alpha_0\frac{A_1}{A_2}\ln Rain + \alpha_1 SI\frac{A_1}{A_2} - \alpha_2 \ln BA_1\frac{A_1}{A_2}$$

$$\frac{\partial BA_2}{\partial A_2} = BA_2\frac{A_1}{A_2}\left(-\ln BA_1 + \alpha_0 \ln Rain + \alpha_1 SI\right)$$

But as $I_1 \rightarrow I_2$

Basal Area Growth

$$\frac{\partial BA_2}{\partial A} = BA_2\frac{1}{A_2}\left(\alpha_0 \ln Rain + \alpha_1 SI - \alpha_2 \ln BA\right) \quad (2)$$

Inserting (2) in (1)

$$\frac{\partial V_2}{\partial A} = V_2\left(\frac{-\beta_1}{A_2^2} + \frac{1}{BA_2}\beta_3\left(\frac{BA_2}{A_2}\left(\alpha_0 \ln Rain + \alpha_1 SI - \alpha_2 \ln BA\right)\right)\right)$$

$$\frac{\partial V_2}{\partial A} = V_2\left(\frac{-\beta_1}{A_2^2} + \beta_3\left(\frac{1}{A_2}\left(\alpha_0 \ln Rain + \alpha_1 SI - \alpha_2 \ln BA\right)\right)\right)$$

Volume Growth

$$\frac{\partial V_2}{\partial A_2} = \frac{V_2}{A_2}\left(-\beta_1 A_2^{-1} + \beta_3\left(\alpha_0 \ln Rain + \alpha_1 SI - \alpha_2 \ln BA\right)\right)$$

In our case study:

$$\ln V_2 = 1.51 - 1.57 A_2^{-1} + 0.05 SI + 0.95 \ln BA_2$$

$$\frac{\partial V_2}{\partial A_2} = Vol\left(1.57 A_2^{-2} + \frac{0.95}{BA_2}\frac{\partial BA_2}{\partial A}\right)$$

$$\ln BA_2 = 0.29\left(1 - \frac{A_1}{A_2}\right)\ln Rain + 0.03\left(1 - \frac{A_1}{A_2}\right)SI + 1.04 \ln BA_1\left(\frac{A_1}{A_2}\right)$$

$$\frac{\partial BA_2}{\partial A} = BA_2 \frac{1}{A_2}\left(0.29 \ln Rain + 0.03 SI - 1.04 \ln BA\right)$$

$$\frac{\partial V_2}{\partial A_2} = \frac{V_2}{A_2}\left(-1.57 A_2^{-1} + 0.95\left(0.29 \ln Rain + 0.03 SI - 1.04 \ln BA\right)\right)$$

Appendix 2. Volume equations by clones used in Western Llanos, Venezuela

Company	Clone	Volume Equation
PAVECA	63	Vol=Exp(-10,738043 + (1,895901 * Ln(DBH)) + (1,246414 * Ln(Ht)))
PAVECA	241	Vol=Exp(-10,387429 + (1,929501 * Ln(DBH)) + (1,085800 * Ln(Ht)))
PAVECA	251	Vol=Exp(-10,695793 + (1,799940 * Ln(DBH)) + (1,277863 * Ln(Ht)))
PAVECA	955	Vol=Exp(-8,463773 + (1,937849 * Ln(DBH)) + (0,489353 * Ln(Ht)))
PAVECA	1084	Vol=Exp(-10,008039 + (1,635381 * Ln(DBH)) + (1,256976 * Ln(Ht)))
PAVECA	1066	Vol=Exp(-10,405714 + (1,759506 * Ln(DBH)) + (1,220003 * Ln(Ht)))
PAVECA	641	Vol=Exp(-10,973142 + (1,978189 * Ln(DBH)) + (1,244169 * Ln(Ht)))
PAVECA	3	Vol=Exp(-9,892651 + (1,828016 * Ln(DBH)) + (1,025138 * Ln(Ht)))
PAVECA	10	Vol=Exp(-10,356968 + (2,051916 * Ln(DBH)) + (0,959371 * Ln(Ht)))
PAVECA	63	Vol=Exp(-11,759092 + (0,024511 * Ln(DBH)) + (3,226213 * Ln(Ht)))
PAVECA	66	Vol=Exp(-10,181593 + (1,399206 * Ln(DBH)) + (1,499044 * Ln(Ht)))
PAVECA	241	Vol=Exp(-10,515166 + (1,389924 * Ln(DBH)) + (1,594925 * Ln(Ht)))
PAVECA	251	Vol=Exp(-9,551258 + (2,118151 * Ln(DBH)) + (0,606046 * Ln(Ht)))
PAVECA	955	Vol=Exp(-10,062378 + (1,936721 * Ln(DBH)) + (1,006725 * Ln(Ht)))
PAVECA	1066	Vol=Exp(-10,135738 + (1,924923 * Ln(DBH)) + (1,035000 * Ln(Ht)))
PAVECA	1084	Vol=Exp(-9,663542 + (1,974209 * Ln(DBH)) + (0,839309 * Ln(Ht)))
PAVECA	1085	Vol=Exp(-10,259374 + (1,673678 * Ln(DBH)) + (1,306969 * Ln(Ht)))
PAVECA	1188	Vol=Exp(-9,112265 + (2,177199 * Ln(DBH)) + (0,503641 * Ln(Ht)))
PAVECA	1265	Vol=Exp(-11,022126 + (1,434834 * Ln(DBH)) + (1,768446 * Ln(Ht)))
PAVECA	1256	Vol=Exp(-9,911552 + (1,868635 * Ln(DBH)) + (0,960561 * Ln(Ht)))
PAVECA	1407	Vol=Exp(-10,296506 + (1,841755 * Ln(DBH)) + (1,148920 * Ln(Ht)))
PAVECA	1432	Vol=Exp(-10,296506 + (1,841755 * Ln(DBH)) + (1,148920 * Ln(Ht)))
PAVECA	1503	Vol=Exp(-10,296506 + (1,841755 * Ln(DBH)) + (1,148920 * Ln(Ht)))
PAVECA	1846	Vol=Exp(-10,296506 + (1,841755 * Ln(DBH)) + (1,148920 * Ln(Ht)))
PAVECA	2159	Vol=Exp(-10,296506 + (1,841755 * Ln(DBH)) + (1,148920 * Ln(Ht)))
PAVECA	2425	Vol=Exp(-10,296506 + (1,841755 * Ln(DBH)) + (1,148920 * Ln(Ht)))
SKCV		Vol=0.000053070*((DBH)^1.729573445)*(HT^1.092641909)-0.000033577*((5**3.287761)/DBH^(3.287761-2)))*(Ht-1.3)

Source: (personal communication)

Appendix 3. Variance Covariance Structures

Unstructured

(TYPE = UN)

$$\begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} & \sigma_{14} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} & \sigma_{24} \\ \sigma_{13} & \sigma_{32} & \sigma_{33} & \sigma_{34} \\ \sigma_{14} & \sigma_{42} & \sigma_{43} & \sigma_{44} \end{bmatrix}$$

First Order Autoregresive

(TYPE = AR(1))

$$\sigma 2 \begin{bmatrix} 1 & \rho & \rho^2 & \rho^3 \\ \rho & 1 & \rho & \rho^2 \\ \rho^2 & \rho & 1 & \rho \\ \rho^3 & \rho^2 & \rho & 1 \end{bmatrix}$$

Variance Components

(TYPE = VC)

$$\begin{bmatrix} \sigma_1^2 & 0 & 0 & 0 \\ 0 & \sigma_1^2 & 0 & 0 \\ 0 & 0 & \sigma_1^2 & 0 \\ 0 & 0 & 0 & \sigma_1^2 \end{bmatrix}$$

Compound Symetry

(TYPE = CS)

$$\begin{bmatrix} \sigma_1^2+\sigma^2 & \sigma_1^2 & \sigma_1^2 & \sigma_1^2 \\ \sigma_1^2 & \sigma_1^2+\sigma^2 & \sigma_1^2 & \sigma_1^2 \\ \sigma_1^2 & \sigma_1^2 & \sigma_1^2+\sigma^2 & \sigma_1^2 \\ \sigma_1^2 & \sigma_1^2 & \sigma_1^2 & \sigma_1^2+\sigma^2 \end{bmatrix}$$

Block Diagonal Matrix

Region 1 **Region 2** **Region 3..n-1** **Region n**

$$\left[\begin{array}{cc:cc:cc:cc} AR(1) & \rho & 0 & 0 & 0 & 0 & 0 & 0 \\ \rho & AR(1) & 0 & 0 & 0 & 0 & 0 & 0 \\ \hdashline 0 & 0 & AR(1) & \rho & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho & AR(1) & 0 & 0 & 0 & 0 \\ \hdashline 0 & 0 & 0 & 0 & .... & . & 0 & 0 \\ 0 & 0 & 0 & 0 & . & .... & 0 & 0 \\ \hdashline 0 & 0 & 0 & 0 & 0 & 0 & AR(1) & \rho \\ 0 & 0 & 0 & 0 & 0 & 0 & \rho & AR(1) \end{array}\right]$$

Table 1. Average, standard deviation (sd), coefficient of variation (CV), maximum (Max) and minimum (min) yearly rainfall in the region of interest (series 1997-2010) and cumulated rainfall by season.

Region	Rainfall Mean (mm)	sd	CV (%)	Max (mm)	min (mm)	Nov-Apr	May-Oct
1. San Carlos	1456	224	15	1869	1033	291	1165
2. El Pinal	1661	362	22	2666	1199	323	1338
3. La Yaguara	1340	283	21	1889	976	268	1072

Table 2. Monthly mean, maximum, and minimum temperature (°C), rainfall (mm), and potential (ETP) and real evapotranspiration (ETR) (mm) in Western Llanos, Venezuela

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Tmax	35	35	36	35	33	31	31	32	32	33	33	33	
Tmin	19	20	21	23	23	22	22	22	22	22	21	20	
Rainfall	9	8	14	91	19	234	250	219	158	139	90	45	1266
ETP	128	141	181	187	166	139	135	140	143	155	140	132	1587
ETR	42	25	23	93	166	139	135	140	143	155	129	91	1281

Table 3. Yearly rainfall time series (1945-2010) at San Carlos, Cojedes, Venezuela

Year	PP(mm)	Year	Rainfall(mm)
1943	1335	1977	1202
1944	1366	1978	1448
1945	1342	1979	1957
1946	1692	1980	1254
1947	1217	1981	1639
1948	1341	1982	1380
1949	671	1983	1678
1950	789	1984	1311
1951	979	1985	1182
1952	1550	1986	1063
1953	1544	1987	1444
1954	2030	1988	1471
1955	1448	1989	891
1956	1383	1990	1343
1957	1353	1991	1602
1958	1321	1992	1473
1959	1720	1993	1095
1960	1294	1994	1393
1961	1191	1995	1557
1962	1361	1996	1467
1963	1617	1997	1466
1964	1195	1998	1702
1965	1618	1999	1521
1966	1508	2000	1288
1967	1149	2001	1333
1968	1265	2002	1524
1969	1977	2003	1699
1970	1804	2004	1868
1971	1272	2005	1541
1972	1459	2006	1548
1973	1356	2007	1149
1974	1039	2008	1327
1975	1447	2009	1033
1976	1622	2010	1381

Table 4. Regions, number of plots, age range, number and years of measurements

Region	Number of Plots	Ages Range	Measurements	Years
1.San Carlos	322	2-9	3-6	1999-2010
2.El Piñal	8	2.5-10	6-7	1997-2004
3.La Yaguara	17	2-11	8	1996-2004

Table 5. Site index (m) equivalency using different base ages (5, 6 and 7 years old).

S5	S6	S7
15	15.9	16.6
16	17.0	17.8
17	18.1	18.9
18	19.1	20.0
19	20.2	21.1
20	21.3	22.2
21	22.3	23.3
22	23.4	24.4
23	24.4	25.5
24	25.5	26.6
25	26.6	27.7
26	27.6	28.9
27	28.7	30.0
28	29.8	31.1
29	30.8	32.2
30	31.9	33.3
31	32.9	34.4
32	34.0	35.5
33	35.1	36.6
34	36.1	37.7

Table 6. Stand characteristics by S classes: number of plots, basal area (BA) volume (Vol), mean annual increment (MAI), and stand density

Site Index (m)	# Plots	BA (m^2 ha^{-1})	Vol (m^3 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})	Density (TPH)
>30	3	22	283.	57	948
25-30	49	17	169	34	970
20-25	164	14	121	24	932
15-20	66	12	86	17	925

Table 7. Analysis of variance, R^2, parameter estimates, and p –values for the guide curve model (Ln (Dominant Height) ~ Age^{-1})

Models

Analysis of Variance Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	71.7151	71.7151	3268.04	<.0001
Error	1392	30.5466	0.0219		
Corrected Total	1393	102.2617			
Adj R-Sq	0.70				

Parameter Estimates Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	3.4952	0.0097	360.79	<.0001
Age^{-1}	1	-1.9054	0.0333	-57.17	<.0001

Table 8. Analysis of variance, parameter estimates, and p –values for the Sullivan Clutter yield model (Ln(Vol) ~ (SI, Age^{-1}, Ln(BA)(age_{i-1}/age_i))

Analysis of Variance Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	135.3468	45.1156	785.4	<.0001
Error	736	42.2779	0.0574		
Corrected Total	739	177.62471			
Adj R-Sq	0.76				

Parameter Estimates Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	3.12476	0.08873	35.22	<.0001
SI	1	0.07818	0.00295	26.48	<.0001
edadinv	1	-3.46426	0.18275	-18.96	<.0001
edaddivlnB2	1	0.25213	0.01989	12.68	<.0001

Table 9. Goodness of fit indicators (-2LogL, AIC, AICC, BIC and Residual Sum of Squares) to compare the different models fitted.

Model Fixed Effects	-2LogL	AIC	AICC	BIC	Residual SS
Original					11.2675
+ Rainfall	-437.3	-435.3	-435.3	-431.1	11.2501
Mixed Effects*					
VC	-440.4	-436.4	-436.4	-436	11.0225
AR(1)	-440.6	-434.6	-434.6	-434	11.0237
CS	-441.2	-435.2	-435.1	-434.6	11.0275

*all the mixed models included rainfall as an explanatory variable

Table 10. Parameter estimates, standard errors, and p-values for the yield model fitted (Mixed effects using a variance-covariance matrix with CS structure)

Effect	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept	3.5509	0.08051	8	44.11	<.0001
SI	0.07638	0.00245	1378	31.18	<.0001
$1/age_2$	-3.9481	0.09486	1378	-41.62	<.0001
$\ln B1(age_1/age_2)$	0.09627	0.01398	1378	6.89	<.0001
$(1-age_1/age_2)$	0.4977	0.05612	1378	8.87	<.0001
$SI(1-age_1/age_2)$	-0.00887	0.001628	1378	-5.45	<.0001
Rainfall $(1-age_1/age_2)$	0.00004	7.89E-06	1378	5.01	<.0001

Table 11. Simulation results in extreme rainfall periods

Wet Period						
Age	Year	Rainfall (mm)	S 25 BA (m^2 ha^{-1})	Volume (m^3 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})	CAI (m^3 ha^{-1} yr^{-1})
2	2001	1333	7.5	35.4	17.7	0.0
3	2002	1524	10.6	87.8	29.3	52.5
4	2003	1700	13.0	122.0	30.5	34.2
5	2004	1868	15.2	153.1	30.6	31.1
6	2005	1541	17.1	180.2	30.0	27.2
7	2006	1548	18.9	206.4	29.5	26.2

Dry Period						
Age	Year	Rainfall (mm)	S 25 BA (m^2 ha^{-1})	Volume (m^3 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})	CAI (m^3 ha^{-1} yr^{-1})
2	1946	1692	7.5	35.4	17.7	0.0
3	1947	1217	10.3	86.0	28.7	50.7
4	1948	1341	12.6	118.1	29.5	32.1
5	1949	671	13.9	140.8	28.2	22.7
6	1950	789	15.3	162.6	27.1	21.8
7	1951	979	16.9	184.9	26.4	22.3

CHAPTER 2: Identifying the Main Constraints to Eucalyptus Productivity in the Venezuela Western Llanos

ABSTRACT

Increasing forest site productivity is a need in many areas. High land prices combined with landowners' desire for increased profitability have motivated forest managers to apply more intensive silvicultural treatments in order to increase forest site productivity. Even if *Eucalyptus* plantations' growth patterns were known in a particular area, the gap between attainable and current productivity is unknown. This information is important to estimate the expected responses to intensive silviculture and will help to decide where it is more convenient to apply silvicultural treatments to maximize investment. Understanding how intensive silviculture practices like weed control and fertilization + weed control affects productivity will permit managers to select the best treatments to increase productivity. Our objectives were: a) using Twin Plots 1) to estimate the gap between current and attainable productivity in Eucalyptus plantations under extra fertilization + weed control, 2) To estimate the treatment effect on light use and light use efficiency, and b) using Triplet Plots: 3) to estimate the gap between current and attainable productivity in Eucalyptus plantations under extra fertilization + weed control and extra weed control. To estimate the gap between current and attainable productivity, we established 53 pairs of plots measured for two years. Each pair consisted of a control plot (Control) which received the management regime regularly applied to the stands and a treated plot (Twin) which received an intensive silviculture treatment (fertilization + weed control) in addition to the operational management applied to the control plots. In 25% of the sites, a third plot (Triplet) was established. Triplet plots were established in those sites where 75% of the surface was covered by weeds. Those plots received only an intensive weed control besides the operational management applied traditionally. After two years, stem biomass growth in control and twin plots was 12.4 and 14.8 Mg ha^{-1} yr^{-1} respectively. This difference represents a gain of 2.4 Mg $ha^{-1}yr^{-1}$ over 2 years. We found significant statistical differences for APAR by twin and control plots, whose averages where 1406 MJ m^{-2} yr^{-1} and 1344 MJ m^{-2} yr^{-1} respectively, representing 4.6% increase. The increase in LUE was higher, reaching 20 %. In average, control plots had a LUE of 0.9 g/MJ and the twin plots of 1.10 g/MJ. We found that the stem biomass increment averaged 13.4, 15.1, and 17.2 Mg ha^{-1} yr^{-1} for the control, weed control, and fertilization + weed control respectively.

Key words: Twin Plots, Intensive Silviculture, site productivity, attainable productivity

1. Introduction

Eucalyptus plantations are needed to supply human demands for wood products. Currently more than 20 million hectares are planted, with South America as one of the main regions. In South America, Eucalyptus has been planted mainly with the aim of producing raw material for the pulp, paper and paperboard industries. In this region, Brazil, Chile, Argentina, and more recently, Colombia are countries with the largest Eucalyptus plantation area in the region. In those countries, the following factors have contributed to a quick growth in the first sector: internal and external needs; land availability; changes in laws and incentives; and the domestic economic growth. However, Venezuela does not have a large Eucalyptus area planted even though there is a large potentiality to develop forest plantations in the country. Venezuela has many advantages that allow the country to develop forest plantations: geographical location; land availability; country infrastructure; experience with forest plantation and more. But political uncertainties and risks are the major reasons to avoid investments in Venezuela (Cubbage et al., 2010). Current constraints on land use and the potentiality for increased forest plantation area make it necessary to understand the limiting factors that are causing Venezuela to avoid reaching higher productivity.

In Venezuela, most of the Eucalyptus plantations are located in the Western Llanos, which has dry and wet seasons that define the growing period in the area. Eucalyptus plantations in this area have an average mean annual increment (MAI) of 25 $m^3ha^{-1}yr^{-1}$, but there is a large variability due to soils, drainage, genetic material, and management. These plantations can be used by researchers to allow for a better understanding of the main constraints of forest productivity besides water, such as nutrition or weed competition. Understanding factors influencing forest site productivity will permit forest developers to make correct decisions to select and apply the treatments necessary to satisfy the demand for forest products by increasing site productivity and resource use efficiency. The attainable productivity, the productivity reached if water or nutrients limitations do not exist at the site (Bouman et al., 1996), is unknown. The gap between the current and attainable productivity is useful to recognize in order to apply those treatments to maximize the gain attained by investment. In other regions of the world, it has been shown that nutrition and weed control affect yield by increasing LAI, canopy nutrition, and water and nutrient competition, thereby affecting Light Use Efficiency (LUE). Forest site productivity, which is understood as the amount of stem dry matter produced per unit of area and time (Whitehead et al., 2004), is tightly related to the amount of solar radiation intercepted, quantum efficiency (the amount of carbohydrates produced by a units of light absorbed) and also to the proportion of carbohydrates allocated to the stem (Watson, 1958; Waring, R.,1983; Vose and Allen, 1988; Battaglia et al., 1998; Bergh et al., 1999; Cannel, 1989; Binkley et al., 2004; Waring and Running, 2007). Treatments, when affecting stand growth, could create a change in different physiological processes.

In our case, we were concerned with how treatments would affect light use (the amount of total radiation intercepted) and light use efficiency (the amount of above ground net primary production by unit of light intercepted). An increase in net primary production could be due to an increase of: 1) APAR=f(PAR, k, LAI) , and 2) LUE, due to the relationship in Eq. 1.

$$\boldsymbol{WNPP = \alpha \cdot APAR \cdot LUE} \tag{1}$$

Where:

$$\boldsymbol{APAR = PAR \cdot (1 - e)^{-k \cdot LAI}} \tag{2}$$

WNPP= Wood Net Primary Production (Mg ha^{-1} yr^{-1})
α= units conversion factor
APAR=Absorbed Photosynthetically Active Radiation (MJ m^{-2} yr^{-1})
LUE=Light Use Efficiency (g MJ^{-1}).
PAR=Photosynthetically Active Radiation (MJ m^{-2} yr^{-1})
k= light extinction coefficient
LAI= Leaf Area Index (m^{2} leaves m^{-2} ground)

Intensive silviculture affects the amount of leaf area displayed (Linder, 1985; Albaugh et al . 1998; Rojas, 2005; Stape et al., 2008; Zani, 2011), increasing the amount of light intercepted

(APAR), which has been proven to have a direct and linear relationship with gross primary production. In addition, intensive silviculture increases light use efficiency (LUE) (Stape et al, 2008).

Other factors such as nutrients, water, pest attacks, diseases, and wind could affect the amount of leaf area displayed, its lifespan, and its quantum efficiency, because they could affect the photosynthesis rate, stomatal conductance, respiration rates or carbohydrates allocation (Cannel, 1989; Binkley et al., 2010, Landsberg and Sands, 2011).

It is not possible to increase the amount of light or CO_2 supplied, but it is possible to manipulate the system in order to get more resources that will permit a larger display of leaf area, which means more light interception and, consequently, a higher Net Primary Production (du Toit, 2008; Alvarez, 2010; Landsberg and Sands, 2011; Landsberg and Gower, 1997). It has been proven by long term forest experiments that the current rates of biomass production in most forest ecosystems are far below the potential level that could be attained whether or not limiting factors exist (Bergh, 1999; Albaugh et al, 2004). Manipulating site resources allows for the possibility of increasing leaf area index and resource use efficiency as well as changing allocation patterns of the carbohydrates produced in the photosynthetic process (du Toit, 2008).

In tropical conditions where there exists an uneven precipitation distribution, thereby generating well-defined dry and wet seasons, and temperatures that do not vary strongly during the year, water could be the main limiting factor in most cases. Rainfall distribution affects water availability and vapor pressure deficit; a consequently, stomatal conductance is affected, restricting CO_2 fixation (de Castro et al, 2008; Almeida et al., 2007; Gholz et al., 1990; Cannell, 1989). Almeida et al. (2007) studied the relationship between the growth and the water balance of *Eucalyptus grandis* hybrid plantations in Brazil, finding that forest growth is affected by water availability, mainly by drought. The same conclusions were found when the system was simulated using a process based model (3PG) for *Eucalyptus* plantations in Brazil, which permitted researchers to assess the effects of drought on productivity (Almeida et al, 2004). The evaluation of water supply is very important for selecting the best harvesting and silvicultural practices, especially for tropical conditions where precipitation amount and distribution are the main limiting factors to reach higher productivities (Gonçalves et al., 2008).

Stape (2004) found that rainfall, leaf area index (LAI), and site index (SI) were the stand and environmental factors with a higher correlation with *Eucalyptus* stands' productivity in a precipitation gradient in northeastern Brazil. It also was found that water use efficiency increased as the water use increased. Nutrients and soil chemical properties were not important factors determining productivity, probably due to the adequate site preparation, fertilization and high efficiency in cycling nutrients in those *Eucalyptus* plantations (Stape, 2004). Under an irrigation experiment using *Eucalyptus grandis X urophylla*, it was found that production increased 52% by the effect of irrigation, water use increased by 15% and water use efficiency by 32% (Stape, et al., 2004).

Not only water affects productivity: nutrients have been proven to have a strong effect on forest site productivity. Substantial response to nitrogen fertilization was found in *Eucalyptus regnans* plantations in southern Tasmania. Annual applications of nitrogen doubled the volume growth from 125 m^3 ha^{-1} to 281 m^3 ha^{-1} (Ringrose and Nielsen, 2005). Campion and Scholes (2003) found that fertilization substantially increased height, dbh, and canopy volume on young *Eucalyptus grandis* plantations in South Africa. Epron et al (2011) found that fertilization with potassium and sodium changed carbon allocation on Eucalyptus plantations in Brazil. More carbon was allocated aboveground and leaf lifespan increased which, as a result, increased forest site productivity. Fertilization with nitrogen and potassium increased leaf lifespan and allocation aboveground in Eucalyptus plantations in Sao Paulo, Brazil (Laclau, et al. 2008). In this study, potassium fertilization increased the stand biomass through an increase in leaf area index and not through an increase in growth efficiency. These studies concluded that the management of residues after harvesting could have an influence on next rotation productivity, because the amount of nutrients in the system is higher. Such results are common in many places around the world, as reported for *Eucalyptus sp* in Congo (Bouillet et al., 2000, Laclau, et al., 2011), *Eucalyptus grandis* in Brazil (Goncalves et al., 2000) India (Sankaran et al., 2010) and South Africa (du Toit, 2000), *Eucalyptus urophylla* in China (Xu et al., 2000).

Attainable productivity was estimated in Brazil using paired inventory plots, which consist of a set of intensive silviculture and control (current company stand management) plots located 20-30 m apart, spread over an area of interest. In that case, it was found that the maximum attainable productivity averaged 10 Mg $ha^{-1}yr^{-1}$ greater than the increment of the control plot (Stape et al., 2006), 4 Mg $ha^{-1}yr^{-1}$ in *Eucalyptus urophylla* plantations in Sao Paulo (Ferreira et al., 2009), and 5 Mg $ha^{-1}yr^{-1}$ in *Eucalyptus grandis* and *E. grandis X urophylla* (da Silva, 2012).

In the particular case of Western Venezuela, it was identified that soil texture is a good predictor of growth of *Eucalyptus urophylla* and *Eucalyptus grandis* plantations. Trees grew better in soils with clay loam textures, and excessive soil moisture was inversely correlated with tree growth in *Eucalyptus grandis* (Henri, 2001). Acosta et al. (2005) also found that productivity in Eucalyptus spp. in western Venezuela are also correlated with physical soil properties, which suggests that water supply is an important factor influencing the productivity. Rojas (2000) studied the relationship between soil factors, foliar nutrients and growth for *Eucalyptus grandis X urophylla* clones in western Venezuela, and found that volume at all ages were positively correlated to soil extractable phosphorus and sand content.

A lack of information in this area about the factors affecting forest site productivity and the gap between current and attainable productivity make it necessary to improve knowledge that could be used for decision making. For that purpose, a Twin-Plot, Triplet Plot design was installed to capture the actual and attainable productivity of 53 Eucalyptus sites in Western Venezuela using Twin Plots 1) to estimate the gap between current and attainable productivity in Eucalyptus plantations under extra fertilization + weed control and 2) to estimate the effect of treatment on light use and light use efficiency, and using Triplet Plots 3) to estimate the gap between current and attainable productivity in Eucalyptus plantations under extra fertilization + weed control and extra weed control.

2. Methods

2.1. Site description

Eucalyptus plantations in this study belong to DEFORSA, a forest company that operates in Cojedes State in Western Venezuela. Its plantations are located at 9°30' N, and 68°30' W (Figure 1). The average elevation is 250 m. Since 1990 more than 6.500 ha have been established using Eucalyptus, and a large proportion of the land is allocated to other uses such as pastures and native forest, over a total surface of 14.000 ha owned by the company. The main goal of DEFORSA is to produce pulpwood (Stape, 2006).

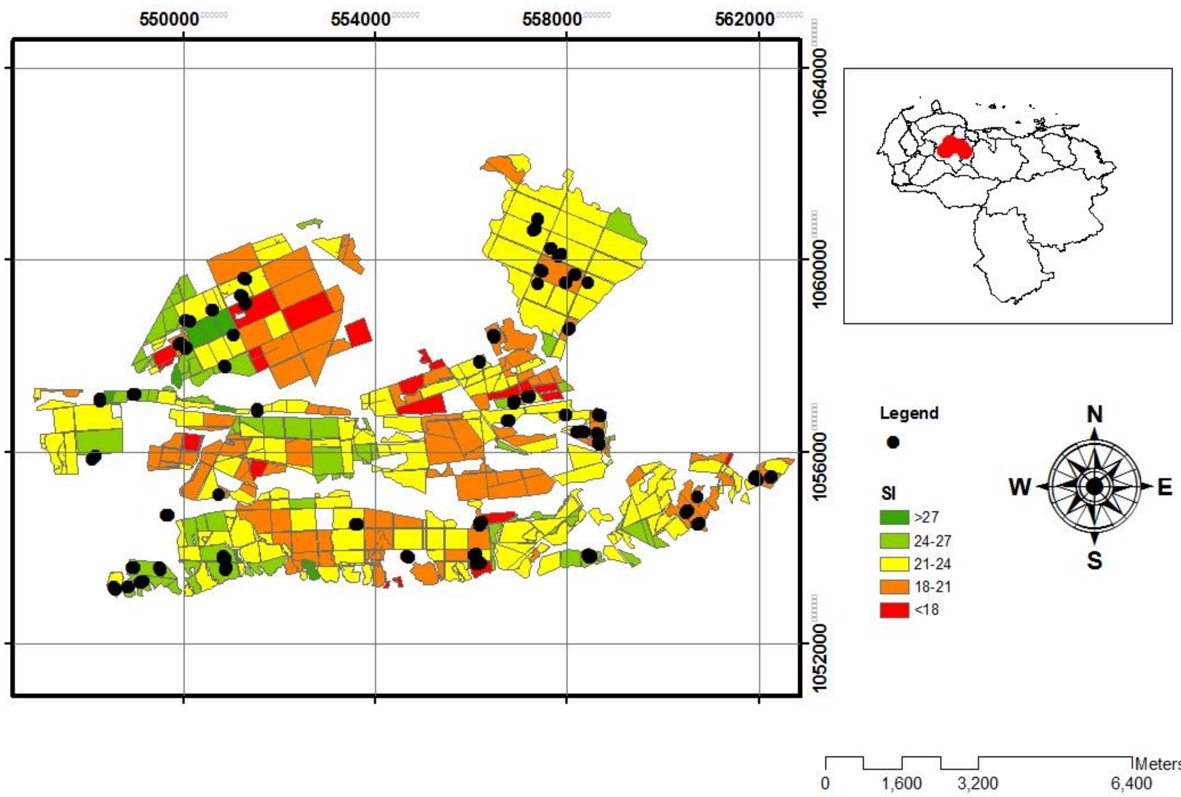

Figure 1. Relative location Cojedes State in Venezuela, and location of twin plots at DEFORSA.

Venezuelan llanos, where DEFORSA is located, is under the influence of the Intertropical Convergence Zone (ITCZ), which influences its climate characteristics, creating two well defined seasons: the rainy season from May to October, and the dry season from November to April (Hetier et al., 2005). Under Koeppen climatic zones, the area of interest is classified as Aw, since average temperature in the coldest month is higher than 18°C, typical of a tropical climate; the dry period occurs during northern hemisphere winter and it lasts more than 2 months; and the maximum average temperature that occurs before summer solstice. Under the Holdridge system, it corresponds to Dry Tropical Forest (bs-T) (Ewell and Madriz, 1968, Paredes, 2009). The mean temperature is 28.5 °C, and the yearly rainfall is 1457 mm

(Paredes, 2009). Monthly maximum and minimum temperature, monthly rainfall, potential evapotranspiration, and actual evapotranspiration assuming a water holding capacity of 165 mm using the methodology proposed by Thornwhite and Mather (1957), is shown in Table 1. Monthly rainfall during the study period and the amounts by season are in Figure 2.

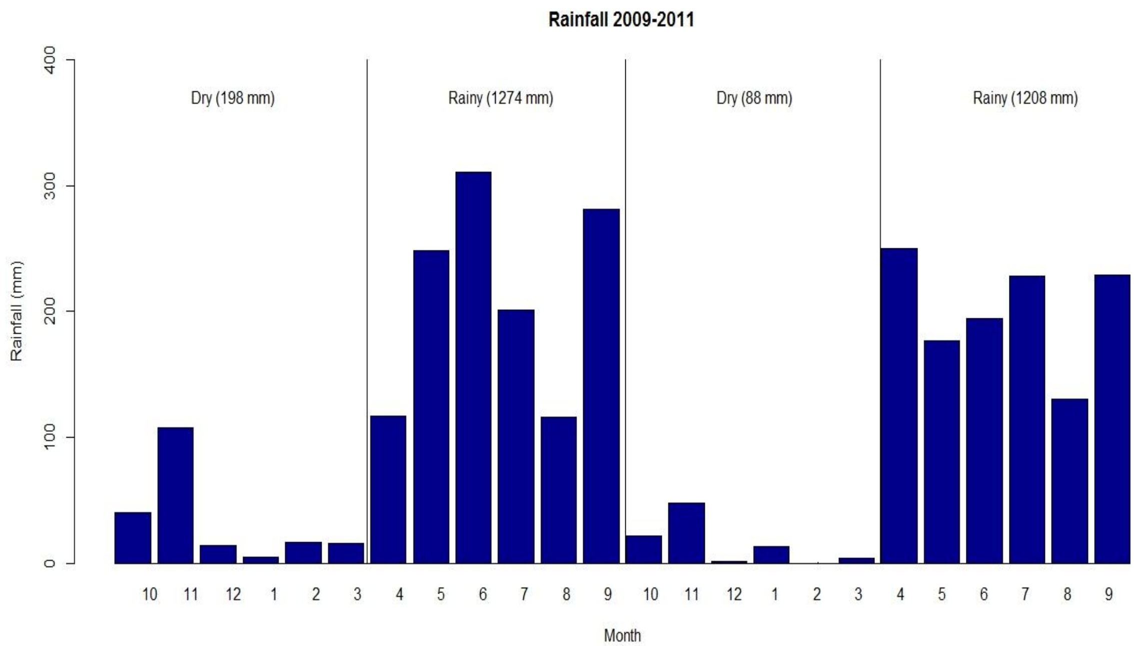

Figure 2. Rainfall and relative rainfall 2009-2011 at DEFORSA.

