Growth sensitivity of *Cariniana ianeirensis* to local and global climate variation and implications for its responses to climate change

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Abstract

It is known that climate parameters are among the most important drivers of tree growth. In this research, the influence of precipitation, temperature and the El Niño Southern Oscillation (ENSO) on the growth rate of Cariniana ianeirensis *was assessed in a transitional forest between the dry Chiquitania forest and the moist Amazonian forest in Bolivia. We collected increment cores and tree disks of 45 trees and analyzed annual growth ring patterns. A chronology of annual tree growth was constructed for the last 30 years. Using multiple regression analysis we evaluated the influence of temperature, precipitation and ENSO on growth of* C. ianeirensis*. These parameters explained 44.6% of the annual variation in tree growth. Growth was positively affected by precipitation and negatively by temperature and ENSO. Also, a positive relation was found between precipitation and temperature of the location of this research. Based on the IPCC 2007 report, two climate change scenarios were used to calculate the effect of climate change on variation from mean diameter growth of* C. ianeirensis*. Our results indicate that the expected increase of temperature and precipitation will lead to an increase in growth of* C. ianeirensis*. The results obtained in this study contributes to a general view of the effect of climate change on tropical forests. Also, if this effect is consistent in other South American tree species future climate changes might result in an increase in carbon sequestration in tropical forests. This way they might partly compensate for the expected increase in atmospheric CO2 levels, which is an additional argument for tropical forest conservation.*

Keywords: Dendrochronology, tropical forest, adult tree-rings, multiple regression analysis, precipitation, temperature, ENSO, climate change, growth predictions.

Introduction

Many applications are known for tree rings throughout the world, mostly in areas with strong seasonal changes in climate. Examples are dating archeological sites (Čufar – 2007, Wang *et al.* – 2008, Haneka *et al*. – 2009, Tegel *et al.* – 2010, von Arbin and Daly – 2012) or famous objects of art (Klein – 1998, Čufar – 2007, Fraiture – 2009, Haneka *et al.* – 2009). In these examples, year-to-year variation in tree growth is linked to variation in climate parameters in a specific era to indicate their age. However, tree rings can also be used to study the effect of e.g. climatological parameters on tree growth. This method is already for a long time in practice in temperate forests (for example Jones – 1959, Mayer – 1980), which resulted in extensive knowledge about tree growth in this regions.

Due to the almost absence of seasonal changes in climate in the tropics, the assumption that tropical trees do not form clear and annual growth rings dominated the field for a long time (Lieberman *et al.* – 1985, Whitmore – 1998, Gerrish & Mueller-Dombois – 1999). In the last decade however, numerous studies show that many tropical tree species form clear annual growth rings (e.g. Fiechtler *et al.* – 2003, Schöngart *et al.* – 2004, Rozendaal & Zuidema – 2011, Soliz-Gamboa *et al.* – 2011). This development is important, because it makes investigations of the effects of climate factors on tree growth worthwhile. This is crucial because tropical forests store approximately 25% of the terrestrial carbon in their biomass (Bonan - 2008). Therefore, even small changes in carbon sequestration, due to for example changing concentrations of CO_2 or changing precipitation patterns, could affect the global carbon cycle (Bonan, 2008). Although there is an ongoing debate on the influence of climate change (e.g. changing patterns of temperature and precipitation) on tropical forests (Reeds 2012), the IPCC predicts a higher temperature but less precipitation for South America (Meehl *et al.* – 2007, Christensen *et al.* – 2007). Therefore it is important to obtain data about the effect of climate parameters on tree growth.

For the location of this research, the United Nation Environmental Program (2005) observed a negative effect of sea surface temperature (NINO3.4, proxy for ENSO) on tree growth. ENSO consists of a El Niño phase and a La Niña phase, which have opposite effects. The El Niño phase of ENSO is thought to increase drought events (McPhaden *et al.* – 2010, Mo & Berbery – 2011) and droughts are often associated with an above-average temperature in the La Niña phase (Dai – 2010). ENSO is also though to affect precipitation negatively at the location of this research (Villar *et al*. – 2009). The effect of ENSO differs between continents and even within continents (Ubilava – 2012).

