Spatio-temporal variability of heartwood proportion in *Pterocarpus erinaceus* Poir.

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Research Article

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Abstract

Pterocarpus erinaceus Poir. is a species found in the Guineo-Sudanian and Sudano-Sahelian zones, known for its high-quality wood. However, there is limited understanding of its forestry and technological properties, which currently prevents its inclusion in reforestation programs. The objective of this study was to analyze the factors influencing heartwood variability in *P. erinaceus.* The study was conducted on 40 wood cores collected from three climatic zones (Sudanian, Guinean, and Sahelian). The results revealed significant variation in the percentage of heartwood across agroecological zones, with the highest percentage observed in the Sahelian zone (90.16 ± 3.21%) and the lowest in the Guinean zone (75.20 ± 6.85%). The study also found a significant correlation between the percentage of heartwood and tree diameter, as well as between the percentage of heartwood and tree age. Duraminization initiation was found to occur early in trees from the Guinean (14 years) and Sudanian (16 years) zones, while in the Sahelian zone, it starts at the age of 21 years. The results also reveal a decrease in duraminization rate with age, regardless of climatic zone.

1. Introduction

Duraminization is the process of forming heartwood, which is caused by the death of parenchyma cells accompanied by chemical and physical changes that affect wood quality and often determine its usability. Chemical changes during duraminization can result in significant changes in density, porosity, or moisture content (Morel 2013). Plazanet (2016) considers duraminization as a key physiological process that determines wood quality, as it contributes to its natural durability. This process can be related to the natural aging phenomenon, accumulation of air in cell tissues, and subsequent devitalization of parenchyma cells by microorganisms or mortality due to the accumulation of polyphenols reaching a threshold of toxicity (Polge 1982). Taylor et al. (2002) suggest that the formation of heartwood is accompanied by changes in enzymatic activity, extract formation, and death of parenchymal cells.

According to Taylor et al. (2002), the duraminization process is discontinuous with periods of inactivity during the year, and the proportion of sapwood in a tree is dependent on cambium growth. If cambial growth is greater than heartwood growth, then the sapwood proportion in a tree should increase, and vice versa. Several studies have shown that the mechanisms governing the transformation of sapwood into heartwood vary from one species to another. In some species, duraminization is rapid, while in others it is gradual, and the transition zone can span several growth zones and extend over several years (Morel 2013). For example, in species such as *Eucalyptus*, heartwood formation begins at around 5 years, 6–8 years in Cryptomeria japonica (Hillis 1987), 35 years in *Pinus canariensis* (Climent et al. 1993), and even over 100 years in *Alstonia scholaris* (Pallardy 2010; Hillis 1987). In Tectona grandis plantations in Togo, the initiation of duraminization is observed between 6 and 8 years depending on the site (Kokutse 2002). Furthermore, the proportion of sapwood to heartwood also varies between individuals depending on species, age (Hillis 1987), growth rate, silvicultural practices (Morataya et al. 1999), and environmental conditions.

Pterocarpus erinaceus, a highly sought-after timber species due to the quality of its wood (Segla et al. 2020), is known for its maximum heartwood with minimum sapwood desired by users. The heartwood of *P. erinaceus* is characterized by its greater hardness (12), density of approximately 0.9 g/cm3, relatively low tangential (5.8%) and radial (3.3%) shrinkage, and high modulus of elasticity (16070 MPa) (Segla et al. 2020). Additionally, *P. erinaceus* heartwood exhibits very high durability (Cirad, 2003), making it suitable for outdoor use, and an attractive color for cabinetmaking (Segla 2016). Therefore, studying the factors influencing heartwood and its variability, as well as understanding the initiation age and expansion rate of heartwood, are crucial for guiding the silviculture of *P. erinaceus* and developing strategies for efficient wood production while preserving its quality. In the case of *P. erinaceus*, incorporating these parameters into breeding programs aligns with the current strategy that emphasizes not only tree growth, survival, and shape traits, but also wood quality criteria (Li et al. 1999). These criteria can be integrated with silvicultural and genetic information of the species to optimize gains in both growth and wood quality.

The main objective of this study is to analyze the factors influencing heartwood variability in *Pterocarpus erinaceus*. More specifically, it involves: (i) analyzing the effect of climatic zones on heartwood proportion, (ii) studying the influence of tree age and diameter on the heartwood proportion, and (iii) determining the age of heartwood initiation in *P. erinaceus*.

2. Materials and methods

2.1. Description of the study area

Data collection was carried out in three West African countries located in different climatic zones (Fig. 1): Burkina Faso, Niger and Togo.

- The Sudanian and the Guinean zone were sampled in Togo. Annual rainfall in the Sudanian zone ranges between 800 and 1 300 mm and in the Guinean zone between 1 000 and1 600 mm. Average temperature ranges from 26 to 28°C in the plain and drops to 24°C at altitude. Average relative humidity ranges from 70 to 90% in Guinea and from 50 to 70% in Sudan. The soils are of the tropical ferruginous type, with some soils developed on alluvium, poorly evolved soils and low humiferous soils in the Sudanian zone. In the Guinean zone, the soils are essentially mainly tropical ferruginous, shallow vertisols, ferralitic and poorly evolved soils, hydromorphic soils, humified with vertisols.

- Only the Sudanian zone was sampled in Burkina Faso. The latitude of the north Sudanian zone is between 11°30' and 14° North, where rainfall ranges from 600 to 900 mm and the average annual temperature is 28°C. The latitude of the south Sudanian zone is south of 11°30' North, rainfall ranges from 900 to 1 200 mm and the average annual temperature is 27°C. Average relative humidity in the southern Sudanian zone varies from 25–85% and in the northern Sudanian zone from 23–75%. Ferric leachates are generally not very fertile (Ouattara et al. 2006).