The area is characterized by the “Galeras,” which occupied the highest position in the landscape. “Galeras” lifted up in the tertiary and are composed by lutites and sandstones. Lowest areas in the landscape are composed by fluvial quaternary deposition material (Ramia, 1993, Schargel, 2005). Slopes in general are between 3-8%. Soil orders common in the area are inceptisols, ultisols, alfisols, and vertisols. Poorly drained soils represents between 20 to 30 % of the area, which could be relevant in the wet season (Stape 2006, Stape, 2004).

Plantation establishment occurs between May and June, using macro-cuttings produced in containers, originated from a local clonal garden (Stape, 2004). Subsoiling (30 cm) combined with disking, bedding, and 4 x 2 m or 4 x 2.25 m spacing (8 or 9 m^2/plant) were used. Pre and post establishment fertilization is used up to 2 years (Table 2). Intensive weed control is applied in the first year, using pre and post establishment herbicides, which is applied manually (Stape, 2006). A combination of mechanical and manual weed control is applied every year up to the fifth year (Table 3). The main competing vegetation on Eucalyptus stands in this area is listed in table 4.

2.2. Treatments

The plots were selected over 950 inventory plots from the regular inventory network. The plots were selected following a stratified sampling to take into account different site qualities, genetic materials and ages. Strata were defined by clones, age, and productivity class. The number of plots by site index (4m each class) ranged from 12-39 (dominant height at 5 years basis <18 m, 18-22 m, 22-26 m and >26 m); by age classes ranged from 6-16 (2, 3, 4, 5 and 6 years old); and 14-26 by soil texture class in the first 20 cm (Sandy- Loamy Sand, Sandy Loam, Silt Loam-Loam-Clay loam).

Treated plots were established around 20 m from the control plot edge and in a lower topographic position to avoid any influence of fertilizers on the control plot (Figure 3). Each plot consisted of 15 X 4 rows of trees (60 trees/plot) in a rectangular shape. The total area varied depending on the spacing used in the stand, but was approximately 540 m^2/plot. Trees were marked and identified with a number. Plots with irregular characteristics (high mortality, presence of diseases or damaged) were avoided.

Figure 3. Control plot (dark) and twin plot (light) field layout.

Two different treatments were applied, and then we established two different type of plots near the control plots (traditional inventory plots):

1) Twin Plots

A total of 53 paired plots were established at DEFORSA in Eucalyptus plantations in July 2009. Each pair consisted of a control plot (Control) which received the management regime regularly applied to the stands, and a treated plot (Twin) which received an intensive silviculture treatment (fertilization + weed control), beside the operational management applied to the control plots. Applied doses are indicated on the table 5. Fertilized + weed control (Twin plots) received extra fertilizer in October 2009 and April 2011. Micronutrients B, Fe, Mn, Cu, Zn, Mo, and Co were also added to avoid any deficiency. 250 kg/ha of a mix (Cosmoquel) was applied with concentrations that were 0.91% B, 0.91% Fe, 0.28% Mn, 0.08% Co, 0.07% Zn, 0.07% Mo, 0.01% Co.

2) Triplet Plots

In order to understand the effect of just weed control on biomass growth, we established in 25% of the sites (14 sites) a third plot (Triplet). Triplet plots were established in those sites where 75% of the surface was covered by weeds, receiving just an intensive weed control beside the operational management applied in DEFORSA. Doses and timing is as described for the weed control on Twin Plots.

All the plots (including the control plots) received the doses (fertilization and weed control) DEFORSA applies to its stands (Glyphosate 3.5 kg/ha) as a part of its regular management. Applications occurred in Nov 2009, Sep 2010, Jan 2011, and Jul 2011.

2.3. Stand growth data

The plots were measured twice: September 2009 and September 2011. DBH was measured for all the trees in the plot. The total height was measured for the first 10 trees on the plot, and also on the 5 tallest trees. The heigths of the other trees were estimated from a DBH-Height hypsometric regression (Eq. 3) (Avery and Burkhart, 2001), for each genotype.

$$\ln(\boldsymbol{Ht}) = \underset{\substack{(0.0210)\\ p<0.0001}}{3.9634} - \underset{\substack{(0.1425)\\ p<0.0001}}{5.4947} \cdot \boldsymbol{dbh}^{-1} - \underset{\substack{(0.0630)\\ p<0.0001}}{1.6836} \cdot \boldsymbol{age}^{-1} \qquad R^2=0.88,\ n=1914 \qquad (3)$$

Where:
Ht=Height (m)
dbh=diameter at breast height (cm)
age= stand age (yr)

The basal area and density per plot were calculated as the sum of the cross sectional area and number of trees alive in the plot. The basal area, the volume and the stand density were calculated as an expansion based on the plot area (540 m^2).

To fit an allometric equation to estimate stem biomass by using dbh, we harvested 170 trees. One tree with average dbh in each plot was harvested, and its stem green biomass (stem, and bark) up to the crown base was weighted (Table 6), which we called wood net primary production (WNPP).

Stem biomass was estimated by using Eq. 3:

$$WNPP = 0.0691 dbh^{2.84} \tag{4}$$

Where: R^2=0.89 n=169

WNPP=Wood Net Primary Production (Kg /tree)

dbh=diameter at breast height (cm)

To transform green weight into dry weight, we estimated a dry/green weight factor. We harvested 36 trees and took 3 discs from the stem at different heights (1.3 m, 50% total height, and at the crown base). We transported them to the lab on the same day in plastic bags inside a cooler. We weighed the discs before and after we oven dried them at 70 °C until constant weight. We divided the dry weight by the green weight for each disc, and we calculated the factor as the factor average for each disc (0.49).

Plot growth was calculated as the difference between plot biomass in two different periods.

$$\Delta Biomass = Biomass_t - Biomass_{t-1} \tag{5}$$

Treatment response was calculated as the difference in growth between treated and control plots

$$TR = \Delta Biomass_{treated} - \Delta Biomass_{control} \tag{6}$$

Plot growth and treatment response are presented in Table 7.

2.4. Leaf Area Index

Leaf Area Index was measured in each plot in August 2010, April 2011, and September 2011 (Table 8). The first measurement was done using LAI-2000, and all the other measurements were done with hemispherical photographs. In the first case, using two sensors (above and below the canopy), we took 14 measurements per plot. We established the "above" canopy sensor in an open area where the closest tree was located at least three times its height from the sensor. Below canopy measurements were taken pointing the sensor to the same direction. We processed measurement using 3 rings to estimate LAI, and avoided LAI corresponding to canopy outside the plot limits. In the hemispherical photos case, we took fourteen photographs per plot (Figure A1) using automatic settings. All of them were processed in Hemisfer 1.4.4 ®. In order to find equivalency between measurements taken by the two different types of equipment, we measured simultaneously with both instruments at the same points inside the stand. We choose 14 stands of different ages and site qualities, and we fitted a linear model (Figure 4).

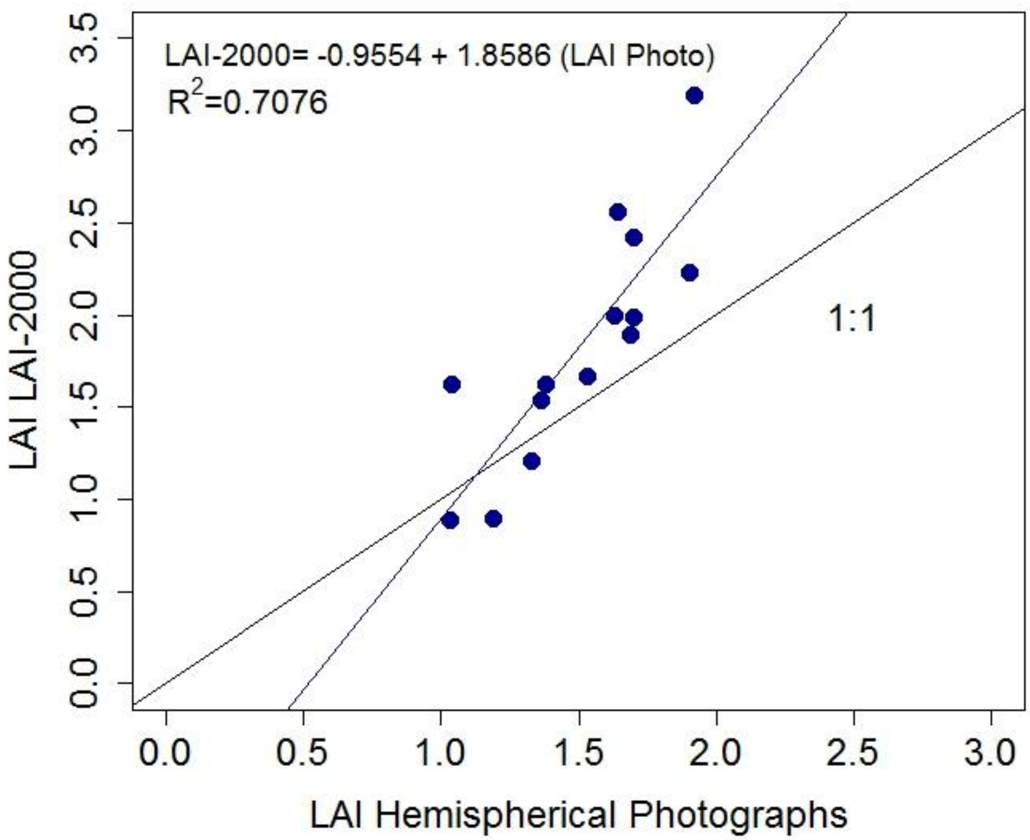

Figure 4. Equivalency between LAI measurements taken by LAI-2000 and Hemispherical Photographs

2.5. Light use and light use efficiency

Global radiation by month was obtained from FAO Clim (FAO, 2011). Photosyntetically Active Radiation (PAR) was calculated as 50% of the global radiation**.** Absorbed Photosyntetically Active Radiation (APAR) was calculated using Beer's Law as stated in Eq.7 (Waring and Running, 2007; Landsberg and Sands, 2011):

$$APAR = PAR \cdot (1 - \exp^{-k \cdot LAI}) \tag{7}$$

Where:

APAR=absorbed phothosynthetically active radiation (MJ m^{-2} $month^{-1}$)

PAR= phothosynthetically active radiation (MJ m^{-2} $month^{-1}$)

k= light extinction coefficient

LAI=Leaf Area Index

To estimate LAI for each month, we used NDVI-MODIS images for the period October 2009-September 2011. NDVI trends were generated for each stand using monthly values. As NDVI has been shown to be well correlated with LAI (Spanner et al., 1990, Turner et al., 1999), we assumed LAI follows the same trend. Using the land measurements of LAI, we interpolated the values for all the other months, assuming that LAI was proportional to the NDVI, which makes sense. LAI in DEFORSA stands are not as high to reach the nonlinear portion of the NDVI-LAI relationship, which is common after reaching a saturation point (Spanner et al, 1990; Turner et al., 1999).

Light use (MJ m^{-2} $month^{-1}$) was calculated as the summation of APAR, for each plot, for the period considered. Light use efficiency was calculated by dividing Wood Net Primary Production (WNPP) by the light use for each plot (Table 10).

2.6. Nutrient concentration and nutrient area index

To assess the foliar nutrient concentration, foliar samples were collected at the end of the growing period in 2011 (October). Samples were collected in every plot established selecting a tree with average diameter. Collection occurred at the upper third of the crown. Leaves were collected from branches in four different sides of the crown. Samples were stored immediately in plastic bags inside a cooler and transported to the lab in a maximum period of 3 hours. Leaves area was estimated by using the software Image J ®. All of them were oven dried for 72 hours at 70° C as well as weighted and grounded before being processed in the lab. Leaves with mechanical, insect, or disease damages were avoided. Specific Leaf Area (SLA) was calculated by dividing leaves area by its corresponding dry weight.

Foliar samples were oven dried at 70° C for 24 hours and weighed. Samples were wet-digested with a mixture of sulfuric acid and hydrogen peroxide (Parkinson and Allen 1975; Forest Research Institute 1984) for N, P, Ca, Mg, Mn, Fe and Zn determination (Table 11). A wet ash digestion using nitric acid was performed for each sample for Cu and B determination. Foliar N was determined colorimetrically by a flow injection analysis using a Lachat QuickChemTM System IV colorimeter (Lachat, 1996). All other nutrients were determined with an emission spectrometer that uses an inductively-coupled plasma source (ILPLasma-200 ICPTM).

Even when foliar nutrient concentration could be a good indicator, it takes neither the amount of foliar dry matter produced under each treatment nor the specific leaf area into consideration (one side leaf area divided by the leaf dry weight). This was also affected by fertilization and weed control. We calculated Nutrient Area Index (NAI, Table 11) using Eq. 8:

$$NAI = \left(\frac{10 \cdot NutC \cdot LAI}{SLA} \right) \tag{8}$$

Where:

NAI=Nutrient Area Index

LAI=Leaf Area Index (m^2 leaves m^{-2} ground)

SLA=Specific Leaf Area (m^2 leaves kg^{-1} leaves dry matter)

NutC= Nutrient Concentration (%)

10 represents a unit conversion factor

By taking into account LAI and SLA, it is possible to compare the absolute amount of foliar nutrients per ground surface.

2.7. Statistical Analysis

A paired t test was used to estimate differences in biomass increment; in light use and light use efficiency between control and treated plots; in foliar nutrient concentration; and on growth when weed control (Triplet plots) and weed control + fertilization (Twin Plots) were applied. Differences were considered statistically significant when $p<0.05$. Function t.test in R 2.10.1 was used.

3. Results

3.1. Effect of treatments on stand growth and site productivity

Stand density was 1060 and 1054 trees per hectare (TPH) for control and twin plot at the beginning of the study period, and no statistical differences were found. After two years, mortality was 40 and 48 TPH for control and twin plots, and was not statistically different (p-0.40).

At plot establishment, control and twin plots had similar values for average: DBH (11.1 and 11.2 cm); height (17.0 and 17.1 m, Figure 5); dominant height (19.36 and 19.92 m, Figure 5); and stem biomass (42.2 and 41.3 Mg ha^{-1}, Figure 6). In those plots, every point represents a paired plot; if a point is located on the 1:1 line, it represents that the control and the twin plot have the same value for a particular variable. Points over/under the line indicate that the twin/control plot has a higher value than control/twin plot. As we expected, after an extra intensive fertilization and weed control, DBH increased significantly (2.6 and 3.1 cm). This represents an absolute response in DBH of 0.5 cm in 2 years, and 20 % in relative terms. A significant statistical difference was found between DBH in the control and twin plot. Higher DBH gains were found in control plots with lower DBH increment. In those plots, the relative gain was higher than 20%, and in some cases it was more than 50%.

We observed height response after two years. Control plots had a height increase of 5.0 m and twin plots of 5.3 m. Significant statistical differences were found for this variable (Figure 5).

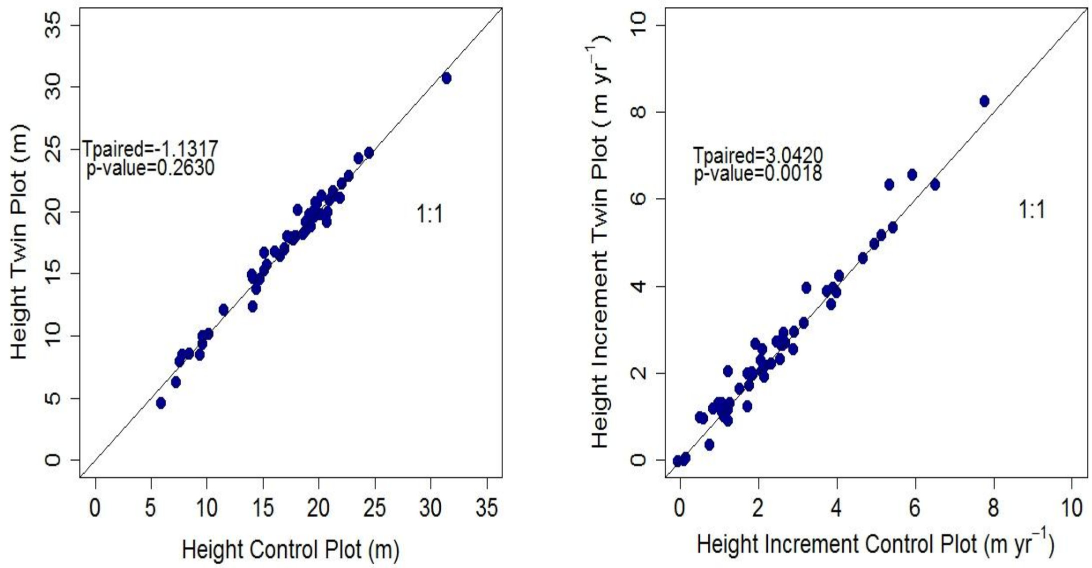

Figure 5. Initial height and increment in height after two years in control and twin plots

Stands with more increment in dominant height after two years of treatment application were those whose site index was lower at the initial moment (2009) (Figure 6). Stands in site index of 12 m had an increase in dominant height up to 17 m, and stands in site index 30 m did not have any increment. Stands in lower site index have more limitations than are alleviated in most of the plots with extra fertilization and extra weed control. For every one meter increase in site index, the dominant height increment diminished 0.72 m.

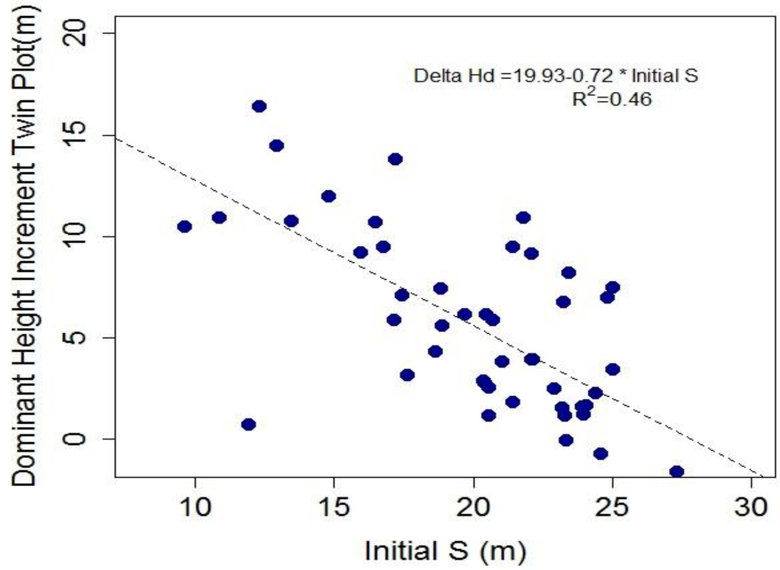

Figure 6. Dominant height increment of twin (2009-2011) and site index showing an inverse relationship.

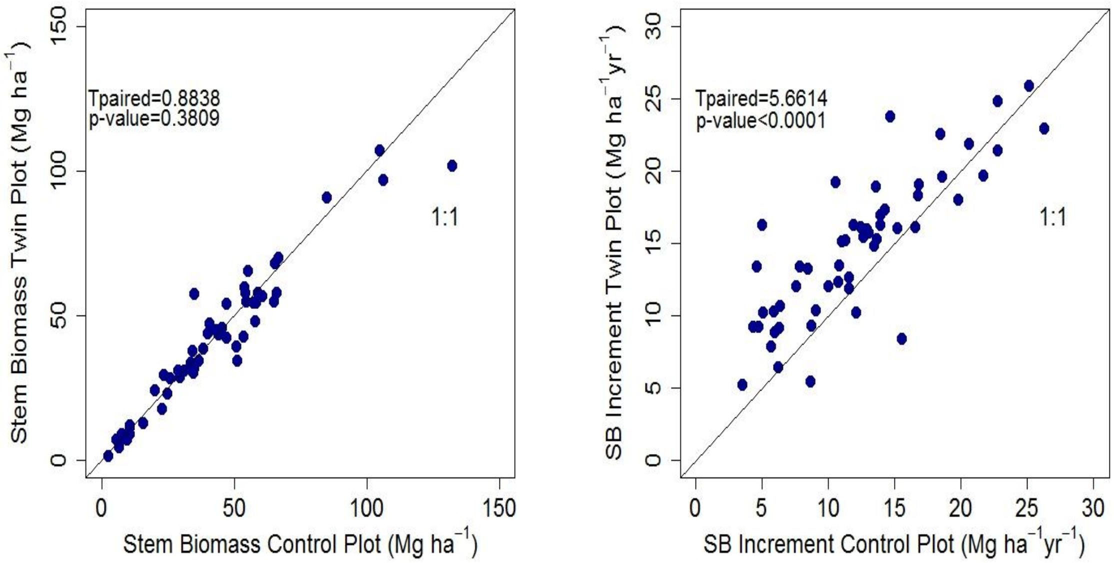

Figure 7. Initial stem biomass and increment in stem biomass after two years in control and twin plots.

The initial stem biomass was similar between control and twin plots (42.2 and 41.4 Mg ha^{-1}) as expected (Figure 7). After two years and due to an intensive management, we found significant statistical differences in stem biomass growth (12.4 and 14.8 Mg ha^{-1} yr^{-1}), which means a treatment gain of 2.4 Mg ha^{-1}yr^{-1} over 2 years. We used a wood density of 0.49 Mg m^{-3}, which was measured from biomass sampling, to estimate a gain of approximately 5 m^{3} ha^{-1} yr^{-1}. This gain is very significant since the value represents the overall average. This gain represents the gap between the current site productivity and the attainable site productivity.

In some plots, the gain is much higher than this average as can be appreciated in Figure 8. In relative terms, this gain represents 20%. In many plots, especially on those whose control plot has a low growth, the relative gain is as large as 100%, and in some cases it is even larger. The distribution of responses shows a range from -7 to 20 Mg ha^{-1} in a period of 2 years. Most of the plots have a response ranging from 0 to 12 Mg ha^{-1} 2 yr^{-1}.

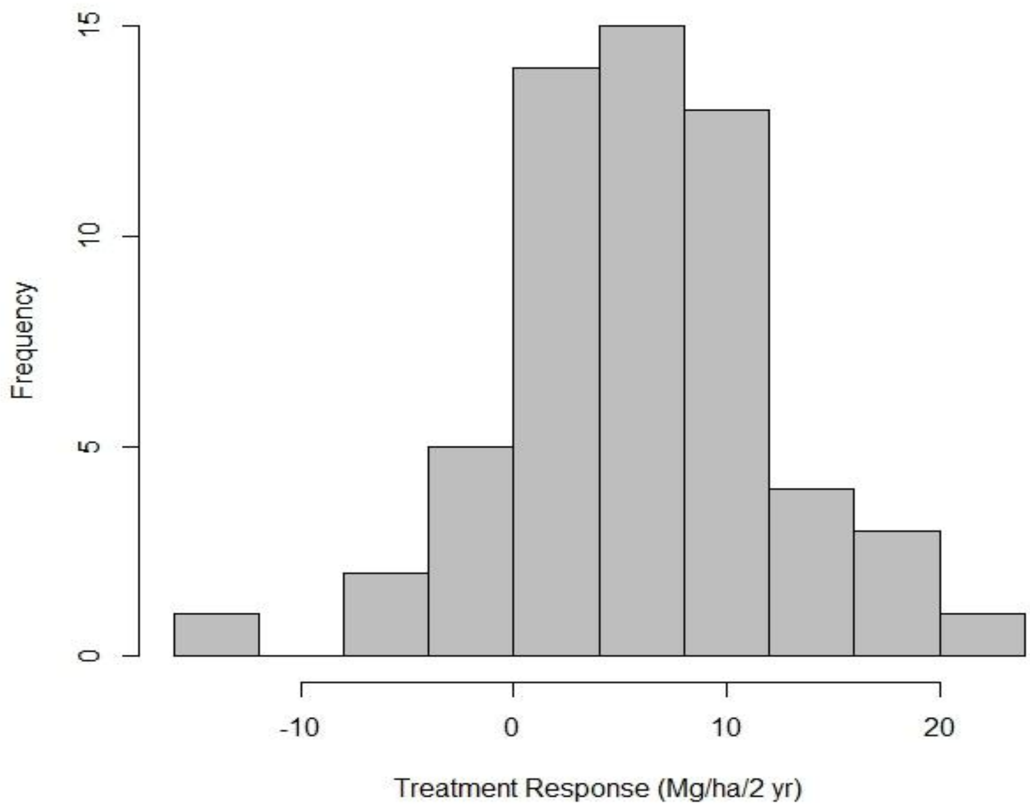

Figure 8. Treatment response distribution after 2 years.

3.2. Effect of treatments on light use and light use efficiency

Total radiation for this area, Leaf Area Index (LAI) displayed, and the Absorbed Photosynthetically Radiation for the study period are plotted month by month (Figure 9). Total radiation graph (upper Figure 9) shows the seasonal variation characteristic of the tropics, where it is common to have rainy and dry seasons. Solar radiation is higher during the dry season when cloudiness is lower. After March, a drop in total radiation is characteristic since the rainy season starts.

The amount of radiation coming to the earth's surface is not enough to explain differences in forest growth; it also requires a surface intercepting the radiation and enabling it to photosynthesize carbohydrates. A higher leaf area index is related with a higher forest growth (Rojas, 2005; Albaugh et al. 1998). LAI by month for a typical stand is showed in Figure 9 (central panel). LAI has a seasonal variation as expected, which is tightly related to the system water balance. Stand age also affects the amount of leaf area displayed. LAI decreases as stand ages since canopy closure. Then LAI varies as stand ages and also through seasons.

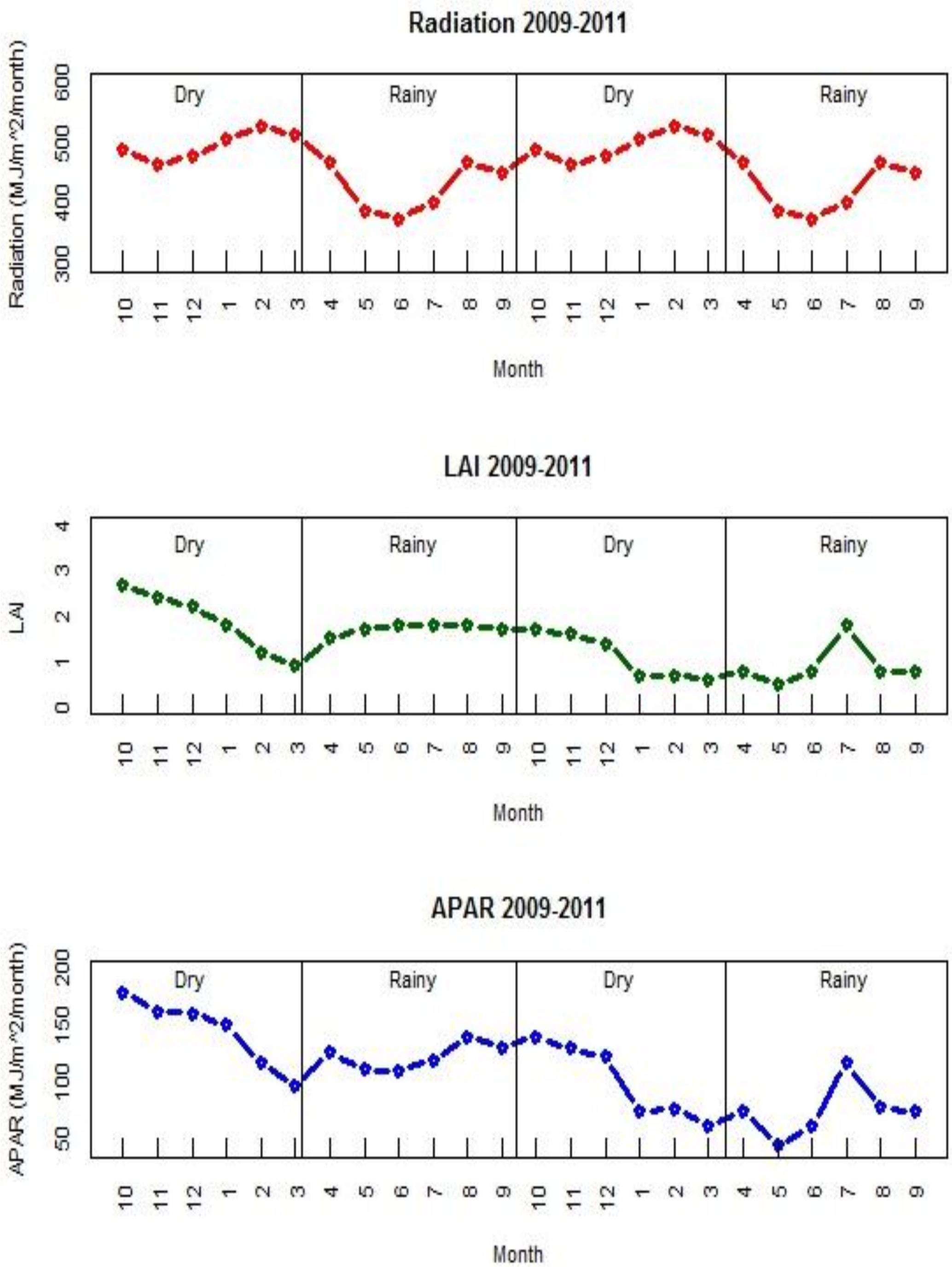

Figure 9. Solar radiation, Leaf Area Index (LAI) and Absorbed Photosynthetically Active Radiation (2009-2011)

A high APAR value is a combination of a high LAI and a high PAR value. Monthly APAR (bottom Figure 9) decreases during the dry season, and it increases during the rainy season. However, during the dry season, it may be higher than during the rainy season because during dry season, PAR is higher (lower cloudiness); also, because at younger ages and depending on the growing conditions during the previous season, LAI could be higher, especially during the first months of the season. During the first dry season (2009-2010), APAR values were higher than in the rest of the period 2009-2011, but with a decreasing trend, which also characterizes the second dry season. The opposite trend occurs during the rainy seasons.

LAI was higher in twin plots than in control plots as we observed in all our measurements periods (September 2010, April 2011 and September 2011). Another significant finding is that the difference between LAI in both treatments became larger through time (Figure 10), which suggests that differences in productivity will be evident after the two year period we considered.

We compared APAR and Light Use Efficiency (LUE) for control and twin plots by using a t-paired test (Figure 11). We found significant statistical differences between treatments for APAR. Control plots averaged 1344 MJ m^{-2} yr^{-1}, and the twin plots' average was 1406 MJ m^{-2} yr^{-1}. Intensive silviculture increased Light Use in 4.6% per year over two years. Because of the neighborhood of the plots, we assumed they received the same amount of photosynthetically active radiation (PAR), and then the difference in APAR between them was due to a difference in LAI. Most of the difference in APAR occurs during few months during the year, when the difference in LAI between both treatments is larger. This could explain the small relative difference found in APAR.

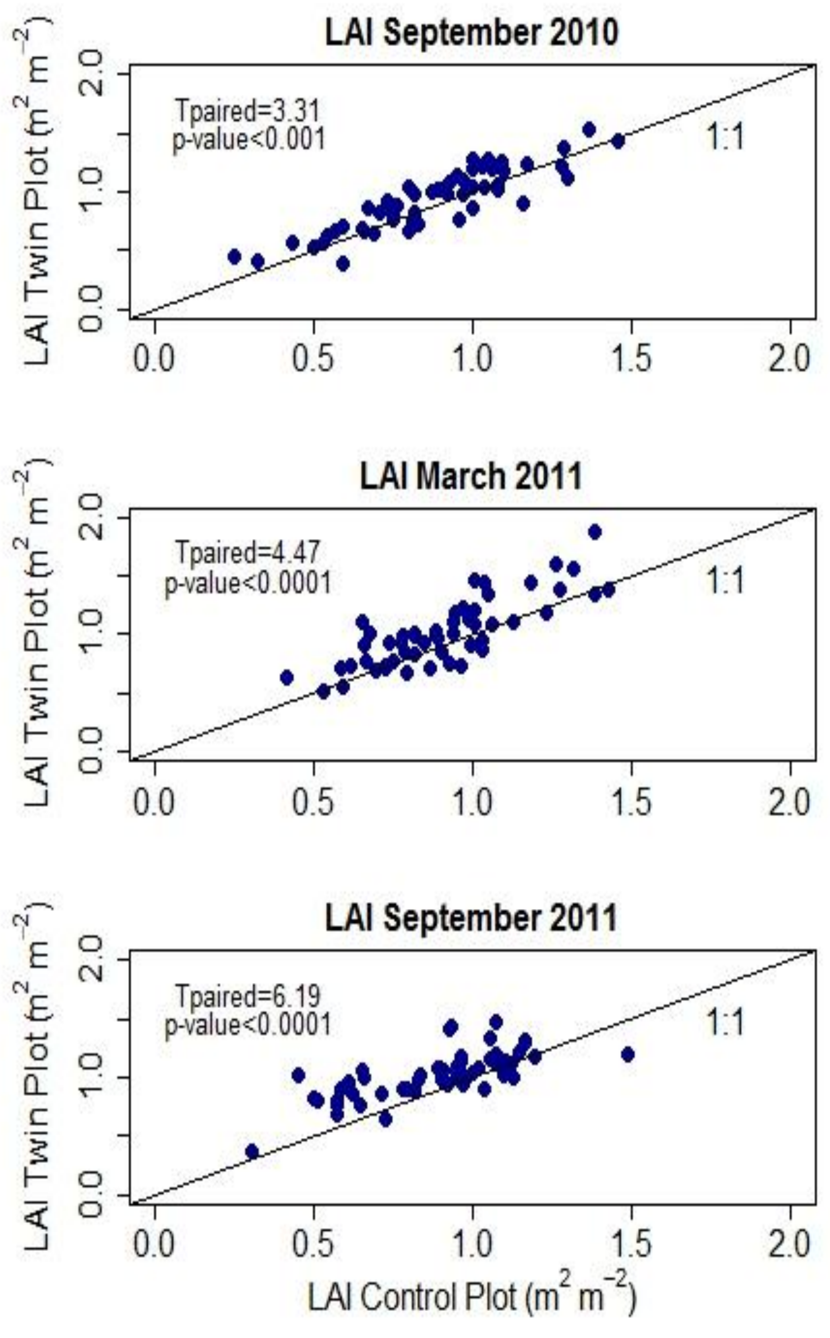

Figure 10. LAI in twin and control plots in September 2010, March 2011 and September 2011.