Global climate parameters, e.g. the El Niño Southern Oscillation (ENSO), can influence the growth of tropical trees, often through local climate parameters, e.g. temperature and precipitation (Collins – 2005, Nordemann *et al.* – 2005). It is known that various tree species show a positive relation between tree growth and precipitation (Brienen & Zuidema – 2005, Higuchi *et al.* – 2011). Temperature, in general, has been shown to negatively influence tropical tree growth in different tree species (Clark *et al.* – 2003, Clark *et al.* – 2010).

This research focuses on variation of growth of the tropical tree species *Cariniana ianeirensis* in the past, to predict potential growth scenarios related to future climate change. Questions in this research project were:

1. To what extent is variation in growth of *C. ianeirensis* influenced by local and global climatological factors?
2. To what extent will changes in these climatological factors influence the variation of growth of *C. ianeirensis* in the future?

Climate parameters were used as drivers in a tree-specific model to explain the variability of growth of *C. ianeirensis* due to climate parameters. This model relies on data generated from tree rings and therefore focuses on the past growth rates of trees. With the use of growth rates and extrapolation, predictions of future tree growth were calculated, taking the effects of changing climate into account.

Methods

Site Description

Fieldwork was performed in the logging concession of Agroindustria Forestal 'La Chonta', which is located 30 km east of Ascención de Guarayos, Department of Santa Cruz, Bolivia (15°47'S, 62°55'W). The forest is a transition between the dry Chiquitania forest and the moist Amazonian forest (Dauber *et al.* – 2000). The area receives an average annual precipitation of 1580 mm. May until September receive <100 mm and in July, evapotranspiration potentially exceeds rainfall (Peña-Claros *et al.* – 2008). In 1995 and 2004, uncontrolled agricultural fires affected parts of the concession (Blate – 2005).

Tree Species

The tree species studied was *Cariniana ianeirensis*, a semi-deciduous, partly shade tolerant tree with commercial value (Peña-Claros *et al.* – 2008). The species can reach a height of approximately 35 meter and a Diameter at Breast Height (DBH) of approximately 130 cm. *C. ianeirensis* sheds its leaves during the dry season, in which it also flowers. Fruits occur in October and November (Mostacedo *et al.* – 2001). This species was chosen for its relatively well distinguishable rings.

Data collection and Data analysis

We sampled 45 trees from which DBH ranged from 15.5 to 125 cm. The trees were collected in an area of 200 ha to avoid site-specific effects, e.g. canopy gaps or the presence of streams. Of the collected trees, 28 were sampled with an increment corer. Of these trees, 2-3 cores were taken, depending on the DBH of the tree. Two cores were taken from trees < 40 cm DBH and three cores were taken from trees > 40 cm DBH. In addition, we collected disks of 17 commercially felled large trees in the same area. The disks and increment cores were mechanically sanded up to grid 1000, after which the tree rings were dated and the width of the tree rings was measured with the programs TSAPwin 6 (tree disks) and WinDendro Reg V2009 (increment cores), both measuring up to 1×10^{-5} cm. For every tre, three radii were measured. The measured radii were on the shortest and the longest side of the tree and one side of average length. For further data analysis, measurements from 1980-2010 were used, due to the availability of reliable climate data. On the tree disks, every 10th ring was crossdated to avoid dating errors. With the increment cores, crossdating was performed in WinDendro.

We measured ring width on 137 radii and corrected for ontogenetic growth patterns by correlating (Pearson) the measured ring width data with time. This determined the detrending method of the 137 radii: Radii with a significant correlation with time were detrended using lineair regression, radii with a non-significant correlation with time were detrended using the average of the measured ring widths. In subsequent analyses, we used deviations of the original growth data, also called 'Ring Index'.

All 137 radii after detrending were correlated with each other. Radii which significantly correlated with at least 10 other radii were put together in one final chronology. Approximately 19% of the measured radii and 38% of the individual trees were used to construct the chronology. Interseries correlation was calculated based on the average of all Pearson's correlation coefficients (r) of the selected deviations with each other.

