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Cumulative diameter growth and biological rotation age for seven tree species in the Cerrado biogeographical province of Bolivia

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ABSTRACT

In this contribution we document the radial growth rates of seven tropical species largely used for timbers in the Bolivian Cerrado, the region with the largest wood production in Bolivia. Inter-annual variations in tree-ring widths were measured on cross-sections from *Amburana cearensis, Cedrela fissilis*, *Platimiscium ulei*, *Centrolobium microchaete, Hymenaea courbaril*, *Anadenanthera colubrina* and *Ficus boliviana*. For a common period of 100 years, the mean annual diametric growth ranged from 0.55 to 1.05 cm $year^{-1}$ in *Platimiscium ulei* and *Ficus boliviana,* respectively. Mean cumulative variations in diameter growth of *Centrolobium microchaete* at six different sites ranged from 32.7 to 38.6 cm over a 100-year period. Variations in tree ages to reach the minimum cutting diameter (MCD) of 40 cm in the Chiquitano district ranged from 32 to >140 years, whereas in the Guarayos district (MCD = 50 cm) from 38 to 140 years. For *Centrolobium microchaete,* temporal variations for reaching the MCD ranged from 35 to 140 years and from 45 to 110 years for the Chiquitano and Guarayos districts, respectively. Since large differences in cumulative diametric growth were recorded between species and between sites for the same species, difference in growth rates between species and sites should be taken into consideration to ensure sustainable forest management in tropical dry forests. Biological rotation ages, estimated on the temporal evolution of the mean and current annual basal area, occur at ages over 80 years for most selected species. This information has significant implications for the management of the forests and suggests that the current cutting cycles of 20 years greatly overestimate the growth rate of tree species in the Boliviano Cerrado forest.

1. Introduction

In many countries of South America, the traditional selective exploitation of the tropical forests is being replaced by a better planned activity of limited impact regulated by forest management principles (Putz et al., 2008). However, these general regulations do not take into account the differences between forest types and, in most cases, are not based on long-term forest sustainability. Most forest practices prescribe a minimum diameter at which trees of commercial species can be harvested, and a cutting cycle that should allow for the recuperation of the harvested timber volume. In Bolivia, these practices are limited to a cutting cycle of at least 20 years, minimum cutting diameters (MCD) of 40–70 cm (depending on species and regions) and a maximum harvest intensity of 80% of the trees of harvestable size, leaving the remaining 20% as seed trees (MDSP, 1998; van Rheenen, 2005). In addition, most regulations are based on mean growth rates from different stands and geographical areas and they do not consider of the differences in growth for the different species and sites in the Bolivian forests (Brienen and Zuidema, 2005; López and Villalba, 2010). These forest practices are clearly aimed at short-term economic and commercial feasibility, raising doubts on the long-term sustainability of forests (Campos et al., 2001; López, 2011).

To establish sustainable forest practices based on appropriate guidelines, accurate field data is needed. In this context, tree rings are an efficient and practical tool to provide in a short period information on growth rates require to estimate the ages and diameters at which trees reach their maximum timber productions (Lieberman and Lieberman, 1985; Brienen and Zuidema, 2006b; López, 2011). In some tropical regions, dendrochronological techniques have recently been used to determine three key variables: tree age, the cutting cycles of rotation and the MCD (Brienen and Zuidema, 2006b; Schöngart, 2008). Once these variables are known, forest managers can make strategic decisions to ensure the long-term sustainability of forests. In this study, our objective was to estimate the rates of diametrical growth as well as the biological rotation ages of seven trees characteristic of the Bolivian Cerrado biogeographical province using dendrochronological methods. For the first time, our results

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provide a long-term perspective on regional changes in diametrical growth of the seven selected forest species. These results are relevant for introducing changes in the current forest management regulations in Bolivia which are largely based on static approaches.

2. Materials and methods

2.1. Species and study sites

The Bolivian Cerrado represents the southwestern part of the Cerrado biogeographical province in South America (Cabrera and Willink, 1973). In Bolivia, Navarro and Maldonado (2004) distinguished four districts in the Chiquitano sector of the Cerrado formation: the Chiquitos, the Guarayos, the Chiquitano–meridional and the Huanchaca districts (Fig. 1). We sampled the localities of Inpa, Santa Anita and Zapocó in the Chiquitano district and the localities of Santa Monica, Makanaté and La Chonta in the Guarayos district (Table 3). The Chiquitos biogeographical district is characterized by shallow and rocky soils in a landscape dominated by small sierras and plateaus. The Guarayos district has moderate to deep soils with a larger capacity for water storage (Navarro and Maldonado, 2004).

Mean annual temperatures at the Concepción and Ascensión de Guarayos meteorological stations, close to our sampling sites, are 24.2 °C and 23.8 °C, respectively. Annual seasonality in monthly temperatures is small in both localities with differences of about 3 °C between the warmest (November) and the coldest (July) months of the year. The total annual precipitation shows a marked seasonality at both sites and varies between 900 and 1200 mm in Concepción and 1200 and 1600 mm in Guarayos. The dry season lasts from April to September in Concepción and from May to September in Guarayos.

The recorded differences in total precipitation and duration of the dry season between sites are reflected in a larger number of species characteristic of the humid tropical forests in the Guarayos than in the Concepción district. In addition, the upper canopy heights reach 20–30 m in the Guarayos district but only 15–25 m in the Concepción district.