Intensive silviculture (fertilization + weed control) also had an effect on the amount of aboveground net primary production (ANPP) per unit of APAR, or, in other words, in LUE. Statistical differences were found at α= 0.05 between LUE for control and twin plots. In average control plots had a LUE of 0.9 g MJ^{-1} and the twin plots of 1.10 g MJ^{-1}, which in relative terms represents 20% increase (Figure 11).

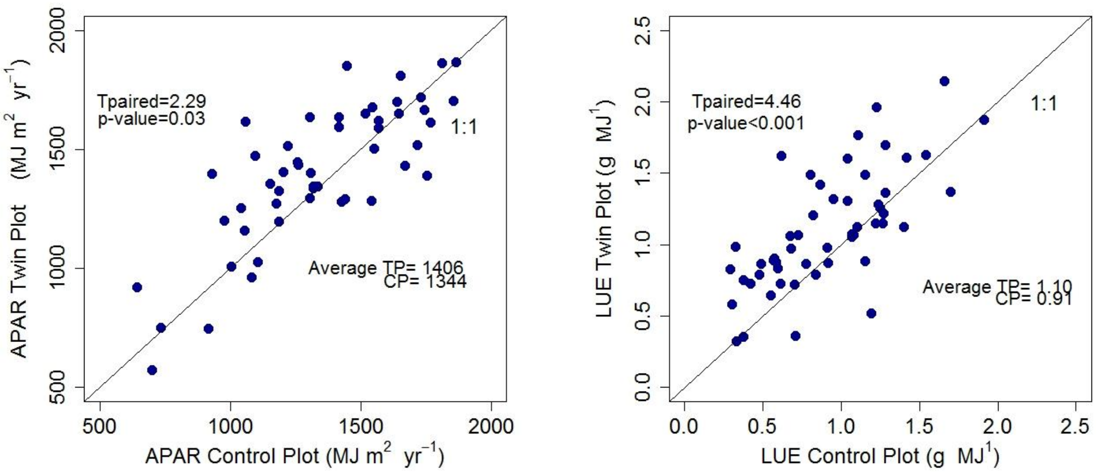

Figure 11. APAR and Light Use Efficiency in twin and control plots for the period 2009-2011.

Fertilization and weed control increased the amount of nutrients supply to the trees, and as a consequence, foliar biomass and foliar nutrients concentration increased in twin plots when compared to control plots. Foliar concentration (left side Figure 12) shows that nitrogen and phosphorus foliar concentration increased in twin plots after two years since the first application. In both cases, statistically significant differences were found at α =0.05. Foliar nutrient concentration could be a good indicator of nutrient deficiency because it permits comparison of the current value to a standard. Measured foliar nutrient concentration values for N, P, K, Ca and Mg are in Table 12 (Bellote and da Silva, 2005).

Leaf Area Index, nutrient concentration, and Nutrient Area index are presented in Figure 12. Statistical differences were found for the three variables and both nutrients, and it is clear that for most of the twin plots the amount is higher than for the control plots. Nutrient Area Index integrates LAI and nutrient concentration in one single index, so differences in the last two variables can be combined and both effects can be better appreciated in the nutrient area index Such is the case for both nutrients shown in Figure 12. In the upper right panel, Nitrogen Area Index (nitrogen amount per square meter) is compared for control and twin plots. In relative terms, the difference between twin and control plots could be more than 100%, especially in those control plots with lower values. For control plots with amounts close the average, the increase is around 50%, which is very significant. In the case of phosphorus (bottom right figure), something similar occurs. In this case the difference is even more evident. .

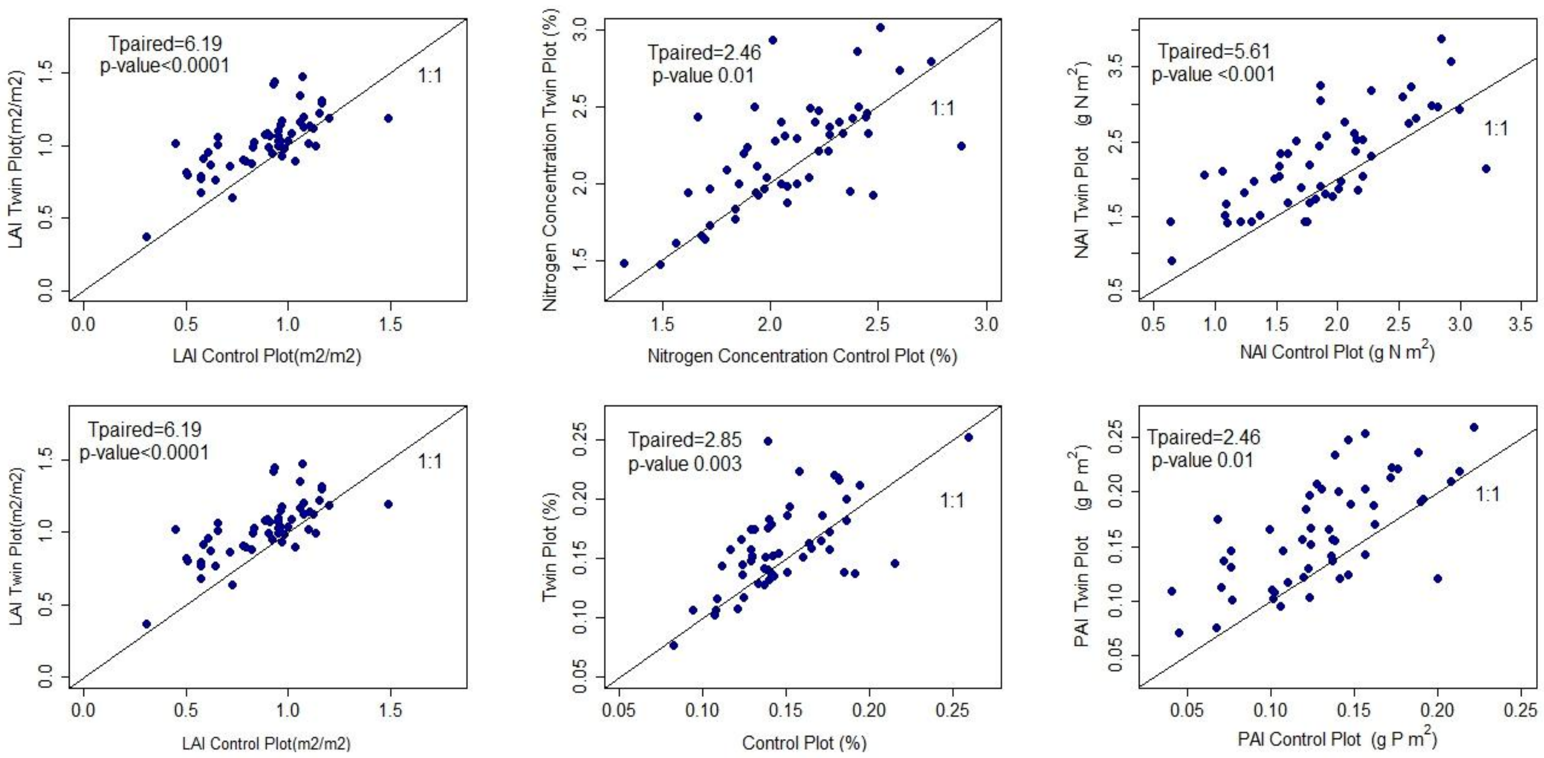

Figure 12. LAI (left), Nitrogen and phosphorus foliar concentration (center) and foliar nitrogen and phosphorus amounts per square meter (right) for twin plot and control plot, showing in both cases a significant increase. But also it shows the advantage of using nitrogen area index (NAI) and phosphorus area index (PAI), since it integrates LAI and nutrient concentration in one single index.

3.3. Average response due to weed control and fertilization + weed control

We found that the stem biomass increment averaged 13.4, 15.1, and 17.2 Mg ha^{-1} yr^{-1} for the control, extra weed control (triplet), and extra weed control + extra fertilization (twin plot) respectively (Table 13). Statistical differences (α=0.10) for stem biomass increment were found between control and twin plots, and between triplet and twin plots. However, we did not found any difference between control and triplet plots (Figure 13). The gain for applying the treatment (fertilization + weed control) was 3.8 Mg ha^{-1} yr^{-1}.

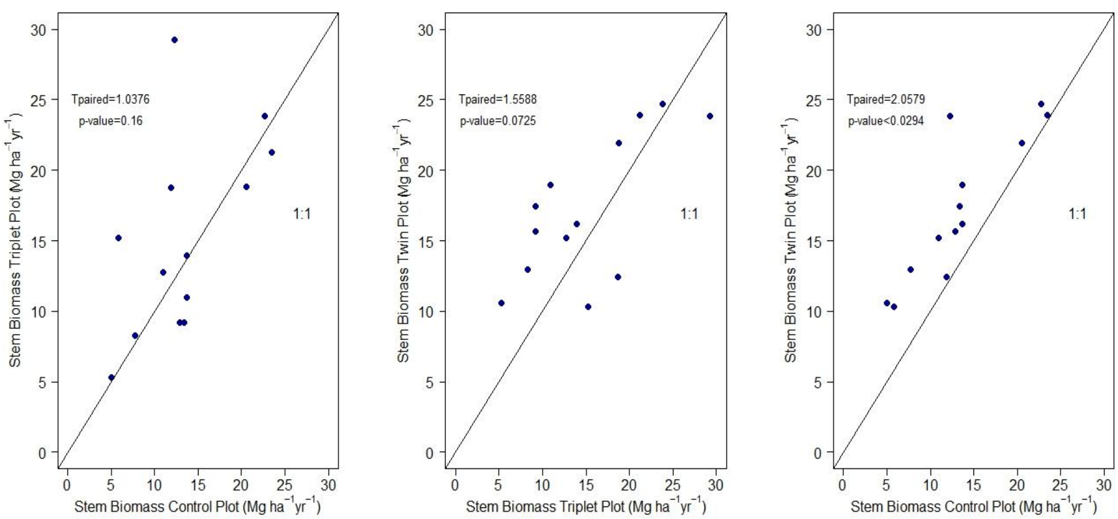

Figure 13. Stem biomass increment comparison between: a) Triplet and Control plots (left), Twin and Triplet plots (center), and c) Twin and Control plots (right)

Total APAR was 2481, 2809 and 2583 MJ m^2 yr^{-1} for control, triplet and twin plots respectively; and we did not find statistical differences between them nor in LAI (Table 14). LUE was 1,08, 1,16 and 1.36 g MJ^{-1}, for control, triplet and twin plots respectively. Statistical differences (α=0.10) were found between control and triplet with twin plots, but not between control and triplet plots.

Foliar nitrogen concentrations were 2.01, 2.05 and 2.23% for control, triplet and twin plots respectively. Statistical differences were not found between control and triplet plots (Figure 14 top), but they were found between triplet and twin plots (Figure 14 center), and between twin and control plots (Figure 14 bottom). Nitrogen deficiency is considered when nitrogen foliar concentration is below 1.8%. Foliar phosphorus concentrations were 0.14, 0.17 and 0.17% for control, triplet and twin plots respectively. Significant statistical differences were found when comparing triplet and control plots (Figure 15 top), and twin and control plots (Figure 15 bottom). In both cases, the increase in foliar phosphorus concentration was 0.03%. However, when comparing twin and triplet plots, no statistical differences were found. Foliar potassium concentrations were 1.34, 1.36, and 1.41% for control, triplet and twin plots respectively. Statistical differences (α=0.10) were found between control and triplet with twin plots, but not between control and triplet plots (Table 15 and 16).

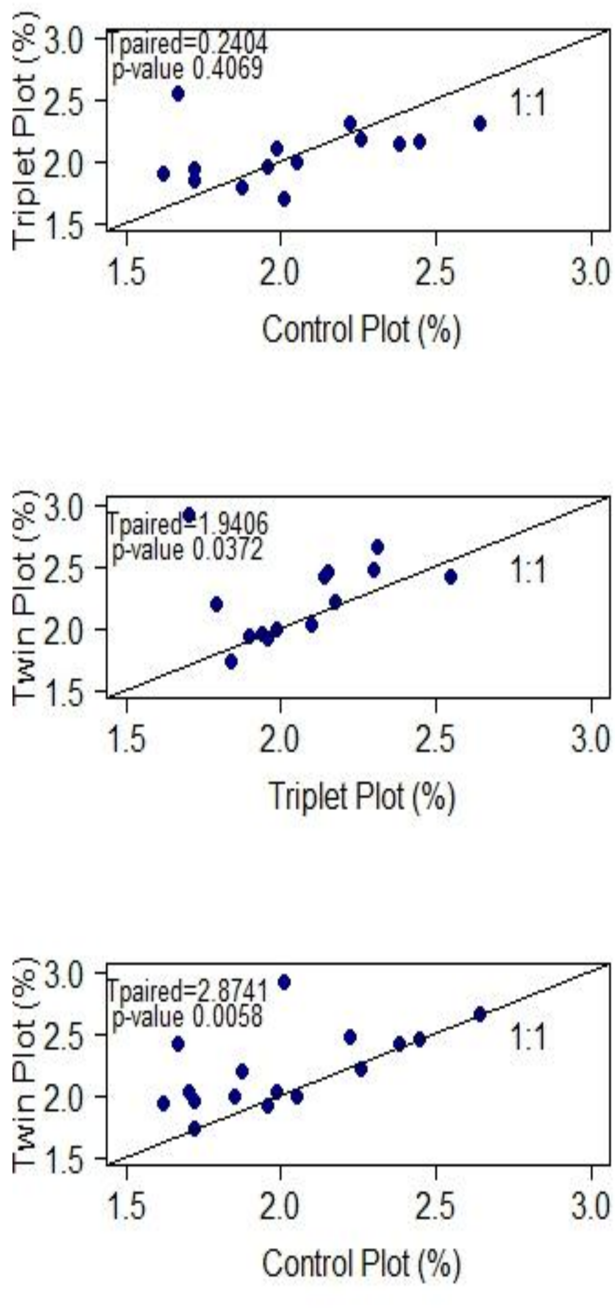

Figure 14. Foliar nitrogen concentration comparison between control, twin and triplet plots.

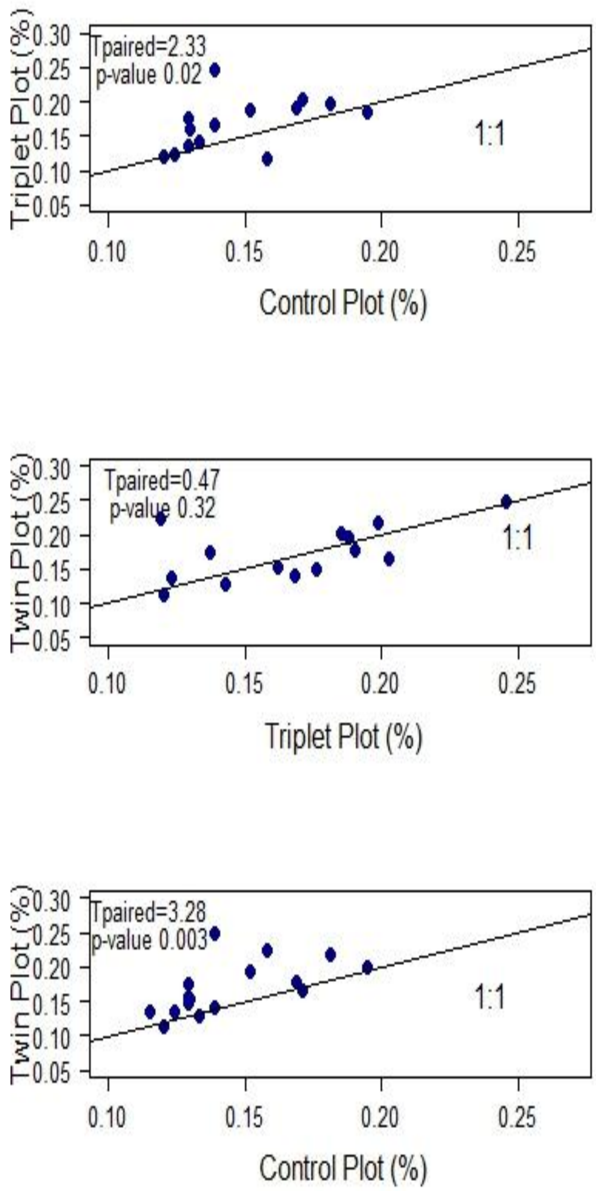

Figure 15. Foliar phosphorus concentration comparison between control, twin and triplet plots

4. Discussion

Stem biomass growth was 12.3 and 14.8 Mg ha^{-1} yr^{-1} for control and twin plots respectively, which represents a gain of 2.5 Mg ha^{-1} yr^{-1}. This gain is important because in relative terms it is higher than 20%, which is a high response in a very short time. The gain represented an average over the whole area of interest; however, there are some sites where the response was up to 10 Mg $ha^{-1}yr^{-1}$. This important gain will permit increased production in some sites in the region of interest that will increase forest productivity and concentrate production. An effort to identify accurately those areas is necessary to apply silvicultural treatments on those sites where it will be profitable.

The response distribution showed that there exists a significant proportion of stands with a response higher than the average. This treatment response distribution could be very useful for planning and decision making, because it will permit developers to assess the probability of reaching a determined investment return of intensive silviculture treatments. This response distribution permits forestry companies to observe and expect that not all the plots respond the same and that some of them are more attractive to be twin than others. A deeper analysis is necessary to characterize the stands with higher responses to identify them.

Comparing the gain obtained in Eucalyptus plantations in Venezuela and those obtained in other studies with the same species, we obtained lower gain than Stape et al (2006), in Eucalyptus plantations in Sao Paulo, Brazil. In their case, the stem biomass increment in the control plot was 19.6 Mg ha^{-1} yr^{-1} and 24.4 Mg ha^{-1} yr^{-1} in twin plots. The gain obtained was 4.8 Mg ha^{-1} yr^{-1} during two years, which represents a 25% gain. Ferreira and Stape (2009), using the same methodology in *Eucalyptus urophylla* plantations in Sao Paulo, Brazil, found a gain of 4.0 Mg ha^{-1} yr^{-1}, which represented a gain of 15% over the current management (control plot) . The stem biomass increment was 27.6 Mg ha^{-1} yr^{-1} for the control and 31.6 Mg ha^{-1} yr^{-1} for the twin plot. In another study, da Silva (2011), in *Eucalyptus grandis* and *Eucalyptus grandis X urophylla* plantations in Sao Paulo, Brazil, found an increment on control plots of 22 Mg ha^{-1} yr^{-1} and 27 Mg ha^{-1} yr^{-1} on twin plots, with a gain of 5

Mg ha^{-1} yr^{-1}, which in relative terms is equivalent to a 22% gain. A summary of growth by treatments and gain can be appreciated in Table 13.

The current annual increment in our study was lower than the studies in Brazil using for the comparison. Rainfall patterns and water availability could be important factors that need a more detailed understanding. In Brazil, tree improvement programs have been developed for many decades, soils are better, and plantation management is intensive, which may explain the difference in productivity and on average treatment response.

The response we have obtained was after 2 years of treatment application. In the future, this gap between current and attainable productivity could be either lower, equal or higher depending on the type of response (Snowdon, 2002). It is common that responses to N application or weed control becomes lower though time (response type C), but responses to P additions remains over time (response type A). For 4 year old and older stands, they will have, at rotation age, the response values obtained in this research. But for younger stands, the response could be different depending on the type of response characteristic of the limiting factor with higher influence on those stands.

We measured LAI in specific moments (the end of the dry and rainy season), but in reality, LAI has a seasonal pattern being lower during dry season than during the rainy season. Also the magnitude of the difference between treatments could change trough time depending on the season (Xavier et al., 2002, Zani, 2011). Differences in LAI between twin and untreated plots, in the last measurement done, suggest that differences in CAI will occur at least in the next season. LAI differences have been increasing over time, which is why we expect that differences in the future will be higher if no other limiting factors become more important. For example a drought could occur, which would diminish the availability of water.

Intensive silviculture (fertilization + weed control) also had an effect on LUE. In relative terms, it represents a 20% increase, which is higher than the increase in APAR. LAI increased in twin plots, increasing the amounts of PAR intercepted (in other words, the amount of APAR). But this increase only represents 4.6%; the difference in LAI between both plots is not constant through time and seasons. LAI decreases after canopy closure and also decreases during dry season, which makes LAI and APAR differences between both plots lower during several months per year, which could explain why the difference in APAR is marginal.

In our study, LUE was 0.9 and 1.1 g MJ^{-1} for control and twin plots. This value is on the lower range for the genus when compared with other studies in other ecosystems. Stape et al. (2008) in *Eucalyptus grandis X urophylla* plantations found that LUE was 1 g MJ^{-1} during dry years and between 1.97-2.39 g MJ^{-1} during wet years. Harrington and Fownes (1995) found a LUE of 1.95 g MJ^{-1} in *Eucalyptus camaldulensis* in Hawaii. Linder (1985) in *Eucalyptus globulus* plantations, in Australia, found a LUE of 0.9 g MJ^{-1}. In our study period rainfall was lower than the average, and then we expected LUE could be higher in our study area. In some of our sites LUE was as high as 2 g MJ^{-1}, which could be a consequence of higher water availability in those specific sites.

LAI has been increasing through time, and in our last measurement, the difference in LAI between treatments was larger than in previous measurements. Thus, we expect treatment responses could increase in the future. This could affect the LU and LUE we found after two years of treatment application.

Extra fertilization and weed control increased nitrogen and phosphorus foliar concentration levels. However, even when nitrogen foliar concentration increased after treatment application, levels found in control plots were over the critical threshold (1.8%) for all the control plots except 6. Treatment application increased foliar phosphorus concentration in twin plots; however, in a large proportion of them (42%), the concentration is still below the critical threshold. A higher phosphorus dose is needed in order to alleviate any deficiency.

Treatment application increased foliar nitrogen and phosphorus concentration by 4% and 6% respectively. However, when foliar nutrient is expressed by area unit, the change in nitrogen and phosphorus represented 18% and 39% respectively. Expressing foliar nutrients by area unit take into account, beside the change in foliar nutrient concentration, the changes produced in LAI and in SLA. Foliar nitrogen in twin plots per unit area was 2.22 g m^{-2}, which is equivalent to 22.2 Kg ha^{-1} , and foliar phosphorus was 0.18 g m^{-2} or 1.8 Kg ha^{-1}. The average amount of foliar nitrogen and phosphorus represents 35% and 26 % of the amount added in the previous fertilization, which is an important percentage to take into account for future stand management.

In those sites where more than 75% of the surface was covered by weeds, fertilization + weed control (twin plots) increased significantly the site productivity. However, we did not find significant statistical differences between stem biomass production between control and weed control (triplet plots), which suggest nutrients limitations in our sites. Although weed control (triplet plots) could increase nutrient availability (beside plant water availability), it seems the amount of nutrients released was not enough to cover trees' demand. No statistical differences in APAR were found, but they were found in LUE between the twin plots and the others (control and triplets), which seem to be a consequence of a higher foliar nutrient concentration. Treatments did not affect LAI in this subset of plots (16 sites where we applied the three treatments). A deeper understanding about the reason and characteristics of those stands is needed in order to enhance operations and also to reach higher productivities in those stands.

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APPENDIX

Appendix 1. Sampling scheme to measure LAI using hemispherical photographs

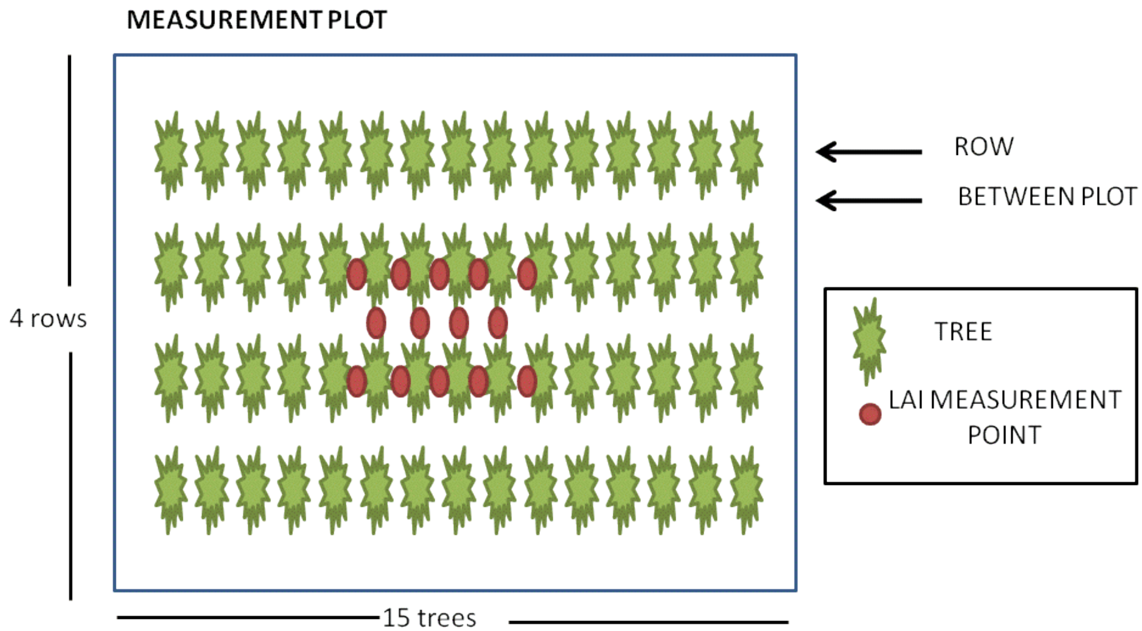

Table 1. Monthly mean, maximum, and minimum temperature (°C), rainfall (mm), and potential and real evapotranspiration (mm) at DEFORSA.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Tmax	34	35	36	35	32	31	30	31	32	32	33	33	
Tmin	18	20	20	22	22	21	21	21	21	22	21	19	
Rainfall	9	8	14	91	19	234	250	219	158	139	90	45	1266
ETP	128	141	181	187	166	139	135	140	143	155	140	132	1587
ETR	42	25	23	93	166	139	135	140	143	155	129	91	1281

Table 2. Operational fertilization at DEFORSA, sources, timing and doses

Fertilizer Source	Application Period	San Carlos Poor drained (kg/ha)	San Carlos- Caño Benito Well drained (kg/ha)
DAP	Pre-Planting	200	200
NPK 12:24:12	30 days	-	111
NPK 10:26:26	30 days	111	-
Borax	120 days	15	15
Dolomite	10 months	-	550
NPK 21:5:23	1 year	-	180
Ammonium sulfate	1 year	250	-
Borax	1.4 years	27	27
NPK 21:5:23	2 year	-	180

Table 3. Operational weed control

Year	Operational	Kg/ha
0	Glyphosate	1.7
1	Glyphosate	1.7
1	Mechanical	
2	Mechanical	
2	Glyphosate	1.7

Table 4. Main Eucalyptus plantation competing vegetation species in Western Venezuela.

Grasses	
Common Name	**Scientific Name**
Gamelote	Panicum maximum
Falso jonhson	Sorghum sp.
Corocillo	Cyperus rotundus
Cortadera	Cyperus ferax
Cadillo	Cenchrus echinatus

Broad leaf	
Common Name	**Scientific Name**
Bledo	Amaranthus dubius
Escoba	Sida sp.
Meloncillo	Cucumis melo
pega pega	Desmodium incanum
suelda con suelda	Commelina benghalensis
Bejuco batatillo	Ipomoea sp.
Bejuco murcielaguito	*Macfadyena* sp.
Fruto de burro	Xylopia aromatica
Manirito	Annona jahnii
Cruceto	Randia armata

Table 5. Elemental fertilizer doses.

Kg/ha	N	P	K	Ca	Mg
Control Plots	164	68	80	120	73
1st Extra	92	48	80	397	237
2nd Extra	63	7	57	0	0
Twin Plot	155	55	137	397	237

Table 6. DBH, Total Height, Crown Height, and Tree Biomass (Bark, Leaves, Branches amd Stem) used to fit the allometric equation to predict tree's biomass.

					Biomass (dry Kg)				
ID	Treatment	DBH (cm)	Total Ht (m)	Crown Base Ht (m)	Bark	Leaves	Branches	Stem	Total
1	C	14.8	22.9	18.4	15.93	2.4255	6.615	77.91	86.95
2	F	17.3	24.5	18.5	15.44	4.116	9.506	114.91	128.5
3	C	15.2	20.9	16.8	19.85	3.087	4.2385	51.695	59.02
4	F	13.7	19.2	15.5	9.555	3.92	8.477	58.555	70.95
5	C	12.7	19.5	15.5	10.29	2.45	5.8555	49.49	57.8
6	F	15.1	21.4	16.8	9.31	3.087	10.29	79.38	92.76
7	C	13.4	18.9	11.8	10.29	3.528	7.742	64.19	75.46
8	F	13.4	19.4	14.8	14.21	3.283	6.762	55.86	65.91
9	C	11.7	15.35	8.5	6.444	4.3855	7.1295	36.946	48.46
10	F	11.5	15.1	8.8	5.488	2.8665	7.2912	35.427	45.58
11	C	12.7	20	12	13.13	2.842	5.5615	56.84	65.24
12	F	13.7	20.6	15.4	9.751	3.43	6.419	74.97	84.82
13	C	16.9	28.5	25.3	22.2	2.646	3.234	132.15	138
14	F	16.1	30	25	23.67	2.45	3.7485	164.59	170.8
15	C	16.2	29.8	27.5	17.64	1.6905	2.499	130.34	134.5
16	F	15.8	30.5	27.3	16.12	0.833	1.029	131.08	132.9
17	C	16.2	23.3	16.8	9.408	2.107	8.3055	86.044	96.46
18	F	17.0	24.3	17.2	22.49	4.851	13.72	109.32	127.9
19	C	15.0	21.2	15.6	17.84	2.597	10.339	72.814	85.75
20	F	16.0	22.7	18	21.51	2.646	9.7755	83.349	95.77
21	C	12.9	19.4	15.8	3.479	0.4655	4.655	55.321	60.44
22	F	15.6	21.3	17.4	10.49	1.029	5.243	82.124	88.4
23	C	14.6	22.6	19.2	3.185	1.3965	1.568	65.905	68.87
24	F	15.1	22.4	18.2	12.74	2.548	2.7734	81.095	86.42
25	C	16.6	26	22	9.065	2.303	2.548	104.13	109
26	F	15.9	24.6	21	13.57	3.7485	4.165	91.63	99.54
27	C	14.0	20.3	16.8	10.29	0.588	3.283	64.435	68.31
28	F	13.4	20.8	14.3	8.085	1.6072	4.0082	54.635	60.25
29	C	11.5	15.5	10.25	7.105	4.5815	5.537	32.585	42.7
30	F	11.4	14.6	10.1	8.085	3.871	4.9	29.841	38.61
31	C	11.7	16.1	12	5.635	2.94	3.6995	35.77	42.41
32	F	11.8	15.6	9.7	4.459	2.646	5.439	54.145	62.23
33	C	12.1	16	9.6	5.145	2.4745	3.038	39.445	44.96
34	F	13.4	17.4	12	7.84	3.7975	4.018	49.98	57.8

Table 6 Continued

35	C	11.3	14.4	10	4.41	1.6905	5.782	30.38	37.85
36	F	11.8	15.2	8.6	6.37	2.254	7.35	31.85	41.45
37	C	10.8	12	8.2	4.41	4.606	6.1495	22.05	32.81
38	F	11.0	12.9	8.9	5.39	6.713	5.88	25.48	38.07
39	C	10.2	13.6	9.4	4.9	0.8575	3.577	22.54	26.97
40	F	9.9	13.2	9.4	3.675	0.294	2.156	20.286	22.74
41	C	7.9	9.3	5.8	1.882	1.6758	3.4986	9.9764	15.15
42	F	8.6	11.1	7	2.391	2.1658	2.8322	13.093	18.09
43	C	10.0	12.5	9.7	4.9	4.0866	3.7142	22.197	30
44	F	10.7	13.3	11	5.498	5.3802	4.3414	26.656	36.38
45	C	10.5	12.9	8	4.479	4.9784	5.684	23.353	34.02
46	F	11.0	13.3	7.2	4.841	6.8894	7.0952	25.833	39.82
47	C	15.1	20.2	14.1	10.94	3.1213	4.214	69.707	77.04
48	F	16.6	22	17	14.67	5.9682	6.1348	102.1	114.2
49	C	10.2	14.3	8.8	5.704	3.2046	5.1548	27.548	35.91
50	F	9.4	13.2	7.5	4.057	1.8424	2.0776	19.277	23.2
51	C	11.1	12.6	6.6	4.694	4.3561	4.8412	23.412	32.61
52	F	10.2	12.8	7	4.155	3.4986	3.479	22.432	29.41
53	C	10.2	14.2	6	4.028	4.4884	3.1752	21.854	29.52
54	F	9.4	12.9	8.3	3.244	3.7338	2.4402	27.391	33.57
55	C	10.7	14.4	6	5.537	5.2822	4.2532	29.694	39.23
56	F	10.3	13.6	6	5.047	4.557	4.8706	25.99	35.42
57	C	14.6	22.1	16	7.791	5.439	7.3696	77.489	90.3
58	F	13.7	21.6	17.5	9.114	4.0082	5.5762	72.579	82.16
59	C	12.4	20.5	14.3	7.301	2.3765	4.1454	56.86	63.38
60	F	14.0	21.8	16	19.83	4.0278	4.9784	69.933	78.94
61	C	16.6	22.5	16.1	15.7	5.8604	8.4084	102.04	116.3
62	F	15.6	21.2	16.7	14.77	3.8906	6.7424	87.886	98.52
63	C	15.9	21.9	17.2	12.54	4.6844	4.9294	88.004	97.62
64	F	13.4	19.6	15	9.016	2.9204	3.675	55.38	61.98
65	C	13.5	18.9	12.67	9.633	3.1262	4.8902	55.076	63.09
66	F	14.6	20	15.8	12.5	5.8408	10.3488	75.352	91.54
67	C	17.7	26.1	20.7	19.26	4.5374	4.4394	0	8.977
68	F	15.6	22.4	18	13.05	2.8714	2.5088	78.919	84.3
69	C	18.7	21	15.2	14.12	3.3418	6.909	97.941	108.2
70	F	18.1	21.3	13.4	15.65	4.3218	8.3692	111.17	123.9
71	C	13.4	17.6	12	3.352	1.666	3.8416	43.806	49.31
72	F	13.6	19	15	9.976	2.8812	3.822	58.281	64.98
73	C	13.5	18.3	13	9.041	2.2932	5.9192	52.866	61.08