Climate data

Climate data of minimum, maximum and average temperature (data generated from KNMI Climate Explorer), precipitation (data generated from KNMI Climate Explorer) and ENSO (through Sea Surface Temperature (SST) measured at NINO3.4 (an area bounded from 5°N to 5°S, and from 170°W to 120°W) were used. For temperature, yearly average, and average of September-October-November (SON), the peak of the rainy season December-January-February (DJF), March-April-May (MAM) and the peak of the dry season June-July-August (JJA) were tested. For precipitation, the yearly sum, and the sum of SON, DJF, MAM and JJA were tested, also to include the peaks of rainy and dry season. In order to comply with the season in which El Niño events often occur, ENSO was tested for the average of October-April and June-July-August. Because of the growth season of the trees (September- August), climate data were restructured to fit this dendrological year, so that these parameters could be compared with tree growth data of the same year. Also, we chose to work with Ring Indexes and climate parameters from 1980-2010, due to availability of reliable climate data.

Predictions of climate parameters for 2080-2099 were obtained from the IPCC 2007 report (Meehl *et al.* – 2007, Christensen *et al.* – 2007). It is predicted that in the research area of this study yearly precipitation will decrease with 0.1 mm day^{-1} and yearly average temperature will increase by 2.5 °C-4 °C. The predictions for ENSO indicate that the global climate will shift to a more El Niño-like state. With these predictions, three scenarios were selected for climate change. Scenario 1 representing no change, Scenario 2 representing -0.1 mm day^{-1} precipitation and 2.5 °C temperature increase and Scenario 3 representing -0.1 mm day^{-1} precipitation and 4 °C temperature increase (Table 1).

Table 1 Three climate scenarios for future climate change based on the IPCC 2007 report (Meehl *et al.* – 2007, Christensen *et al.* – 2007).

Scenario	**Temperature change**	**Precipitation change**
Scenario 1	0	0
Scenario 2	+ 2.5 °C	-0.1 mm d^{-1}
Scenario 3	+ 4 °C	-0.1 mm d^{-1}

Statistical analysis

The data obtained were checked for normal distribution. A multiple regression analysis was then performed to clarify the year-to-year variation in diameter growth and to obtain the necessary standardized and unstandardized coefficients. The results of this model were used to extrapolate the effect of predicted future climate conditions (Table 1) on the diameter growth of *C. ianeirensis*.

Extrapolations to future growth trends were calculated using the following equation:

Y = a1*X1 + a2*X2 + a3*X3 + *b*

In this equation, [Y] is defined as tree growth, [a] are the unstandardized coefficients obtained from the multiple regression analysis, [X1] represents precipitation (mm day^{-1}) , [X2] represents temperature (°C), [X3] represents ENSO (NINO3.4 anomaly, °C) and [*b]* is a constant. When specified for *C. ianeirensis*, the formula is transformed into (Table 2):

Y = 0.13*X1 – 0.152*X2 – 0.658*X3 + 0.008

This extrapolation results in preliminary indications for deviations of mean diameter growth of *C. ianeirensis* in 2080-2099.

Results

Rings in Cariniana ianeirensis

C. ianeirensis is a relatively fast growing species, with rings widths up to 15 mm. Every ring boundary can be distinguished through the marginal parenchyma band often in combination with a dark coloring (Figure 1). In the tree disks, wedging rings were observed regularly. False rings (Priya & Bhat – 1998) were observed less frequent, but were present as well.

Figure 1 Annual tree rings of *C. ianeirensis*. P = Pith, B = Bark. Triangles indicate rings boundary.

The annual nature of the growth rings was proven by the significant correlation between the chronology and the ENSO anomaly values (Figure 2; Pearson's r: -0.373, p=0.03).

After selecting the best correlating radii, a Ring Index graph was constructed (Figure 2). This chronology visualizes the deviation of the annual growth per year in millimeter. The intercorrelation of the included radii is 0.14.

