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Tree-ring analysis of an African long-lived pioneer species as a tool for sustainable forest management

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ABSTRACT

Improved forest management in the tropics is hampered by the limited availability of quantitative data, especially in tropical Africa. Important management parameters such as the minimum logging diameter (MLD), the associated biological rotation age (BRA) and the timing of silvicultural treatments are too often based on merchantable dimensions and state regulations instead of ecological data and tree growth. This study combines inventory data and bootstrapped tree-ring curves of natural and planted trees of the long-lived pioneer species *Terminalia superba* Engl. & Diels. A growth-oriented MLD was calculated, and the need and timing of silvicultural treatments was estimated based on the analysis of growth releases and suppressions. Study sites were situated in the Congolese Mayombe forest and western Ivory Coast. Tree rings from 41 natural forest trees (stem discs) and 29 plantation trees (increment cores) were measured, along with diameter and height measurements. Planted and natural forests showed considerable differences in mean growth rate and growth curves. More than 50% of the trees nevertheless reached the canopy without growth releases or suppressions, confirming that *T. superba* does not require intensive management. The growth-oriented MLD not only differs considerably between sites but bootstrapping revealed large differences within forest regions/types. Furthermore, volume-based MLD and BRA are on average larger than basal area-based calculations. The modified monocyclic management system is suggested, especially for planted forests with light-demanding, fast-growing tree species. One small-scale thinning during the juvenile phase is recommended before a final harvest that includes all trees above the growth-oriented MLD. The introduction of sustainable management for *T. superba* therefore primarily depends on forest type and cannot be generalized at the species level.

1. Introduction

Tropical forests hold about half of the world's terrestrial biomass (Pan et al., 2011). These forests need to be managed properly if they are to supply the necessary resources in addition to performing their social and ecological functions. These functions should be described and well-balanced in management plans. This is a complicated task, especially in the tropics, where complex forest structures (Whitmore, 1990), increasing human pressure (Iloweka, 2004), and a lack of systemic research are common. Moreover, every year millions of hectares of tropical forest are lost or seriously degraded. Although the amount of sustainably managed forest increased slightly worldwide between 2005 and 2010 and even tripled in Africa, these forests only account for less than 8% of the world's forests area (Blaser et al., 2011). Successful sustainable management depends on the collection of quantitative data. This study will focus on one of the main elements within the framework of sustainable management – sustained yield – in keeping with the principle that log removal should not exceed the capacity of the growing population to replace the removed tree volume (Sands, 2005).

Timing of log removal should mostly be based on the biological rotation age (BRA) and the adjoined minimum logging diameter (MLD). Governments, scientists, and others define the MLD differently. Legally, the MLD is mostly defined as the minimum diameter cutting limit for tree species. This means that the MLD is not calculated, but fixed by national regulations and/or set at values that coincide with merchantable wood volumes (Sist et al., 2003; Schöngart, 2008). From a scientific point of view, the MLD is calculated based on tree growth. For example, Junk et al. (2011) defined the MLD in the Amazonian floodplain forests as the diameter at the age of maximum current volume increment rates. This study follows Philip (1994) and Rondeux (1999), who define the optimum MLD as the diameter at the age of maximum mean volume or basal-area increment rates. This age of maximum mean increment rates corresponds with the BRA.

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Both volume and basal-area based calculations depend on tree growth data, collected periodically in permanent sample plots (PSPs) or during one inventory with extraction of stem discs or increment cores for tree-ring analysis. Although tree rings are not always easy to distinguish in the tropics (Schweingruber, 1988), they have proven to be a reliable management tool (Baker et al., 2005; Schöngart et al., 2007; Schöngart, 2008). Because of the frequent occurrence of tree-ring anomalies, Brienen and Zuidema (2005) recommend the use of stem discs for tree-ring analysis. Sampling stem discs is not only destructive, it is also difficult, because logging in the tropics is not straightforward. This mostly results in small sample sizes with large variability in growth rate. Computer simulations such as bootstrapping (Efron, 1979; Brienen et al., 2006; Rozendaal et al., 2010) are useful tools to counter such variability and make a more reliable estimate of the MLD.

The definition of sustainable forest management nevertheless involves more than the calculation of annual allowable cut and the calculation of the MLD (Sist et al., 2003). Silvicultural treatments often improve diameter/volume increments (Peña-Claros et al., 2008; Villegas et al., 2009), but the timing and number of these treatments is usually only based on experimental modelling and national regulations. Again, tree-ring data can be used to, e.g., calculate and study the presence and frequency of so-called growth releases and suppressions. The definition of these major changes in growth rates is based on the percentage of growth change, with thresholds for growth releases and suppressions (Nowacki and Abrams, 1997; Brienen and Zuidema, 2006). Those releases and suppressions mark critical moments in the trees' lifespan (Baker et al., 2005; Brienen and Zuidema, 2006) when management could influence the growth of trees positively.