Table 6 Continued

74	F	13.8	18.5	12.7	9.633	2.205	7.4578	56.517	66.18
75	C	13.1	19.7	12.6	7.301	0.9604	4.9	52.263	58.12
76	F	13.7	20.3	14	8.467	0.9114	4.41	60.525	65.85
77	C	13.1	20.4	15.23	7.948	0.539	2.7048	53.792	57.04
78	F	13.9	21.1	15.3	9.188	2.6166	2.5382	63.592	68.75
79	C	12.6	17.1	11.36	7.085	1.4994	3.5182	43.561	48.58
80	F	12.7	18.2	11.2	7.301	1.4798	2.2834	44.482	48.25
81	C	12.6	16	10.6	2.617	4.2924	6.615	21.834	32.74
82	F	12.4	15.8	8.75	10.27	2.7146	5.8212	37.73	46.27
83	C	13.1	20.4	14.66	8.183	1.8718	5.0078	60.515	67.39
84	F	15.4	21.1	12	13.2	2.7636	5.3018	82.193	90.26
85	C	15.3	20	14	9.604	5.145	11.6816	65.738	82.57
86	F	14.0	20.9	14	9.81	2.1462	4.508	65.738	72.39
87	C	18.9	22	16.65	16.82	5.9878	6.811	96.461	109.3
88	F	14.1	21.4	16.2	12.27	4.2042	4.8118	74.176	83.19
89	C	13.4	18.4	10.9	9.467	6.8208	6.6248	56.791	70.24
90	F	13.5	18.4	9.7	10.26	7.8204	7.0854	58.584	73.49
91	C	13.2	19	11.4	7.585	4.3414	3.185	57.8	65.33
92	F	13.1	18.9	13	7.958	4.7138	3.2144	58.232	66.16
93	C	13.7	19.7	12.4	10.57	3.7632	5.2136	61.593	70.57
94	F	13.4	19.3	12.4	8.555	4.6501	4.6354	55.899	65.18
95	C	17.7	22.4	13	13.23	5.5664	4.6648	72.696	82.93
96	F	13.8	22.7	13.5	13.68	6.321	4.2238	77.175	87.72
97	C	15.0	19.7	12.3	14.13	2.891	7.7714	67.796	78.46
98	F	15.9	21	15	14.87	4.2826	9.4962	84.241	98.02
99	C	13.2	19.2	12.07	10.37	4.3708	5.0813	58.163	67.62
100	F	12.7	19.5	13	8.261	2.058	2.6264	50.45	55.13
101	C	12.4	17.3	9.6	7.889	3.136	3.7926	41.601	48.53
102	F	12.4	17.2	9.5	7.575	3.7436	3.92	43.061	50.72
103	C	11.3	16.9	9.5	6.233	0.7203	3.5966	32.271	36.59
104	F	12.3	17.9	12.1	6.537	0.9702	4.165	37.877	43.01
105	C	10.8	13.1	8	4.322	2.3324	4.4688	23.5	30.3
106	F	11.4	13.9	9.55	4.469	2.3422	2.94	26.489	31.77
107	C	14.5	22	16.7	11.15	1.4308	4.2434	74.892	80.57
108	F	15.3	22.1	15.7	12.42	2.254	6.3308	80.507	89.09
109	C	14.8	22.2	16.4	12.07	3.6456	7.9674	84.692	96.3
110	F	14.4	20.7	15.6	10.53	2.3618	10.4664	72.442	85.27
111	C	11.3	16	12.16	6.772	2.0874	7.5852	36.133	45.81
112	F	15.0	19.8	13.3	10.51	3.1262	5.9976	68.992	78.12

Table 6 Continued

113	C	14.3	22.5	18.05	7.918	3.087	4.7628	81.507	89.36
114	F	14.9	22.5	15	11.94	4.4688	9.6922	87.847	102
115	C	14.0	21.5	17.4	11	3.1164	5.3018	68.855	77.27
116	F	16.9	25	29	13.62	4.5178	9.359	116.11	130
117	C	11.9	15.5	9.9	6.223	1.8816	5.9976	35.623	43.5
118	F	11.8	16.9	11.3	6.537	1.323	3.8612	38.602	43.79
119	C	10.2	14.2	10.5	3.724	1.568	4.0278	0	5.596
120	F	9.7	13.08	8.3	4.361	1.225	3.78525	24.892	29.9
121	C	13.7	17.6	10.8	7.771	3.9592	5.4488	48.608	58.02
122	F	13.7	17.5	12.4	8.149	3.9102	6.6346	52.675	63.22
123	C	14.3	18.4	12.7	9.153	3.1948	5.9584	59.986	69.14
124	F	14.3	17.8	12	9.869	3.6848	6.9482	57.751	68.38
125	C	11.4	15.2	10	5.38	1.519	5.1156	30.498	37.13
126	F	11.6	14.6	8.6	5.067	2.0384	4.7236	30.125	36.89
127	C	13.5	20.3	14.3	8.144	3.381	3.8416	55.292	62.51
128	F	14.3	20.1	14.3	8.389	2.6362	3.3222	56.526	62.48
129	C	11.5	17.4	12.1	6.154	2.2148	4.3904	38.906	45.51
130	F	11.1	16.5	12	6.115	2.7146	3.92	37.495	44.13
131	C	13.3	19.9	13.2	10.65	2.4304	6.076	57.487	65.99
132	F	12.6	17.8	12.3	8.967	2.9008	6.9188	46.785	56.6
133	C	10.8	14	9.2	5.909	2.4696	2.5382	26.362	31.37
134	F	10.5	14.1	9.8	5.655	2.352	2.058	23.324	27.73
135	C	10.9	17.4	11.8	9.349	3.5182	3.9984	42.591	50.11
136	F	11.9	17.5	11.5	8.438	2.7244	3.0625	40.807	46.59
137	C	13.4	20.2	14.6	10.58	3.5966	4.1258	58.731	66.45
138	F	13.1	20.7	16.2	10.57	2.7244	4.116	60.819	67.66
139	C	13.0	18.6	13.3	9.545	2.4157	3.1605	48.99	54.57
140	F	13.4	18.2	14.2	9.33	1.8032	2.695	47.53	52.03
141	C	12.5	18	12.3	10.09	5.0764	6.713	49.372	61.16
142	F	13.5	19.7	12.98	10.54	4.5864	6.1936	61.789	72.57
143	C	12.8	16.45	10.8	6.223	2.156	4.6844	41.63	48.47
144	F	11.9	16.5	11.2	6.135	1.6758	4.165	39.563	45.4
145	C	11.7	16.44	12.3	6.047	1.4308	3.2046	37.171	41.81
146	F	12.0	16.06	12.9	6.821	1.6464	5.1058	39.514	46.27
147	C	13.8	17.8	12.8	7.771	3.2242	3.724	50.627	57.58
148	F	14.3	17.2	11.1	5.89	5.096	9.702	58.996	73.79
149	M	11.3	13.1	9.8	2.45	4.949	4.5325	28.91	38.39
150	M	14.0	20.3	14.9	12.45	2.45	7.007	65.464	74.92
151	M	15.3	20	14	9.604	5.145	11.6816	66.826	83.65

Table 6 Continued

153	M	12.9	18.2	10.4	8.467	5.4684	5.7771	51.401	62.65
154	M	14.0	19.4	12.7	9.261	1.0584	6.9874	60.152	68.2
155	M	14.2	17.7	11.4	10.31	3.7534	14.8274	59.251	77.83
156	M	12.7	19.7	13.4	7.703	2.3716	7.1344	49.01	58.52
157	M	14.5	22.7	18.3	18.97	2.9302	5.4782	74.215	82.62
158	M	13.1	16.4	11	7.977	3.5378	6.2328	46.129	55.9
159	M	16.9	19.4	13.4	14.36	6.1446	12.152	89.258	107.6
160	M	14.2	20.3	14.6	3.744	2.94	3.2732	61.279	67.49
161	M	12.7	18.2	12	9.702	2.94	6.2426	50.989	60.17
162	M	11.6	18.1	11.44	7.86	1.9796	3.528	39.523	45.03
163	M	14.6	21.4	16.2	13.17	4.4296	4.4982	74.294	83.22
164	M	12.1	16.5	10.8	4.753	2.7048	6.0172	39.984	48.71
165	M	13.1	17.3	12	7.752	1.5043	4.802	45.266	51.57
166	M	13.7	19.9	15	10.56	3.332	5.7428	62.22	71.3
167	M	15.3	23.3	18.67	5.782	0.931	5.2038	88.396	94.53
168	M	9.9	13.1	9.8	3.43	0.6125	2.891	20.58	24.08
169	M	12.1	17.9	10.5	6.801	4.5864	2.8812	47.236	54.7
170	M	14.2	19	13.25	10.44	3.8612	5.7428	48.706	58.31

Table 7. Wood Net Primary Production (Mg ha^{-1} yr^{-1}) increment for the growing period October 2009- October 2011 on Control and Twin Plots.

	Control Plot			Twin Plot		
ID	Stem Biomass 2011 (Mg ha^{-1})	Stem Biomas 2009 (Mg ha^{-1})	delta Stem Biomass (Mg ha^{-1} $2yr^{-2}$)	Stem Biomass 2011 (Mg ha^{-1})	Stem Biomass 2009 (Mg ha^{-1})	delta Stem Biomass (Mg ha^{-1} $2yr^{-2}$)
1	130.8	106.1	24.8	129.1	96.8	32.3
2	77.6	55.1	22.5	95.8	65.4	30.4
3	67.0	57.9	9.2	75.2	48.3	26.9
4	74.9	29.4	45.5	71.7	28.8	42.9
5	56.5	47.0	9.4	72.6	54.2	18.4
6	147.8	132.1	15.7	128.6	101.7	26.9
7	94.7	84.8	`	123.5	91.0	32.5
8	77.8	65.5	12.3	81.1	68.3	12.8
9	127.9	104.8	23.1	130.9	107.2	23.7
10	41.4	20.0	21.4	49.1	24.3	24.8
11	65.9	15.7	50.2	64.7	12.9	51.8
12	52.8	7.4	45.5	56.8	7.2	49.6
13	41.1	10.7	30.4	44.1	12.0	32.0
14	15.0	2.5	12.5	19.9	1.5	18.3
15	58.9	6.4	52.5	50.4	4.5	45.9
16	64.2	43.2	21.0	83.7	45.3	38.5
17	38.3	10.5	27.8	41.6	9.0	32.6
18	32.8	7.6	25.2	40.2	9.3	30.9
19	42.3	5.5	36.8	52.2	7.1	45.1
20	52.9	9.6	43.3	46.6	7.2	39.4
21	72.6	44.1	28.5	78.2	43.5	34.7
22	42.8	25.9	16.8	54.9	28.4	26.5
23	93.8	60.8	33.1	88.9	56.7	32.2
24	81.9	58.2	23.7	87.1	54.6	32.5
25	90.7	57.1	33.6	92.6	54.5	38.2
26	81.1	53.9	27.2	90.5	59.8	30.7
27	71.6	54.2	17.4	76.5	57.8	18.7
28	82.1	64.8	17.3	65.9	55.0	10.9
29	43.5	23.6	20.0	53.7	29.5	24.2
30	71.7	34.6	37.1	69.6	30.4	39.2

Table 7 Continued

31	92.3	66.6	25.8	102.2	70.2	32.0
32	57.7	50.7	7.0	50.0	39.5	10.5
33	98.6	59.0	39.6	94.2	58.2	36.0
34	75.4	34.2	41.2	76.4	32.6	43.8
35	68.5	45.5	23.1	71.0	45.7	25.3
36	73.9	47.1	26.8	72.0	42.3	29.7
37	87.0	53.6	33.4	79.6	42.9	36.7
38	61.7	40.1	21.6	71.1	44.0	27.0
39	43.5	34.9	8.6	50.6	32.0	18.5
40	28.6	10.5	18.1	32.1	11.4	20.7
41	50.7	40.6	10.1	67.9	47.4	20.5
42	97.1	66.0	31.1	74.9	58.0	16.9
43	46.4	34.8	11.6	78.1	57.5	20.7
44	40.2	29.0	11.3	47.1	31.3	15.8
45	34.4	22.7	11.8	35.8	18.0	17.8
46	60.7	33.5	27.2	71.8	33.9	37.9
47	67.5	38.2	29.3	86.1	38.6	47.5
48	37.5	24.8	12.7	44.7	23.3	21.3
49	76.6	54.7	21.9	85.1	54.8	30.4
50	75.4	51.3	24.1	54.9	34.5	20.4
51	62.7	36.7	26.0	65.9	34.4	31.5
52	46.2	31.2	15.0	55.4	31.3	24.1
53	62.1	34.4	27.7	71.9	38.0	33.9

Table 8. LAI by treatments in 2009 (August), 2010 (August), 2011a (March) and 2011b (August) on Control and Twin Plots.

	LAI Control Plot				LAI Twin Plot			
ID	2009	2010	2011 a	2011b	2009	2010	2011 a	2011b
1	2.96	1.10	1.38	1.08	2.69	1.18	1.34	1.13
2	2.67	0.89	1.28	0.83	2.60	1.02	1.38	0.99
3	2.73	1.08	0.88	0.95	2.53	1.01	0.98	0.99
4	0.00	0.71	1.06	0.96	0.00	0.83	1.09	1.03
5	2.54	0.98	0.99	0.90	2.32	1.02	1.13	1.09
6	3.12	1.30	1.03	1.17	2.88	1.12	0.88	1.31
7	2.68	0.97	0.94	1.17	2.94	1.10	1.12	1.30
8	3.13	0.97	1.05	0.84	3.17	0.98	1.34	1.02
9	2.58	1.04	0.97	1.02	2.85	1.03	1.22	1.09
10	2.14	0.83	0.42	0.57	1.57	0.73	0.63	0.68
11	3.10	1.00	1.23	1.06	2.97	1.28	1.19	1.35
12	1.28	1.17	0.87	0.95	2.44	1.23	0.71	1.07
13	1.48	0.80	0.79	0.79	1.55	1.04	0.67	0.89
14	0.85	0.92	0.59	0.50	0.95	1.05	0.72	0.82
15	1.06	1.37	1.03	1.10	1.00	1.54	0.96	1.02
16	1.54	1.16	0.66	0.97	2.11	0.90	0.91	1.17
17	1.17	0.66	0.74	0.57	1.09	0.67	0.92	0.77
18	2.07	1.08	0.65	0.78	2.59	1.05	1.11	0.91
19	1.98	0.75	0.85	0.98	1.98	0.83	0.92	0.98
20	1.54	1.28	1.26	1.12	0.80	1.21	1.61	1.12
21	2.11	1.00	0.73	1.00	3.00	1.19	0.72	1.04
22	2.46	0.73	1.00	0.57	1.48	0.92	0.90	0.79
23	2.15	1.05	1.01	1.08	1.29	1.28	1.21	1.20
24	2.16	0.95	1.18	1.06	2.37	1.13	1.45	1.17
25	1.99	0.69	0.91	0.91	1.93	0.64	0.86	1.07
26	2.45	1.09	0.93	0.95	2.69	1.26	0.75	1.10
27	2.91	0.67	0.94	0.93	2.18	0.86	1.00	1.42
28	2.10	1.00	0.75	1.07	2.02	1.03	0.77	1.47
29	1.47	0.25	1.04	0.61	1.59	0.45	1.44	0.96
30	2.08	0.92	1.32	1.20	2.00	0.98	1.56	1.19
31	1.48	0.93	0.89	0.93	2.14	1.07	0.97	1.44
32	1.87	0.80	0.96	0.73	2.24	0.66	0.73	0.64
33	3.39	1.46	1.43	1.49	3.55	1.43	1.39	1.19

Table 8 Continued

34	2.50	0.82	0.67	0.95	1.82	0.97	0.77	1.03
35	1.83	0.43	0.79	1.04	1.68	0.56	0.84	0.90
36	2.80	0.81	1.01	0.97	2.31	0.76	1.08	0.93
37	2.29	0.96	1.01	0.90	2.03	0.76	1.47	0.99
38	1.01	0.65	0.70	0.64	0.51	0.69	0.70	0.77
39	0.89	0.75	0.61	0.58	0.94	0.77	0.73	0.91
40	1.25	0.53	0.53	0.31	1.29	0.56	0.51	0.37
41	0.32	0.50	0.68	0.45	1.55	0.52	1.02	1.02
42	2.18	0.76	0.89	1.10	2.09	0.89	1.02	1.14
43	2.30	1.03	1.13	0.96	2.45	1.22	1.11	1.15
44	1.17	0.59	0.95	0.62	0.86	0.38	1.18	0.87
45	1.85	0.57	0.72	0.66	1.82	0.67	0.73	1.06
46	1.48	1.00	0.82	1.15	1.70	0.87	1.00	1.22
47	2.42	1.06	0.78	0.82	2.18	1.19	0.94	0.88
48	0.98	0.32	0.59	0.51	0.85	0.40	0.56	0.80
49	1.18	1.29	0.82	0.89	1.28	1.37	0.98	1.08
50	1.79	0.82	1.38	1.13	1.78	0.83	1.88	0.99
51	0.55	0.54	0.82	0.72	0.63	0.63	0.83	0.86
52	1.94	0.59	0.78	0.66	1.98	0.71	0.99	1.01
53	2.08	0.87	0.91	0.92	2.47	0.99	0.85	0.95

Table 9. Critical and measured foliar nutrient concentration in twin and control plots.

Nutrient	Foliar Concentration (%) Control Plot				Foliar Concentration (%) Twin Plot		
	Threshold	Control	min	Max	Mean	min	Max
N	1.5	2.09	1.32	2.88	2.18	1.47	3.01
P	0.15	0.15	0.08	0.26	0.16	0.08	0.25
K	0.9	1.37	0.66	2.02	1.43	0.59	1.92
Ca	0.8	1.52	0.40	1.52	0.86	0.43	1.28

Table 10. Absorbed Photosynthetically Active Radiation (APAR) and Light Use Efficiency (LUE) for two years growing period (2009-2011) by treatments on Control and Twin Plots.

	APAR and LUE Control Plot		APAR and LUE Twin Plot	
ID	APAR (MJ m^{-2} yr^{-1})	LUE (g/MJ^{-1})	APAR (MJ m^{-2} yr^{-1})	LUE (g/MJ^{-1})
1	3432.29	0.80	3036.93	1.19
2	3342.17	0.80	2865.50	1.24
3	3140.15	0.34	3242.74	1.00
4	3735.38	1.44	3736.35	1.36
5	3139.41	0.36	3179.79	0.69
6	3277.51	0.52	3397.09	0.88
7	3035.84	0.36	3300.81	1.09
8	3307.04	0.36	3622.48	0.37
9	3292.35	0.78	3304.62	0.79
10	1859.46	1.44	2795.39	1.10
11	3538.31	1.73	3225.65	2.00
12	2374.04	2.47	2648.56	2.40
13	1830.81	2.13	1495.92	2.73
14	2211.00	0.81	2053.79	1.26
15	3087.46	2.18	3356.67	1.72
16	2610.86	0.95	2587.10	1.71
17	2165.82	1.67	1921.73	2.21
18	3085.06	1.08	2570.80	1.57
19	2895.93	1.69	3706.29	1.57
20	3539.23	1.54	2008.89	2.48

Table 10 Continued

21	2304.47	1.46	2711.95	1.52
22	2836.84	0.74	3190.58	1.02
23	3103.80	1.25	3004.17	1.23
24	3489.28	0.73	3334.96	1.14
25	2617.89	1.52	2801.79	1.59
26	2521.96	1.26	2869.30	1.24
27	2855.42	0.73	2560.28	0.85
28	2442.95	0.84	3029.60	0.42
29	3625.61	0.68	3729.24	0.78
30	3564.87	1.26	2443.83	1.93
31	2836.56	1.05	3272.97	1.08
32	2115.95	0.28	3231.25	0.29
33	3715.13	1.18	3410.94	1.19
34	2669.42	1.84	2690.97	1.94
35	2519.36	1.08	2892.64	1.05
36	3464.54	0.91	3435.15	1.03
37	3512.65	1.08	2776.35	1.55
38	1953.15	1.32	2400.63	1.31
39	1399.34	0.76	1143.03	1.99
40	1288.99	1.86	1842.76	1.48
41	2410.58	0.50	2812.46	0.85
42	2610.59	1.36	3268.02	0.52
43	2375.96	0.61	2395.54	1.01
44	2990.70	0.47	2104.79	0.93
45	2011.49	0.76	2017.76	1.15
46	2355.27	1.37	2545.25	1.77
47	2639.45	1.30	2690.06	2.07
48	1465.68	1.09	1498.54	1.81
49	2108.39	1.23	2320.00	1.55
50	2877.95	0.99	2581.21	0.97
51	2081.60	1.51	2508.62	1.52
52	2636.30	0.69	2671.19	1.10
53	2191.42	1.49	2945.73	1.36

Table 11. Foliar nutrient concentration N, P, K, Ca, Mg, Mg (%) and Mn, Zn, B, Co (ppm) on Control and Twin Plots.

	Foliar Nutrients Control Plot									Foliar Nutrients Twin Plots								
ID	N	P	K	Ca	Mg	Mn	Zn	B	Co	N	P	K	Ca	Mg	Mn	Zn	B	Co
1	1.93	0.14	1.32	0.67	0.25	1507.65	14.24	28.03	7.31	2.50	0.18	1.54	0.74	0.24	1224.55	19.74	19.40	7.68
2	2.88	0.19	1.51	0.77	0.30	1106.13	23.40	32.14	8.78	2.24	0.14	1.20	0.72	0.29	1029.01	17.89	35.22	7.86
3	2.51	0.15	1.45	0.77	0.29	370.74	16.85	32.25	6.90	3.01	0.19	1.60	0.79	0.30	418.83	19.30	32.59	7.36
4	2.27	0.14	1.39	0.67	0.43	298.24	17.88	30.02	7.55	2.21	0.14	1.29	0.61	0.43		17.61	37.78	7.34
5	1.97	0.16	1.66	0.50	0.26	289.93	14.58	19.14	10.90	1.97	0.16	1.73	0.62	0.33	482.95	16.15	25.37	11.26
6	1.70	0.11	0.73	0.45	0.28		18.00	33.21	8.19	1.63	0.10	0.69	0.50	0.32		17.53	55.11	8.06
7	2.12	0.12	1.09	0.45	0.25	535.47	12.87	26.78	7.18	2.30	0.15	1.26	0.59	0.27	555.48	17.44	30.73	7.55
8	2.38	0.17	1.48	0.75	0.29	760.33	22.53	34.81	5.42	2.42	0.17	1.38	0.85	0.26		19.63	41.85	4.90
9	2.34	0.13	1.53	0.40	0.31	873.52	20.43	27.01	6.74	2.33	0.15	1.69	0.43	0.33	885.59	22.73	30.50	9.65
10	2.23	0.13	1.23	0.77	0.39	527.54	15.53	33.85	5.56	2.21	0.12	1.39	0.74	0.36	671.03	14.99	35.66	5.57
11	2.32	0.14	1.23	0.52	0.36	494.64	18.05	37.78	7.74	2.40	0.13	1.21	0.62	0.41	576.04	17.66	30.93	7.23
12	1.99	0.14	1.37	0.95	0.54	1044.68	18.20	45.65	7.56	2.03	0.14	1.27	0.95	0.58	1245.31	18.99	47.65	7.48
13	2.28	0.14	1.30	0.75	0.35	1524.67	21.66	61.37	10.66	2.32	0.15	1.39	0.65	0.36	613.30	21.33	52.10	11.25
14	2.07	0.13	1.19	1.52	0.34	837.73	39.38	40.72	15.15	2.31	0.18	1.64	1.27	0.32	697.65	35.53	43.06	17.54
15	1.49	0.08	0.66	0.60	0.31	638.11	10.71	86.56	11.15	1.47	0.08	0.59	0.59	0.39	863.36	8.62	68.72	8.57
16	1.93	0.11	1.17	0.87	0.31	413.39	9.67	39.53	10.48	1.94	0.14	1.57	0.98	0.39	483.30	13.41	42.75	12.33
17	1.89	0.12	1.36	0.90	0.31	525.98	18.28	43.49	9.74	2.23	0.17	1.47	0.90	0.36	761.04	23.39	47.06	11.37
18	2.21	0.19	1.78	1.07	0.57	641.88	33.30	44.62	11.81	2.40	0.20	1.92	0.88	0.57	604.35	28.72	42.19	13.55
19	1.84	0.14	0.70	0.78	0.43	1180.68	13.11	59.47	14.73	1.84	0.15	0.76	0.95	0.43	2034.23	15.95	73.48	14.78
20	2.45	0.16	0.86	0.52	0.37	943.69	16.22	51.35	8.94	2.33	0.15	0.98	0.55	0.38	1182.72	16.01	46.60	8.37
21	2.48	0.22	1.79	0.86	0.38	753.96	29.47	52.95	11.17	1.93	0.15	1.26	0.58	0.37	569.24	21.46	49.66	11.91
22	2.28	0.18	1.56	0.84	0.44	790.70	33.11	47.59	12.32	2.37	0.22	1.81	0.80	0.39	660.98	32.33	43.97	12.27
23	1.94	0.14	1.60	1.24	0.44	1187.71	23.95	33.30	8.17	2.11	0.14	1.47	1.02	0.42	847.73	22.08	31.75	8.18
24	2.12	0.14	1.50	1.04	0.43	780.22	20.33	34.79	8.11	2.00	0.13	1.66	1.07	0.39	654.03	18.76	32.36	8.01

Table 11 Continued

25	1.80	0.14	1.05	1.04	0.43	582.41	22.07	20.70	10.68	2.09	0.18	1.40	0.94	0.36	460.47	21.49	27.62	13.36
26	1.84	0.14	1.22	1.08	0.37	699.83	20.71	31.98	14.56	1.77	0.14	1.10	1.17	0.43	907.18	23.17	37.57	13.32
27	2.08	0.15	1.74	1.00	0.29	985.23	28.19	31.67	11.90	1.87	0.14	1.60	1.04	0.28	623.64	31.13	44.02	13.19
28	2.18	0.17	1.86	0.91	0.29	691.52	29.11	28.12	11.26	2.49	0.19	1.78	0.96	0.24	859.13	30.58	29.40	11.22
29	2.44	0.17	1.52	1.02	0.30	919.20	33.54	42.76	6.72	2.43	0.16	1.51	1.10	0.30	756.44	32.80	39.51	6.54
30	2.75	0.19	2.02	1.10	0.41	599.04	43.33	34.62	11.18	2.79	0.18	1.61	1.21	0.49	937.89	38.66	33.73	13.18
31	2.05	0.13	1.49	0.81	0.31	679.92	22.68	35.88	9.15	1.99	0.13	1.35	0.82	0.30	547.19	18.67	40.39	8.96
32	2.05	0.12	1.41	0.79	0.36	1043.70	24.66	27.13	7.67	2.40	0.16	1.84	0.74	0.34	702.27	26.03	27.86	8.24
33	1.94	0.12	0.89	0.81	0.37	512.85	13.48	44.74	7.25	1.92	0.11	0.79	0.68	0.39	615.65	11.59	58.38	9.02
34	1.62	0.13	0.84	1.01	0.58	1146.60	16.32	82.11	13.93	1.94	0.15	0.74	0.85	0.56	519.17	13.29	85.05	18.02
35	2.23	0.15	1.46	0.86	0.37	786.45	25.38	42.98	9.96	2.48	0.19	1.61	1.07	0.40	665.65	29.92	41.58	9.21
36	1.68	0.11	0.93	0.82	0.36	712.34	25.78	31.11	7.72	1.66	0.11	1.01	0.88	0.35	634.61	23.91	28.25	7.68
37	2.41	0.19	1.59	1.01	0.43	783.35	32.66	41.93	8.51	2.50	0.21	1.76	0.92	0.41	980.56	34.14	41.70	10.28
38	2.37	0.19	1.65	0.85	0.38	773.54	27.94	40.97	9.12	1.95	0.14	1.20	0.92	0.44	608.83	21.22	49.36	10.82
39	1.85	0.13	1.60	0.98	0.29	1229.96	39.08	33.05	11.45	2.00	0.16	1.63	0.93	0.30	1447.35	40.28	32.16	11.50
40	2.02	0.14	1.39	0.81	0.44	926.09	34.06	42.60	5.48	2.28	0.18	1.84	0.97	0.34	971.91	34.63	36.21	5.56
41	1.72	0.13	1.55	1.13	0.33	1012.82	33.50	34.41	9.88	1.73	0.15	1.66	0.96	0.36	1093.33	31.53	33.32	10.24
42	2.08	0.15	1.73	0.73	0.27	735.62	19.18	24.14	7.34	1.98	0.15	1.73	0.79	0.30	647.18	18.41	29.24	7.21
43	1.88	0.13	1.40	1.18	0.38	559.87	32.02	25.82	10.05	2.20	0.18	1.76	1.03	0.37	540.89	31.39	28.89	11.12
44	2.18	0.18	1.70	0.95	0.33	902.98	35.60	29.60	9.90	2.04	0.16	1.87	0.75	0.23	647.64	32.68	38.29	11.61
45	2.08	0.18	1.63	1.04	0.34	538.42	35.19	43.74	12.38	1.98	0.17	1.69	0.92	0.35	747.87	31.84	47.04	11.85
46	2.45	0.18	1.75	0.85	0.42	540.89	23.63	24.37	10.01	2.46	0.22	1.89	0.75	0.47	402.22	28.88	22.92	13.76
47	2.01	0.16	0.88	0.80	0.42	447.52	22.33	70.51	8.94	2.93	0.22	0.79	1.28	0.34	480.17	41.38	36.46	11.26
48	1.56	0.11	1.41	0.97	0.63	296.87	11.23	28.01	7.76	1.61	0.12	1.26	0.89	0.56	396.72	10.57	40.44	7.33
49	1.72	0.12	1.30	1.09	0.54	1226.66	16.79	32.62	9.48	1.96	0.14	1.44	1.07	0.47	1039.00	17.78	35.01	11.40
50	1.32	0.09	1.14	1.07	0.59	1230.33	13.18	28.98	7.76	1.48	0.11	1.12	0.86	0.55	1152.57	10.62	38.20	7.49
51	2.60	0.26	1.63	1.04	0.37	673.15	30.38	39.03	7.64	2.74	0.25	1.56	0.94	0.34	669.80	29.27	39.55	9.72

Table 11 Continued

52	2.40	0.18	1.63	0.73	0.37	974.23	35.89	43.83	7.27	2.86	0.22	1.85	0.79	0.40	672.80	41.08	39.96	7.71
53	1.67	0.14	0.86	1.22	0.55	759.10	31.66	51.34	14.34	2.43	0.25	1.45	0.78	0.49	279.34	33.07	28.37	13.99

Table 12. Nutrient Area Index N, P, K, Ca, Mg (g m^{-2}) on Control and Twin Plots.

	Nutrient Area Index Control Plot (g nutrient m^{-2})					Nutrient Area Index Twin Plot (g nutrient m^{-2})				
ID	NAI	PAI	KAI	CaAI	MgAI	NAI	PAI	KAI	CaAI	MgAI
1	2.59	0.19	1.77	0.91	0.33	3.23	0.24	1.99	0.96	0.31
2	2.21	0.15	1.15	0.59	0.23	2.04	0.12	1.09	0.66	0.26
3	2.92	0.18	1.69	0.90	0.34	3.58	0.22	1.89	0.94	0.36
4	2.20	0.14	1.35	0.65	0.42	2.52	0.16	1.47	0.70	0.49
5	2.28	0.19	1.91	0.57	0.30	2.30	0.19	2.03	0.72	0.38
6	2.58	0.16	1.10	0.68	0.42	2.74	0.17	1.16	0.84	0.54
7	2.76	0.16	1.43	0.59	0.33	2.97	0.19	1.63	0.76	0.35
8	2.06	0.15	1.28	0.65	0.25	2.77	0.19	1.57	0.97	0.30
9	2.52	0.14	1.66	0.43	0.33	3.10	0.20	2.25	0.57	0.44
10	1.21	0.07	0.67	0.42	0.21	1.43	0.08	0.90	0.48	0.23
11	2.84	0.17	1.51	0.63	0.44	3.88	0.21	1.96	1.00	0.66
12	1.77	0.12	1.22	0.85	0.48	2.19	0.15	1.37	1.02	0.63
13	2.15	0.13	1.23	0.71	0.33	2.53	0.17	1.52	0.71	0.40
14	0.64	0.04	0.37	0.47	0.10	1.43	0.11	1.02	0.79	0.20
15	1.90	0.11	0.84	0.76	0.39	1.81	0.09	0.73	0.73	0.48
16	1.31	0.08	0.79	0.59	0.21	1.97	0.15	1.59	0.99	0.39
17	1.08	0.07	0.78	0.51	0.18	1.52	0.11	1.00	0.61	0.24
18	1.85	0.16	1.49	0.90	0.48	2.44	0.20	1.95	0.90	0.58
19	1.81	0.14	0.69	0.77	0.42	1.73	0.14	0.71	0.89	0.41
20	2.16	0.14	0.76	0.46	0.32	1.86	0.12	0.78	0.44	0.31
21	1.75	0.15	1.26	0.61	0.27	1.44	0.11	0.94	0.43	0.27
22	1.24	0.10	0.85	0.46	0.24	1.81	0.17	1.39	0.61	0.30
23	1.52	0.11	1.25	0.97	0.35	2.17	0.15	1.51	1.05	0.43
24	1.86	0.12	1.31	0.91	0.37	1.91	0.12	1.59	1.02	0.37
25	1.60	0.12	0.93	0.92	0.38	2.34	0.20	1.57	1.05	0.40
26	2.01	0.16	1.33	1.18	0.41	1.87	0.14	1.16	1.23	0.45
27	1.66	0.12	1.40	0.80	0.23	2.51	0.18	2.14	1.39	0.38
28	2.64	0.21	2.25	1.10	0.35	2.81	0.21	2.01	1.08	0.27
29	1.06	0.07	0.66	0.44	0.13	2.10	0.14	1.31	0.95	0.26
30	2.82	0.19	2.07	1.12	0.42	2.97	0.19	1.71	1.29	0.52
31	1.91	0.12	1.39	0.75	0.29	2.57	0.17	1.74	1.06	0.38
32	1.76	0.10	1.21	0.68	0.31	1.68	0.11	1.28	0.52	0.23
33	3.21	0.20	1.47	1.33	0.62	2.14	0.12	0.88	0.76	0.44
34	1.48	0.12	0.77	0.93	0.53	1.99	0.16	0.76	0.88	0.57

Table 12 Continued

35	2.02	0.14	1.33	0.78	0.34	1.98	0.15	1.29	0.85	0.32
36	1.60	0.10	0.89	0.77	0.34	1.68	0.11	1.02	0.89	0.36
37	2.14	0.17	1.41	0.90	0.38	2.62	0.22	1.84	0.96	0.43
38	1.30	0.10	0.90	0.46	0.21	1.44	0.10	0.88	0.68	0.33
39	1.09	0.08	0.94	0.58	0.17	1.67	0.13	1.36	0.78	0.25
40	0.64	0.04	0.44	0.26	0.14	0.90	0.07	0.73	0.38	0.14
41	0.91	0.07	0.82	0.60	0.17	2.05	0.18	1.96	1.14	0.43
42	1.95	0.14	1.63	0.68	0.25	1.76	0.14	1.54	0.70	0.26
43	2.27	0.16	1.70	1.43	0.46	3.19	0.25	2.55	1.49	0.54
44	1.36	0.11	1.07	0.59	0.20	1.52	0.12	1.39	0.56	0.17
45	1.54	0.13	1.21	0.77	0.25	2.34	0.20	1.99	1.08	0.42
46	2.99	0.22	2.14	1.04	0.51	2.93	0.26	2.25	0.89	0.56
47	1.86	0.15	0.81	0.74	0.39	3.26	0.25	0.88	1.42	0.38
48	1.10	0.08	0.99	0.68	0.44	1.41	0.10	1.10	0.78	0.49
49	1.70	0.12	1.28	1.07	0.53	1.88	0.13	1.38	1.02	0.45
50	1.73	0.12	1.49	1.40	0.77	1.43	0.10	1.09	0.83	0.53
51	2.14	0.21	1.34	0.85	0.30	2.37	0.22	1.35	0.82	0.29
52	1.86	0.14	1.26	0.56	0.29	3.04	0.23	1.96	0.84	0.42
53	1.53	0.13	0.79	1.12	0.50	2.03	0.21	1.21	0.65	0.41

Table 13. Wood Net Primary Production (Mg ha^{-1} yr^{-1}) increment for the growing period October 2009- October 2011 on Control, Twin and Triplet Plots.