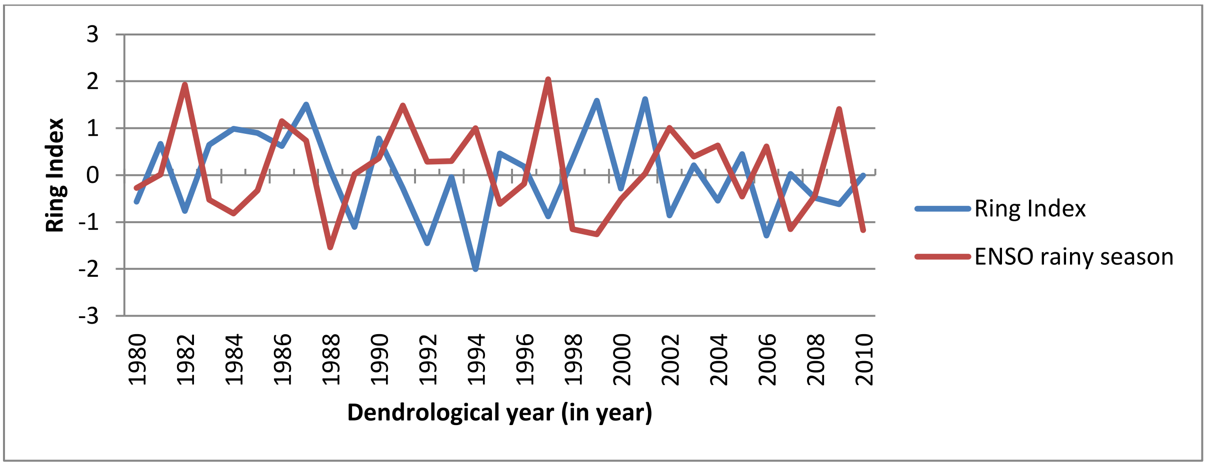

Figure 2 Deviation from mean annual tree growth of *C.ianeirensis* in mm year^{-1} and ENSO anomaly (NINO3.4 anomaly, °C) (Pearson's r: -0.373, p=0.03).

Multiple regression analysis

In the multiple regression analysis the Ring Index and the multiple variables of the climate parameters (temperature, precipitation and ENSO) were used. The multiple regression analysis showed three parameters that significantly influence tropical tree growth (Figure 3, Figure 4 and Table 2). Total precipitation per year, average temperature in DJF and ENSO from October until April explain 44.6% of the variation in the ring index (Table 2). The results were checked for collinearity between the parameters, for which no indications were found (Table 2). For ENSO, average Sea Surface Temperature (NINO 3.4) from October until April showed a negative significant relation with Ring Index (Table 2, Figure 4a). For precipitation, the total amount of precipitation per year showed a positive significant relation with the ring index (Table 2, figure 4b). For temperature, the mean of the average temperature in December, January and February showed a negative significant relation with the ring index (Table 2, Figure 4c). Temperature (mean of average temperature in DJF) with precipitation (sum of precipitation per year) showed a positive significant relation (Pearson's r: 0.991, p = 0.000, Figure 4d). The relations between ENSO and precipitation and ENSO and temperature were not significant in the multiple regression analysis. Further analysis of climate parameters resulted in significant relations between ENSO from October-April and average maximum, mean and minimum temperature from October-April (Table 3).

Table 2 Summary of the outcome of the Multiple Regression Analysis of the ring index with temperature, precipitation and ENSO. Variance Inflation Factor (VIF) should be < 10, tolerance levels > 0.1. (O'Brien – 2007). The constant resulting from this analysis was 0.008.