A total of 347 trees from seven commercially important species were sampled (Table 1). The sampled species grow as dominant trees in the upper canopy of old growth forests. The seven species selected are the most important timbers economically exploited and sold to both domestic and international markets (Bolfor II, 2008; IBCE, 2009). Given the current intensity of their harvesting, it is now relatively easy to obtain complete cross-sections from these tree species. The seven selected species have visible growth rings (López, 2011).

The species *Amburana cearensis* (Allemão) A. S. Smith, *Cedrela fissilis* Vell., *Platimiscium ulei* Harms and *Centrolobium microchaete* (C. Martius ex Benth.) Lima ex G. P. Lewis have the most valuable timbers in the Cerrado Boliviano. *Anadenanthera colubrina* (Vell. Conc.) Benth and *Hymenaea courbaril* L. present the heaviest wood in the region, whereas *Ficus boliviana* C.C. Berg is the most lightweight. The seven species have a distinctly tropical and subtropical distribution; *F. boliviana* and *C. microchaete* are endemic and limited to the forests of the Bolivian Cerrado biogeographical province (Killeen et al., 1993; Justiniano and Fredericksen, 1998). The species *A. colubrine* and *A. cearensis* have a wider distribution and they are also present in adjacent countries to Bolivia including Brazil, Peru and Argentina (Killeen et al., 1993). Finally, *H. courbaril, P. ulei and C. fissilis* are widely distributed from Mexico to Paraguay and northern Argentina (Gentry, 1988; Killeen et al., 1993; Brown, 1995).

2.2. Sample collection

Several factors make it difficult to obtain samples for analysis of tree rings in the dry tropics of South America using traditional

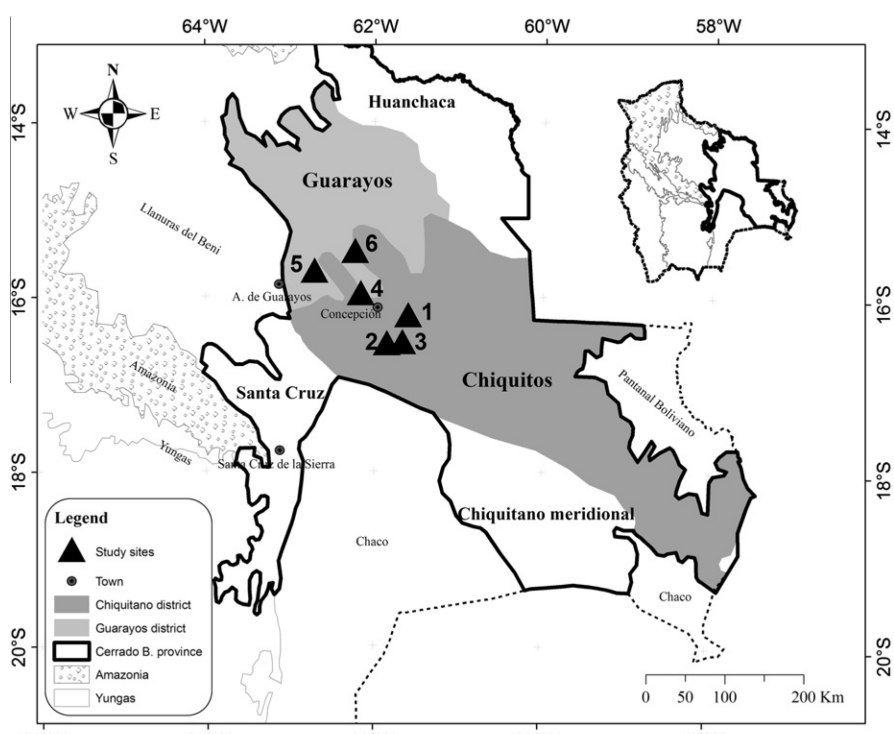

Fig. 1. Biogeographical provinces in Bolivia, South America. The Cerrado biogeographical province (Navarro and Maldonado 2004) is delimited by a continuous thick black line, and the two biogeographical districts (Chiquitano and Santa Cruz) within the Cerrado province shown in gray colors. The four botanical districts in the Chiquitano dry forests are identified by their respective names. Location of the sampling sites (▲): 1. Concepción, 2. Santa Anita, 3. Zapocó, 4. Santa Mónica, 5. La Chonta, and 6. Makanaté.

Table 1
The seven study species, number of trees and canopy status within the forests of the Bolivian Cerrado biogeographical province.

Specie	Family	Common name	Number of trees	Canopy status
Amburana cearensis	Leguminosae	Roble	35	Dominant
Anadenanthera colubrina	Mimosaceae	Curupaú	31	Dominant
Cedrela fissilis	Meliaceae	Cedro	27	Dominant
Centrolobium microchaete	Leguminosae	Tarara amarilla	171	Dominant
Ficus boliviana	Moraceae	Bibosí	13	Emergent
Hymenaea courbaril	Caesalpiniaceae	Paquío	36	Emergent
Platimiscium ulei	Leguminosae	Tarara colorada	30	Dominant

dendrochronological tools (López, 2003, 2011). Due to the high density of most woods in the region, traditional increment borers cannot be used to collect samples, as most increment borers have been designed for conifers with relatively low-density woods. In addition, the precise definition of growth rings in dry tropical forests is facilitated by the use of sections wider than the 5-mm wide, commonly recovered using standard increment corers. Cross sections, which provide a larger field of observation, make the delineation of the annual growth increments easier. Based on these considerations, field sampling was undertaken in areas where native forests were being harvested at the time of the collection.