- In Niger, the Tamou Wildlife Reserve and the W Park located in the Sahelian zone were sampled. Average annual rainfall recorded at Tamou weather station for the period 1988 to 2007, was 606 mm. The average annual temperature is around 36.7°C.

2.2. Sampling

The study was conducted on wood cores with a diameter of 10 mm from the aforementioned three climatic zones (Segla et al. 2020). In Burkina Faso, 10 core samples were collected from Cassou forest. In Niger, 10 core samples were taken from Tamou Wildlife Reserve located in the Sahelian zone. In Togo, 20 core samples were taken from three different sites: Oti-Kéran Park (7 trees) in the Sudanian zone, Abdoulaye forest (7 trees) in the Guinean zone, and Togodo Wildlife Reserve (6 trees) also in the Guinean zone. The trees studied were sampled from observation plots of 1000 m² (40 m x 25 m) in *P. erinaceus* stands characterized by densities of 1.17 ± 0.8 trees/ha in the Sahelian zone, 35.05 ± 41.2 trees/ha in the Sudanian zone, and 74.9 ± 1.4 trees/ha in the Guinean zone, respectively (Table 1). The average tree diameter ranged from 26.63 ± 7.89 cm in the Guinean zone to 49.63 ± 19.44 cm in the Sahelian zone, with noticeable variability (CV = 53.6%) in the Sudanian zone, where the average diameter was 29.02 ± 15.44 cm. A significant difference for this parameter was also observed among the three zones (P < 0.001). The annual increase in diameter (AID) and annual increase in height (AIH) did not show any significant differences between the zones in these stands (Table 1) (Segla et al. 2020).

Table 1
Forest characteristics of *P. erinaceus* according climatic zone.

Structural parameters		Zones			Probability
		Sahelian	Sudanian	Guinean	
Density (trees/ha)	av ± sd	1.2 ± 0.8^{a}	35.05 ± 41.2^{b}	74.9 ± 1.4^{c}	< 0,001
	CV (%)	64.1	117.5	1.92	
Diameter (cm)	av ± sd	49.63 ± 19.44	29.02 ± 15.44	26.63 ± 7.89	0.01
	CV (%)	39.16	53.2	40.68	
AID (cm/an)	av ± sd	1.10 ± 0.1^{a}	0.94 ± 0.04^{a}	1.03 ± 0.04^{a}	> 0.05
	CV (%)	33	19	20	
AIH (m/an)	av ± sd	0.35 ± 0.02^{a}	0.41 ± 0.02^{a}	0.40 ± 0.02^{a}	> 0.05
	CV (%)	28	42	36	

NB: av. = average; sd = standard deviation; Superscript letters are different when the corresponding values for the parameter described are significantly different among the three zones.

AID: Annual increase in diameter; AIH: Annual increase in height

2.3. Data taken from wood cores

For each core sample, total rings number (tree age), duraminized rings number (heartwood age) and number of rings in sapwood (sapwood age) are determined by counting annual growth rings. The rings were read on an uncut half of each wood core. The cross section of each half wood core was smoothed using sandpaper with successively finer grains. A binocular magnifying glass connected to a computer was used to read the annual dark circles, which rendered the ring boundaries visible (Photo 1). The axial parenchyma cells made it possible to delimit the growth rings thanks to alternating bands that are thicker, shorter and sinuous at the beginning of the increase and thinner and straighter at the end of the increase. The narrowness of the rings in some trees made counting difficult but double counting made it possible to judge the age to approximately a year.

2.4. Data processing

The measurements allowed for the determination of the heartwood proportion of *P. erinaceus* using Rolland's (1996) formula:

$\mathrm{HP} = \mathrm{HRL}.\frac{(2.\mathrm{CSL}-\mathrm{HRL})}{\mathrm{CSL}}.100(\%\ )$. HP = heartwood Proportion; HRL = heartwood radial length (cm) and CSL = core sample length (cm). Thus, the variability of heartwood was analyzed according to climatic zones, as well as tree diameter and tree age. The measurements also enabled the determination of the initiation age of heartwood in *P. erinaceus* using regression analysis, with the number of heartwood rings as the explained factor and the total age as the explanatory factor. The intersection point of the two axes represents the initiation age of duraminization. The general linear form [$y = a.x + b$] was chosen for this analysis, although a polynomial model of order 2 [$y = a.\ x^2+b.x + c$] can also be used. However, it should be noted that while the polynomial model has shown good fit in some literature examples, adjustments to data may sometimes result in a negative initiation age (Longuetaud 2005; Rhabi et al. 2014). The expansion rate of *P. erinaceus* heartwood was also assessed by estimating the duraminization rate in centimeters per year (Rhabi et al. 2014). The correlations between tree age and heartwood proportion, as well as between tree diameter and heartwood proportion, were also analyzed.

3. Results

3.1. Variability in heartwood proportion across climatic zones

Variability in heartwood proportion according to agroecological zones was analyzed for *P. erinaceus*, and differences were observed among the three zones considered (Fig. 2). The highest heartwood proportion was found in the Sahelian zone (90.16 ± 3.21%), while the lowest was in the Guinean zone (75.20 ± 6.85%). In the Sudanian zone, it was 81.02 ± 6.72%. Variance analysis revealed that the differences observed among these three zones were statistically significant ($P < 0.001$).

3.2. Effect of age on heartwood proportion in *P. erinaceus*

The results show that tree age significantly influences the heartwood proportion of *P. erinaceus* in all three climatic zones ($P < 0.05$) (Table 2). Specifically, the heartwood proportion increases with tree age, as observed in Fig. 3. The average rate of annual increase in heartwood is higher in the Guinean zone (3%/year), while it is 2.63%/year and 2.37%/year in the Sudanian and Sahelian zones, respectively.