	Standardized Coefficient	Unstandardised Coefficient	p-value	Collinearity statistics	
				Tolerance	VIF
Average temperature DJF	-1.348	-0.152	0.002	0.142	7.028
Total precipitation per year	1.095	0.130	0.008	0.152	6.587
ENSO October-April	-0.658	-0.658	0.000	0.825	1.212

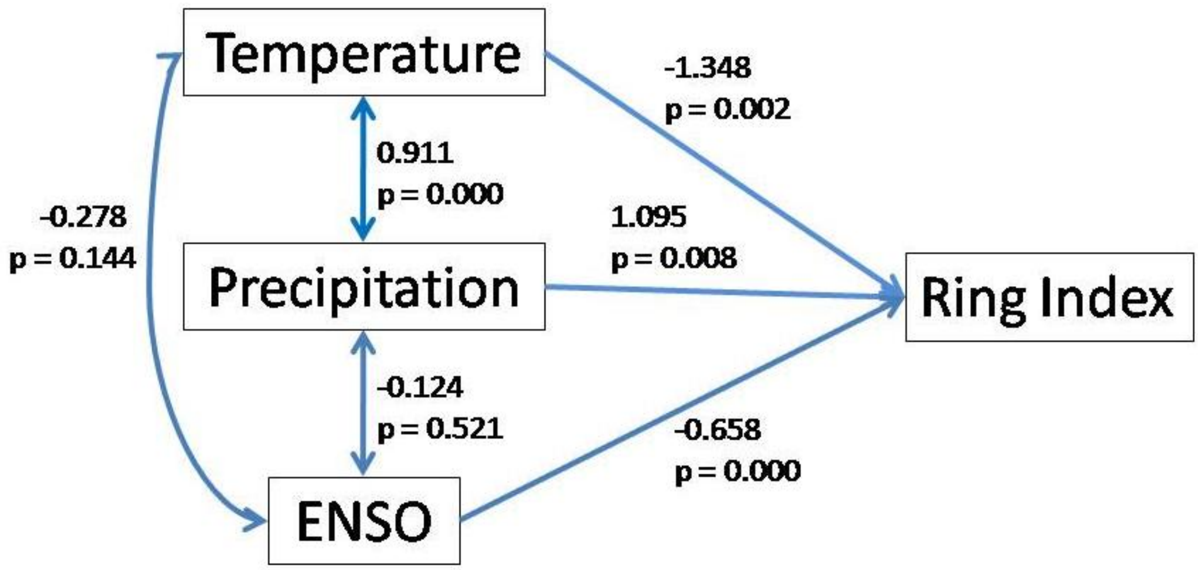

Figure 3 Visualization of the Multiple Regression Analysis of the three climate parameters (precipitation, temperature and ENSO). Data shown are the multiple regression standardized coefficients (direct paths from precipitation, temperature and ENSO to Ring Index) and Pearson's r's (Paths between precipitation, temperature and ENSO) with their p-values.

Table 3 Pearson's r's of ENSO with different temperature & precipitation parameters.

	Average annual maximum temperature	Average maximum temperature October-April	Average average temperature October-April	Average minimum temperature October-April
ENSO October-April	NS	r = 0.370 p = 0.048	r = 0.494 p = 0.006	r = 0.508 p = 0.005