Before tree felling, the logging company recorded diameter at breast height (dbh) and tree height. Before trees were removed from the cutting block, we collected a cross section at the base of the recently logged tree bole. According with current forestry regulations in Bolivia, selected trees had a diameter at breast height over 40 cm (minimum harvest diameter). Sampled trees showed good external morphological characteristics in their stems. At least 13 trees were selected for each species. *Ficus boliviana* Wilde has the smallest sample size. The maximum number of sampled of 171 trees correspond to *Centrolobium microchaete* (see Table 1 for a complete description of the sampled species).

2.3. Laboratory methods

Cross sections were dried at room temperature and polished with sandpaper of decreasing granulometry (80–1200) until the anatomical features related to ring boundaries were clearly identified. We examined the cross-sections using a microscope (10 × magnifications) and dated the wood based on ring width patterns. For that, we identified 'marker' or characteristic rings that were relatively narrow compared to the neighboring rings. This pattern of marker rings was visually identified in all samples from each site. Once a common pattern of ring width variations was recognized between tree radii and between trees at a particular site, we proceed to measure the tree-ring widths. Ring widths were measured with a Velmex dendrometer (measurement precision >0.01 mm) connected to a personal computer.

Annual and accumulated diameter increments were calculated by averaging the values obtained from two radii (generally opposing) within a same cross-section. Cross-dating and measuring quality were checked with the program COFECHA (Holmes, 1983). This program calculates correlation coefficients between ring width series and provides a solid criterion for the identification of absent or false rings.

2.4. Data analysis

Statistics on tree growth for each species and site (mean, standard deviation, variance and extreme values) were estimated using Infostat 2011 (Di Rienzo et al., 2011). To compare the growth rates between species and sites, all series were reduced to a common growth period of 100 years.

Annual series of radial and basal area increments were estimated using the program AGE from the Directory Program Library for Dendrochronology (Holmes, 1983). Program AGE estimates current and mean annual basal area increments for each tree and mean time series for sites (Table 1).Current (BA CAI) and mean annual (BA MAI) basal area increments were calculated using the formulae:

$$\text{BA CAI}_t = \pi(r_t^2 - r_{t-1}^2)$$

and

$$\text{BA MAI}_t = \frac{\pi(r_t^2)}{t}$$

where r_t is the ring width in the year t.

To highlight long-term trends in basal area increments, the inter-annual fluctuations in the original time series were filtered out using a cubic spline function designed to reduce 50% of the variance in a sine wave with a periodicity of 15 years (Cook and Peters, 1981). Finally, biological rotation ages (BRA) were estimated as the time needed for each stand to reach the maximum mean annual basal area increment. Similarly, diameters at the BRA were also estimated for the seven species. The biological rotation age represents the time of highest biological productivity and is reached when the average annual increase is equal to the current annual growth. The biological rotation age coincides with the age at which trees reached the maximum average basal area increment (Assmann, 1970).

For the purpose of analyzing the site-species interactions, annual increments from *Centrolobium microchaete* were compared between trees growing in different sites. Differences in growth were evaluated for common periods including the largest number of individuals in the compared sites based on the total number of individuals collected. A square root transformation was applied to the mean diameter growth and to the maximum mean basal area increment (Rokal and Rohlf, 1995). Then, statistically significant differences ($^*p < 0.05$) between sample populations were evaluated using a Tukey analysis of variance, assuming no-normal distribution of the variables (Tukey, 1977).

3. Results

3.1. Growth differences

The diametric growth varies considerably between species. During a 100 year-interval, the mean diameter growth from species in the Chiquitano district ranges between 0.45 cm year^{-1} for *Platimiscium ulei* to 0.58 for *Amburana cearensis*. For the species from the Guarayos district, the rates of diametric growth over a 100 year-interval vary from 0.55 cm year^{-1} for *Hymenaea courbaril* and 1.05 cm year^{-1} for *Ficus boliviana* (Table 2). The mean ages for minimum cutting diameter (MCD) for the species from the Chiquitano district vary from 68 years for *Amburana cearensis* to 85 years for *Platimiscium ulei*. For the Guarayos district, the ages require to reach the MCD vary from 43 year for *Ficus boliviana* to 100 year for *Cedrela fissilis* (Fig. 2). The trees of the Chiquitano district the diameter at the BRA varies between 45 and 69 cm for *Platimiscium ulei* and

Table 2
The means and standard deviations of the diameter growth increment (MAI) and means and standard deviations of the basal growth increment (BA-MAI) in the trees Chiquitano and Guarayos districts. All estimates were evaluated over a common growth period of 100 years. Number of trees used for estimating MAI and biological rotation ages (BRA, years, cm). Different letters (abc) indicate statistically significant differences at a confidence level of 0.05.