Table 2
Effect of age on the heartwood proportion

Zone	Coefficient de Pearson	P value
Guinean	0.65	0.002
Sudanian	0.69	0.000
Sahelian	0.62	0.017

3.3. Influence of tree diameter on heartwood proportion

Heartwood proportion increases significantly ($P < 0.05$) with tree diameter regardless of the climatic zone, as shown in Fig. 4. Therefore, heartwood proportion in P. *erinaceus* stands is dependent on tree diameter. Variations in heartwood proportion among different climatic zones could be explained by differences in growth rate. Comparison of tree diameters from the climatic zones revealed significant differences ($P = 0.012$), with trees in the Sahelian zone being, on average, the largest and oldest, and therefore having the highest heartwood proportion. The variation in tree diameter and age can be attributed to the different uses of the species in the various zones. In the Sahelian zone, *P. erinaceus* is rarely or never exploited as timber but is frequently pruned to feed livestock, resulting in stands consisting of trees with large diameters.

3.4. Initiation of duraminization

Regression analyses involving heartwood age and tree age to determine heartwood initiation age in *P. erinaceus* yielded significant models ($P = 0.000$) with R^2 values ranging from 0.96 to 0.98 (Table 3 and Fig. 5). The results indicate that duraminization, or heartwood initiation, occurs at an earlier age for trees from the Guinean and Sudanian zones, starting at approximately 14 and 16 years of age, respectively. In the Sahelian zone, duraminization begins at around 21 years of age. These findings suggest the existence of a duraminization initiation gradient that takes into account climatic zones, with trees growing in arid climates tending to delay the onset of this process.

Table 3 Models of the heartwood age as a function of the tree age

Zone	Model	R^2	P value	X: Y=0
Guinean	HA = 1.31TA – 18.49	0.98	0.000	14.11
Sudanian	HA = 1.10TA– 17.03	0.96	0.000	15.58
Sahelian	HA = 1.21TA – 27.40	0.98	0.000	20.91

HA: Heartwood age; TA Tree age

3.5. Heartwood expansion in P. erinaceus

The expansion of heartwood in *P. erinaceus* does not vary significantly according to climatic zones (Fig. 6) ($P > 0.05$). Trees in the Guinean zone have an average annual duraminization rate of 0.42 ± 0.08 cm/year. In this zone, the rate varies from 0.29 cm/year to 0.64 cm/year. In the Sudanian zone, the average duraminization rate is 0.46 ± 0.087 cm/year. In the Sahelian zone, this rate is on average 0.42 ± 0.072 cm/year, varying from 0.22 cm/year to 0.62 cm/year.

The results also reveal a decrease in duraminization rate with age, regardless of climatic zone (Fig. 7). The curves exhibit the same profile, indicating that ecological factors do not significantly affect this trend. However, it should be noted that the decrease rate in duraminization is relatively higher and statistically significant in the Sahelian zone.

4. Discussion

The present study has enabled the collection of information on the spatio-temporal evolution of duraminization in *P. erinaceus*, which can guide its silviculture practices that have not been well understood until now. The results indicate that the initiation age of duraminization in *P. erinaceus* is early in the Guinean zone (14 years) and Sudanian zone (16 years), while in the Sahelian zone, it begins at 21 years. These findings reveal the existence of a duraminization gradient that is influenced by climatic zones, taking into account the vitality of the stands and the bioclimatic position of the trees, as demonstrated by Rabhi et al. (2014) in their study on *Cedrus atlantica Manetti*. In fact, trees growing in arid climates tend to delay the onset of duraminization. De Kort (1993) and Björklund (1999) concluded that duraminization tends to start at very early ages in most trees under favorable environmental conditions. However, the initiation of duraminization may vary depending on the species and provenance. In teak, for example, duraminization begins quite early (around 7 years) in Togo (Kokutse 2002). Björklund (1999) also confirms that initiation age varies within the same species; in Pinus sylvestris, for example, it is 30–40 years in Finland and Germany (Kuhn 1918), but 25 years in Sweden (Fries and Ericsson 1998). Today, strategies must be adopted to produce wood in a minimal time frame while preserving its quality. Establishment of plantations in Guinean and Sudanian zones based on results obtained in terms of heartwood initiation age, which is early in these zones, will not only allow for rapid reconstitution of degraded stands of *P. erinaceus* (Segla et al. 2015), but will also enable the production of heartwood with interesting technological characteristics. This is because, according to Segla et al. (2020, 2015), *P. erinaceus* wood properties are not influenced by cambial age. In these two zones, for trees aged 30 to 35 years, on average, 79.04% and 80.77% of the wood surface is transformed into heartwood (in Guinean and Sudanian zones, respectively) for average diameters of 32.5 cm and 31.93 cm, respectively. This shows that the minimum exploitation diameter of 35 cm, as determined by Segla et al. (2015) for *P. erinaceus* in the Guinean and Sudanian zones, for a rotation period estimated at 20 years, is appropriate.