ID	Control Plot delta WNPP	Twin Plots delta WNPP	Triplet Plot delta WNPP
1	12.3	12.8	-51.8
2	45.5	49.4	47.6
3	25.8	31.4	18.3
4	46.9	47.8	42.5
5	41.2	43.8	37.6
6	23.7	24.8	37.5
7	9.8	18.5	-12.8
8	10.1	21.1	10.6
9	11.6	20.7	30.5
10	14.7	3.1	
11	27.4	37.9	21.9
12	24.6	47.7	58.5
13	15.4	25.9	16.5
14	26.8	34.9	18.5
15	21.9	30.4	25.5
16	27.4	32.4	27.9

Table 14. LAI by treatments in 2009 (August), 2010 (August), 2011a (March) and 2011b (August) on Control, Twin and Triplet Plots.

ID	LAI Control Plot				LAI Twin Plot				LAI Triplet Plot		
	2009	2010	2011 a	2011b	2009	2010	2011 a	2011b	2010	2011 a	2011b
	LAI2009C	LAI2010C	LAI2011aC	LAI2011bC	LAI2009T	LAI2010T	LAI2011aT	LAI2011bT	LAI2010M	LAI2011aM	LAI2011bM
1	3.1	1.0	1.1	0.8	3.2	1.0	1.3	1.0	1.0	1.3	0.9
2	1.3	1.2	0.9	1.0	2.4	1.2	0.7	1.1	1.9	0.7	1.0
3	1.5	0.9	0.9	0.9	2.1	1.1	1.0	1.4	0.9	0.9	0.8
4	2.3	1.3	1.1	1.0	2.2	1.0	1.0	0.9	1.4	1.3	0.9
5	2.5	0.8	0.7	0.9	1.8	1.0	0.8	1.0	0.8	0.8	0.9
6	1.8	0.4	0.8	1.0	1.7	0.6	0.8	0.9	0.7	0.9	1.0
7	0.9	0.8	0.6	0.6	0.9	0.8	0.7	0.9		0.7	
8	0.3	0.5	0.7	0.4	1.6	0.5	1.0	1.0	0.8	0.9	0.8
9	2.3	1.0	1.1	1.0	2.5	1.2	1.1	1.1	1.1	1.1	1.5
10	1.2	0.7			1.3	1.2			0.9		
11	1.5	1.0	0.8	1.2	1.7	0.9	1.0	1.2	0.7	1.0	0.9
12	2.4	1.1	0.8	0.8	2.2	1.2	0.9	0.9	1.2	0.9	0.8
13	2.4	0.6	0.8	1.0	1.3	0.7	0.9	1.1	0.7	0.9	0.9
14	0.6	0.4	0.8	0.9	0.7	0.5	0.8	1.0	0.7	0.8	0.8
15	1.2	1.3	0.8	0.9	1.3	1.4	1.0	1.1	0.6	0.8	1.1
16	2.1	0.9	0.9	0.9	2.5	1.0	0.8	0.9	1.0	1.0	0.9

Table 15. Foliar nutrient concentration N, P, K, Ca, Mg, Mg (%) and Mn, Zn, B, Co (ppm) on Control, Twin and Triplet Plots.

	Foliar Nutrients Control Plot									Foliar Nutrients Twin Plots									Foliar Nutrients Triplet Plots								
ID	N	P	K	Ca	Mg	Mn	Zn	B	Co	N	P	K	Ca	Mg	Mn	Zn	B	Co	N	P	K	Ca	Mg	Mn	Zn	B	Co
1	2.4	0.2	1.5	0.8	0.3	760.3	22.5	34.8	5.4	2.4	0.2	1.4	0.8	0.3		19.6	41.9	4.9	2.1	0.2	1.6	0.8	0.3	938.2	23.8	51.4	7.7
2	2.0	0.1	1.4	1.0	0.5	1044.7	18.2	45.7	7.6	2.0	0.1	1.3	1.0	0.6	1245.3	19.0	47.7	7.5	2.1	0.2	1.4	0.8	0.5	1054.8	19.7	49.0	8.3
3	2.1	0.1	1.5	0.8	0.3	679.9	22.7	35.9	9.2	2.0	0.1	1.4	0.8	0.3	547.2	18.7	40.4	9.0	2.0	0.1	1.1	0.9	0.3	457.2	19.4	45.4	8.1
4	2.0	0.1	0.9	0.6	0.5	1702.3	12.0	58.1	10.8	1.9	0.1	1.0	0.5	0.4	1333.5	12.4	56.6	10.1	2.0	0.1	0.8	0.6	0.4	1635.6	11.7	61.8	9.8
5	1.6	0.1	0.8	1.0	0.6	1146.6	16.3	82.1	13.9	1.9	0.2	0.7	0.9	0.6	519.2	13.3	85.1	18.0	1.9	0.2	0.8	0.9	0.5	910.5	14.7	83.4	17.4
6	2.2	0.2	1.5	0.9	0.4	786.5	25.4	43.0	10.0	2.5	0.2	1.6	1.1	0.4	665.7	29.9	41.6	9.2	2.3	0.2	1.4	1.2	0.4	736.5	36.5	53.2	7.7
7	1.9	0.1	1.6	1.0	0.3	1230.0	39.1	33.1	11.5	2.0	0.2	1.6	0.9	0.3	1447.4	40.3	32.2	11.5									
8	1.7	0.1	1.5	1.1	0.3	1012.8	33.5	34.4	9.9	1.7	0.1	1.7	1.0	0.4	1093.3	31.5	33.3	10.2	1.8	0.2	1.5	0.9	0.3	783.7	32.9	39.1	9.2
9	1.9	0.1	1.4	1.2	0.4	559.9	32.0	25.8	10.1	2.2	0.2	1.8	1.0	0.4	540.9	31.4	28.9	11.1	1.8	0.1	1.4	0.9	0.3	517.2	28.7	23.2	8.8
10	1.7	0.1	1.6	0.6	0.3	713.7	16.2	29.7	5.7	2.0	0.1	1.5	0.7	0.3	903.3	21.5	32.1	6.9									
11	2.4	0.2	1.7	0.9	0.4	540.9	23.6	24.4	10.0	2.5	0.2	1.9	0.7	0.5	402.2	28.9	22.9	13.8	2.2	0.2	1.5	0.9	0.4	525.8	26.8	35.0	11.3
12	2.0	0.2	0.9	0.8	0.4	447.5	22.3	70.5	8.9	2.9	0.2	0.8	1.3	0.3	480.2	41.4	36.5	11.3	1.7	0.1	0.6	1.2	0.5	575.1	15.9	64.3	13.2
13	2.6	0.2	1.5	0.9	0.4	478.1	24.8	31.4	8.8	2.7	0.2	1.5	1.0	0.4	460.6	25.4	40.2	10.7	2.3	0.2	1.2	0.9	0.3	419.7	22.3	38.6	8.3
14	2.3	0.2	1.5	0.9	0.4	906.3	19.3	29.7	10.4	2.2	0.2	1.6	0.8	0.4	944.9	18.9	36.0	11.7	2.2	0.2	1.5	1.0	0.5	1142.6	21.1	52.6	9.1
15	1.7	0.1	1.3	1.1	0.5	1226.7	16.8	32.6	9.5	2.0	0.1	1.4	1.1	0.5	1039.0	17.8	35.0	11.4	1.9	0.1	1.3	1.2	0.5	1219.5	16.8	36.4	8.9
16	1.7	0.1	0.9	1.2	0.5	759.1	31.7	51.3	14.3	2.4	0.2	1.5	0.8	0.5	279.3	33.1	28.4	14.0	2.5	0.2	1.5	0.7	0.5	315.1	31.0	30.4	13.6

Table 16. Nutrient Area Index N, P, K, Ca, Mg (g m^{-2}) on Control, Twin and Triplet Plots.

	Nutrient Area Index Control Plot (g nutrient m^{-2})					Nutrient Area Index Twin Plot (g nutrient m^{-2})					Nutrient Area Index Triplet Plot (g nutrient m^{-2})				
ID	NAI	PAI	KAI	CaAI	MgAI	NAI	PAI	KAI	CaAI	MgAI	NAI	PAI	KAI	CaAI	MgAI
1	2.1	0.1	1.3	0.7	0.3	2.8	0.2	1.6	1.0	0.3	2.5	0.2	1.9	1.0	0.4
2	1.8	0.1	1.2	0.8	0.5	2.2	0.2	1.4	1.0	0.6	2.4	0.2	1.5	0.9	0.6
3	1.9	0.1	1.4	0.8	0.3	2.6	0.2	1.7	1.1	0.4	2.5	0.2	1.4	1.1	0.4
4	1.7	0.1	0.8	0.5	0.4	1.8	0.1	0.9	0.5	0.4	1.8	0.1	0.7	0.5	0.4
5	1.5	0.1	0.8	0.9	0.5	2.0	0.2	0.8	0.9	0.6	1.7	0.1	0.7	0.8	0.4
6	2.0	0.1	1.3	0.8	0.3	2.0	0.2	1.3	0.9	0.3	2.1	0.2	1.3	1.1	0.4
7	1.1	0.1	0.9	0.6	0.2	1.7	0.1	1.4	0.8	0.2					
8	0.9	0.1	0.8	0.6	0.2	2.0	0.2	2.0	1.1	0.4	2.2	0.2	1.8	1.0	0.4
9	2.3	0.2	1.7	1.4	0.5	3.2	0.3	2.6	1.5	0.5	1.8	0.1	1.4	0.9	0.3
10															
11	3.0	0.2	2.1	1.0	0.5	2.9	0.3	2.2	0.9	0.6	2.5	0.2	1.7	1.0	0.5
12	1.9	0.1	0.8	0.7	0.4	3.3	0.2	0.9	1.4	0.4	1.9	0.1	0.7	1.3	0.6
13	3.0	0.2	1.8	1.0	0.4	3.3	0.2	1.9	1.2	0.4	3.0	0.2	1.6	1.1	0.4
14	2.1	0.2	1.4	0.8	0.4	2.2	0.2	1.6	0.8	0.4	2.4	0.2	1.6	1.1	0.5
15	1.7	0.1	1.3	1.1	0.5	1.9	0.1	1.4	1.0	0.5	2.0	0.1	1.4	1.2	0.5
16	1.5	0.1	0.8	1.1	0.5	2.0	0.2	1.2	0.6	0.4	2.3	0.2	1.4	0.7	0.4

Table 17. CAI and gains comparison with similar studies in South America.

Study	Species	CAI ($Mg\ ha^{-1}\ yr^{-1}$)		Gain	Gain
		Control	Twin	($Mg\ ha^{-1}\ yr^{-1}$)	(%)
Carrero (2012)	E. urophylla	12.3	14.8	2.5	20
Stape et al. (2006)	E. grandis and E.grandis X urophylla	19.6	24.4	4.8	24
Ferreira and Stape (2009)	E. urophylla	27.6	31.6	4	14
da Silva (2012)	E. grandis and E.grandis X urophylla	22	27	5	23

CHAPTER 3: Estimating the Profitability of Eucalyptus Silvicultural Practices Under Treatment Response Uncertainty

ABSTRACT

Increasing forest site productivity is in general possible by applying intensive silviculture; however, it is not financially feasible everywhere. It is a common practice to make decisions based on the treatment response average from a few trials, and to apply the silvicultural prescription in other sites with different conditions. To increase profitability based on silvicultural treatments, it is necessary to take into account site responses variability; otherwise, incorrect decisions could be made. The objectives of this research were: (1) to assess the financial feasibility of intensive silviculture at the landscape level; (2) to estimate the Net Present Value (NPV) bias when decisions are made using few trials; (3) to determine the stand characteristics where the expected response is large enough to reach the breakeven point; (4) to estimate the value of the research information. To assess the profitability of intensive silviculture at the landscape level in *Eucalyptus* plantations, we established 53 pairs of plots, covering different site conditions. Each pair consisted of a control plot which received the same management regime regularly applied to the stands and a treated plot which received an intensive silviculture treatment (extra fertilization + extra weed control), beside the operational management applied to the control plots. Plots were measured for two years with the average treatment response being 2.6 Mg ha^{-1} yr^{-1} (standard deviation of 3.02 Mg ha^{-1} yr^{-1}). Using this average, the NPV, at a discount rate of 8%, was estimated as 402 USD ha^{-1}. The advantage of using multienvironmental trial average response when compared with few trials' average response was shown. The average NPV bias done by using just few trials was estimated in 460 USD ha^{-1} , and it increased exponentially as the site conditions were more variable. A linear model was fitted to identify the profitable responsive stands through soil and stand characteristics. Biomass growth of the control plot, landscape position and pH were identified as the main variables for this goal. The NPV considering the probability of misclassifying responsive and no responsive stands was estimated in 224 USD ha^{-1}. Two strategies were tested to eliminate the classification uncertainty: (1) long term: diminish the model error by a fitting a better predictive model, and (2) short term: applying the treatment in the most responsive sites, which means to shift the median response to the right, but at the same time the proportion of treated stands will diminish. The NPV was 568 and 364 USD ha^{-1} respectively.

Key words: Risk analysis, Intensive Silviculture, silviculture profitability, response model

1. Introduction

In Latin America, Eucalyptus is widely used as raw material for different industries. Currently there are more than 5 million ha of Eucalyptus plantation, and this area is expected to continue growing in the near future. Due to social conflicts for land use as well as to the forest companies' goal of using resources more efficiently allocated to forest production, there is a need to increase site productivity. In the specific case of Venezuela, the difficulty of importing raw material for the pulp and paper industry makes it even more important to increase site productivity.

During the last decades, forest managers have been more interested in understanding the limiting factors affecting tree growth in order to alleviate them and to increase productivity (Landsberg and Sands, 2011). Water and nutrients have been identified among the most limiting factors in Eucalyptus production in the tropics (Almeida et al., 2007; Stape et al., 2004; Binkley et al., 2010; Zani, 2012). However, productivity increase alone is not enough for forest companies if their objective is to maximize profit, and large monetary losses could occur when treatments are applied to non-responsive stands (Jokela, Harding, and Troth, 1988). It is also necessary to demonstrate that intensive silviculture is profitable; otherwise, forest managers will not allocate resources to those practices. Profitability of intensive silviculture has been estimated in many cases around the world. However, analysis could differ because silvicultural treatments have different effects on trees, stands, and wood properties, all of which affect profit. Also, the analysis could be done for just one rotation or multiple rotations, at the stand level or at the forest level. Through fertilization it is possible to get a higher stand growth (Keipi, 1972; Miller and Fight, 1979; Berger, 1980; Moller, 1986), but also as trees increases in diameter, stumpage value increases for two reasons: (1) market price for larger dimension trees is higher, and (2) because harvesting and transport unit costs are inversely related with tree diameter. Consequently, the stumpage value, which is calculated as the subtraction of harvesting and transport cost from the timber price at the mill, is higher. However, the effect of diameter distribution shift is not always taken into account, and when taken into account, the way to consider it changes.

Ondro and Constantino (1990) used an equation to relate DBH and logging cost. Others like Smethurst et al (2001) and Gonzalez et al. (2005) did not consider the effect of diameter increase due to fertilization on harvest and logging cost. Silvicultural treatments could have an impact on wood properties; however, Keipi (1972) pointed out that the effect of fertilization on stem form is small and the decrease on wood density (5%) has an insignificant effect on fiber quality. It could, however, have an effect on pulpmill yields, which were not taken into account in his analysis. Basic density, pulp yield and chemicals used for conversion were not modified significantly by intensive management (Cromer et al., 1977). A change in optimal rotation also could occur since growth rate is affected. Hailey (1976) proposed a subtraction of the Land Expectation Value (LEV) corresponding to non-fertilized case from the LEV corresponding to the fertilized case, to estimate the effect of shifting optimal rotation on profitability. Berger (1980), assessing the profitability of fertilization on *Eucalyptus saligna* in Brazil, incorporated, beside the effect of a higher growth and a change on diameter distribution, the effect of optimal rotation reduction, obtaining a higher profitability. Moller (1986) and Binkley (1993) mentioned the effect of growth increase at the forest level, since harvesting stands sooner could change the harvest schedule of the forest.

Internal rates of return (IRR) between -4 and 14% were found for fertilization of *Eucalyptus* plantations in Tasmania (Smethurst et al., 2001). Treatment consisting of fertilization and weed control was financially assessed in *Pinus radiata* in Australia. It was profitable to apply the treatment, and it was more convenient when land cost or the discount rate is higher (Cromer et al., 1977). Rodriguez and Alvarez (2010) estimated IRR>7% for fertilization in *Pinus radiata* in Chile. Ondro and Constantino (1990) estimated an IRR between -8% and 16.3% for fertilization of lodgepole pine in Canada. They suggested fertilizing stands closer to the rotation since that will give a higher IRR. Mid rotation N+P fertilization in slash pine plantations was financially evaluated by Martin, Bailey, and Jokela (1999), estimating an IRR of 14%. They pointed out that midrotation fertilization also decreased the optimal rotation, increasing the IRR. Fertilization alternatives were assessed financially in *Eucalyptus urophylla* plantations in Venezuela (Gonzalez, et al., 2005). Treatments consisted of different frequency and timing of application. They used marginal analysis to financially assess the treatment's effect. The best alternative was fertilizing 2 times, one of them at the establishment moment. Knott et al (1996) found an IRR of 28% for fertilization after thinning in *Pinus radiata* plantations.

It has been shown that silvicultural practices were profitable in many cases, but it is also necessary to keep in mind that profitability is dynamic since it depends on stumpage values, labor and input costs, discount rate, and treatment responses, none of which is constant through space or time. The same treatment can have a different spatial response since sites, and stand conditions are different. Also, for the same site the response can be different depending on stand age and rainfall variability through time. Thus it is necessary to identify the stand characteristics and the response magnitude associate with them, which will permit decision makers to select those stands where treatment responses will be profitable.

Few attempts exist to incorporate treatment response variability into the analysis. Most of the financial analyses done to assess silvicultural treatments are based on the mean treatment response. Few studies have determined the probability distributions of treatment responses since it implies to have a multienvironmental trial. The most common way to incorporate variability into the financial analysis of silvicultural treatments is through a sensitivity analysis. Sensitivity analyses have been applied to identify the most critical variables influencing profitability (Stearns-Smith et al., 1992; Knott et al., 1996; Smethurst et al., 2001; Rodriguez and Alvarez, 2010). Assessing the financial feasibility of fertilizer treatments in *Pinus radiata*, Knott et al. (1996) used a stochastic approach by incorporating probability distributions of productivity gains, cost, inflation rate and prices. They assumed a triangular probability density function for productivity gains, and a normal distribution for prices. Productivity gains distribution was fitted using 21 different values which may be not enough. In any case, incorporating risk analysis through the triangular probability density function is a valid approach that permits forest managers to make better decisions. They applied Monte Carlo simulation using the probability distributions already mentioned, and used cumulative distributions for comparison between alternatives. They were able to estimate the probability of achieving a determined IRR. The effects of drainage and fertilization on profitability were estimated in a *Picea mariana* forest in Canada. Net Present Value (NPV) was estimated by using probabilities distribution for prices and growth; however, those distributions were assumed. The analysis permitted researchers to estimate probabilities of getting a particular NPV (Payandeh, 1988).

Few studies consider spatial variability of treatment responses, and when they did, it corresponded to region-wide studies covering large areas where prices and costs vary significantly. In most cases, profitability of silvicultural treatment is assessed using just one location trial, and assumes that the response value obtained is the same for other sites and stands that will not necessarily have the same response. The objectives of this research were: (1) to assess the financial feasibility of intensive silviculture at the landscape level for Eucalyptus sp.in western Venezuela, (2) to estimate the NPV bias when decision are made using few trials, (3) to develop diagnostic tools to classify profitable and no profitable responsive stands, (4) to estimate the value of the forestry research information.

2. Methods

2.1. Site description and climatic data

The region of interest is located in Cojedes State in Western Venezuela, 20 Km away from San Carlos city. Eucalyptus plantations are located nearly 9°30’ N, and 68°30’ W and the plantations in this area belong to DEFORSA, which produces paper products. Since the early 1990’s, DEFORSA has established approximately 6.000 hectares primarily of clonal

Eucalyptus urophylla. Plantation establishment occurs between May and June using macro-cuttings produced in containers, originated from a local clonal garden. Subsoiling combined with disking (30 cm), bedding and 3x3 m, 4 x 2 m or 4 x 2.25 m spacing (8 or 9 m^2/plant) was used. Pre and post establishment fertilization were used up to 2 years. Intensive weed control was applied in the first year, using pre and post establishment herbicides, which was applied manually (Stape, 2006). A combination of mechanical and manual weed control was applied every year up to the fifth year. Fertilization doses and timing can be found in Table 1. The average elevation is 250 m. Venezuela's Llanos, where Eucalyptus plantations are located, is under the influence of Intertropical Convergence Zone (ITCZ), which influences its climate characteristics, creating two well defined seasons: the rainy season (80% of total rainfall) from May to October, and the dry season (20% of total rainfall) from November to April (Hetier et al., 2005). The mean annual temperature is 28.5 °C, and the yearly rainfall varies between 1300 and 1700 mm. Maximum and minimum monthly temperature, rainfall distribution, potential evapotranspiration and real evapotranspiration assuming a water holding capacity of 165 mm and Thornwhite and Mather (1955) methodology (Table 2).

2.2. Financial feasibility assessment of intensive silviculture at the landscape level

2.2.1. Treatments

With the aim of evaluating responses to midrotation fertilization and vegetation control, we established 53 paired plots (Twin Plots) in Eucalyptus plantations in the Venezuelan Western Llanos in July 2009. We used the company inventory network composed of more than 950 permanent plots. Plots were composed of 60 trees (4 rows x 15 trees), and its area covered approximately 540 m^2. Each pair consisted of a control plot (Control), which received the management regime regularly applied to the stands, and a treated plot (Twin Plot), which received extra fertilization + extra weed control. The twin plots were selected following a stratified sampling, based on age, genetic material, and site index (S), to cover the whole plantation area. To establish the plots, we took into account different site qualities, clones and ages. The number of plots by age and site index can be found in Tables 3 and 4. A more detailed description of treatments can be found in Chapter 2.

2.2.2. Stand growth and treatment responses.

The plots were measured twice: September 2009 and September 2011. DBH was measured for all the trees in the plot. The total height was measured for the first 10 trees on the plot as well as on the 5 tallest trees. The heights of the other trees were estimated from a DBH-Height hypsometric regression (Eq 1), as suggested by Avery and Burkhart (2001).

$$\ln(\boldsymbol{Ht}) = \underset{\substack{(0.0210)\\ p<0.0001}}{3.9634} - \underset{\substack{(0.1425)\\ p<0.0001}}{5.4947} \cdot \boldsymbol{dbh}^{-1} - \underset{\substack{(0.0630)\\ p<0.0001}}{1.6836} \cdot \boldsymbol{age}^{-1} \qquad (1)$$

R^2=0.88
n=1914

Where:

Ht=Height (m)

dbh=diameter at breast high (cm)

age= stand age (yr)

To fit an allometric equation to estimate stem biomass by using dbh, we harvested 170 trees. One average dbh tree in each plot was harvested, and its stem + bark biomass was weighted. Dry weights were estimated based on a dry/green weight factor. From 36 trees we took 3 discs from the stem at the different height (1.3 m, 50% total height, and at the crown base). We transported them to the lab on the same day in plastic bags inside a cooler. We weighted the discs and we oven dried them at 70 °C, until constant weight. We divided the dry weight by the green weight for each disc, and we calculated the factor as the weighted factor average for each disc. The average factor was estimated as 0.49. Stem biomass was estimated by using Eq. 2:

$$WB = 0.0691 dbh^{2.84}$$

(n=170, R^2=0.89, $p < 0.0001$) (2)

Where:

WB=Wood Biomass (Kg/tree)

dbh=diameter at breast height (cm)

The summation of all trees WB expanded to the hectare generates the plot biomass in a particular moment. Plot biomass growth was calculated as the difference between plot biomass in two different periods.

$$WNPP = \Delta Biomass = Biomass_t - Biomass_{t-1}$$

(3)

Treatment response was calculated as the difference in growth between treated and control plots

$$TR = \Delta Biomass_{treated} - \Delta Biomass_{control}$$

(4)

To obtain the treatment response probability density function (PDF), which is necessary for the analysis to be performed, we fitted the model using the treatment response of every plot. We tested different distributions and we selected the one with the lowest chi square, which was used as goodness of fit index (Table 5). The distributions were fitted by maximum likelihood using @Risk 5.7 ®.

2.2.3. Plot attributes, soil sampling and laboratory analysis.

In order to determine the attributes that are more associated with treatment responses, in each plot we gathered stand (DBH, stand density, SI, CAI, MAI, LAI) and soil physical and chemical properties (Texture, pH, sum of bases, C/N ratio, cation exchange capacity, and soil nutrient contents), besides the landscape position where the plot was located.

Leaf Area Index was measured in each plot in August 2010, April 2011, and September 2011. The first measurement was done using LAI-2000, and all the other measurements were done with hemispherical photographs. In the first case, using two sensors (above and below the canopy), we took 14 measurements per plot. We established the “above” canopy sensor in an open area where the closest tree was located at least three times its height from the sensor. Below canopy measurements were taken pointing the sensor to the same direction. We processed measurement using 3 rings to estimate LAI, and avoid LAI corresponding to canopy outside the plot limits. In the hemispherical photos case, we took 14 photographs per plot using automatic settings. All of them were processed in Hemisfer 1.4.4 ®. In order to find equivalency between measurements taken by the two different equipments, we measured simultaneously with both instruments at the same points inside the stand. We chose 16 stands of different ages and site qualities, and we fitted a linear model.

$$\begin{aligned} LAI - 2000 &= -0.9554 + 1.8586 \cdot LAI_{Photo} \\ R^2 &= 0.71 \end{aligned} \tag{5}$$

Soil sampling and laboratory analyses were made in order to try to establish correlations between treatment responses and some soil physical or chemical variables, which will ultimately allow us to better identify sites where intensive silviculture should be applied to obtain a larger profitability. Soil samples were taken in every control plot at two positions: between rows and at the row, at two depths (0-20, 20-40 cm). For every position and depth, a composited soil sample was obtained from single samples. Samples were oven dried for 72 hours and sent to the lab for analysis.

Texture was determined by Bouyoucos method. Since the twin plot was located near to the control plot, we assumed that they had the same texture (Table 6), and that they had the same chemical properties (Table 7 and Table 8) before treatment application. Total carbon and nitrogen were run on an Elemental vario MAX CNS analyzer. Extractable nutrients were estimated by the "Mehlich III" extraction and were run on a Varian Vista MPX ICP . Exchangable acidity was determined by KCl extraction, and pH was determined in water.

We classified sites, in three categories, depending on the landscape position, which we defined as: (1) High (slope > 15%), (2) Medium (5% < slope < 15), and (3) Low (slope < 5%). The proportion of plots in each position class was: 17 %, 72 %, and 11% respectively.

2.2.4. Costs, and intensive silviculture financial feasibility

Costs of fertilizers, herbicides, and labor were obtained for Venezuela from the case study forest company (Table 9). We used a stumpage value of 129.8 US$ m^{-3} , which is much higher than values in other countries in the region because in Venezuela there are some importation restrictions; in addition, the total Eucalyptus plantation area is low. We used a wood basic density of 0.49 Mg m^{-3} to transform biomass into volume. We assumed that additional revenues were due just to growth increase. We supposed the stumpage value was constant even when the treated plots had higher average diameter. We also assumed that the optimal rotation (7 years)..

Inflation rate was not considered since we used current prices, even if the cost occurred in the past. Discount rate was assumed constant at 8%, which is the corporate opportunity cost; this value is also the approximate value used internationally in the sector (Cubbage et al., 2010).

Net Present Value (NPV), as shown in equation (4), was used to financially assess the treatments applied. For the assessment we used the marginal analysis approach, by using just the additional cost and income due to treatments (Klemperer, 2003). Additional revenues and cost are estimated as the difference between those values for twin and control plots. Control plots cost (traditional management are in Table 10.

$$NPV = \frac{\sum_{n=0}^{n=t} \Delta R_n - \Delta C_n}{(1+i)^n} \tag{4}$$

Where:
NPV= Net Present Value (US$/ha)
t = rotation (years)
ΔR_n = additional revenues in year n (US$/ha)
ΔC_n = additional costs in year n (US$/ha)
i = discount rate
n = year in the planning horizon

We calculated the breakeven point, which represents the minimum value a specific variable could reach in order to get a NPV equal to zero. In our case, the variable of interest was the treatment response magnitude. This value permitted us to classify the stands as either profitable and unprofitable responsive stands.

We estimated the NPV by using the average treatment response. In reality, this is an oversimplification because not all the stand responded the same. When using only the average value, some information is missing. We can estimate the NPV using the treatment responses distribution, which will approach to what happens in reality, and also we can discretize the distribution creating classes. The simplest classification is in profitable and unprofitable stands, which along with the proportions they represent for the whole area were used to estimate a weighted average NPV.

2.3. The bias of making decisions based on few trials (value of the stochastic solution)

Decisions making about applying a particular treatment sin several cases are made using the treatment mean response. As a result, the decision depends on the site conditions and the response obtained where the trials were established. However, the trials could be established in different sites, some of them with higher probabilities of being selected than others. Every site and its corresponding treatment response are associated with a particular NPV value as shown in Figure 1.

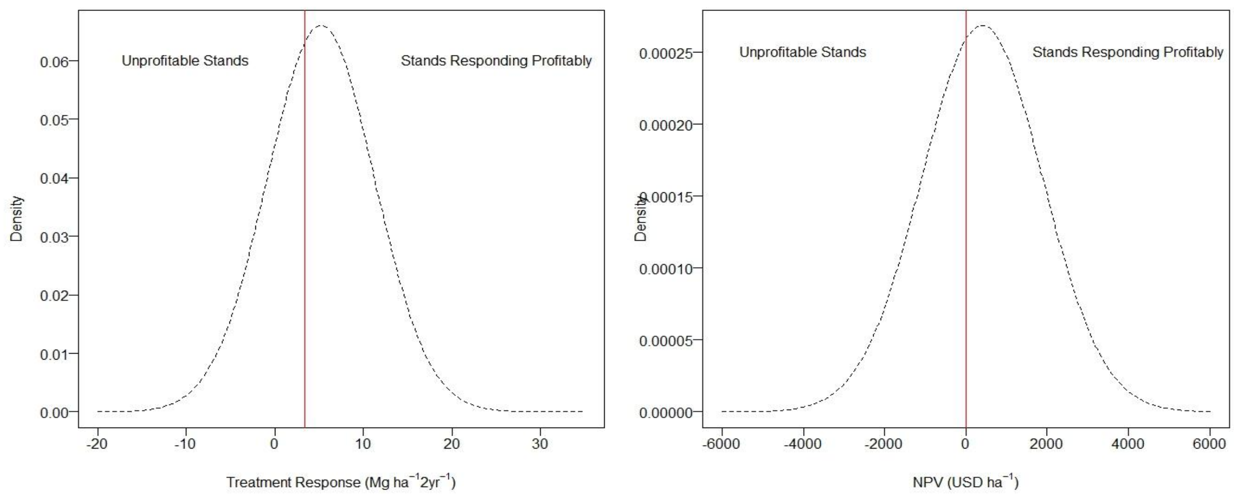

Figure 1. Treatment response probability density function (PDF) and its corresponding NPV PDF. Each treatment response value generates a NPV value. The vertical line in the left panel represents the breakeven point and in the right panel is located at NPV=0.

In a particular area, sites could be very different, and we refer to them as site population; this can be represented by a probability density function as the one in Figure 1 (left) with its corresponding average response and variability. Every treatment response value will be associated with a particular NPV value (Figure 1 right), generating a NPV probability density function.

In general, decisions are based on the treatment response from one or the average of few trials located in specific sites. This average does not necessarily coincide with the population average; and when assuming that the sites where the trial information is coming from are representative of any other site in the population, a bias exists because responses and their corresponding NPVs can be over- or underestimated. For a particular site, the NPV bias could be estimated as:

$$\Delta NPV_S = NPV_S - NPV_\mu \tag{5}$$

Where:

ΔNPV_s = NPV bias for the particular site S
NPV_S = NPV for the particular site S
NPV_μ = average NPV for the site population
S = a particular site

However, the NPV_S vary depending on the site selected, the we can get as many ΔNPVas different sites exist. However, the probability of selecting sites is different (Figure 1). There are some sites close to the population average with a higher probability of occurrence. If we add all the possible solutions weighted by their corresponding probabilities, we get the weighted average bias or the value of the stochastic solution (VSS). This value represents the advantage of including probabilities (solution from probabilistic models) over the deterministic solution generated from results from a single trial or the average of few trials.