Scientific name of species study	No. of trees	MAI (cm)	BA-MAI ($cm^2/year^{-1}$)	Biological rotation age (BRA, years)	Diameter at BRA (cm)
Amburana cearensis	35	0.58 ± 0.1bc	2.24 ± 0.89a	>120	>69
Anadenanthera colubrina	31	0.49 ± 0.1a	1.43 ± 0.51a	98	48
Platimiscium ulei	30	0.45 ± 0.1a	1.19 ± 0.64a	>100	>45
Mean Chiquitano district	32				
Ficus boliviana	13	1.05 ± 0.2d	5.27 ± 3.33c	80	84
Hymenaea courbaril	36	0.55 ± 0.2abc	3.72 ± 1.23b	>120	>66
Cedrela fissilis	27	0.60 ± 0.1c	3.53 ± 1.68d	>90	>54
Mean Guarayos district	25				

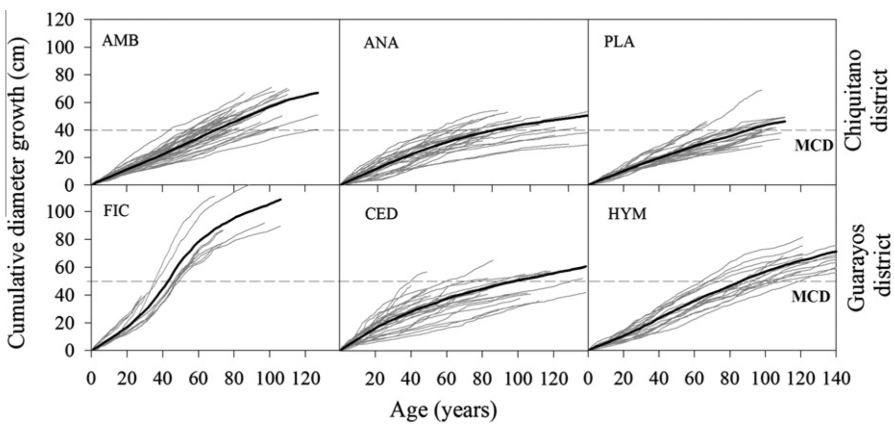

Fig. 2. Cumulative diameter growth for the six species collected in the two biogeographical district: AMB, *Amburana cearensis*; ANA, *Anadenanthera colubrine*; PLA; *Platimiscium ulei* in the Chiquitano district, and FIC, *Ficus boliviana*; CED, *Cedrela fissilis*; HYM; *Hymenaea courbaril* in the Guarayos district. Thin transverse lines correspond to minimum cutting diameter (MCD) of 40 cm in the Chiquitano district and 50 cm in the Guarayos district of the Cerrado Boliviano biogeographical province.

Amburana cearensis, respectively. For the species from the Guarayos district, the diameters at the BRA vary from >54 cm for *Cedrela fissilis* to 84 cm for *Ficus boliviana* (Table 2). The analysis of variance indicates that *Ficus boliviana* growth is significantly larger than the growth for the other species in the Guarayos district. No significant differences in tree growth were recorded between the *Anadenanthera colubrina, Platimiscium ulei* and *Hymenaea courbaril* (Table 2). Also, no significant differences in tree growth were recorded between the *Amburana cearensis, Hymenaea courbaril* and *Cedrela fissilis*. Finally, for the species with at least 100–year record, the mean cumulative diameter growth varies between 45 cm and 105 cm for *Platimiscium ulei* and *Ficus boliviana*, respectively (Fig. 2).

3.2. Growth differences for *Centrolobium microchaete* between sites

Species growth varies largely between sites (Table 3). The mean diameter growth of *Centrolobium microchaete* during a 100 year-interval varies from 0.36 cm $year^{-1}$ to 0.41 cm $year^{-1}$ for the Inpa and Santa Anita, respectively, in the Chiquitano district. Over a 100 year-interval, the mean diametric growth for sites in the Guarayos district varies between, 0.54 cm $year^{-1}$ and 0.64 cm $year^{-1}$ for the Santa Mónica and La Chonta, respectively (Table 3). For *Centrolobium microchaete* in the Chiquitano district, mean ages for reaching the MCD vary between 98 and 110 years for Inpa and Zapocó, respectively. In the Guarayos district, mean ages to reach the MCD are very similar between sites (80–83 years; Fig. 3). For the specie from the Chiquitano district, the diameters at the BRA vary from 47 cm for Santa Anita to 58 cm for Inpa. The diameters at the BRA in the Guarayos district vary between 35 and 65 cm for Makanaté and Santa Mónica, respectively (Table 3). The analysis of variance indicates that tree growth in La Chonta is significantly higher than in the other two sites in the Guarayos district (Table 3). No significant differences in tree growth were recorded between the sites in the Chiquitano district. The mean cumulative diameter growth for *C. microchaete* during 100 years varies between 54 cm in Santa Mónica and 64 cm in La Chonta, all sites in the Guarayos district (Fig. 3). For the sites in the Chiquitano district, the mean cumulative diametric growths during the first 100 years are 36 and 41 cm at Inpa and Santa Anita, respectively (Fig. 3).

3.3. Biological rotation ages

Based on basal area increments, we estimated that the mean biological rotation ages (BRA) between species varies between 98 (*Anadenanthera colubrina*) and >120 years (*Amburana cearensis*) in the Chiquitano district, and between 80 (*Ficus boliviana*) and >140 -years (*Hymenaea courbaril),* in the Guarayos district (Fig. 4 and Table 2).