In terms of variability, the proportion of heartwood varies significantly among different zones. The highest proportion of heartwood is obtained in the Sahelian zone, while the lowest proportion is observed in the Guinean zone. This variability is related to the differences in growth rates, including the diameter of trees studied in the three zones. The average diameter of trees is significantly different among the three zones, which may explain the variations in heartwood proportion. The differences in tree diameter studied are associated with the different uses of *P. erinaceus* in the various zones. In the Sahelian zone, where *P. erinaceus* is rarely or never harvested as timber but frequently cut for livestock feed, stands consist of large-diameter trees. This is consistent with the findings of Rabiou et al. (2015). Regardless of the effect of diameter on the heartwood proportion, the results seem to show a trend of heartwood evolution according to a climatic gradient (decreasing rainfall), from humid to arid. These results are consistent with those of Rabhi et al (2014) who noted a trend in the evolution of the proportions of Atlas cedar heartwood according to a bioclimatic gradient, from very humid to semi-arid. According to Pinto et al. (2004), the most favorable growth conditions are conducive to the formation of a thick sapwood. This is confirmed by Climent et al. (1993), who affirm that sapwood is more closely linked to annual precipitation than heartwood

The proportion of heartwood in *P. erinaceus* is also influenced by tree age, regardless of the climatic zone considered. These results align with the observations of Rabhi et al. (2014) on *Cedrus atlantica*, where tree age was found to influence heartwood proportion. Similarly, De Kort (1993) showed that the oldest balsam fir trees have the lowest rate of sapwood, unlike the youngest trees. Thus, age can be considered a predictor of heartwood proportion in *P. erinaceus*. This information can be useful for foresters and end-users to predict timber quality in stands and make decisions on when to harvest *P. erinaceus*, a species that is highly exploited for timber. However, it should be noted that cambial activity decreases with tree age. In the present study, there is a decrease in heartwood rate expansion as a function of tree age, regardless of the climatic zone. Curves with similar profiles confirm that ecological factors do not significantly affect the rate of duraminization. The rate of duraminization is measured as 0.42 ± 0.08 cm/year in the Guinean zone, 0.46 ± 0.087 cm/year in the Sudanian zone, and 0.42 ± 0.072 cm/year in the Sahelian zone. This result is consistent with the findings of Kokutse (2002) who demonstrated in teak that duraminization reaches its maximum level around 35–40 years. According to Kokutse (2002), beyond this age, the proportion of heartwood no longer varies significantly even if growth in trunk diameter is favored. This is also supported by Ferguston (1934), who stated that sapwood width remains constant even if the diameter of the trunk increases beyond this age.

5. Conclusion

The present study aimed to analyze the duraminization process in *P. erinaceus*. The results showed variability in heartwood proportion depending on climatic conditions, with the Sahelian zone exhibiting a higher proportion of heartwood, which can be explained by the variations in tree diameter between the different climatic zones. The study also revealed that climatic zones influence the initiation age of duraminization in *P. erinaceus*, with duraminization starting early (14 years) in the Guinean zone and late (21 years) in the arid zone. Furthermore, the heartwood expansion rate was found to decrease with tree age and was not dependent on environmental conditions. These findings provide useful information for foresters regarding the behavior of this species, which may be subject to plantation programs.

Declarations

Acknowledgements

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Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by KNS, HR, KA, DG, PL and GC. The first draft of the manuscript was written by KNS and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability

The datasets collected, generated and analysed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

There is no confict of interest.