This value shows the advantage of using a multienvironmental trial instead of installing one or few trials (one for each management unit) for decision making, and can be calculated as in Eq (6):

$$Bias = \int_{NPV_S=-\infty}^{NPV_S=\infty} \left(NPV_S - NPV_\mu\right) f(NPV_S)\, d_{NPV_s} \qquad (6)$$

Where:

Bias	=	Bias generated from making decision from one or few trials (USD ha^{-1})
NPV_S	=	NPV when the average response of a particular site is used (USD ha^{-1})
NPV_μ	=	NPV when the average response of the sites population is used (USD ha^{-1})
$f(NPV_S)$	=	sites probability density function
S	=	site

A more formal demonstration can be found in Appendix 1.

At a first glance, we can think the bias (VSS) is equal to 0 when the distribution is symmetric, because a NPV over the average (the NPV corresponding to the installation site over the breakeven point) is compensated by a same magnitude NPV under the average. Then we will have the same absolute value with opposite signs and the same probability of being selected. This is true for the area between 0 and 2µ (represented by a and b in Figure 2) if the average (continuous line) is greater or equal than 0.

However, when selecting a site below the breakeven point (NPV= 0), which generates a negative NPV, the decision will be to not apply any treatment over the whole area, making the NPV will be 0. Then the NPV to the left of line “a” (NPV=0) should be 0, and the area to the right of line “b” (2µ) will not be compensated by the area to the left of line “a”. This NPV average bias is the error we will make when decisions are based on treatments gains from few sites; in other words, this represents the advantage of using a multi-environmental trial for decision making, which we called the Value of the Stochastic Solution.

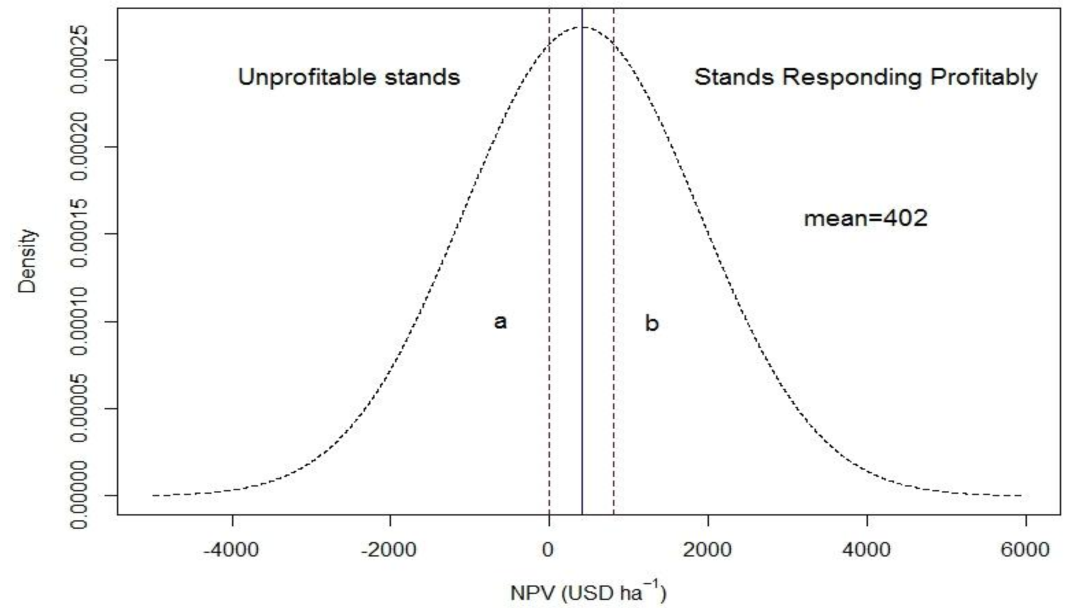

Figure 2. NPV probability distribution indicating the average and the area over and under the average which compensate each other (area between lines a (0) and b (2µ)).

Notice that the bias estimation has three components corresponding to each one of the sections on the probability density function showed on Figure 2. Then the Bias was calculated as Eq (7) (deduction of the equation could be found in Appendix I):

$$Bias = -NPV\mu \cdot F(0) + 0 + \int_{s=2\mu}^{s=\infty} \left(NPV_S - NPV_\mu\right) f(NPV_S)\, d_{NPV_s} \qquad (7)$$

Where:

Bias = Bias generated from making decision from one or few trials (USD ha^{-1})
NPV_S = NPV when the average response of a particular site is used. (USD ha^{-1})
NPV_μ = NPV when the average response of the sites population is used. (USD ha^{-1})
S = site
F(0) = Cumulative probability up to NPV = 0
$f(NPV_S)$ = NPV probability density function

To explore how the bias can change depending of the site variability, which will affect NPV variability, we simulated different probability density functions by changing the variability (standard deviation) and keeping the same average. This sensitivity analysis permits us to evaluate how bias increases or decreases as variability changes.

2.4. Diagnostic tool

In order to determine the site characteristics where the expected response is large enough to reach the breakeven point, we fitted a linear model to estimate the effect of different stand and site atrributes on treatment response. We used stand characteristics (age, control plot growth, site index, genetic material group, leaf area index), and also soil properties (landscape position, proportion of sand, clay and silt, chemical properties), and their interactions.

To identify the variables with higher correlations with the treatment response in order to be included in the model, we estimated Pearson correlation (Table 11) and selected just those statistically significant variables ($p < 0.10$). We considered a variable statistically significant if its p-value was lower than 0.10. We just select variables easily available in the field in order to generate a model operational useful. To fit the model, we used procedure GLM of SAS 9.2.

2.5. The value of research information

The value of the perfect information represents the maximum amount we will be able to expend on research to eliminate uncertainty by classifying correctly responsive and non responsive stands. We calculated it as the difference between the value obtained under perfect information and the value obtained by the stochastic solution Eq (8).

$$EVPI = NPV_{\mu} - NPV_{PI}$$

(8)

Where:

EVPI = Expected Value of Perfect Information (USD ha^{-1})

NPV_{μ} = NPV when the average response of the sites population is used. (USD ha^{-1})

NPV_{PI} = NPV when the perfect information is available

The NPV_{PI} is calculated when it is possible to identify correctly every stand as profitable responsive or not. However, the response model cannot predict perfectly what stands will be responsive, because there exists some proportion of the variance unexplained (error), which it is assumed follows a normal distribution around the model (the predicted value). In consequence when predicting a particular value there exist some probability of misclassifying a stand as responsive when it is not. When predicting a particular treatment response value, 50 % of the time the prediction will be underestimated or overestimated. In the last case, the model can predict a particular value but in reality we will obtain a lower value in the field, and in some proportion the value will be even lower than the breakeven point, which we called the misclassification error.

When simplifying the treatment response probability density function, we split it in two categories: profitable and unprofitable. We assume that responsive stands have the same response (their median response). From the median and using the model error, we estimated the probability of misclassifying a stand as responsive when it is not. Using the probability, we generated a decision tree to take into account in the first node the proportion area treated and not treated, and at the second node we considered the probability of misclassifying a stand as responsive and not responsive.

We considered two strategies to decrease the uncertainty and increase profit: (1) Long term strategy: reduce the standard deviation (square root of the model error), which will decrease the probability of misclassifying a stand and which could be done by getting a better understanding of the system through research, and (2) Short term strategy: use a higher median response value, which will shift the distribution to the right with the same mean and variance, which will diminish uncertainty, but at the same time will change the proportion of treated stands (less stands with this condition).

2.6. Sensitivity Analysis

Venezuelan prices and costs are distorted because there exist importation restrictions, subsidies, monopoly and monopsony practices, and some laws that constraint land use. In consequence prices and cost could be very different than in other countries in the region. For this reason we made a sensitivity analysis in order to compare results with other countries in Latin America, but also to understand what could happen in cases some variables changes. We performed a sensitivity for the NPV, the NPV when uncertainty was taken into account and the NPV under perfect information. The analysis was done by changing stumpage prices (10, 40, 70, 100 and 130 USD m^{-3}) and discount rates (4%, 8%, 12% and 16%).

3. Results

3.1. Treatment responses

The sites where the plots were located were characterized by loamy sand, sandy loam and loam soil textures (88.6 %) (Table 12). The pH ranged from 4.3 to 5.4; the sum of bases ranged from 191 and 787 mmol dm^{-3}; and C/N ratio varied between 10.3 and 15.4.

After two years of treatment, response averaged 2.6 Mg ha^{-1} yr^{-1}, with a standard deviation of 3.0 Mg $ha^{-1}yr^{-1}$. Using the average wood density (0.49 Mg m^{-3}), this represents a gain of approximately 5.3 m^3 ha^{-1} yr^{-1}, which is significant because this value represents the overall average. In some plots, the gain was much higher than this average (Figure 3). In relative terms, the average gain represents 20% for two years. In many plots, especially those whose control plot has a low growth, the relative gain is as large as 100%, and in some cases it is even larger. The distribution of responses shows a range from -7 to 20 Mg ha^{-1} in a period of 2 years. 62% of the plots have a response ranging from 0 to 12 Mg ha^{-1} 2 yr^{-1}. Although the normal distribution was ranked second, we chose it to represent the treatment response distribution because its goodness of fit was fairly close to the distribution ranked first (logistic), and also because of the well-known properties of the normal distribution (Table 5).

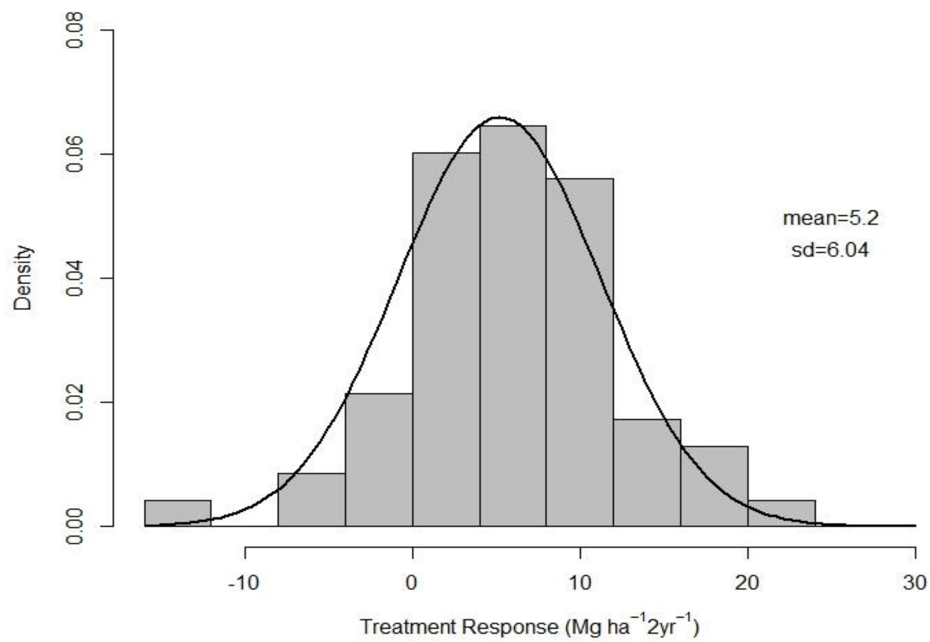

Figure 3. Treatment response distribution after two years. The average response was 5.2 Mg ha^{-1} 2 yr^{-1}. Most of the sites had a response between 0 and 12 Mg ha^{-1} 2 yr^{-1}. However some sites could have responses between 20-24 Mg ha^{-1} 2 yr^{-1}.

3.2. Financial profitability

Costs, income and net income were gathered and estimated from company records for the study period (Table 13). Using a discount rate of 8% and using eq. 4 we calculated the NPV as 402 US$ ha^{-1}. Determining the treatment response necessary to get a NPV=0 we were able to estimate the breakeven point as 3.4 Mg ha^{-1} 2yr^{-1}, and in consequence the proportions of profitable responsive stands was 0.62 (Figure 4).

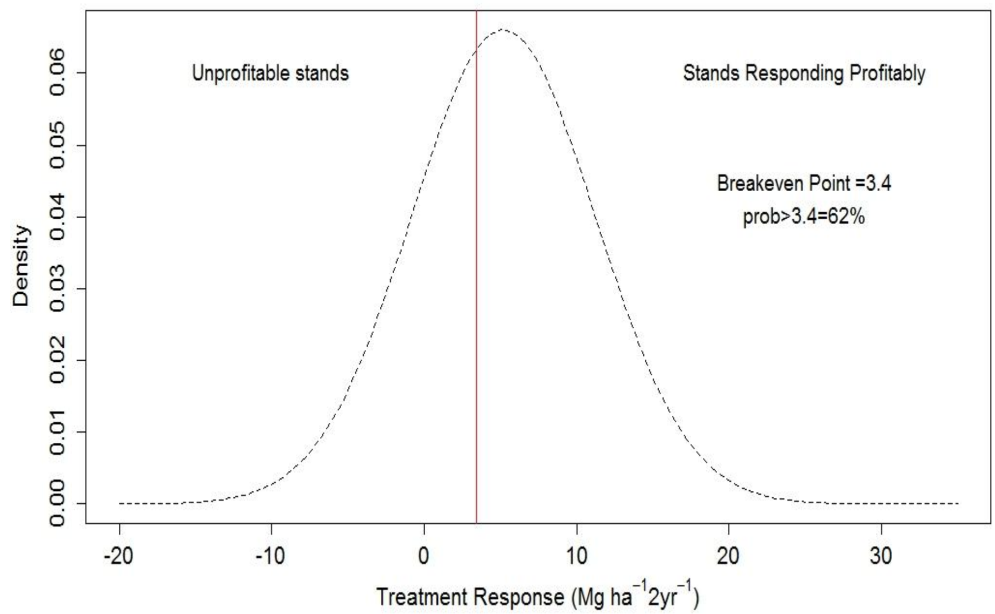

Figure 4. Breakeven point and proportion of responsive stands of Eucalyptus plantations in western llanos, Venezuela.

Unprofitable stands had an average response of 0 Mg ha^{-1} 2yr^{-1}, and profitable stands had an average of 8.4 Mg ha^{-1} 2yr^{-1}. Using those values, a decision tree was created (Figure 5), and the weighted average was calculated. The NPV of profitable stands is 1219 US$ ha^{-1}, which represent 62% of the area, and -777 US$ ha^{-1} for unprofitable stands, which represent 38%. When the treatment response distribution is simplified in just two categories—profitable and unprofitable stands—as a weighted NPV could be estimated, and in our case was 451 USD ha^{-1}. Notice that this value is lower than the average NPV estimated previously (402 USD ha^{-1}), but the difference is due to the simplification done when assuming all the profitable stands will have the same response magnitude

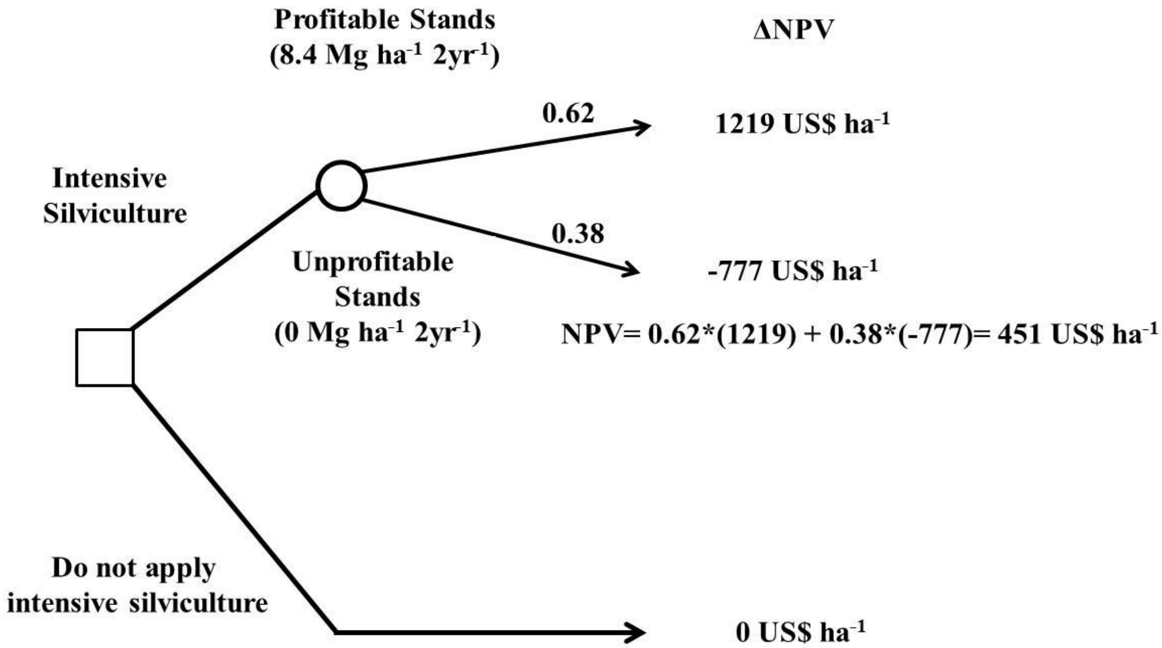

Figure 5. Weighted average NPV considering two categories: profitable responsive and unprofitable stands.

3.3. The bias of making decisions based on few trials (value of the stochastic solution)

The bias of making decisions based on one or few trials is estimated as a weighted average of differences between NPV value for a particular site and the NPV population average time the probability of occurrence of a particular site. As shown in Appendix 1, we can split the NPV probability density function in three sections to estimate the bias (Figure 6).

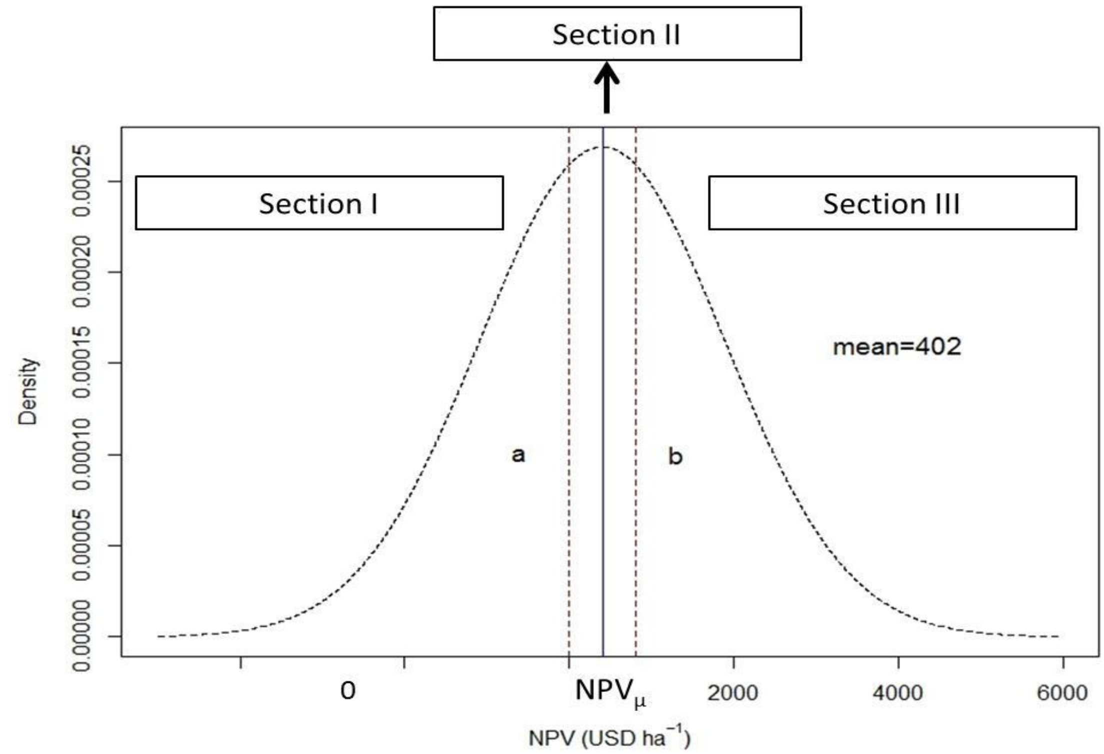

Figure 6. Bias (Value of the Stochastic Solution) represented by three different sections: I) below NPV 0, if we established base our decision on the NPV obtained from a trial established in this section, we will avoid applying the treatment to the rest of the area which is why NPV=0; II) In this section, the overestimation area is compensated by the underestimation area having the same magnitude and different sign and in consequence they cancel each other, and III) The integral of the PDF in this section represents an overestimation.

Using Eq. 7, we estimated the bias by sections. The component of Bias corresponding to Section I is equal to:

$$-NPV\mu \cdot F(0) = -157.32$$

The component of Bias corresponding to Section II is zero as demonstrated in Appendix 1:

The component of Bias corresponding to Section III is equal to:

$$\int_{s=2\mu}^{s=\infty} \left(NPV_S - NPV_\mu\right) f\,(NPV_S)\,d_{NPV_s} = 571.84$$

$Bias = 414.51$ USD ha^{-1}

This value represents the average overestimation we can get if we base our decision on the treatment response average from few sites. The bias we can get if we base our decision on few trials in our case study area could be significant. The dotted lines in Figure 7 show the bias obtained in our case study based on real data. Other values correspond to the same average treatment response but assume different variability. We simulated different Bias (VSS) using the NPV average but varied the NPV standard deviation, and it is possible to see that the bias (VSS) increases as the NPV standard deviation increased, which depends on site variability (Figure 7). These findings reflect the importance of using multi-environmental trials for decision making, especially in areas whose sites are more variable, otherwise we can make large NPV overestimations.

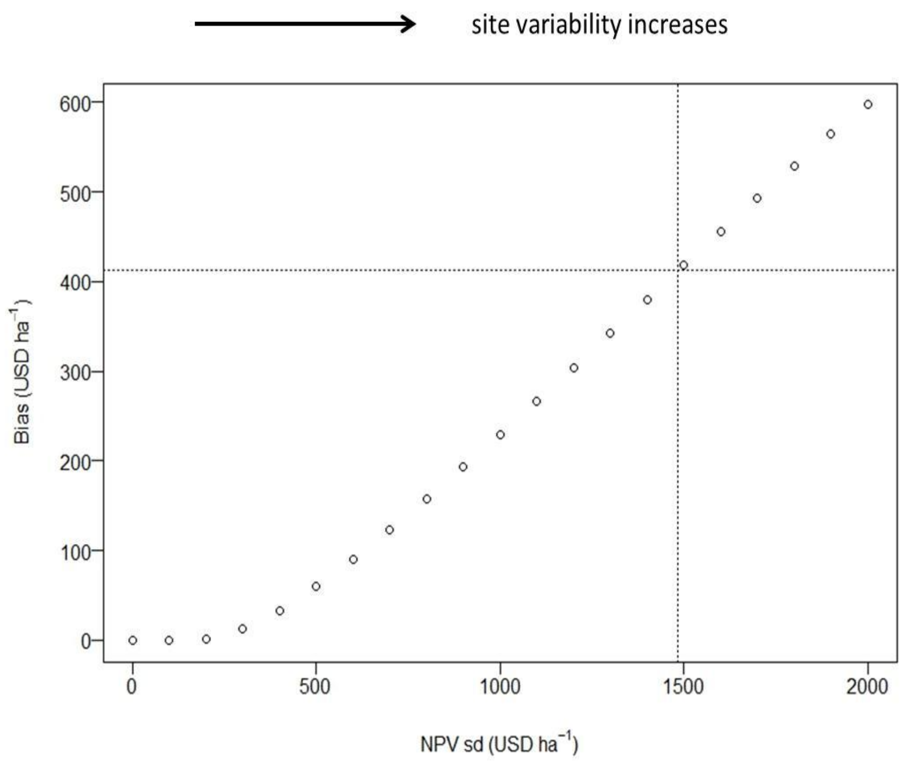

Figure 7. Relationship between the bias and the NPV standard deviation showing that NPV overestimations by making decisions based on the average of one or few installations increases exponentially as the NPV variability increases, which depends on site variability.

3.4. Diagnostic tool

In the previous analysis, we applied the treatment to the whole area: profitable and unprofitable stands. However, if we are able to identify just the profitable stands we will enhance the NPV by applying intensive silviculture just in those stands where we will have a positive financial return.

In order to identify those stands, we looked for the variables with high correlation with the treatment response. Treatment responses and the CAI of the control plots were inversely related (Figure 8 top). Larger responses were found in those stands with lower CAI increment. Treatment response was larger in low and medium landscapes positions and smaller in upper landscape positions because water availability could be a constraint in the higher positions (Figure 8 center). On average, treatment response was higher in older stands than in younger stands (Figure 8 bottom).

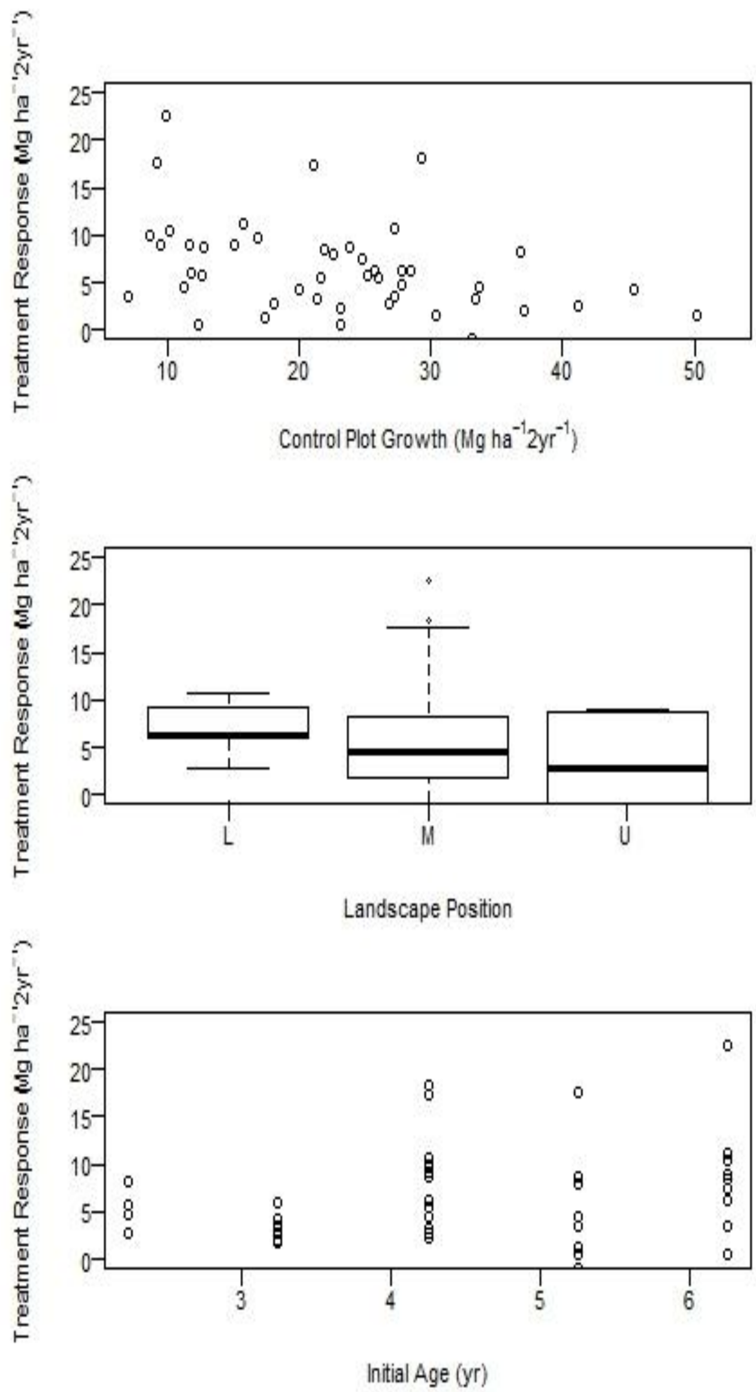

Figure 8. Treatment response relationship with: (1) Current annual increment in the control plot (top) and (2) landscape position (center), and (3) age (bottom).

We fitted two models for stands younger and older than 4 years (Tables 14-19) because canopy closes around 3 years and we expected a different treatment response patterns for young and old stands. For the first group, just the biomass growth on control plots was the explanatory variable (Figure 9 left). As expected, plots with a larger growth on control plots had a lower response, since a faster growth occurs on sites with less productivity limitations. For stands older than 4 years, beside the biomass growth on control plots, the interaction between this variable and the landscape position occupied by the plot was significant.

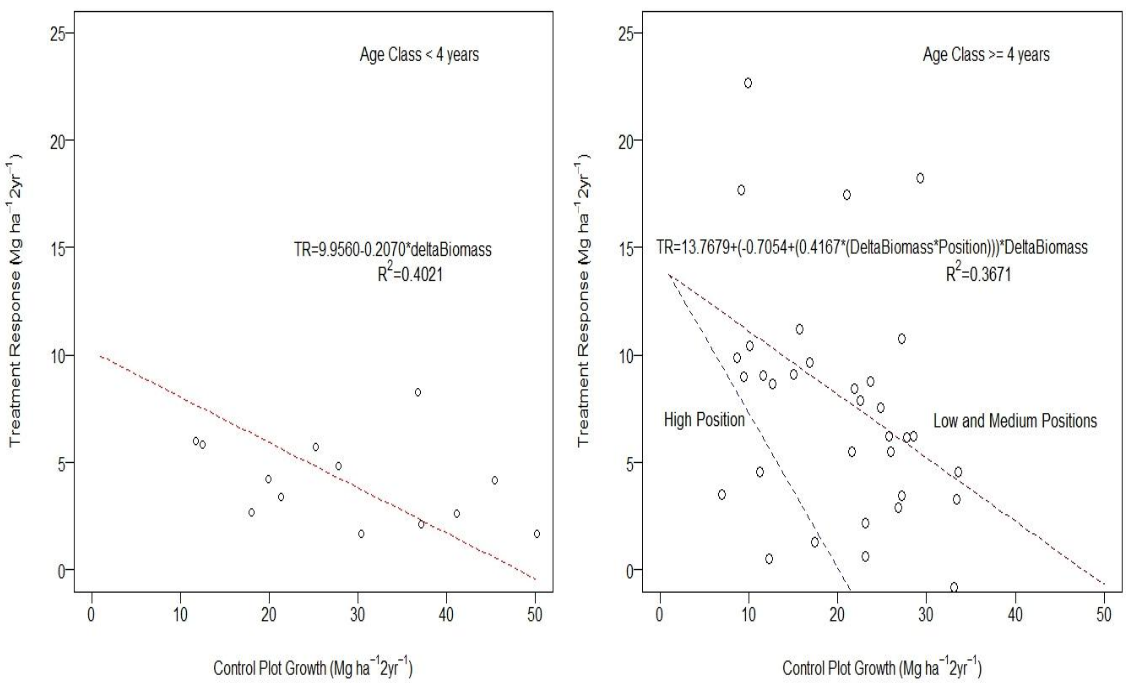

Figure 9. Treatment response models:1) for stands younger than 4 years, and 2) for stands older than 4 years. In both cases the treatment response decreased as the biomass growth on control plots increased. But in older stands this relationship also depended on the interaction between the biomass on control plots and the landscape position occupied by the stand.

Based on the third model fitted, we found biomass growth of control plots is a significant explanatory variable. But its effect depends on the landscape position the stand is occupying; stands located at low and medium landscape position have a larger response for the same level of biomass growth on control plots than plots located at upper or lower positions. Plots where the pH was higher had a lower response. Those relationships and its magnitudes are presented in Eq (9). Model analysis of variance, parameters estimates and its significance are in Tables 20-22.

$$\mathrm{Re}\boldsymbol{s} = 40.58 + -3.42\,\boldsymbol{pH} + (-1.1011 + 0.9512 \cdot \boldsymbol{Position}) \cdot \boldsymbol{WNPP} \qquad (9)$$

Where:

Res= treatment response (Mg ha^{-1} $2yr^{-1}$)
WNPP= Wood Net primary Production (Mg ha^{-1} $2yr^{-1}$)
Position= Landscape position (0 for upper position, 1 otherwise)
pH= soil pH on the first 20 cm.

3.5. The value of the information

If the response model were able to discriminate perfectly between profitable responsive and no responsive stands, we would have perfect information. In this case, we can treat just those sites that will show a response higher than the breakeven point, and we will avoid treating those sites where the treatment response does not reach a NPV of 0. Additionally, we will not misclassify any stand, and the NPV on unprofitable stands will be equal to 0 because we will not fertilize any of them. Figure 10 (left) shows treatment response distribution (dashed line); breakeven point (continuous vertical line); median treatment response for profitable responsive stands (dashed vertical line); and model error around the median of responsive stands (continuous line). Notice that there is some probability of misclassifying sites as responsive when they are not (13%). To eliminate this uncertainty, we tried two options. The first option was to reduce the error model and shrink the confidence limit around the mean

(Figure 10 top right), and the second option consisted of shifting the average to the right by just applying the treatment on the most responsive sites while maintaining the same variability (Figure 10 bottom right).