In contrast to other species, the growth rate of *Platimiscium ulei* during the juvenile stages is relatively slow. Annual increments stabilize at about 90 years and gradually decline at ages over 110 years. The biological rotation age at *Hymenaea courbaril* is close to 140 years. For *Cedrela fissilis* in the Guarayos district, the growth rate during the juvenile stage is relatively slow compared to other species in the same district. In the Chiquitano district, annual increments in mean basal area vary from 1.19 cm^2 for *Platimiscium ulei* to 2.24 cm^2 for *Amburana cearensis*. In the Guarayos district, increments in mean basal area range from 3.53 cm^2 $year^{-1}$ for *Cedrela fissilis* to 5.27 cm^2 $year^{-1}$ for *Ficus boliviana* (Table 2).

Based on basal area increments, we estimated mean BRAs for *C. microchaete* for the sites in the Chiquitano district between 115 and 140 year, whereas for the sites in the Guarayos district vary

Table 3
The means and standard deviations of the diameter growth increment (MAI) and means and standard deviations of the basal growth increment (BA-MAI) for *Centrolobium microchaete* at different sites in the Chiquitano and Guarayos districts in the Bolivian Cerrado biogeographical province. These estimates were evaluated over a common growth period of 100 years. Different letters (abc) indicate statistically significant differences at a confidence level of 0.05. Number of selected trees and biological rotation ages (BRA, years, cm) for *Centrolobium microchaete* are indicated for the six sampling sites in the Chiquitano and Guarayos districts.

	Chiquitano district			Guarayos district		
	Inpa	Santa Anita	Zapocó	Santa Mónica	Makanaté	La Chonta
Latitude	16° 22′	16° 32′	16° 27′	15° 58′	15° 29′	15° 38′
Longitude	61° 55′	61° 55′	61° 44	62° 22′	62° 17′	62° 46′
Altitude (m.s n.m.)	503	423	464	420	246	250
Cutting Cycle (CC)	20	20	20	20	20	20
Minimum Cutting Diameter (MCD)	40	40	40	50	50	50
No. of trees	38	41	22	50	26	24
MAI (cm)	0.36 ± 0.03a	0.41 ± 0.03a	0.40 ± 0.04a	0.54 ± 0.03b	0.56 ± 0.04bc	0.64 ± 0.04c
BA-MAI ($cm^2/year^{-1}$)	1.22 ± 0.49abc	1.13 ± 0.62ab	0.88 ± 0.37a	2.00 ± 0.89 d	1.72 ± 0.99 cd	1.59 ± 0.10bcd
Biological rotation age (BRA, year)	140	115	>120	>120	65	>65
Diameter at BRA (cm)	50	47	48	65	35	>42

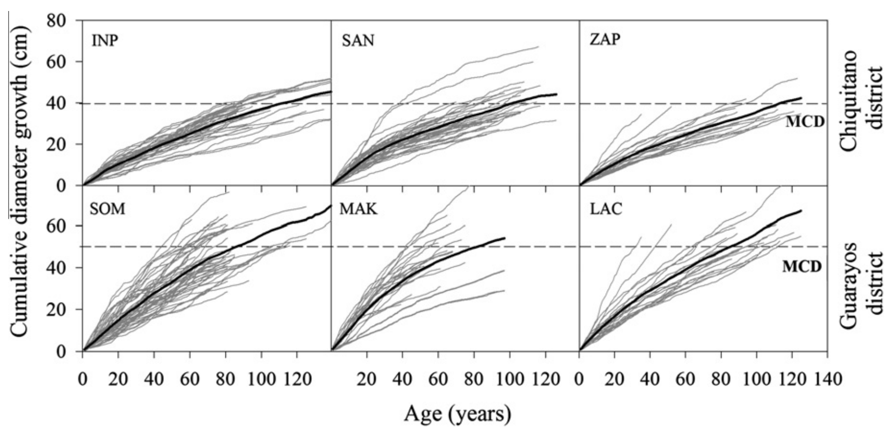

Fig. 3. Cumulative diameter growth for *Centrolobium microchaete* at six sites in two different districts, INP, Inpa; SAN, Santa Anita and ZAP, Zapocó in the Chiquitano district, and SMO, Santa Monica; MAK, Makanaté and LAC, La Chonta in Guarayos district. Thin transverse lines correspond to minimum cutting diameter (MCD) of 40 cm in the Chiquitano district and 50 cm in the Guarayos district of the Cerrado Boliviano biogeographical province.