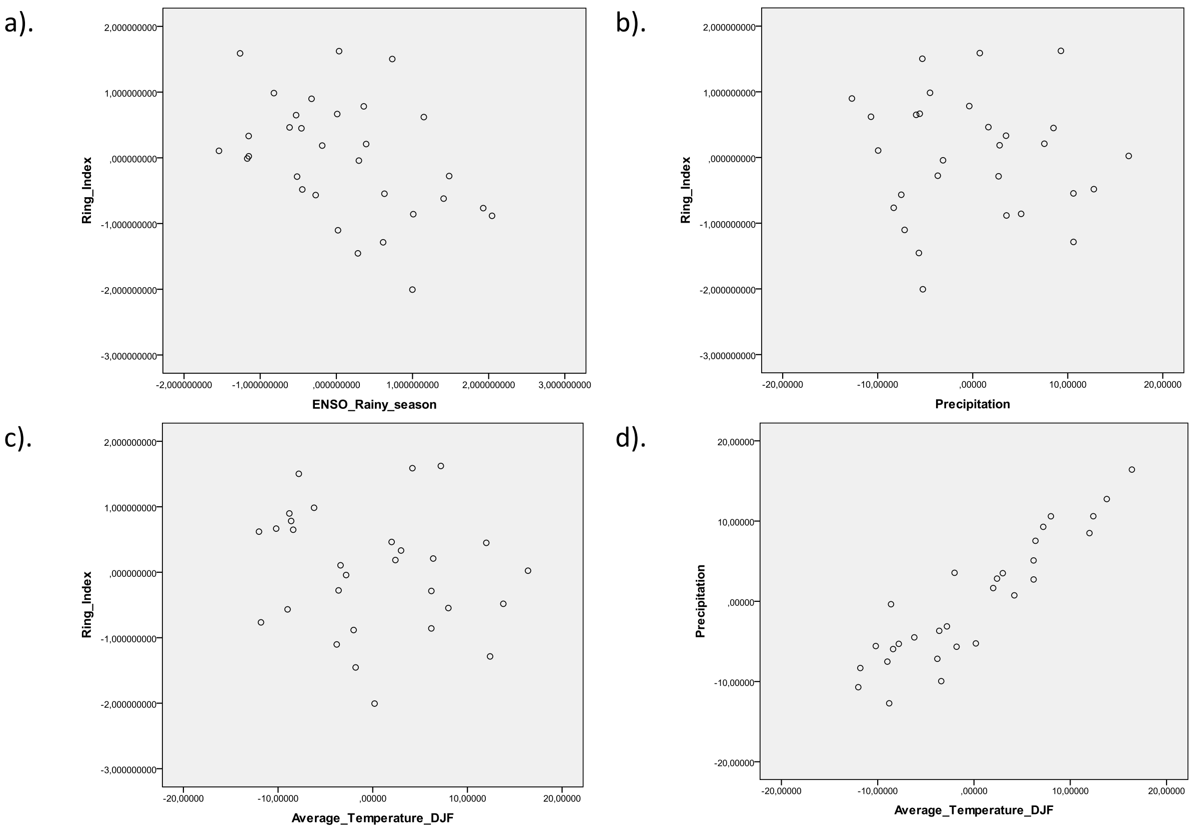

Figure 4 Scatterplots of a). the Ring Index with ENSO (Standardized coefficient: -0.659, p = 0000), b). Ring Index with precipitation (Standardized coefficient: 1.095, p = 0.008), c). Ring Index with temperature (Standardized coefficient: -1.348, p = 0.002) and d). Precipitation with temperature (Pearson's r: 0.991, p = 0.000).

Extrapolations to 2080-2099

Deviation from average growth of *C. ianeirensis* in 2080-2099 under scenario 1 (Figure 5, blue), in average ENSO years (with average sea surface temperatures) is approximately 0 due to the constant *b* in the formula. In an extreme La Niña year, the model indicates deviations from mean growth to be more positive. In an extreme El Niño year, it is indicated that growth rates will decrease. For scenario 2 (Figure 5, red), annual growth of *C. ianeirensis* will be more positive under average ENSO years than under scenario 1. In extreme La Niña years, the model predicts that annual growth of *C. ianeirensis* will also be more positive than under average ENSO circumstances as under scenario 1. During extreme El Niño years on the other hand, deviation of mean growth of *C. ianeirensis* is predicted to be more positive as well, but less than in average ENSO years (Figure 5).

The predictions for the third climate scenario (Figure 5, green) follow a similar pattern as the second climate scenario. Under scenario 2 and 3, a positive change in deviation from mean growth is predicted. Figure 5 visualizes the results of the extrapolation for future growth perspectives for *C. ianeirensis*. In comparison with the Ring Index (Figure 2), where deviation from mean growth ranges from -2 to 2, the indications for future growth of *C. ianeirensis* are 4 times higher (+8, Figure 5) than the variation from mean growth observed in the past.