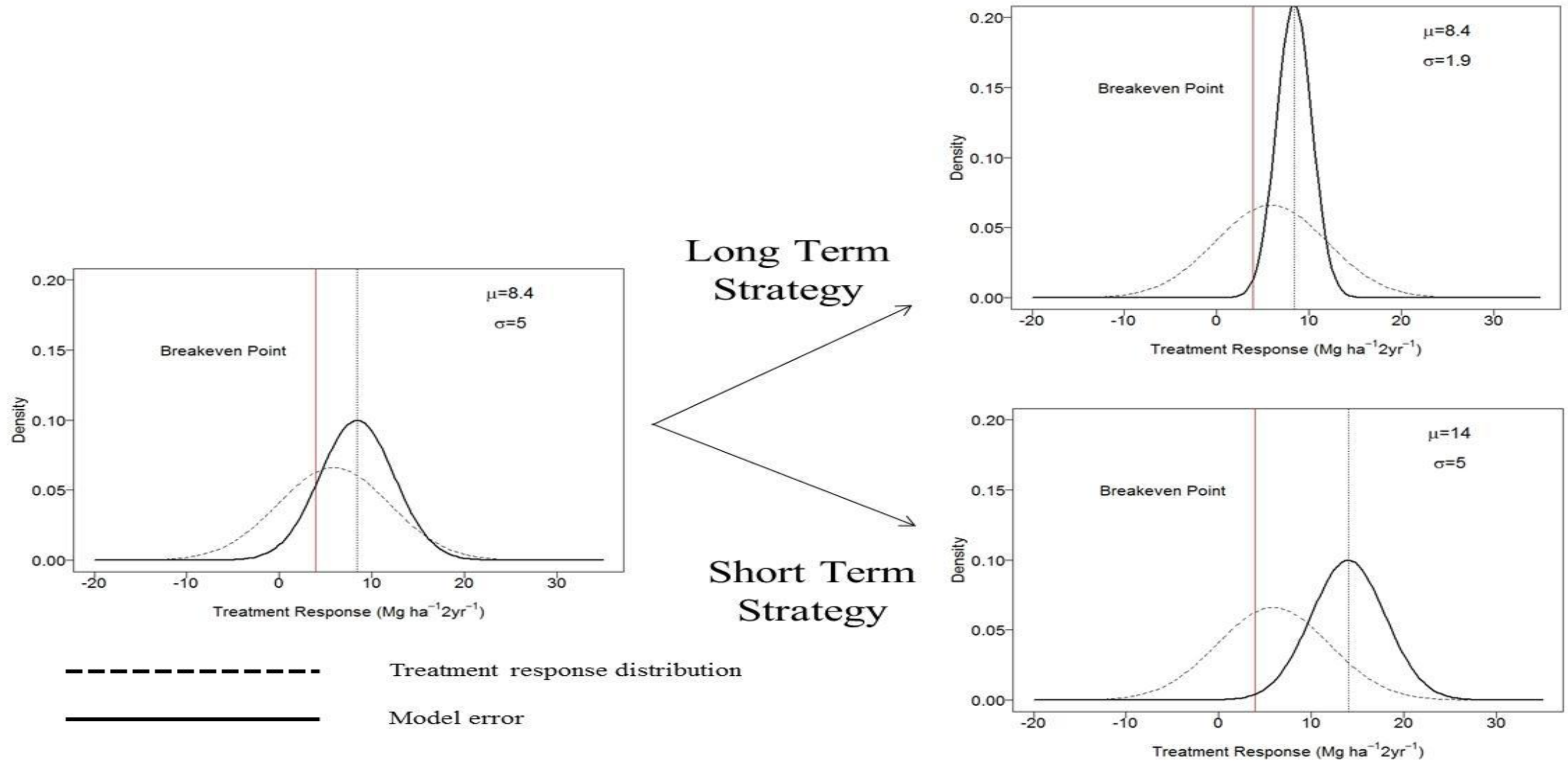

Figure 10. Treatment response distribution (dashed line); breakeven point (continuous vertical line); median treatment response for the profitable responsive stands (vertical dashed line); and error probability density function (continuous line). There is a probability of misclassifying a stand as responsive when it is not (left panel). Two strategies were tested in order to reduce this error: a) Decreasing model error through a better understanding of the system through research (top right panel), and b) Treating the most responsive sites or in other words shifting the median response to the right and keeping the same model error (bottom right panel).

Based on the treatment response distribution obtained, the proportion of stands over the breakeven point (3.4 Mg ha^{-1} 2 yr^{-1} or a NPV > 0) was 62%. Just using the proportion of profitable responsive stands, we determined the median of this subset (8.4 Mg ha^{-1} 2 yr^{-1}), which we used as the response magnitude for the profitable responsive stands (vertical dashed line in Figure 10). When using the diagnostic model to identify those stands whose treatment responses is equal or greater than the median already determined, we could potentially misclassify stands as responsive due to the model error (continuous distribution Figure 10). The magnitude of this error is 25.17 (mean square error Table 20), and the standard deviation is 5.04 Mg ha^{-1} 2 yr^{-1}, which we used as a parameter for the model error distribution. So when we predict that a stand will have a treatment response of 8.4 Mg ha^{-1} 2 yr^{-1} , there is a probability of misclassifying the stand, which is represented by the area under the continuous distribution to the left of the breakeven point (continuous vertical line) which correspond to a NPV=0. In our case this probability is equal to 13%

In our case study, the weighted NPV was 651 US$ ha^{-1}. A 13% probability of misclassifying stands as profitable responsive when they are not, represents 99 US$ ha^{-1}, which is the drop in NPV when compared with the situation using perfect information.

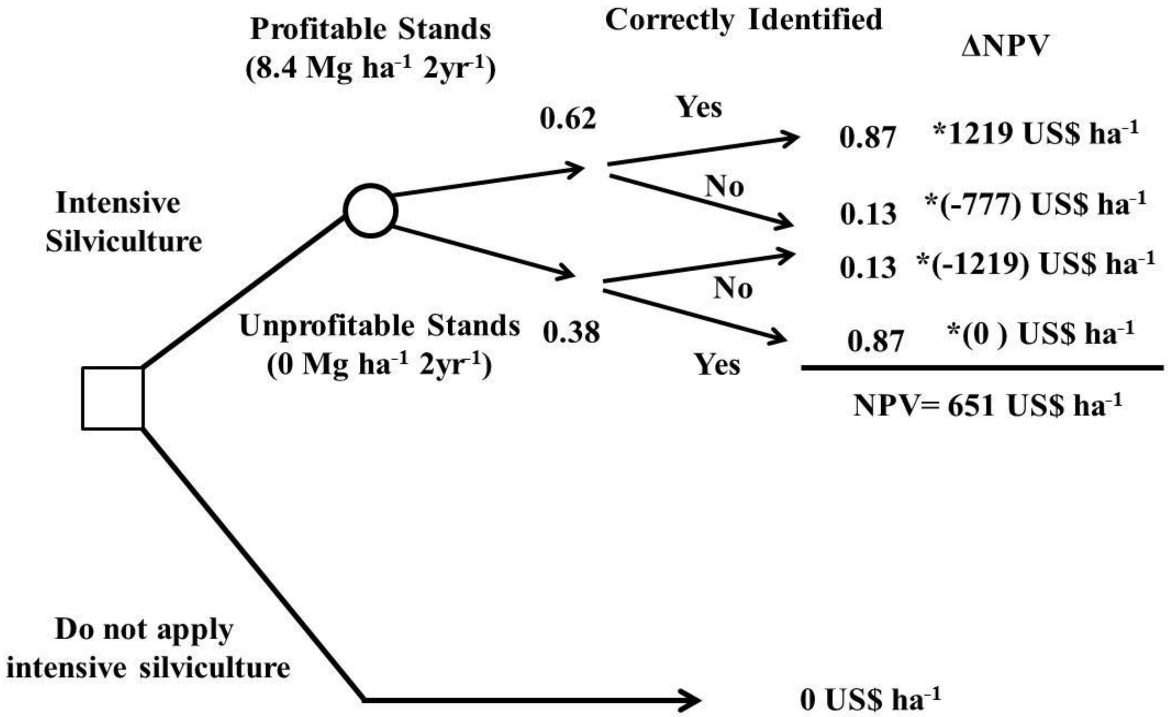

Figure 11. Decision tree to estimate the weighted NPV when using 3.4 Mg ha^{-1} 2 yr^{-1} as breakeven point. The proportion of profitable responsive and no responsive stands were 0.62 and 0.38 respectively, and the probability of misclassifying a profitable responsive stand was 0.13.

The NPV on the responsive stands was 1219 US\$ ha^{-1}, but as they represent 62% of the total area, the average NPV for the total area was 750 US\$ ha^{-1}.

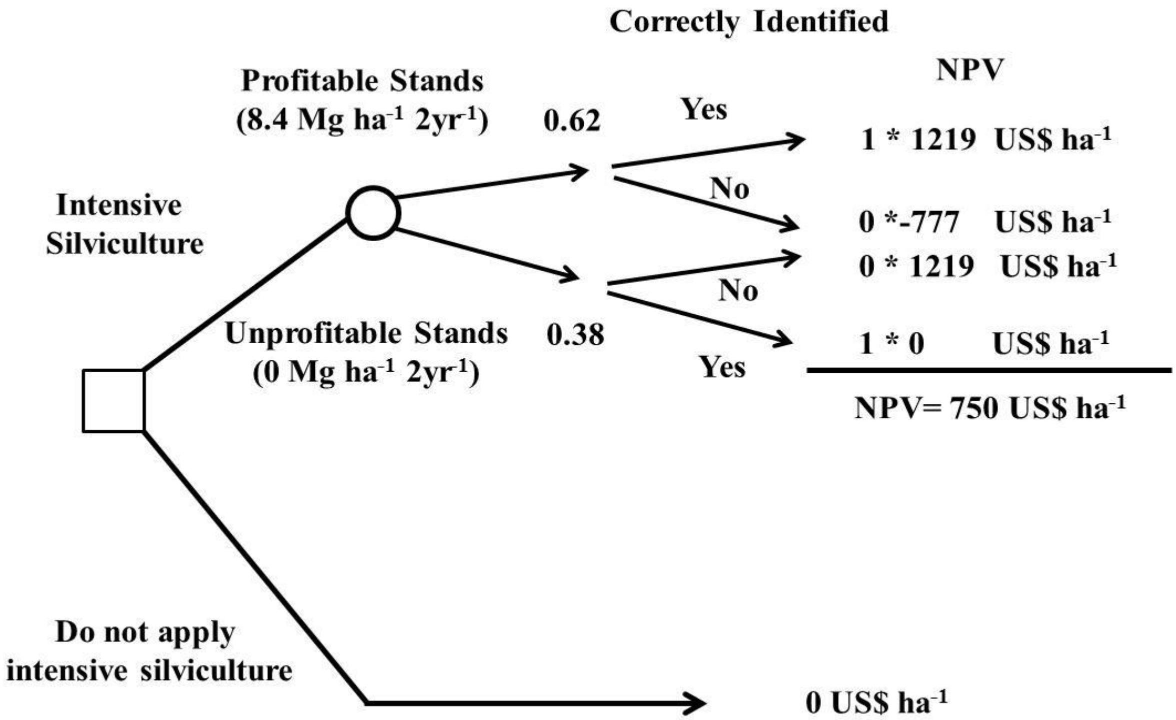

Figure 12. Long term strategy decision tree. To estimate the weighted NPV when using 3.4 Mg ha^{-1} 2 yr^{-1} as breakeven point, the proportion of profitable responsive and no responsive stands were 0.63 and 0.37 respectively, and the probability of misclassifying a profitable responsive stand was 0, under the first strategy tested.

The value of perfect information was:

$$\boldsymbol{EVPI} = \boldsymbol{NPV}_{\mu} - \boldsymbol{NPV}_{\boldsymbol{PI}} = 451 - 750 = -299$$

The NPV_{μ} in this case was 451 US\$ ha^{-1}, and not 402 US\$ ha^{-1} as estimated for VSS. In that case, we used a continuous distribution instead of a discrete distribution (responsive and no responsive stands) used to estimate the first value. The value of the perfect information (299 US\$ ha^{-1}) represents the maximum amount of money that could be spent on research in order to eliminate the uncertainty.

Another option to eliminate uncertainty is to shift to the right the treatment response distribution of possible stands to be treated by selecting a higher breakeven point such that the probability of misclassifying sites becomes 0. In this case, the proportion of stands to be treated became 18%, but the probability of correctly classifying a stand became 1. As we shifted the breakeven point, the response distribution the median became larger (14 Mg ha^{-1} 2yr^{-1}), which increased the NPV obtained by applying a treatment in those stands (Figure 13). Notice that the probability of applying the treatment on no responsive sites is 0, because we correctly identified responsive stands. The weighted NPV was 364 US$ ha^{-1}, which is obtained by just fertilizing the stands with higher responses and identifying them correctly.

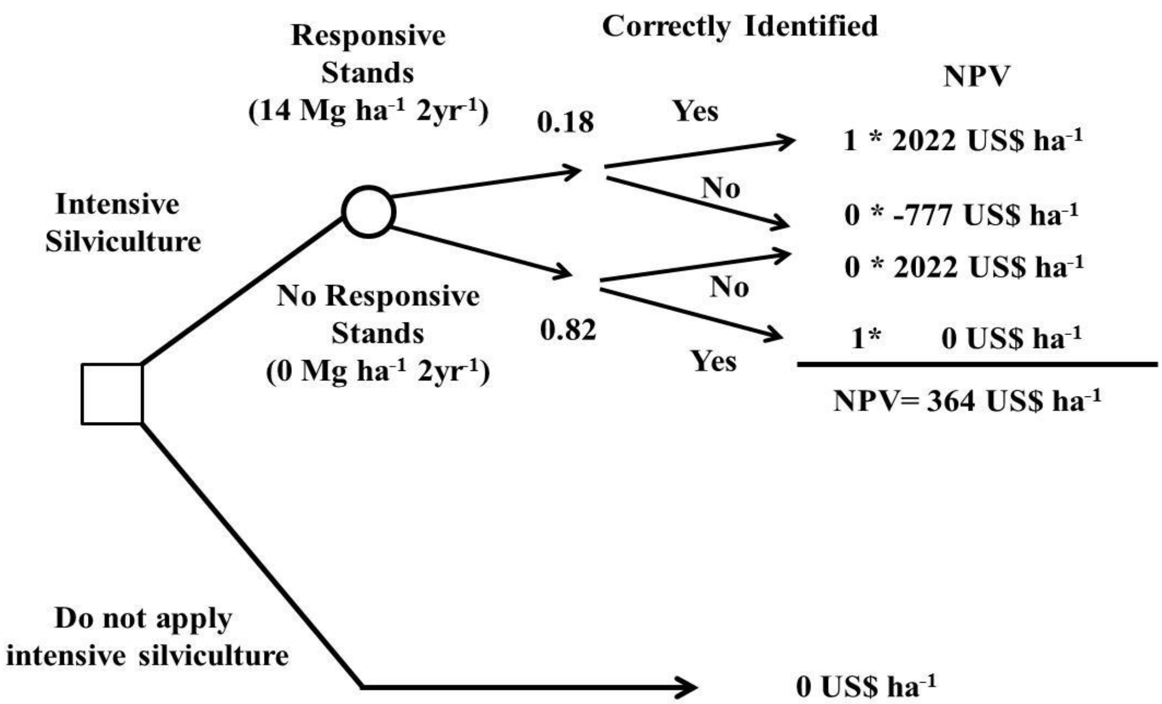

Figure 13. Short term strategy decision tree. To estimate the weighted NPV when using 3.4 Mg ha^{-1} 2 yr^{-1} as breakeven point, the proportion of profitable responsive and no responsive treated stands were 0.18 and 0.82 respectively, and the probability of misclassifying a profitable responsive stand was 0, under the second strategy tested.

3.6. Sensitivity Analysis

Breakeven points for different stumpage prices and discount rates were calculated (Table 23), the corresponding proportion of profitable stands, those to the right of the breakeven point (Table 24), and the median response of the profitable stands in each case (Table 25).

With the previous information we were able to calculate the NPV for each combination of stumpage prices and discount rates. We performed the sensitivity analysis in the case when we applied the treatment in the whole area (Table 26), and it showed that it was profitable when stumpages prices were higher than 100 US m^{-3}, which is the special case of Venezuela.

When we tried to identify the stands with a response higher than the breakeven point by using a diagnostic model we found that the NPV was close to 0 when stumpages prices were near to 40 USD m^{-3} (Table 27). Under this situation a positive value could be obtained in other countries or regions where costs were lower than in Venezuela and/or treatments responses were higher, like in Brazil (Stape et al., 2006; Ferreira and Stape, 2009; da Silva (2011); Zanni, 2012; CEDEAGRO, 2012). However in the last case the misclassification error decrease the NPV some stands are treated when should not receive any treatment. Additional information from new research could enhance model goodness of fit, and decrease and even eliminate uncertainty, which is translated into a higher NPV. A sensitivity analysis was performed when the misclassification error was eliminated (Table 28), in that case for all combinations of stumpage prices and discount rates the NPV was positive. Using prices around 40 US\$ m^{-3} we found the NPV was between 42 and 57 US\$ ha^{-1}, depending on the stumpage price and the discount rate.

4. Discussion

In the Western llanos of Venezuela, a set of 53 paired plots were established in Eucalyptus plantations to understand the effect of extra fertilization + weed control on forest productivity and profitability. The average treatment response was 5.2 Mg ha^{-1} $2yr^{-1}$ (21% over the control plot), and its standard deviation was 6.04 Mg ha^{-1} $2yr^{-1}$ with ranges from -12 to 24

Mg ha^{-1} 2yr^{-1}. The gain obtained in this study was in the range of similar studies done with Eucalyptus in Brazil. Stape et al. (2006) and da Silva (2011) obtained a gain of 24% and 23% respectively, in *Eucalyptus grandis* and *E. grandis x E. urophylla*. In *Eucalyptus urophylla* a gain of 14% was obtained by Ferreira and Stape (2009) in Sao Paulo, Brazil. In our study, intensive silviculture (fertilization + weed control) was profitable in a large proportion of stands (62 %). The upper side of the distribution represents a large potential area where to apply intensive silviculture and obtain a positive financial return. Even when the total plantation area is smaller than 10.000 ha, the site variability found will permit forest managers to apply intensive silviculture treatments in a significant proportion of the area. Such treatment decisions will increase profitability while permitting the company to increase forest productivity. Under Venezuela's current situation, where there exist land use constraints and governmental rejection of using land for Eucalyptus plantations, this seems to be a good alternative method to increase forest production without increasing land surface under forest plantations.

Average treatment profitability was estimated in 402 USD ha^{-1} at discount rate of 8% and a stumpage price of 130 USD m^{-3}, which seems high if compared with the profitability obtained in other South American countries when silvicultural treatments are applied. Venezuelan timber prices are higher than timber prices in other countries in the region, which is due to domestic market conditions. To give a point of comparison, NPV for a whole Eucalyptus rotation varies in Latin America, and could be between 2000 and 5000 US ha^{-1} (Cubbage et al., 2010). So the profitability of silvicultural treatments in our case represents around 10% of the whole rotation NPV, and between 25 and 10% when compared with the NPV in other Eucalyptus plantations in Latin America. The breakeven point was estimated in 3.4 Mg ha^{-1} 2yr^{-1}. It is necessary to point out that profitability could change through space and the moment when the study occurs, even when we get the same treatment response. Input costs, product prices and discount rates are very dynamic, and some alternatives that are not attractive in a specific place or time could become attractive when market conditions change.

Traditionally, operative decisions are made from few field trials established on characteristic sites of every management unit. However, management units could be very large or variable, and decisions made from one or few trials per management unit could be unrepresentative.

In some cases, the single trial could be established in better (or worse) sites than the average site generating a NPV higher (or lower) than the average NPV. The average error, which is the sum of the differences between the NPV associated with a particular site and the average NPV, times the probability of selecting the particular site, and summing them for all possible sites in the area of interested, becomes higher as the site variability increases. Multienvironmental studies have advantages over single trials, especially when site variability increases. Thus, decisions based on such information generated by these studies should be more accurate. In our specific case, the bias (VSS) or the NPV average error was estimated in 414 USD ha^{-1}, a significant amount that could justify the establishment of multienvironmental trials. Our area of interest is small, less than 10.000 ha; however, sites and treatment responses have a large variability that should be taken into account for decision making. Otherwise, we may overestimate the returns obtained from treatment application. Some sites could be treated when they do not need it if this variability is not taken into account, thereby decreasing the total investment return.

When the treatment response distribution is simplified in just two categories—profitable responsive and unprofitable stands—a weighted NPV could be estimated, which in our case was 451 USD ha^{-1}. Notice that this value is larger than the average NPV estimated previously (402 USD ha^{-1}), but the difference is due to the simplification done when assuming all the responsive stands will have the same response magnitude. However, we simplified the distribution to show a practical and easy way to assess the uncertainty value. This value corresponds to the average return expected if the whole area were treated.

Higher returns could be obtained if we were able to identify profitable responsive stands. The model fitted to discriminate and identify easily between responsive and no responsive stands is a good tool to decide where to apply the treatments in the future. Based on stands and soils characteristics, it will be possible to quickly identify stands that should be treated. However, the model does not identify perfectly predict responsive stands because it has some error, which is assumed normal distributed around the mean. The model fitted predicts larger responses in sites where stands grew less, which was due to the existence of limiting factors. Treatment (extra fertilization, weed control, or both) alleviates in some of the limitations if they consisted of nutrient or water deficit, and in those site we obtained higher responses. This is why treatment responses were higher where pH was lower. However, even when the initial stand growth was inversely correlated with treatment response, this depended on the landscape position occupied by the stand. In upper positions, the responses were lower; as a result, the slope of the relationship treatment response and initial control plot growth was steeper. In upper positions, water flows faster downstream because with the steepest slopes, the water holding capacity is lower because soil is less deep, and also because water inputs are lower because the area in higher positions over those stands in smaller. So even when treatment application could alleviate in some proportion those limitations, it continues limiting growth.

We estimated the NPV (651 USD ha^{-1}) when we took into account the probability of misclassifying a stand as responsive. This value is higher than the average NPV obtained when applying the treatment over the whole area but without considering the error of misclassification (451 USD ha^{-1}). The long and short term strategies generate additional 750 and 364 USD ha^{-1}, respectively. By just treating a smaller area where stands were more responsive, we were able to lose 87 USD ha^{-1} (451-364 USD ha^{-1}). A better understanding of the system through research will permit us to get a treatment investment profitability of 750 USD ha^{-1}, yet as previously stated, it is necessary to invest in research to obtain this NPV. The maximum amount justified to invest in research to diminish the uncertainty (in 50% in our case study) is 299 USD ha^{-1} (750-451 USD ha^{-1}). If we invest more than this amount, it will be better to choose the second option and apply the treatment just in the most responsive sites. The short term strategy seems useful when the company does not have enough cash

flow to invest money in research, but the second strategy will permit the company to get a higher return for several rotations.
In this case, the total planted area is around 6.000 ha. The total amount justified to diminish uncertainty and get a higher return is 299 USD ha^{-1} * 6.000 ha = US$ 1.794.000. In other cases, the total area could be much higher (more than 100.000 ha), which will permit companies to justify a much higher amount dedicated to research.

In the future treatment responses could be even larger affecting the analysis presented here. The assessment period in our case study was two years, but the difference in leaf area index, between treated plots and control plots has been increasing over time. Leaf area index has been shown is well correlated with forest productivity, and as the difference in leaf area index increased over time we expect the treatment responses will be larger in the future if a major event, as drought, diseases, etc , does not occur. This is a hypothesis to be tested, but if it is true the profitability, of applying extra fertilization and extra weed control, should be larger.

Optimal rotation could be affected by treatment application, which is an interesting topic in future research. In those stands where the growth rate is higher than the discount rate it is justified to left the stand growth at least one more year, because the marginal returns is larger than the marginal cost and in consequence the profitability increases (Klemperer, 2003, Nautiyal, 2011, Wagner, 2012). A comparison should be done with the alternative of establishing a new plantation in the same area.

A sensitivity analysis varying stumpage prices and discount rates was performed and permitted us to compare our results with situations where stumpages prices are not so high as in our case. Using a stumpage price of 40 US$ m^{-3}, we found that applying the treatment over the whole area will generate a negative NPV. But when we tried to identify the profitable stands by using the diagnostic model the NPV was close to 0, and when we eliminate uncertainty by getting extra information allowing us to fit a better model the NPV became between 42 and 57 US$ ha^{-1}, which demonstrated the advantage of using multi-environmental trials that permitted us to use the response variability for decision making. By identifying where to apply intensive silviculture it will be possible to get a higher return.

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APPENDICES

Appendix 1. Value of the Stochastic Solution

If we make decisions based on a single trial, we can over or underestimate the NPV to be obtained in the whole area to be treated, since sites could be different than the site where the trial was established, thereby generatimg a different treatment response. To try to quantify this bias, the following calculations were done and the methodology proposed.

If we select a particular site to establish a trial, from their results we can estimate a NPV_S in that particular site (S) from which we can make the decision of applying the treatment in the rest of the area. As sites are different and they have different responses, their NPV_x will be different. So (NPV_S-NPV_x) represent the NPV bias between the site where the trial was established and the NPV at any other site. Adding this bias for all possible site and weighting them by its probability we obtain:

$$\Delta NPV = \int_{NPV_x=-\infty}^{NPV_x=\infty} \left(NPV_S - NPV_x\right) f\left(NPV_x\right) d_{NPV_x}$$

$$\Delta NPV = \int_{NPV_x=-\infty}^{NPV_x=\infty} \left(NPV_S\right) f\left(NPV_x\right) d_{NPV_x} - \int_{NPV_x=-\infty}^{NPV_x=\infty} \left(NPV_x\right) f\left(NPV_x\right) d_{NPV_x}$$

$$\Delta NPV = NPV_S \int_{NPV_x=-\infty}^{NPV_x=\infty} f\left(NPV_x\right) d_{NPV_x} - \int_{NPV_x=-\infty}^{NPV_x=\infty} \left(NPV_x\right) f\left(NPV_x\right) d_{NPV_x}$$

$$\Delta NPV = NPV_S - NPV_\mu$$

Which means that the NPV bias weight average, is equal to the NPV at trial site minus the NPV population average.

But trial site could be any other possible site, and we assumed the probability to be selected is equal to the proportion it represents in the area of interest. Then selecting all possible site to establish the trial, and adding all the possible NPV bias we have:

$$\int_{NPV_S=-\infty}^{NPV_S=\infty} \Delta NPV d_S = \int_{NPV_S=-\infty}^{NPV_S=0} (NPV_S - NPV_\mu) f(NPV_S) d_{NPV_S} + \int_{NPV_S=0}^{NPV_S=2\mu} (NPV_S - NPV_\mu) f(NPV_S) d_{NPV_S} + \int_{NPV_S=2\mu}^{NPV_S=\infty} (NPV_S - NPV_\mu) f(NPV_S) d_{NPV_S}$$

Where:

NPV_S = NPV when the average response of a particular site is used (USD ha^{-1})
NPV_μ = NPV when the average response of the sites population is used (USD ha^{-1})
$f(NPV_S)$ = sites probability density function
S = a particular site

Where:
NPV= Net Present Value
S=NPV in site S selected to establish a trial
μ= NPV site population average
f(S)= NPV probability density function

Notice we divide the whole PDF in three sections, with different characteristics as could be seen below.

Section I

NPV_S=0 for all sites if trial NPV is negative. Or in other words if the trial NPV is negative, the decision will be not to apply the treatment in the rest of the area.

$$\int_{NPV_S=-\infty}^{NPV_S=0} \Delta NPV_S \, d_{NPV_S} = \int_{NPV_S=-\infty}^{NPV_S=0} \left(0 - NPV_\mu\right) f\left(NPV_S\right) d_{NPV_S}$$

$$\int_{S=-\infty}^{S=0} \Delta NPV d_S = -NPV_\mu \int_{NPV_S=-\infty}^{NPV_S=0} f\left(NPV_S\right) d_{NPV_S}$$

$$\int_{NPV_S=-\infty}^{NPV_S=0} \Delta NPV_S \, d_S = -NPV_S\left(F(0) - F(-\infty)\right)$$

$$\int_{NPV_S=-\infty}^{NPV_S=0} \Delta NPV_S \, d_S = -NPV_S\left(F(0)\right)$$

Section II

As the PDF in our case is symmetric the area over the average is equal to the area under the average if the range is equal (± μ in our case). As we are calculating differences with respect to the average, both areas will have the same magnitude but different signs. In consequence the sum is equal to 0.

$$\int_{NPV_S=0}^{NPV_S=2\mu} \Delta NPV_S \, d_S = \int_{NPV_S=0}^{NPV_S=2\mu} \left(NPV_S - NPV_\mu\right) f\left(NPV_S\right) d_{NPV_S}$$

$$\int_{NPV_S=0}^{NPV_S=2\mu} \Delta NPV_S \, d_{NPV_S} = \int_{NPV_S=0}^{NPV_S=\mu} \left(NPV_S - NPV_\mu\right) f\left(NPV_S\right) d_{NPV_S} + \int_{NPV_S=\mu}^{NPV_S=2\mu} \left(NPV_S - NPV_\mu\right) f\left(NPV_S\right) d_{NPV_S}$$

But as NPV_S-NPV_μ = - (NPV_μ-NPV_S)

$$\int_{S=0}^{S=2\mu} \Delta NPV d_S = \int_{S=0}^{S=\mu} -\left(\mu - S\right) f(S) d_S + \int_{S=\mu}^{S=2\mu} \left(S - \mu\right) f(S) d_S$$

$$\int_{S=0}^{S=2\mu} \Delta NPV d_S = -\int_{S=0}^{S=\mu} (S) f(S) d_S + \int_{S=\mu}^{S=2\mu} (S) f(S) d_S - \int_{S=0}^{S=\mu} (\mu) f(S) d_S - \int_{S=\mu}^{S=2\mu} (\mu) f(S) d_S$$

In our case f(S) is symmetric (normal distribution), then :

$$\int_{NPV_S=0}^{NPV_S=2\mu} \Delta NPV_S d_{NPV_S} = 0$$

Section III

$$\int_{NPV_S=2\mu}^{NPV_S=\infty} \Delta NPV_S d_{NPV_S} = \int_{NPV_S=2\mu}^{NPV_S=\infty} \left(NPV_S - NPV_\mu\right) f\left(NPV_S\right) d_{NPV_S}$$

Putting all sections together:

$$\int_{NPV_S=-\infty}^{NPV_S=\infty} \Delta NPV_S d_{NPV_S} = -NPV_\mu F(0) + 0 + \int_{NPV_S=2\mu}^{NPV_S=\infty} \left(NPV_S - NPV_\mu\right) f\left(NPV_S\right) d_{NPV_S}$$

Appendix 2. Program in R to calculate VSS.

```
#Integral VSS

mean<-400
mean2<-2*mean
NPVsum<-c()
step<-0.1

for (NPV  in seq(mean2,4000,step)){

	NPVw<-((NPV-mean)*(dnorm(NPV,mean=400,sd=1216,log=FALSE)*step))
	NPVsum<-c(NPVsum,NPVw)
	NPVw<-0
}

VSS<-sum(NPVsum)
VSS
```

Table 1. Fertilizer sources, doses and timing

Fertilizer Source	Application Period	San Carlos Poor drained (kg/ha)	San Carlos- Caño Benito Well drained (kg/ha)
DAP	Pre-Planting	200	200
NPK 12:24:12	30 days	-	111
NPK 10:26:26	30 days	111	-
Borax	120 days	15	15
Dolomite	10 months	-	550
NPK 21:5:23	1 year	-	180
Ammonium sulfate	1 year	250	-
Borax	1.4 years	27	27
NPK 21:5:23	2 year	-	180

Table 2. Monthly mean maximum and minimum temperature (°C), rainfall (mm), and potential and real evapotranspiration (mm) in Western Llanos, Venezuela.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Tmax	34	35	36	35	32	31	30	31	32	32	33	33	
Tmin	18	20	20	22	22	21	21	21	21	22	21	19	
Rainfall	9	8	14	91	19	234	250	219	158	139	90	45	1266
ETP	128	141	181	187	166	139	135	140	143	155	140	132	1587
ETR	42	25	23	93	166	139	135	140	143	155	129	91	1281

Table 3. Number of plots by ages

Age	# Plots
2	6
3	16
4	13
5	10
6	12

Table 4. Number of plots by SI

S (m)	# Plots
<18	31
18-22	34
22-26	39
>26	12

Table 5. Distributions goodness of fitting

Distribution	Chi-Square value
Logistic	12.6157
Normal	13.0254
Weibull	14.5552
Triangular	21.3633
Uniform	61.0719
Exponential	103.5474

Table 6.Proportion of sand, clay and silt at two different depths= A. 0-20 cm and B. 20-40 cm In control and twin plots.