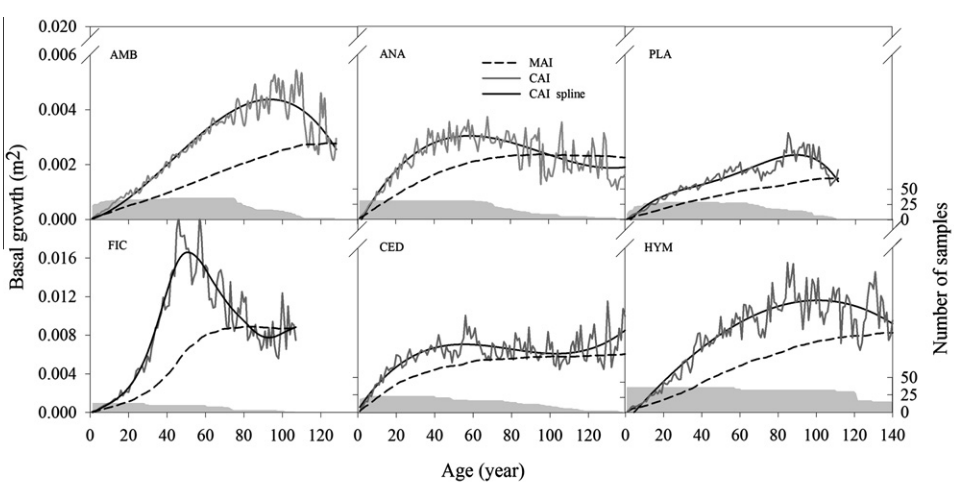

Fig. 4. Current (CAI) and mean (MAI) annual basal area increments in relation to tree ages for six different species. Upper panel, sites corresponding to the Chiquitano district: AMB, *Amburana cearensis*; ANA, *Anadenanthera colubrina* and PLA, *Platimiscium ulei*. Lower panel, sites corresponding to the Guarayos district: FIC, *Ficus boliviana*; CED, *Cedrela fissilis* and HYM, *Hymenaea courbaril*. The gray areas represent the number of trees used for estimating CAI and MAI, for each selected species.

between 65 and >100 years (Fig. 5). The marked reduction in the number of trees over 80 years limited the precise determination of the BRAs at La Chonta and Santa Mónica. However, based on trends in current and mean basal increments, we suggest a rotation age >100 years for these sites.

In contrast to other sites, the growth rate of *C. microchaete* during the juvenile stage at Inpa is relatively slow. Annual increments stabilize at about 80 years and gradually decline at ages over 140 years. The BRA at Inpa is close to 140 years. For the site Santa Monica in the Guarayos district, the growth rate during the

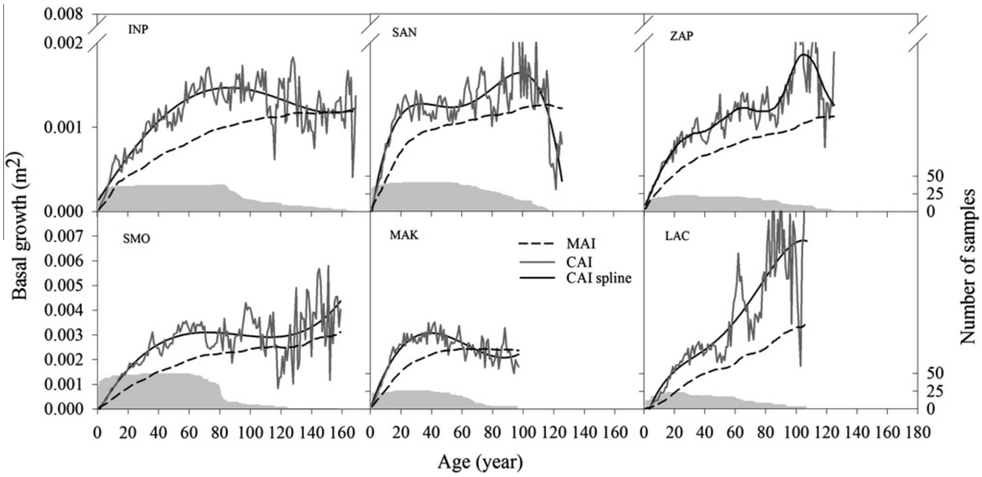

Fig. 5. Current (CAI) and mean (MAI) annual basal area increments in relation to tree ages for *Centrolobium microchaete*, at six sites in two different districts. Upper panel, sites corresponding to Chiquitano district: INP, Inpa; SAN, Santa Anita and ZAP, Zapocó. Lower panel, sites corresponding to Guarayos district: SMO, Santa Monica; MAK, Makanaté and LAC, La Chonta. The gray areas represent the number of trees used for estimating CAI and MAI, for each study site.

juvenile is relatively slow compared to other sites in the same district. For the Chiquitano district, annual increments in mean basal area vary between sites from 0.88 cm^2 at Zapocó to 1.22 cm^2 at Inpa. For the Guarayos district, increments in mean basal area vary from 1.59 cm^2 $year^{-1}$ at La Chonta to 2.00 cm^2 $year^{-1}$ at Santa Mónica (Table 3). The diameters reached by the seven selected species at the BRAs are indicated in Tables 2 and 3.

4. Discussion and conclusions

Forest management practices in Bolivia are based on traditional estimations of growth rates in tropical forests. However, these estimates in the long-term context have rarely been assessed through detailed surveys. For the first time, we provide an evaluation of the mean growth rates of seven tree species based on tree-ring measurements from 347 cross-sections in the Bolivian Cerrado province. During a 100 year-interval, the mean diameter growth of the seven selected species ranges from 0.45 cm $year^{-1}$ in *Platimiscium ulei* to 1.05 cm $year^{-1}$ in *Ficus boliviana* (Table 2). Based on these rates, individuals of *Anadenanthera colubrina* would have a diameter increment of approximately 10 cm in 20 years, whereas the *Ficus boliviana* trees would increase 24 cm in the same interval. In the best situation, trees require ages over 50 years to reach the MCD established by the Bolivian forest regulations (Fig. 2).