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Photos

Photo 1 is available in the Supplementary Files section

Figures

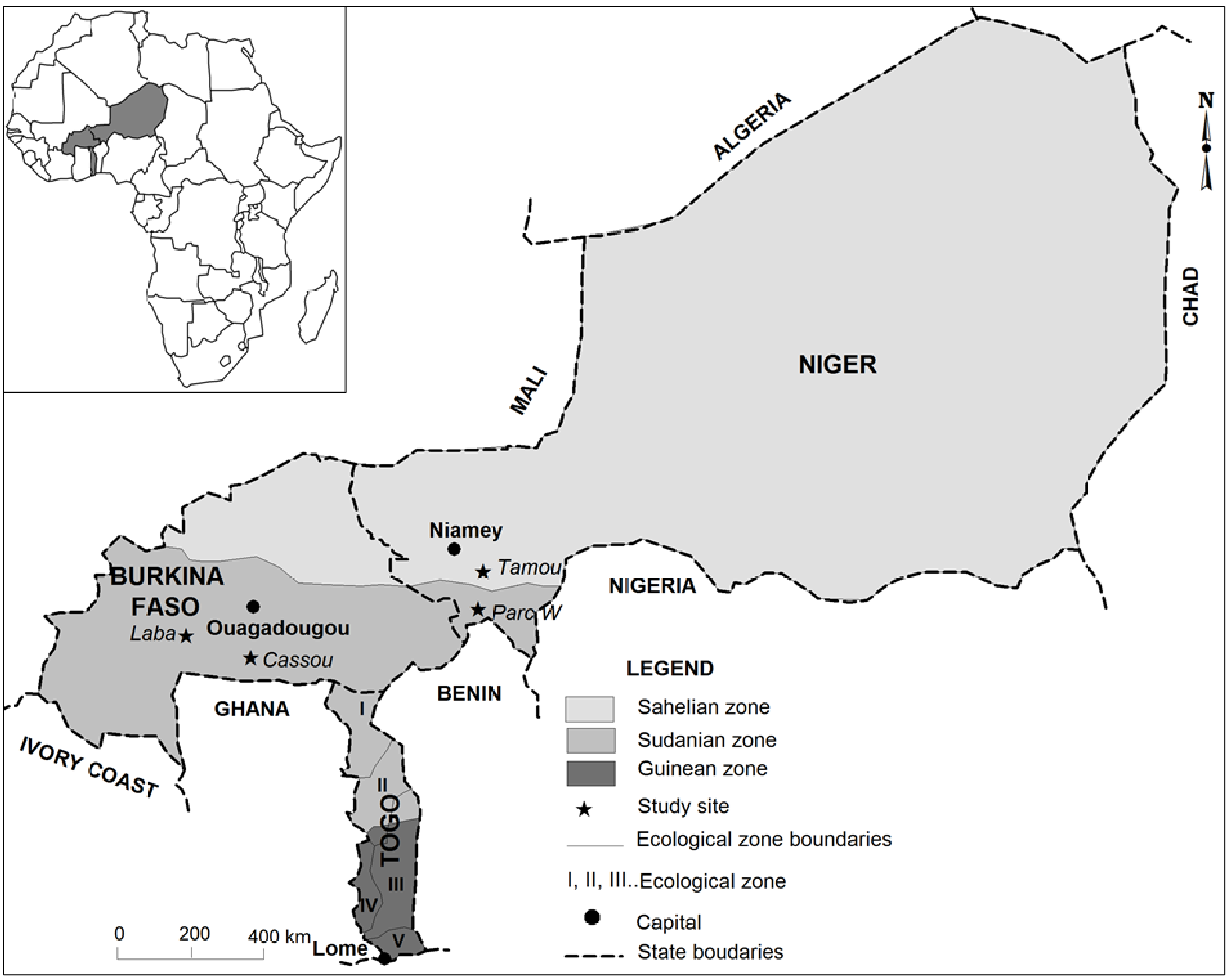

Figure 1

Location of the study area

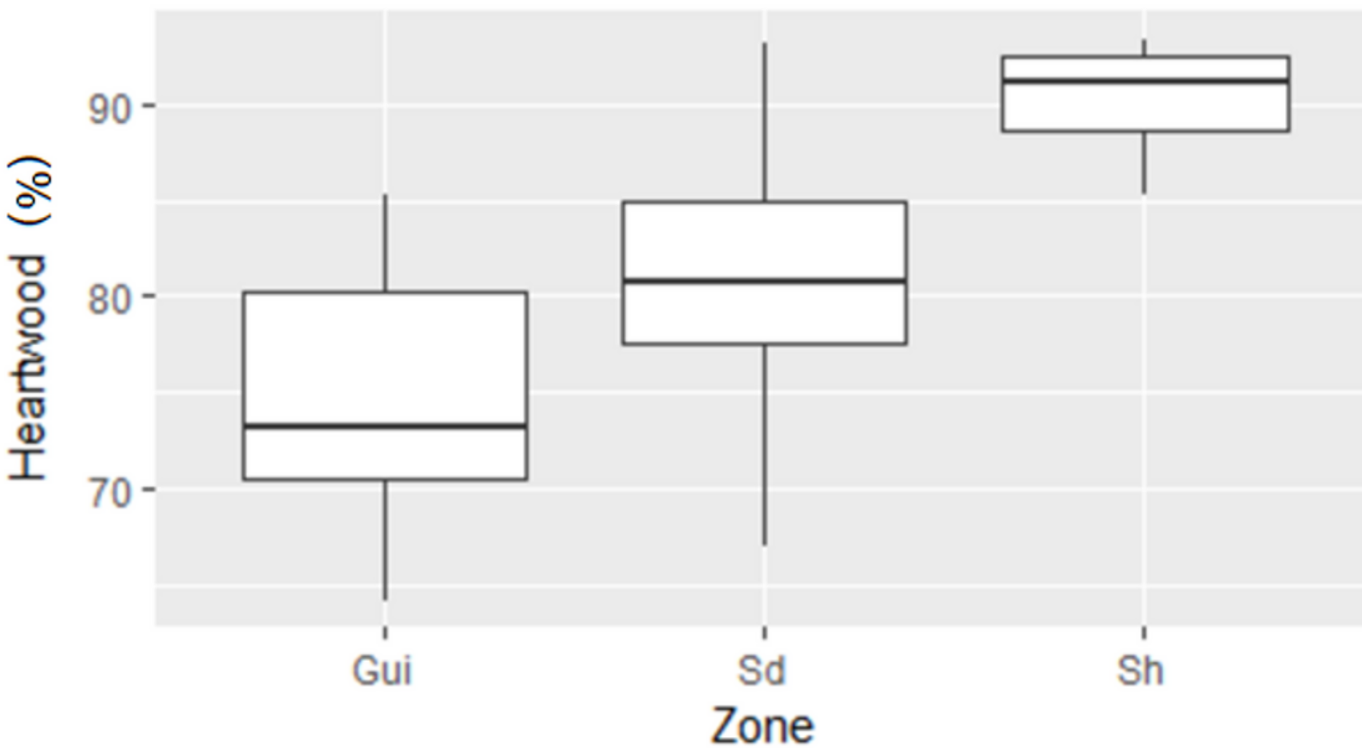