		Between Rows						Rows					
Plot	Treatment	sandA	ClayA	SiltA	sandB	ClayB	SiltB	sandA	ClayA	SiltA	sandB	ClayB	SiltB
1	Control	88.0	4.0	8.0	84.0	8.0	8.0	86.0	4.0	10.0	84.0	6.0	10.0
2	Twin	88.0	4.0	8.0	84.0	8.0	8.0	86.0	4.0	10.0	84.0	6.0	10.0
3	Control	78.8	4.0	17.2	72.8	6.0	21.2	74.8	2.0	23.2	74.8	4.0	21.2
4	Twin	78.8	4.0	17.2	72.8	6.0	21.2	74.8	2.0	23.2	74.8	4.0	21.2
5	Control	76.8	4.0	19.2	68.8	10.0	21.2	74.8	4.0	21.2	74.8	6.0	19.2
6	Twin	76.8	4.0	19.2	68.8	10.0	21.2	74.8	4.0	21.2	74.8	6.0	19.2
7	Control	84.0	8.0	8.0	76.0	14.0	10.0	84.0	4.0	12.0	82.0	10.0	8.0
8	Twin	84.0	8.0	8.0	76.0	14.0	10.0	84.0	4.0	12.0	82.0	10.0	8.0
9	Control	72.0	12.0	16.0	64.0	14.0	22.0	76.0	8.0	16.0	62.0	14.0	24.0
10	Twin	72.0	12.0	16.0	64.0	14.0	22.0	76.0	8.0	16.0	62.0	14.0	24.0
11	Control	78.0	2.0	20.0	80.0	2.0	18.0	78.0	2.0	20.0	80.0	2.0	18.0
12	Twin	78.0	2.0	20.0	80.0	2.0	18.0	78.0	2.0	20.0	80.0	2.0	18.0
13	Control	84.0	5.6	10.4	86.0	9.6	4.4	84.0	3.6	12.4	78.0	9.6	12.4
14	Twin	84.0	5.6	10.4	86.0	9.6	4.4	84.0	3.6	12.4	78.0	9.6	12.4
15	Control	76.8	2.0	21.2	74.8	4.0	21.2	74.8	2.0	23.2	74.8	2.0	23.2
16	Twin	76.8	2.0	21.2	74.8	4.0	21.2	74.8	2.0	23.2	74.8	2.0	23.2
17	Control	84.0	6.0	10.0	70.0	16.0	14.0	82.0	6.0	12.0	74.0	12.0	14.0
18	Twin	84.0	6.0	10.0	70.0	16.0	14.0	82.0	6.0	12.0	74.0	12.0	14.0
19	Control	82.8	1.2	16.0	76.8	5.2	18.0	84.8	1.2	14.0	82.8	1.2	16.0
20	Twin	82.8	1.2	16.0	76.8	5.2	18.0	84.8	1.2	14.0	82.8	1.2	16.0
21	Control	84.0	2.0	14.0	86.0	4.0	10.0	88.0	2.0	10.0	84.0	4.0	12.0

Table 6 Continued

22	Twin	84.0	2.0	14.0	86.0	4.0	10.0	88.0	2.0	10.0	84.0	4.0	12.0
23	Control	72.0	12.0	16.0	58.0	26.0	16.0	74.0	6.0	20.0	62.0	4.0	34.0
24	Twin	72.0	12.0	16.0	58.0	26.0	16.0	74.0	6.0	20.0	62.0	4.0	34.0
25	Control	86.0	4.0	10.0	80.0	10.0	10.0	86.0	4.0	10.0	86.0	6.0	8.0
26	Twin	86.0	4.0	10.0	80.0	10.0	10.0	86.0	4.0	10.0	86.0	6.0	8.0
27	Control	66.0	10.0	24.0	56.0	22.0	22.0	70.0	6.0	24.0	70.0	6.0	24.0
28	Twin	66.0	10.0	24.0	56.0	22.0	22.0	70.0	6.0	24.0	70.0	6.0	24.0
29	Control	78.0	6.0	16.0	66.0	14.0	20.0	80.0	4.0	16.0	78.0	6.0	16.0
30	Twin	78.0	6.0	16.0	66.0	14.0	20.0	80.0	4.0	16.0	78.0	6.0	16.0
31	Control	75.6	5.6	18.8	73.6	9.6	16.8	79.6	3.6	16.8	75.6	5.6	18.8
32	Twin	75.6	5.6	18.8	73.6	9.6	16.8	79.6	3.6	16.8	75.6	5.6	18.8
33	Control	29.6	30.0	40.4	33.6	36.0	30.4	39.6	24.0	36.4	35.6	26.0	38.4
34	Twin	29.6	30.0	40.4	33.6	36.0	30.4	39.6	24.0	36.4	35.6	26.0	38.4
35	Control	53.6	17.6	28.8	45.6	21.6	32.8	53.6	9.6	36.8	45.6	19.6	34.8
36	Twin	53.6	17.6	28.8	45.6	21.6	32.8	53.6	9.6	36.8	45.6	19.6	34.8
37	Control	71.6	10.0	18.4	57.6	20.0	22.4	73.6	10.0	16.4	73.6	8.0	18.4
38	Twin	71.6	10.0	18.4	57.6	20.0	22.4	73.6	10.0	16.4	73.6	8.0	18.4
39	Control	73.6	10.0	16.4	63.2	16.0	20.8	77.2	4.0	18.8	75.6	8.0	16.4
40	Twin	73.6	10.0	16.4	63.2	16.0	20.8	77.2	4.0	18.8	75.6	8.0	16.4
41	Control	80.4	6.0	13.6	76.4	10.0	13.6	80.4	2.0	17.6	80.4	2.0	17.6
42	Twin	80.4	6.0	13.6	76.4	10.0	13.6	80.4	2.0	17.6	80.4	2.0	17.6
43	Control	64.4	14.0	21.6	58.4	20.0	21.6	72.4	10.0	17.6	60.4	16.0	23.6
44	Twin	64.4	14.0	21.6	58.4	20.0	21.6	72.4	10.0	17.6	60.4	16.0	23.6
45	Control	48.0	4.0	48.0	40.0	20.0	40.0	48.0	2.0	50.0	44.0	8.0	48.0
46	Twin	48.0	4.0	48.0	40.0	20.0	40.0	48.0	2.0	50.0	44.0	8.0	48.0
47	Control	38.0	8.0	54.0	58.0	16.0	26.0	32.0	12.0	56.0	36.0	16.0	48.0

Table 6 Continued

48	Twin	38.0	8.0	54.0	58.0	16.0	26.0	32.0	12.0	56.0	36.0	16.0	48.0
49	Control	56.0	6.0	38.0	38.0	20.0	42.0	42.0	6.0	52.0	36.0	10.0	54.0
50	Twin	56.0	6.0	38.0	38.0	20.0	42.0	42.0	6.0	52.0	36.0	10.0	54.0
51	Control	87.6	6.0	6.4	83.6	14.0	2.4	45.6	4.0	50.4	43.6	6.0	50.4
52	Twin	87.6	6.0	6.4	83.6	14.0	2.4	45.6	4.0	50.4	43.6	6.0	50.4
53	Control	41.6	6.0	52.4	35.6	24.0	40.4	39.6	6.0	54.4	35.6	12.0	52.4
54	Twin	41.6	6.0	52.4	35.6	24.0	40.4	39.6	6.0	54.4	35.6	12.0	52.4
55	Control	37.6	11.6	50.8	41.6	25.6	32.8	37.6	7.6	54.8	37.6	11.6	50.8
56	Twin	37.6	11.6	50.8	41.6	25.6	32.8	37.6	7.6	54.8	37.6	11.6	50.8
57	Control	46.0	6.0	48.0	52.0	14.0	34.0	54.0	6.0	40.0	46.0	6.0	48.0
58	Twin	46.0	6.0	48.0	52.0	14.0	34.0	54.0	6.0	40.0	46.0	6.0	48.0
59	Control	50.0	6.0	44.0	54.0	10.0	36.0	62.0	4.0	34.0	50.0	6.0	44.0
60	Twin		6.0	44.0	54.0	10.0	36.0	62.0	4.0	34.0	50.0	6.0	44.0
61	Control	52.0	12.0	36.0	48.0	32.0	20.0	58.0	6.0	36.0	52.0	14.0	34.0
62	Twin	52.0	12.0	36.0	48.0	32.0	20.0	58.0	6.0	36.0	52.0	14.0	34.0
63	Control	48.0	18.0	34.0	42.0	30.0	28.0	46.0	14.0	40.0	42.0	22.0	36.0
64	Twin	48.0	18.0	34.0	42.0	30.0	28.0	46.0	14.0	40.0	42.0	22.0	36.0
65	Control	74.4	4.0	21.6	74.4	6.0	19.6	76.4	4.0	19.6	74.4	4.0	21.6
66	Twin	74.4	4.0	21.6	74.4	6.0	19.6	76.4	4.0	19.6	74.4	4.0	21.6
67	Control	57.6	10.0	32.4	57.6	14.0	28.4	63.6	6.0	30.4	61.6	7.6	30.8
68	Twin	57.6	10.0	32.4	57.6	14.0	28.4	63.6	6.0	30.4	61.6	7.6	30.8
69	Control	56.4	10.0	33.6	52.4	14.0	33.6	58.4	6.0	35.6	56.4	10.0	33.6
70	Twin	56.4	10.0	33.6	52.4	14.0	33.6	58.4	6.0	35.6	56.4	10.0	33.6
71	Control	56.0	14.0	30.0	40.0	24.0	36.0	42.0	10.0	48.0	36.0	20.0	44.0
72	Twin	56.0	14.0	30.0	40.0	24.0	36.0	42.0	10.0	48.0	36.0	20.0	44.0
73	Control	60.0	6.0	34.0	46.0	18.0	36.0	66.0	4.0	30.0	56.0	10.0	34.0
74	Twin	60.0	6.0	34.0	46.0	18.0	36.0	66.0	4.0	30.0	56.0	10.0	34.0

Table 6 Continued

75	Control	60.0	8.0	32.0	50.0	20.0	30.0	60.0	8.0	32.0	50.0	16.0	34.0
76	Twin	60.0	8.0	32.0	50.0	20.0	30.0	60.0	8.0	32.0	50.0	16.0	34.0
77	Control	70.4	6.0	23.6	58.4	18.0	23.6	72.4	4.0	23.6	66.4	8.0	25.6
78	Twin	70.4	6.0	23.6	58.4	18.0	23.6	72.4	4.0	23.6	66.4	8.0	25.6
79	Control	41.6	29.6	28.8	47.6	29.6	22.8	33.6	33.6	32.8	39.6	29.6	30.8
80	Twin	41.6	29.6	28.8	47.6	29.6	22.8	33.6	33.6	32.8	39.6	29.6	30.8
81	Control	60.0	7.2	32.8	58.0	11.2	30.8	62.0	4.8	33.2	56.0	10.8	33.2
82	Twin	60.0	7.2	32.8	58.0	11.2	30.8	62.0	4.8	33.2	56.0	10.8	33.2
83	Control	60.0	4.8	35.2	54.0	12.8	33.2	56.8	5.6	37.6	50.8	15.6	33.6
84	Twin	60.0	4.8	35.2	54.0	12.8	33.2	56.8	5.6	37.6	50.8	15.6	33.6
85	Control	50.8	11.6	37.6	40.8	23.6	35.6	50.8	9.6	39.6	46.8	21.6	31.6
86	Twin	50.8	11.6	37.6	40.8	23.6	35.6	50.8	9.6	39.6	46.8	21.6	31.6
87	Control	48.0	8.0	44.0	52.0	10.0	38.0	48.0	10.0	42.0	50.0	10.0	40.0
88	Twin	48.0	8.0	44.0	52.0	10.0	38.0	48.0	10.0	42.0	50.0	10.0	40.0
89	Control	44.0	14.0	42.0	34.0	18.0	48.0	38.0	12.0	50.0	36.0	12.0	52.0
90	Twin	44.0	14.0	42.0	34.0	18.0	48.0	38.0	12.0	50.0	36.0	12.0	52.0
91	Control	62.0	20.0	18.0	54.0	8.0	38.0	64.0	16.0	20.0	56.0	12.0	32.0
92	Twin	62.0	20.0	18.0	54.0	8.0	38.0	64.0	16.0	20.0	56.0	12.0	32.0
93	Control	60.4	10.0	29.6	56.4	14.0	29.6	50.4	10.0	39.6	46.4	16.0	37.6
94	Twin	60.4	10.0	29.6	56.4	14.0	29.6	50.4	10.0	39.6	46.4	16.0	37.6
95	Control	50.0	22.0	28.0	40.0	30.0	30.0	54.0	18.0	28.0	46.0	24.0	30.0
96	Twin	50.0	22.0	28.0	40.0	30.0	30.0	54.0	18.0	28.0	46.0	24.0	30.0
97	Control	44.0	18.0	38.0	40.0	28.0	32.0	48.0	12.0	40.0	44.0	24.0	32.0
98	Twin	44.0	18.0	38.0	40.0	28.0	32.0	48.0	12.0	40.0	44.0	24.0	32.0
99	Control	60.0	8.0	32.0	54.0	16.0	30.0	60.0	8.0	32.0	58.0	12.0	30.0
100	Twin	60.0	8.0	32.0	54.0	16.0	30.0	60.0	8.0	32.0	58.0	12.0	30.0
101	Control	76.0	8.0	16.0	60.0	20.0	20.0	68.0	8.0	24.0	60.0	14.0	26.0

Table 6 Continued

102	Twin	76.0	8.0	16.0	60.0	20.0	20.0	68.0	8.0	24.0	60.0	14.0	26.0
103	Control	60.0	10.0	30.0	54.0	18.0	28.0	66.0	6.0	28.0	66.0	8.0	26.0
104	Twin	60.0	10.0	30.0	54.0	18.0	28.0	66.0	6.0	28.0	66.0	8.0	26.0
105	Control	62.0	8.0	30.0	52.0	18.0	30.0	64.0	6.0	30.0	60.0	10.0	30.0
106	Twin	62.0	8.0	30.0	52.0	18.0	30.0	64.0	6.0	30.0	60.0	10.0	30.0

Table 7. Soil chemical properties at depth= A. 0-20 cm, in control and twin plots.

Plot	pHA	ExAcdA	% NA	% CA	CNA	AlA	CaA	FeA	KA	MgA	MnA	PA	ZnA
1	5.40	0.75	0.03	0.40	15.36	254.07	173.20	57.91	14.19	33.81	33.21	36.66	1.69
2	4.88	0.59	0.03	0.39	13.14	224.12	48.00	81.44	9.20	36.30	6.83	8.14	.
3	4.68	0.42	0.02	0.38	15.33	308.70	73.58	92.83	23.05	20.24	3.19	12.51	.
4	5.11	0.15	0.03	0.42	14.38	212.97	118.61	53.25	63.12	33.76	13.23	10.81	0.28
5	4.25	1.44	0.04	0.65	15.92	612.54	61.14	182.20	18.80	11.09	0.37	28.56	14.76
6	4.86	2.00	0.03	0.43	16.22	315.19	126.25	209.57	12.64	22.06	8.66	19.89	0.33
7	4.10	1.96	0.03	0.56	19.48	284.20	49.86	82.08	13.26	12.72	9.00	13.04	0.28
8	5.28	0.23	0.03	0.50	14.35	274.60	242.78	120.24	20.47	40.82	52.59	43.60	1.38
9	4.65	0.46	0.03	0.45	15.46	254.73	72.22	60.79	15.41	29.27	6.48	5.94	0.26
10	5.28	1.06	0.03	0.43	12.84	265.04	180.38	46.64	17.32	28.72	16.82	13.68	.
11	4.64	0.30	0.03	0.47	14.93	246.43	104.99	94.71	19.29	20.47	19.33	17.08	0.80
12	4.92	0.18	0.05	0.52	11.31	301.99	122.55	68.18	43.10	28.68	149.21	5.76	0.86
13	4.86	1.80	0.02	0.32	13.50	201.15	56.61	63.51	20.96	15.42	6.21	10.47	.
14	4.51	1.06	0.07	0.81	11.57	581.28	198.45	173.84	19.17	51.88	5.79	7.19	0.28
15	4.58	0.62	0.03	0.39	11.89	350.26	43.53	142.05	31.21	15.18	6.37	6.66	0.31
16	4.41	1.15	0.05	0.75	15.49	409.24	108.22	153.68	22.14	31.69	4.90	10.55	0.79
17	4.41	1.02	0.13	1.25	9.30	1128.44	72.96	231.59	43.75	38.50	4.18	5.91	0.46

Table 7 Continued

18	4.53	1.49	0.08	0.80	9.66	752.46	44.04	198.42	40.39	26.83	1.87	10.75	0.70
19	4.38	0.83	0.04	0.41	10.28	459.43	33.26	114.98	15.62	13.51	5.46	7.93	0.40
20	4.45	0.82	0.05	0.59	11.63	396.74	88.67	178.34	27.30	25.08	19.07	20.22	0.82
21	4.33	0.89	0.03	0.36	12.05	299.87	37.22	87.21	18.53	11.19	4.37	8.02	0.26
22	4.53	1.34	0.07	0.76	10.27	714.47	102.28	90.52	62.69	42.19	6.24	8.01	0.50
23	5.10	0.13	0.07	0.89	12.13	375.29	786.46	226.87	41.15	156.89	27.07	4.64	1.52

24	4.90	0.59	0.08	0.79	10.32	397.48	551.93	305.82	33.65	140.64	19.42	6.90	.
25	5.00	0.22	0.07	0.94	12.73	348.55	611.34	299.86	30.56	147.09	16.14	5.32	1.38
26	5.45	0.24	0.08	0.90	11.62	388.99	557.58	220.06	34.93	188.36	24.69	3.98	1.19
27	5.19	0.15	0.07	0.78	11.53	320.53	590.31	255.19	37.73	134.67	11.93	5.05	1.70
28	5.31	0.30	0.08	0.91	12.00	479.70	717.77	256.12	41.62	114.08	23.91	3.61	1.02
29	5.71	0.03	0.08	0.89	11.18	223.21	942.61	225.26	34.03	123.94	20.33	4.92	2.30
30	5.40	0.03	0.08	0.86	11.38	233.05	706.03	191.28	27.46	117.82	26.80	5.72	2.20
31	4.45	0.79	0.06	0.66	10.37	466.41	226.89	185.38	38.50	79.22	10.37	7.14	2.42
32	4.08	2.18	0.09	1.07	11.58	905.21	97.15	260.51	42.15	39.84	4.46	7.69	0.72
33	5.96	0.06	0.04	0.50	11.17	245.13	433.84	67.59	22.38	50.40	130.57	5.08	1.33
34	5.44	0.04	0.05	0.60	11.85	326.97	429.58	212.51	42.54	81.12	17.52	14.44	0.82
35	4.94	0.18	0.06	0.71	11.44	426.87	330.34	103.90	71.67	87.26	17.37	8.01	0.94
36	4.61	1.14	0.07	0.83	12.16	488.42	279.66	229.67	36.70	127.15	13.49	6.84	0.74
37	6.34	0.08	0.07	0.94	13.30	291.60	####	211.37	101.51	148.74	32.28	7.44	2.33
38	4.59	0.99	0.06	0.70	10.88	355.68	225.76	128.75	29.56	96.62	37.52	7.83	0.60
39	4.74	0.45	0.04	0.41	10.31	308.83	92.69	121.21	39.93	25.23	20.72	8.75	0.58
40	4.27	5.02	0.28	3.19	11.24	1394.16	832.86	520.12	101.25	222.49	28.93	3.24	7.22
41	4.38	0.93	0.04	0.47	11.38	338.45	49.10	288.72	17.71	21.51	2.18	4.74	0.59
42	5.01	0.28	0.05	0.53	11.68	310.94	190.36	124.75	16.18	63.08	68.49	3.33	0.45
43	4.67	1.03	0.07	0.76	11.42	444.21	256.06	233.44	25.50	91.29	7.78	8.45	0.99

Table 7 Continued

44	4.36	1.89	0.06	0.71	10.98	369.93	58.55	220.15	26.13	24.39	4.89	4.42	0.61
45	4.22	0.62	0.07	0.78	11.55	603.76	74.56	355.44	41.98	44.98	2.56	8.27	0.91
46	4.47	1.19	0.04	0.60	13.77	374.08	95.70	124.96	25.23	26.21	5.46	5.29	0.26
47	4.20	1.30	0.04	0.48	13.66	344.49	102.76	254.34	11.28	20.69	3.96	5.02	.
48	5.10	1.97	0.16	1.39	8.79	921.63	234.67	172.46	80.71	259.01	0.97	2.26	0.26
49	4.44	2.28	0.08	0.95	11.60	796.97	140.30	164.83	32.65	91.07	5.23	4.20	0.75
50	4.64	1.36	0.06	0.69	11.13	468.67	120.01	224.01	19.71	75.07	8.18	3.86	0.80

51	4.41	0.89	0.05	0.64	12.62	388.38	88.91	203.81	19.00	35.42	3.33	9.64	0.45
52	4.36	0.63	0.04	0.58	13.38	424.35	90.78	203.45	17.37	45.76	3.48	5.63	0.67
53	5.03	0.28	0.06	0.79	12.37	447.25	321.70	189.05	49.83	73.99	6.54	10.72	0.41

Table 8. Soil chemical properties at depths B. 20-40 cm in control and twin plots.

Plot	pHEB	ExAcdEB	% NEB	% CEB	CNEB]	AlEB	CaEB	FeEB	KEB	MgEB	MnEB	PEB	ZnEB
1	4.73	0.80	0.01	0.20	14.65	291.52	51.68	71.14	13.37	29.72	5.24	19.93	0.42
2	4.56	0.32	0.02	0.32	16.56	296.76	25.65	114.71	17.40	7.73	1.29	3.53	.
3	4.33	0.85	0.02	0.27	17.06	353.74	42.57	66.97	18.60	5.71	0.20	4.98	.
4	4.50	0.62	0.02	0.31	15.28	302.49	56.36	33.09	21.92	19.41	3.42	4.47	.
5	4.19	0.19	0.06	0.70	12.41	829.18	31.51	80.20	6.93	1.67	.	10.08	.
6	4.37	1.81	0.01	0.19	13.37	256.74	55.52	122.27	2.88	5.27	1.42	3.51	.
7	3.99	0.76	0.02	0.42	18.14	336.68	39.68	39.68	3.88	2.50	14.25	3.77	0.08
8	4.93	1.02	0.03	0.43	14.78	307.79	161.85	115.99	18.21	18.17	41.12	39.80	0.65
9	4.16	0.26	0.03	0.39	15.11	417.58	42.63	54.79	9.82	15.36	0.56	3.30	.
10	4.56	-0.01	0.02	0.23	13.26	310.28	49.35	53.58	14.62	10.17	0.96	7.87	.
11	4.51	0.35	0.02	0.31	14.47	238.45	62.26	97.21	14.98	7.58	8.02	7.57	0.33
12	4.24	0.03	0.04	0.67	18.61	475.91	128.73	51.58	36.74	31.09	124.28	3.01	.
13	4.23	0.58	0.02	0.29	14.83	457.60	32.72	113.20	14.80	7.21	2.30	6.50	.
14	4.27	2.79	0.06	0.59	9.35	989.34	151.68	91.97	17.88	43.22	1.58	4.12	.
15	4.17	1.19	0.04	0.39	8.99	567.44	24.55	85.19	27.02	10.76	1.22	2.85	0.22
16	4.29	1.77	0.04	0.55	14.18	503.65	82.88	111.85	11.72	14.70	1.34	4.84	7.25
17	4.69	2.03	0.10	0.71	7.00	1036.08	21.85	73.63	26.59	14.65	1.29	2.67	0.37
18	4.46	1.53	0.06	0.37	6.22	883.91	8.10	72.46	27.73	12.26	.	3.60	0.50
19	4.06	1.32	0.05	0.39	7.68	754.43	19.29	76.44	18.28	6.45	2.09	3.70	0.35
20	4.22	1.71	0.04	0.29	7.70	821.53	26.39	100.10	26.02	6.27	1.33	5.70	0.42
21	4.18	1.43	0.03	0.37	11.80	430.71	39.28	102.95	16.65	7.10	2.39	4.25	0.39
22	4.42	1.51	0.04	0.44	10.37	738.07	33.42	23.85	41.37	11.72	0.51	2.67	3.63
23	6.13	0.04	0.04	0.47	10.89	515.72	1518.94	69.58	66.89	456.23	24.76	1.14	0.53
24	6.49	0.09	0.03	0.35	12.36	409.47	1216.66	93.21	53.85	357.97	19.69	1.94	1.36
25	6.33	0.01	0.04	0.49	14.00	480.91	1198.73	128.49	60.28	374.61	21.19	1.26	0.48

Table 8 Continued

26	7.04	0.01	0.05	0.52	10.98	554.00	679.36	83.86	38.88	337.11	22.36	1.32	.
27	6.44	0.02	0.03	0.41	12.09	349.49	1295.74	76.11	78.58	401.88	67.15	0.97	1.12
28	5.94	0.13	0.05	0.63	12.65	706.87	1199.48	108.14	51.83	218.55	23.43	1.07	0.50
29	6.74	0.04	0.03	0.36	13.02	282.44	1155.82	109.90	55.75	314.87	30.80	1.08	1.37
30	6.39	0.01	0.02	0.29	12.53	264.42	769.48	85.14	35.67	217.23	15.32	0.93	0.51
31	4.32	1.68	0.05	0.51	9.97	838.35	212.85	100.72	30.85	101.21	3.15	3.98	7.99
32	4.24	2.74	0.07	0.82	11.28	1066.44	86.45	112.45	33.31	24.09	1.45	3.72	0.58
33	5.82	0.03	0.03	0.28	8.33	247.67	328.29	39.36	17.74	41.56	84.92	1.86	0.56
34	4.46	1.36	0.04	0.33	8.85	498.74	70.33	152.23	20.30	37.34	2.17	3.51	0.46
35	4.56	1.34	0.04	0.41	9.89	443.53	141.92	42.79	57.31	53.77	1.61	3.23	0.25
36	4.44	3.72	0.06	0.61	9.85	799.44	104.89	154.63	30.18	86.55	2.93	3.84	0.38
37	5.60	0.03	0.05	0.47	10.28	317.28	377.33	120.35	143.19	117.79	7.95	26.81	1.49
38	4.42	1.15	0.07	0.67	9.81	612.56	187.86	93.82	37.84	143.34	21.18	5.03	0.46
39	4.17	1.34	0.05	0.39	8.26	570.76	119.77	132.45	41.61	34.15	7.28	6.02	0.28
40	4.38	7.55	0.21	2.42	11.29	1273.13	876.61	328.40	56.82	139.71	12.09	1.68	3.53
41	4.28	1.23	0.03	0.28	10.87	517.39	52.63	121.94	10.66	5.75	0.68	2.51	0.32
42	4.62	1.05	0.03	0.29	9.15	502.41	116.29	55.72	14.79	26.26	58.40	2.16	.
43	4.40	3.23	0.06	0.56	9.69	940.83	164.94	82.24	23.86	50.74	2.21	3.00	0.48
44	4.46	1.88	0.03	0.41	12.01	323.92	36.59	94.56	7.55	4.76	0.36	1.99	0.30
45	4.18	2.00	0.04	0.45	11.82	685.13	52.97	179.39	22.02	33.21	0.61	6.82	0.53
46	4.28	2.46	0.05	0.65	11.99	797.76	138.38	99.15	30.25	39.46	2.13	4.73	.
47	4.29	0.78	0.03	0.41	12.96	466.27	89.19	185.75	9.46	17.37	0.95	3.61	.
48	5.56	3.57	0.10	0.91	8.98	1002.76	156.51	112.17	66.82	254.91	0.64	1.60	.
49	4.34	5.18	0.08	0.77	9.49	1038.08	77.08	68.58	24.51	39.88	1.14	2.12	0.85
50	4.50	2.48	0.05	0.54	10.27	885.54	85.05	174.42	20.18	51.00	2.13	3.57	0.40
51	4.19	1.81	0.03	0.43	13.48	674.52	29.79	134.21	10.94	9.72	0.32	4.15	0.25
52	4.22	0.97	0.04	0.51	12.89	507.41	43.17	68.74	13.16	18.34	0.70	3.54	0.28

Table 8 Continued

53	4.14	2.90	0.04	0.60	13.29	739.92	82.06	167.22	39.92	28.68	0.79	4.94	.

Table 9. Extra fertilization, extra weed control and application labor cost in Venezuela (2010).

Fertilizer	Application (US$ ha^{-1})	Fertilizer (US$ ha^{-1})	Total (US$ ha^{-1})
Year 0			**373.3**
Dolomite	25.7	175.8	
NPK 10-20-10	9.9	80.2	
NPK 21-05-23	9.9	51.2	
Borax	11.9	8.7	
Year 1			**61.0**
NPK 21-5-23	9.9	51.2	

Weed Control	Application (US$ ha^{-1})	Herbicide (US$ ha^{-1})	
Year 0			**93.7**
Glyphosate	51.4	42.3	
Year 1			**187.4**
Glyphosate 1st application	51.4	42.3	
Glyphosate 1st application	51.4	42.3	
Year 2			**93.7**
Roundup	51.4	42.3	

Table 10. Traditional management cost (control plot cost) in DEFORSA (2010)

Year	Costs (US$ ha^{-1})	
0	879	Site preparation, seedlings, plantation, fertilization, overhead
1	360	Fertilization, weed control,overhead
2	227	Weed control, overhead
3	93	Weed control, overhead
4	72	Weed control, overhead
5	72	Weed control, overhead
6	72	Weed control, overhead
7	72	Weed control, overhead

Table 11. Correlation between stand and soils variables with treatment response

Variable	Correlation	p
Age09	0.1278	0.3619
SI09	0.0965	0.5004
SI10	0.1062	0.4823
SI11a	0.0402	0.7774
StemBiomass control plot 09	0.1749	0.2104
WNPP control plot 11b09	**-0.4748**	**0.0003**
LAI09C	-0.0134	0.924
LAI10C	-0.0134	0.924
LAI11aC	**-0.2488**	**0.0724**
LAI11bC	-0.2258	0.104
NFC	0.0433	0.7584
PFC	0.052	0.7118
KFC	-0.0672	0.6328
CaFC	-0.0037	0.9791
MgFC	-0.051	0.717
ZnFC	0.0127	0.9281
BFC	-0.0628	0.6553
aEA	0.0985	0.4829
ArEA	0.0806	0.5661
LEA	-0.1594	0.2544
pHEA	**-0.3947**	**0.0034**
ExAcid	0.2723	0.0485
NEA	-0.0887	0.5278
CEA	-0.0593	0.6732
CNEA	0.15	0.13
AlEA	0.0606	0.6667
CaEA	**-0.2788**	**0.0432**
FeEA	-0.0061	0.9654
KEA	-0.1601	0.2521
MgEA	-0.1877	0.1784
PEA	0.0335	0.8118
BasesEA	**-0.2725**	**0.0484**

Table 12. Number, proportion of plots, pH, sum of bases (ppm), C/N ratio by textural classes in the first 20 cm.

Textural Class	Number of Sites	pH	Sum of Bases
Sandy	1	5.4	221.0
Loamy Sand	13	4.8	191.0
Sandy Loam	27	4.8	382.0
Loam	7	4.5	286.0
Silt Loam	3	5.1	787.0
Clay Loam	2	4.3	656.0

Table 13. Incremental cost, income and net income in US\$ ha^{-1} by year

Venezuela

Year since treatment	Cost				Income	Net Income
	Fertilizer	Herbicide	Labor	Total		
0	316	42	109	467		-467
1	51	85	113	248		-248
2	0	42	51	94	1376	1282

Table 14. Analysis of variance, R^2, C.V., and independent variable for the model fitted for stands younger than 4 years.

Source	DF	Sum of Squares	Mean Square	F-Value	Pr>F
Model	3	81.0785	27.0262	2.47	0.0968
Error	11	120.557	10.9597		
Corrected Total	14	201.6356			

R-Square	C.V	Root MSE	Independent Variable Mean
0.4021	116.1842	3.3105	2.8494

Table 15. Degrees of freedom, sum of squares, mean square, F value, and p-value for the model fitted for stands younger than 4 years

Source	DF	Type III SS	Mean Square	F Value	Pr>F
WNPP control plot	1	42.9968	42.9968	3.92	0.0732
WNPP control plot * Position	2	10.4694	5.2347	0.48	0.6325

Table 16. Parameter estimates, standard error, t value and p-value for the model fitted for stands younger than 4 years

Parameter	Estimate	Standard Error	t Value	Pr > t
Intercept	9.956	2.9136	3.42	0.0058
WNPP control plot	-0.307	0.2063	-1.49	0.1649
WNPP control plot * Position L	-0.0763	0.2239	-0.34	0.7396
WNPP control plot * Position M	0.0972	0.1687	0.58	0.5763
WNPP control plot * Position U	0	.	.	.

Table 17. Analysis of variance, R^2, C.V., and independent variable for the model fitted for stands older than 4 years.

Source	DF	Sum of Squares	Mean Square	F-Value	Pr>F
Model	3	676.4068	225.4689	6.57	0.0013
Error	34	1166.1598	34.2988		
Corrected Total	37	1842.5666			

R-Square	C.V	Root MSE	Independent Variable Mean
0.3671	100.4001	5.8565	5.8332

Table 18. Degrees of freedom, sum of squares, mean square, F value, and p-value for the model fitted for stands older than 4 years

Source	DF	Type III SS	Mean Square	F Value	Pr>F
WNPP control plot	1	526.1204	526.1204	15.34	0.0004
WNPP control plot * Position	2	319.4909	159.7455	4.66	0.0163

Table 19. Parameter estimates, standard error, t value and p-value for the model fitted for stands younger than 4 years

Parameter	Estimate	Standard Error	t Value	Pr > t
Intercept	13.7679	2.4628	5.59	<0.0001
WNPP control plot	-0.7054	0.1604	-4.4	0.0001
WNPP control plot * Position L	0.4167	0.1511	2.76	0.0093
WNPP control plot * Position M	0.3799	0.1301	2.92	0.0062
WNPP control plot * Position U	0	.	.	.

Table 20. Analysis of variance, R^2, C.V., and independent variable for the complete model

Source	DF	Sum of Squares	Mean Square	F-Value	Pr>F
Model	6	982.09	163.68	6.5	<0.0001
Error	46	1157.86	**25.17**		
Corrected Total	52	2139.95			

R-Square	C.V	Root MSE	Independent Variable Mean
0.4589	100.57	5.0171	4.9887

Table 21. Degrees of freedom, sum of squares, mean square, F value, and p-value for the complete model fitted

Source	DF	Type III SS	Mean Square	F Value	Pr>F
pH	1	123.65	123.65	4.91	0.0316
WNPP control plot	1	347.90	347.90	13.82	<0.005
Position	2	104.47	52.23	2.07	0.1372
WNPP control plot * Position	2	213.18	106.59	4.23	0.0205

Table 22. Parameter estimates, standard error, t value and p-value for the complete model fitted

Parameter	Estimate	Standard Error	t Value	Pr > t
Intercept	40.5815	10.0067	4.06	0.002
pH	-3.4269	1.5461	-2.22	0.0316
WNPP control plot	-1.1011	0.3043	-3.62	0.0007
Position L	-15.9270	8.2895	-1.92	0.0609
Position M	-13.2387	6.9068	-1.92	0.0615
Position U	0	.	.	.
WNPP control plot* Position L	0.9922	0.3741	2.65	0.0109
WNPP control plot* Position M	0.8845	0.3118	2.84	0.0067
WNPP control plot* Position U	0	.	.	.

Table 23. Breakeven point (Mg ha^{-1} 2 yr^{-1}) for different stumpage prices and discount rates

	Discount rate			
Stumpage (\$ m^{-3})	4%	8%	12%	16%
10	42.0	44.4	46.9	49.5
40	10.5	11.1	11.7	12.4
70	6.0	6.4	6.7	7.1
100	4.2	4.5	4.7	4.9
130	3.2	**3.4**	3.6	3.8

Table 24. Proportion of stands with a treatment response larger than the breakeven point for different stumpage prices and discount rates

	Discount rate			
Stumpage ($ m^{-3})	4%	8%	**12%**	16%
10	0.00	0.00	**0.00**	0.00
40	0.19	0.16	**0.14**	0.12
70	0.45	0.42	**0.40**	0.38
100	0.56	0.55	**0.53**	0.52
130	0.63	**0.62**	**0.60**	0.59

Table 25. Median treatment response for profitable stands (with a treatment response larger than the breakeven point) for different stumpage prices and discount rates

	Discount rate			
Stumpage ($ m^{-3})	4%	8%	12%	16%
10	85.3	90.1	95.1	100.1
40	26.2	27.2	28.2	29.3
70	19.6	20.1	20.5	21.0
100	17.4	17.6	17.9	18.2
130	16.3	**16.5**	16.7	16.9

Table 26. NPV, for different stumpage prices and discount rates, in the case where the treatment is applied in the whole area.

	Discount rate			
Stumpage ($ m^{-3})	4%	8%	12%	16%
10	-777.4	-777.4	-777.4	-777.4
40	-562.4	-598.6	-628.1	-656.2
70	-138.7	-199.6	-252.1	-299.7
100	218.2	140.9	71.3	8.3
130	548.4	**450.9**	363.4	284.4

Table 27. NPV, for different stumpage prices and discount rates, in the case where the treatment is applied to the stands identified as profitable by using the diagnostic model with the current error model (with misclassification error).

	Discount rate			
Stumpage ($ m^{-3})	4%	8%	12%	16%
10	-22.0	-20.3	-18.7	-17.2
40	-4.8	-5.9	-7.0	-7.8
70	146.6	129.6	113.3	98.5
100	357.2	319.7	286.2	256.0
130	585.7	**651.3**	478.9	433.6

Table 28. NPV, for different stumpage prices and discount rates, in the case where the treatment is applied to the stands identified as profitable by using the diagnostic model, but with a smaller error model (without misclassification error)

	Discount rate			
Stumpage ($ m^{-3})	4%	8%	12%	16%
10	0.0	0.0	0.0	0.0
40	57.2	51.8	46.6	42.6
70	273.4	248.9	225.2	204.0
100	540.7	491.6	447.7	408.1
130	821.4	**750.0**	686.1	628.6