Variations in tree growth rates between sites were also observed for *C. microchaete*. The *C. microchaete* annual diametrical growth is 0.64 cm $year^{-1}$ in La Chonta but only 0.36 cm $year^{-1}$ in Inpa (Table 3). Based on these estimates, the diameter increment during the 20-year period between two consecutive harvest operations established by the Bolivian Forestry Law, would be around 7.2 cm and 12.8 cm at Inpa and La Chonta, respectively (López, 2011). This implies that none of the remaining trees with dbh < 20 cm after the first harvest would reach a diameter of 40 cm for the next harvest in 20 years. In addition, the rate of growth of *C. microchaete* is largely affected by variations in precipitation (López and Villalba, 2010). The occurrence of severe droughts, which significantly reduces radial growth, should also be taken into account in the process of determining rotation periods for harvesting in native forests (López and Villalba, 2010).

The information on growth rates presented here compares well with the estimates from measurements in permanent plots over relatively short periods (5–7 years) in the Chiquitano and Guarayos forests (Dauber et al., 2005). Our values also compare well with the estimates for similar species in the Amazonía Boliviana (Brienen and Zuidema, 2006a; Brienen and Zuidema, 2006b; Rozendaal, 2010). The growth reported for *C. microchaete* and *P. ulei* in sites for the Chiquitano district are similar to those reported from measurement in permanent plots in the same district. For instance, Dauber et al. (2005) reported mean annual increments of 0.35 cm $year^{-1}$ and 0.32 cm $year^{-1}$ for *C. microchaete* and *P. ulei*, consistent with our long-term estimates for these species. In the Guarayos district, diameter growth values are also highly comparable to those reported for this species in the region (Dauber et al., 2005; Mostacedo et al., 2009). The growth rates reported for *Amburana cearensis* and *Cedrela fissilis* are similar to those recorded for both species at sites located in the Amazonía Boliviana (Brienen and Zuidema, 2006b). Larger differences in diameter growth between the rates reported here and in other studies were observed for *Anadenanthera colubrine* and *Ficus boliviana* in the Chiquitano and Guarayos district (Dauber et al., 2005). Dauber et al. (2005) reported mean annual increments of 0.20 cm and 0.32 cm for *Anadenanthera colubrine* and *Ficus* sp., rates significantly lower than our long-term estimates of 0.49 cm and 1.05 cm for these species, respectively. This variation may be due to several factors including sites differences or the lower rates of growth in old trees from both species. To our knowledge, the rate of growth of *Hymenaea courbaril* has not been previously reported, hampering any comparison with the rates reported in this study.

For several tropical species in the Bolivian Cerrado there is no information on basal area growth. This fact limits the determination of the harvest rotation period in almost all tree species. Forest management regulations in Bolivia are largely based on estimates of growth rates from tropical forests elsewhere and the establishment of similar rotation cycles and harvest intervals for most species even in different regions. Harvest interval and intensity, expressed as the percentage of basal area that is removed in each cut, provide the basic principles for the sustainable management of forests, which should be proposed based on the actual growth rates for the different species and sites. Based on imprecise estimates of tree growth, many species might be cut before they reach their optimum harvest time. Our analyses indicated that the BRA in the Chiquitano district varies between 98 and 130 years forthe selected species (Table 2). For species in the Guarayos district, the BRAs should be over 80 years (Fig. 4). Similar results were obtained when comparing *Centrolobium microchaete* at different sites in both the Chiquitano and Guarayos districts (Fig. 5). Our results are comparable to those reported by previous studies in few species of the

Bolivian Amazon forest. For example, it has been estimated that the period require to reach the cutting cycles for five Amazonian species vary between 61 and 179 years (Brienen and Zuidema, 2006b; López, 2011).

Many studies suggest that cutting cycles for tropical species must be raised four to five times longer than currently practiced (Brienen and Zuidema, 2006b; Schöngart, 2008). Considering the annual growth rates and the cumulative diameters reached by the seven species analyzed in this study (Figs. 2 and 3), the harvest intervals of 20 years, in combination with a removal of 80% of all trees larger than the MCD, proposed by the Bolivian Forestry Law appears to be extremely short. Indeed, for keeping the dry tropical forests as a sustainable source of timber in the long-term context, it is necessary to extend the harvest intervals to periods over 60-year long or significantly increased the percentage of trees to remains in the field after the harvesting. In 60 years, those trees that did not reach the MCD for the first cycle will have a diametrical increment larger than 20 cm at the time of the second cycle. Several trees will reach more than 50 cm of diameter at the time of the second cycle. Our results indicate that in order to reach a MCD of 40 cm, trees from the different species require 60 to >90 -years (Fig. 2), and this time is increased from 80 to >120 years for a MCD of 50 cm. Therefore, the difference in years between the times needed to reach the MCD and the BRA provide a good estimate to prolong the permanence of the trees in the stand until they reach a diameter close to those associated with the BRAs (Tables 2 and 3). Such increase in time will allow most species maximize their biological productivity, which in turn will add values for maintaining larger trees in the forests. We observed that trees reach mean diameters of 50 cm at ages between 80 and 100 years, when many of the studied species reach their optimum wood production. In addition, longer time spam will allow the preservation of the structure and composition of forests as sources of wood production and biological conservation. In conclusion, information on species growth rates and site considerations are needed to ensure sustainable forest management in tropical dry forests.

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References

Assmann, E., 1970. The Principles of Forest Yield Study. Pergamon Press, Oxford, U.K.

Bolfor II, 2008. Informe final. Proyecto, BOLFOR II, Santa Cruz, Bolivia.

Brienen, R.J.W., Zuidema, P.A., 2005. Relating tree growth to rainfall in Bolivian rain forests: a test for six species using tree ring analysis. Oecologia 146, 1–12.