Figure 2

Heartwood proportion according to climatic zones

Gui: Guinean; Sd: Sudanian; Sh: Sahelian

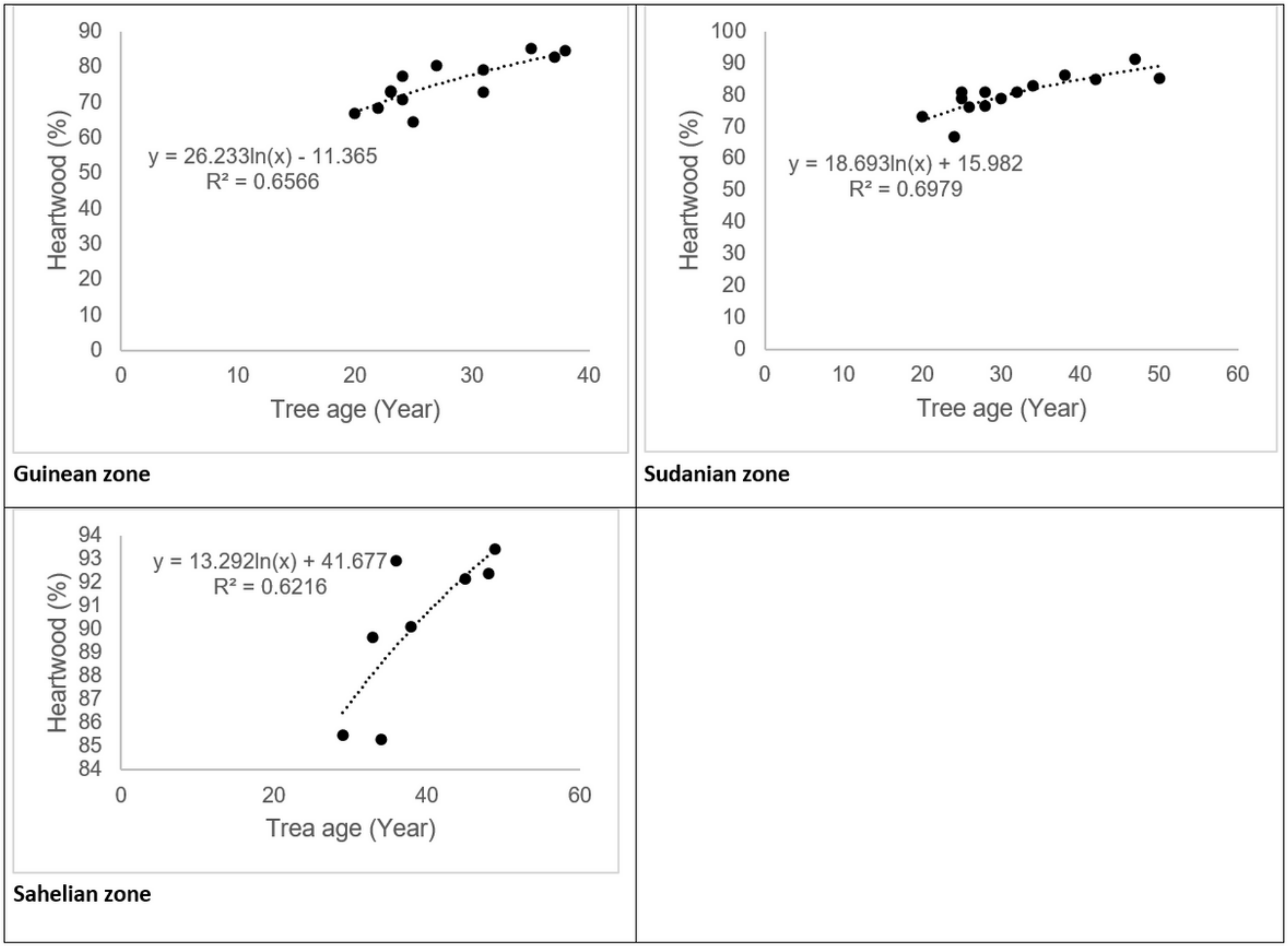

Figure 3

Evolution of heartwood proportion as a function of age

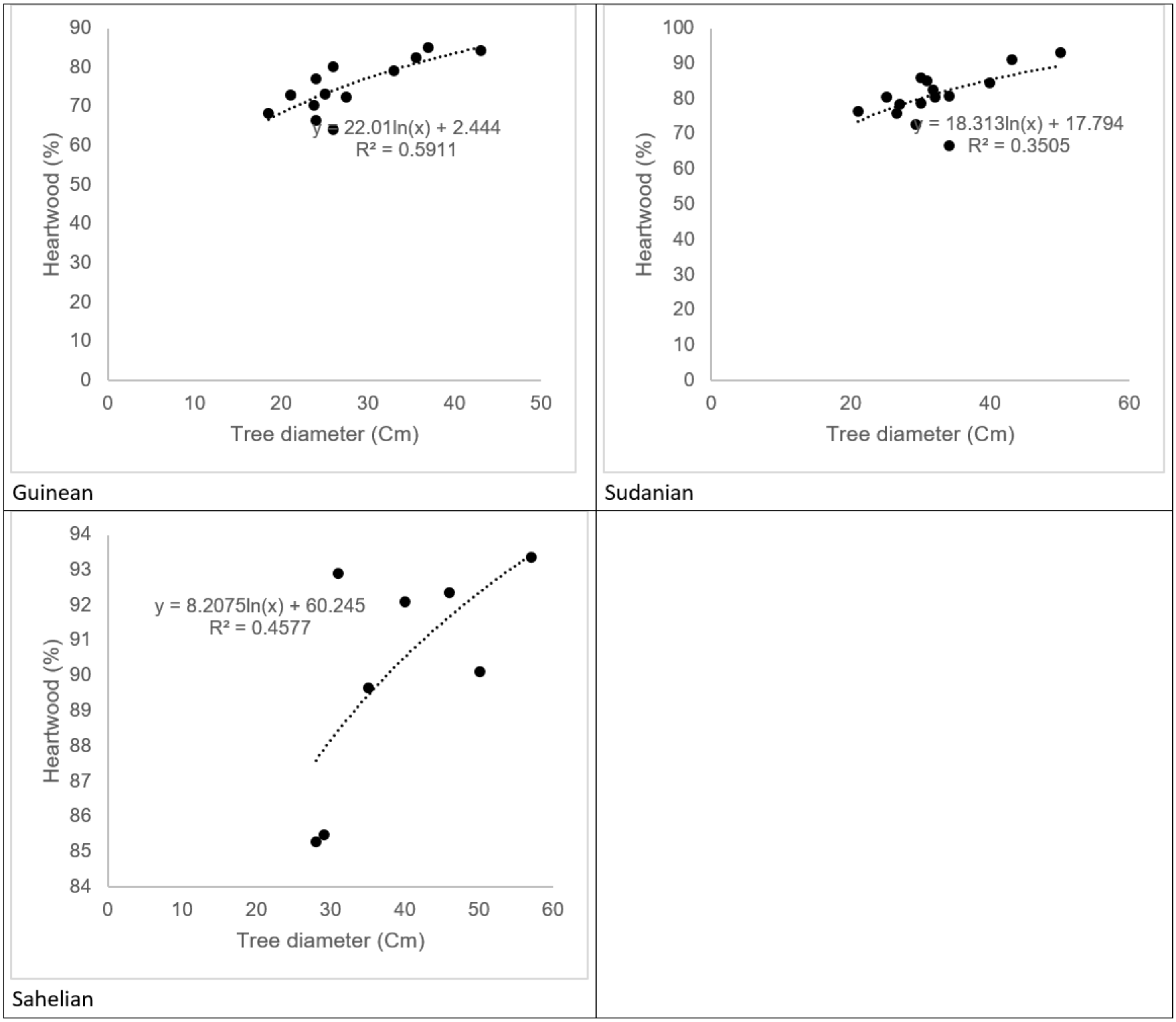