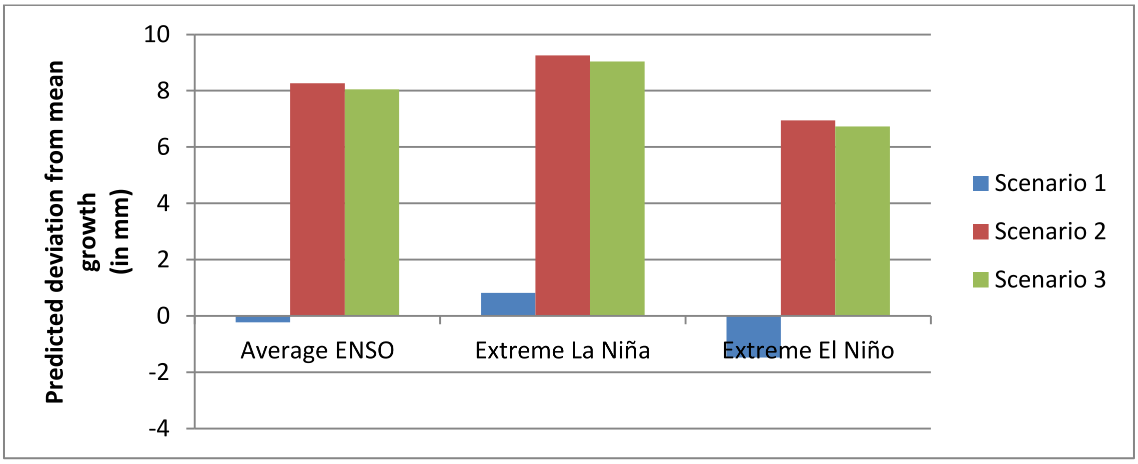

Figure 5 Future perspectives of the deviation of mean growth of *C. ianeirensis* in 2080-2099 under different climate scenarios (1,2 and 3) and ENSO conditions (average ENSO years, extreme La Niña and extreme El Niño years).

Discussion

In this study the influence of precipitation, temperature and ENSO on diameter growth of *Cariniana ianeirensis* was studied. Subsequently, future growth under different climate change scenarios was predicted. We expected that tree growth of *C. ianeirensis* was positively influenced by precipitation (Brienen & Zuidema – 2005, Higuchi *et al.* - 2011) but negatively influenced by temperature (Clark *et al.*- 2003, Clark *et al.* – 2010). The United Nation Environmental Program (2005) observed a negative effect of sea surface temperature (Nino 3.4) on tree growth. For the underlying relations between ENSO, temperature and precipitation we expected that ENSO has a positive effect on temperature and a negative effect on precipitation.

The model that resulted from calculations with the ring index of *C. ianeirensis* explained 44.6% of the variation in growth of this tree species, described by the three parameters tested. Multiple regression analysis resulted in significant relations between Ring Index and the total amount of precipitation per year (Table 2), Ring Index and the average temperature in December, January and February (Table 2) and Ring Index and ENSO from October until April (Table 2). Between the climate parameters studied, one significant relation was found, namely between precipitation and temperature (0.911, $p = 0.000$).

With this model, predictions were calculated for growth of *C. ianeirensis* in 2080-2099 under changing climate conditions. The results show that under the two scenarios which include increased temperature and decreased precipitation, tree growth will increase in comparison with the scenario in which climate remains constant. This result was observed in average ENSO years, but also in extreme El Niño and La Niña years. Both 2.5°C and 4°C temperature increase will have a similar impact on diameter growth in *C. ianeirensis*.

In contrast to more temperate regions, tropical tree species show less distinctive parenchym bands as temperate forest tree species, due to less clear climatological differences in the tropics. Therefore, measuring errors could occur more often which can result in lower radii intercorrelation than in temperate zones. For *C. ianeirensis*, more radii could be added to the Ring Index, to increase this intercorrelation.