Brienen, R.J.W., Zuidema, P.A., 2006a. Lifetime growth patterns and ages of Bolivian rain forest trees obtained by tree ring analysis. Ecology 94, 481–493.

Brienen, R.J.W., Zuidema, P.A., 2006b. The use of tree rings in tropical forest management: projecting timber yields of four Bolivian tree species. Forest Ecology and Management 226, 256–267.

Brown, A.D., 1995. Fitogeografía y conservación de las selvas de montaña del noroeste de Argentina. In: Baas, P., Kalman, K., Geesink, R. (Eds.), The Plant Diversity of Malesia. Kluwer Academic Publishers, Dordrecht, pp. 147–160.

Cabrera, A.L., Willink, A., 1973. Biogeografía de América Latina. OEA (Organización de los Estados Americanos), Washington, DC.

Campos, J.J., Finegan, B., Villalobos, R., 2001. Management of goods and services from neotropical forest biodiversity: diversified forest management in Mesoamerica. In: Cook, P.E.R., Peters, K. (Eds.), The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. Tree-Ring, Bulletin, pp. 5–16.

Cook, E.R., Peters, K., 1981. The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. Tree-Ring Bulletin 41, 45–53.

Dauber, E., Fredericksen, T.S., Peña, M., 2005. Sustainability of timber harvesting in Bolivian tropical forests. Forest Ecology and Management 214, 294–304.

Di Rienzo, J., Balzarini, M., Casanoves, F., Gonzalez, L., Tablada, E., Robledo, C., 2011. Infostat Software Estadístico versión 2011. Grupo InfoStat, FCA, Universidad Nacional de Córdoba, Argentina.

Gentry, A., 1988. Tree species richness in Amazonian forests. In: Proceedings of the National Academy of Sciences of the United States of America 95, pp. 156–159.

Holmes, R.L., 1983. Dendrochronology Program Librery (DPL). Use manual by laboratory of tree-ring research. University of Arizona, Tuczon. Arizona.

IBCE, 2009. Certificación Forestal en Bolivia: beneficios para las comunidades, empresas y bosques. In: Instituto Boliviano de Comercio Exterior. Publicación informativa 18. Certificación Forestal en Bolivia, Santa Cruz.

Justiniano, M.J., Fredericksen, T.S., 1998. Ecología y Silvicultura de Especies Menos Conocidas-Tarara Amarilla, Centrolobium microchaete, Papilionoideae. El país, BOLFOR, Santa Cruz.

Killeen, J.T., Garcia, E., Berck, G.S., 1993. Guía de arboles de Bolivia. Herbario Nacional de Bolivia, Missouri Botanical Garden. Quipus S.R.L., La Paz.

Lieberman, M., Lieberman, D., 1985. Simulation of growth curves from periodic increment data. Ecology 66, 632–635.

López, L., 2003. Estudio de anillos de crecimiento en once especies forestales de Santa Cruz–Bolivia. Universidad Autónoma Gabriel René Moreno. Tesis de Ingeniería Forestal, Santa Cruz.

López, L., 2011. Una aproximación dendrocronológica a la ecología y el manejo de los bosques tropicales secos del Cerrado Boliviano. Universidad Nacional del Comahue. Tesis doctoral, San Carlos de Bariloche, Rio Negro, Argentina.

López, L., Villalba, R., 2010. Climate influences on the radial growth of *Centrolobium microchaete*, a valuable timber species from the tropical dry forests in Bolivia. Biotropica 43, 41–49.

MDSP, 1998. Normas técnicas para la elaboración de instrumentos de manejo forestal (inventarios, planes de manejo, planes operativos, mapas) en propiedades privadas o concesiones con superficies mayores a 200 hectáreas. In: Ministerio de Desarrollo Sostenible y Planificación. Resolución Ministerial N° 248/98, La Paz.

Mostacedo, B., Villegas, Z., Licona, J.C., Alarcón, A., Villarroel, D., Peña-Claros, M., Fredericksen, T.S., 2009. Ecología y Silvicultura de los Principales Bosques Tropicales de Bolivia. Instituto Boliviano de Investigación Forestal, Santa Cruz.

Navarro, G., Maldonado, M., 2004. Geografía Ecológica de Bolivia: Vegetación y Ambientes Acuáticos. Centro de Ecología Simón Patiño, Santa Cruz.

Putz, F.E., Sist, P., Fredericksen, T., Dykstra, D., 2008. Reduced-impact logging: challenges and opportunities. Forest Ecology and Management 256, 1427–1433.

Rokal, R.R., Rohlf, J., 1995. Biometry. The Principles and Pactice of Statistcs in Biological Research, Trird, New York.

Rozendaal, D.M.A., 2010. Looking backwards: using tree rings to evaluate long-term growth patterns of Bolivian forest tres. Scientific Series 12, PROMAB, Riberalta.

Schöngart, J., 2008. Growth-Oriented Logging (GOL): a new concept towards sustainable forest management in Central Amazonian várzea floodplains. Forest Ecology and Management 256, 46–58.

Tukey, J.W., 1977. Exploratory Data Analysis. Addison-Wesley, Reading MA.

van Rheenen, H., 2005. The role of seed trees and seedling regeneration for species maintenance in logged-over forests – a study in the Bolivian Amazon rainforest. Utrecht University. PhD thesis, Utrecht, The Netherlands.