Figure 4

Relationship between heartwood proportion of tree diameter

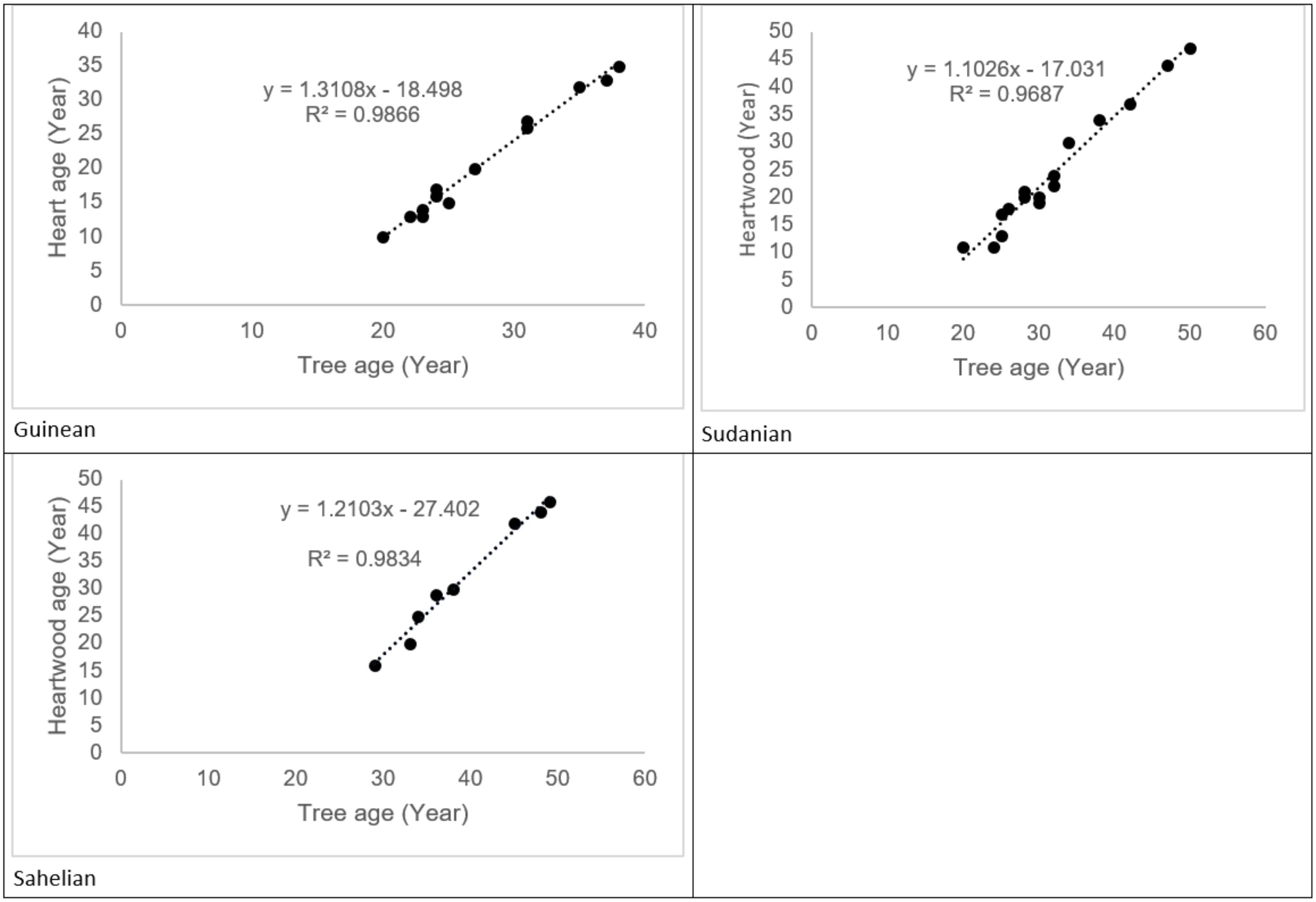

Figure 5

Models of heartwood age as a function of tree age

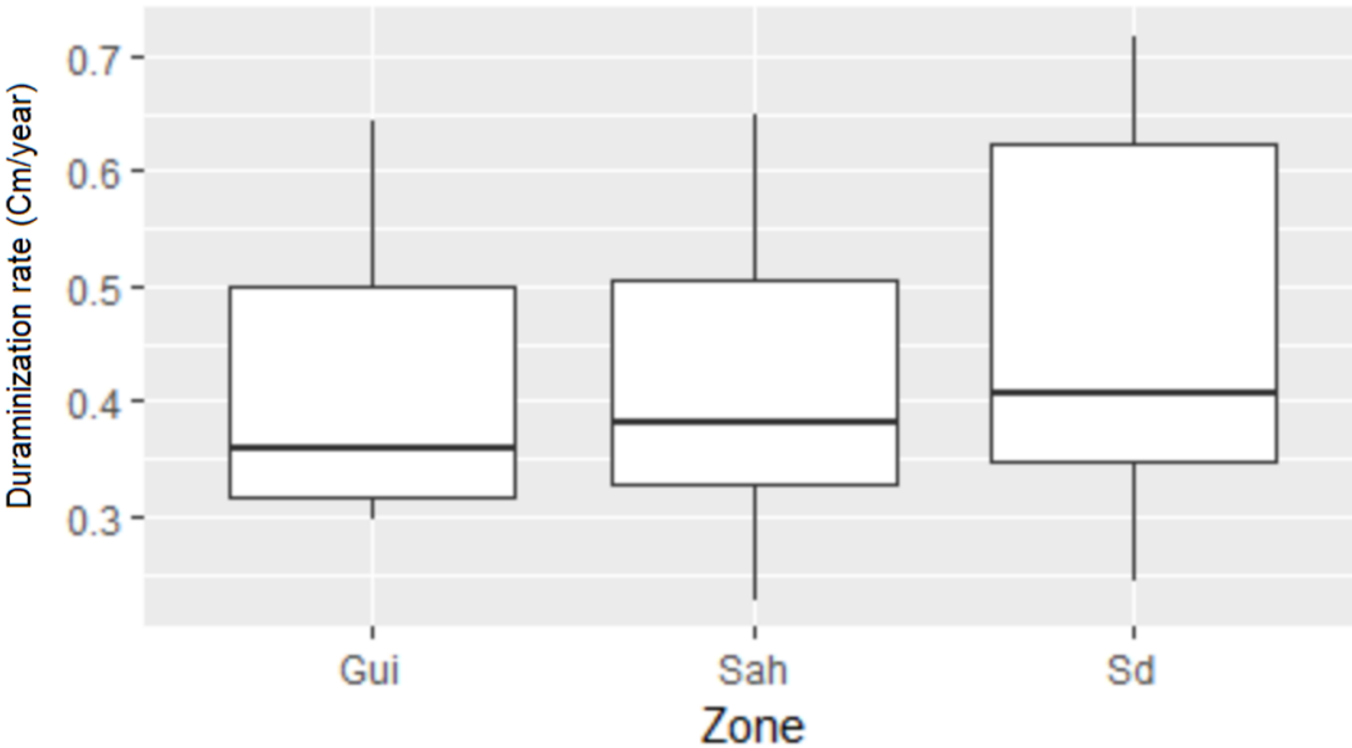

Figure 6

expansion rate of heartwood