The positive relation between tree growth and precipitation, and the negative relation between tree growth and temperature and ENSO found in this study are consistent with evidence found in literature. In South America, for dry-forest species in lowland northwest coast of Peru (Rodríguez *et al*. – 2005) and for *Centrolobium microchaete* in the dry Chiquitano forest in Bolivia (López & Villalba – 2010) similar results were found for the relation of precipitation with tree growth. But also on other continents, a similar relation was found, for example in a semi-deciduous Mayombe forest in the Democratic Republic of Congo (Couralet *et al.* – 2010) and Benin (Schöngart *et al.* – 2006). In contrast, a study on juvenile tree growth in northern Bolivia showed a negative relation between tree growth and precipitation in two species and a positive relation between tree growth and precipitation in another (Soliz-Gamboa *et al.* – 2011). These positive but also negative responses to precipitation could arise through juveniles growing under low light conditions and being evergreen in the understory, which can result in complex reactions of climate parameters on tree growth (Worbes, 1999). For temperature, similar results as in the current study are found for tree species in South America (Enquist & Leffner – 2001, López & Villalba – 2010).

However, in Lao P.D.R., a positive relation between temperature and annual tree growth was found, possibly caused by the effect of light availability on tree growth and not high temperature *per se* (Buckley *et al.* – 2007). The negative relation of ENSO with annual tree growth found in the current research is in accordance with the research of Schöngart *et al.* (2004) in which a negative relation was found of ENSO with tree growth. Because ENSO has different effects throughout the world, it can affect trees differently, depending on location of growth (Trouet *et al.* – 2001, Therrel *et al.* – 2006, Buckley *et al.* – 2007).

In the model, no significant relations were found between ENSO and local temperature and precipitation. Further analysis showed a positive significant relation between ENSO from October until April and the average minimum, average and maximum temperature in these months. Therefore we concluded that there is a relation between ENSO and the three temperature parameters, which are not included in the model. Further specification of these relations in the extrapolation contributes to the trustworthiness of the predictions. Also, for our study site, no relation was found between ENSO and local precipitation.

Predictions of the variation of mean annual growth of *C. ianeirensis* in the future indicate a growth increase in both scenarios. This is in contrast with findings of Brienen *et al*. (2010), in which a growth decrease was found. This study was conducted in a Mexican dry forest on a fast growing pioneer tree species. This is in contrast with the transitional forest where this research was conducted.

In the current study, a direct negative effect of ENSO on tree growth was found. This effect is not often found in literature. The effect of ENSO on tree growth is assumed to run through temperature and/or precipitation (Vincent *et al.* – 2009, Brienen *et al.* – 2010, Granzow-de la Cerda *et al.* – 2012) but also light availability in ENSO years could play a role. Further research to multiple tree species could include a more detailed investigation of direct and indirect effects of ENSO on tree growth in tropical forests and relations between light availability, ENSO and tree growth.

What will happen to the variability of ENSO is unclear, due to the contradictory results obtained out of numerous models (Meehl *et al.* – 2007, Christensen *et al.* – 2007). Sea surface temperature however, is predicted to increase (Meehl *et al.* – 2007, Christensen *et al.* – 2007). This is likely to affect ENSO. To make predictions more reliable, further research could investigate the variability of ENSO in 2080-2099.

The future indications of variation in growth of *C. ianeirensis* are based on growth in 1980-2010. Therefore, results of the extrapolation do not include adjustments of trees to climate change. Few studies present this type of predictions, although some focus on future tree growth in a more general physiological response (Corlett – 2011). The potential of plastic physiological responses of *C. ianeirensis* (e.g. stomatal density) and other trees to gradually changing climate is worth investigating. Caution is always needed when interpreting models and therefore also for this model (Knutti *et al.* - 2010).

This study adds another tree species to a list of species (Rozendaal & Zuidema – 2011) from which tree growth is studied through tree rings. The dendrological approach used in this study offers opportunities to study the effects of climate parameters on tree growth. The results of the model indicate future growth of *C. ianeirensis* to increase when climate parameters change. This knowledge contributes to a general view of the effect of climate change on tropical forests. Also, if this effect is consistent in other South American tree species, future climate changes could result in an increase in carbon sequestration in tropical forests. Potentially, these changes in growth could compensate for the expected increase in atmospheric CO_2 levels (Meehl *et al.* – 2007). This could imply new legislations for the conservation of tropical forests.

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