This study explores the use of combined growth data from a forest inventory and tree-ring analysis to formulate recommendations for sustainable management of West and Central African forests. The studied tree species is the long-lived pioneer *Terminalia superba* Engl. & Diels. This species has a vast natural distribution area, stretching from Sierra Leone to Angola (Groulez and Wood, 1985). Due to its fast growth, straight stems, and high commercial heights (Groulez and Wood, 1985), large plantations were installed in the Democratic Republic of Congo (DRC) beginning in 1948. *T. superba* is listed by the International Tropical Timber Organisation (ITTO) as one of the major tropical species traded and is used for, among other things, interior joinery, furniture, veneer, and plywood (Groulez and Wood, 1985). The presence of distinct annual tree rings in Central and West Africa (Mariaux, 1969; De Ridder et al., 2013) allows us to raise the following research questions:

(1) Is it possible to suggest silvicultural treatments based on tree-ring patterns of a long-lived pioneer species? If so, can the need and the timing of these treatments be determined based on the analysis of growth releases and suppressions?
(2) How do MLD and BRA vary within and between sample sites? Is it possible to define one MLD for all forest regions/types, similar to current regulations?
(3) Combining the results of the first two research questions, is there an important difference in the management of a planted or a natural forest? In other words, does the introduction of sustainable management with silvicultural treatments and a final harvest based on MLD/BRA depend on forest region/type or can it be generalised at the species level?

2. Material and methods

2.1. Study sites

All study sites belong to the Guineo–Congolian regional centre of endemism (White, 1983). The Ivorian study sites are part of the evergreen moist rainforest. The Congolese study sites are situated within a drier semi-evergreen rainforest. A map with detailed information is available in De Ridder et al. (2013).

The three Congolese study sites are situated on the southern border of the Mayombe Forest, which covers the western parts of Gabon, the Republic of Congo, the DRC and Cabinda (Angola). Two study sites were chosen within the Luki Biosphere Reserve (05°30′ to 05°45′S and 13°07′ to 13°15′E). The first study site in Luki is a natural forest stand; the second is located in Monzi, 15 km away, in a *T. superba* plantation established between 1955 and 1957. Plantations were installed at planting distances of 8×12 m and no structured management was carried out (De Ridder et al., 2010). A third study site was selected in a natural forest stand in Tshela, about 70 km to the north. All study sites were situated at altitudes below 300 m above sea level. The average annual precipitation, based on precipitation data from the Luki climate station from 1959 to 1996, is 1168 mm, but some years are particularly dry. The region is characterised by a dry season of 4–5 months (May to September–October) and a short period with less precipitation (January–February). The proximity of the ocean and the associated high relative humidity likely buffer the intensity of the dry season. Temperatures oscillate around 26 °C in the rainy season and drop to a minimum of 20 °C in the dry season. The soils of the Luki Reserve are classified as orthic Ferralsols, while Tshela is characterised by ferric Acrisols (FAO, 2008). Most soils are argillaceous, with a pH of between 4 and 6 and a C/N of between 4 and 9.

In western Ivory Coast (06°07′ to 07°15′N, 07°30′ to 08°15′W), four study sites are situated in natural forests (mostly secondary forests), some of them more than 100 km apart. Study sites were situated between 200 and 370 m above sea level. The average annual precipitation, based on precipitation data from six climate stations from 1959 to 1996, is 1650 mm. In this region, the dry season generally lasts for 3 months (December to February). In July and August, a period of less precipitation is observed. Relative humidity drops about 20% in the dry season. Annual mean temperature is 25 °C, with a minimum of 18 °C in January and a maximum of 33 °C in February/March (Van Oldenborgh and Burgers, 2005). Soils have a pH of between 4 and 7 and a C/N of 8–12, and are classified as Ferralsols and Acrisols, i.e., typical acid soils for tropical lowlands (FAO, 1986).

2.2. Sampling and tree-ring analysis

Stem discs and increment cores were collected for tree-ring analysis. In natural forests, a total of 12 stem discs from the Mayombe and 29 stem discs from western Ivory Coast were sampled. Trees' stem height (until the first branch) and diameter were measured in the natural forests. In the plantations of the Mayombe, two perpendicular increment cores were taken per tree, but no stem height or diameter measurements are available. Tree rings were measured on 60 plantation trees. All samples were air dried to prevent fungal infestation, and increment cores were frozen for 2 weeks to prevent insect infestation. Stem discs were too large for freezing and therefore only superficially disinfected before storage in the Tervuren Xylarium. All discs and cores were sanded with grits increasing gradually from 50 to 600 or 1200.

The procedure for tree-ring measurements is described in detail in De Ridder et al. 2013). Ring widths were measured to the nearest 0.01 mm using a stereo-microscope and a Lintab measuring device with TSAP-Win software (Rinn, 2003). Approximate age is therefore known for the sampled trees, in addition to diameter. For increment cores without pith, it is better to use the number of rings than approximate age. Missing pith was not corrected for due to many samples with pith eccentricity and large variations in juvenile ring-widths. The time necessary to grow to the sampling