Gui: Guinean; Sd: Sudanian; Sh: Sahelian

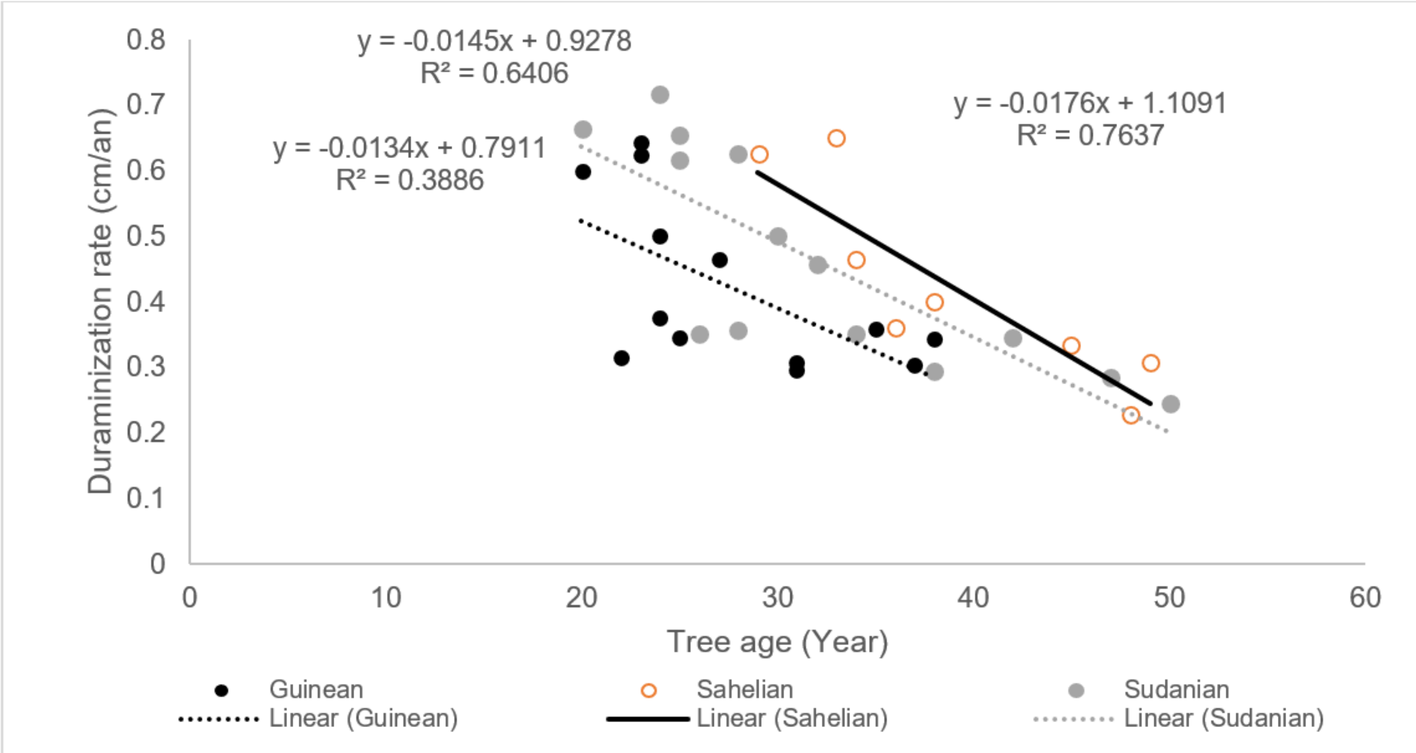

Figure 7

Evolution of duraminization rate in *P. erinaceus*as a function of tree age

Supplementary Files

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- P1.png