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Post Debarking Response of *Prunus africana* (Hook. F) Kalkman (*Rosaceae*) Trees at Two Exploitation Sites in North Kivu (Eastern Democratic Republic of Congo)

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Abstract

Prunus africana is a species of great economic, medicinal and ecological importance. Due to its multiple uses, unsustainable exploitation methods and low regeneration capacity in tropical rainforests, this species is threatened with extinction. Present and exploited in the eastern part of DR Congo, knowledge of the dynamics of post-bark regeneration of *Prunus africana* remains fragmentary and poorly known. In North Kivu province, this species thrives in both afromontane forest and lowland tropical rainforest habitats. In order to contribute to the rational and sustainable exploitation of *Prunus africana* in this province, this paper was carried out with the objective of contributing to the knowledge of the dynamics of the regeneration of post-harvest bark of *Prunus africana* in two exploitation sites (low and high altitude). To achieve this objective, the inventory was conducted on 16 plots of 25 hectares each, with 8 plots per site. Dendrometric parameters (diameter at breast height (DBH), total tree height) and tree growth and regeneration parameters, i.e., stem bark thickness of the unharvested and harvested portions of the trees (bark reconstitution) were measured. A total of 716 barked stems of *Prunus africana* in 2016 in 25 hectares constituted the study sample. Results show that sites do not influence diameter at breast height of *P. africana* trees ($p > 0.05$) or total tree height. The bark diameter of harvested trees and the bark diameter of unharvested trees varied significantly by site ($p < 0.05$). In contrast, the annual growth rate of bark differed with altitude; the highest rate was observed in trees growing at high altitude (2.97 ± 0.9 mm/yr) compared to 2.23 ± 0.74 mm/yr at low altitude. In view of these results, this study indicates that a half-rotation of 7 years could allow an effective reconstitution of the bark of *Prunus africana* at the second passage on the remaining side of the same stem.

Keywords

Dendrometric Parameters, Regeneration Capacity, Tree Reconstitution Rate, Debarking, *Prunus africana*, DR Congo

1. Introduction

Tropical forests, including those of the Congo Basin, are important carbon storage sinks (Robert & Saugier, 2003; Laporte et al., 2010; Lewis et al., 2013). They address the crucial issue of climate balance in the world (Lescuyer & Cerutti 2013). These forests are a source of survival because of the different ecosystem services they provide to local communities (food and medicinal plant supply, sacred places of cultural initiations and traditional rites, global climate regulation, water purification, heat island mitigation, etc.) (Martinez et al., 2009; Dinerstein et al., 2013; Cuni-sanchez et al., 2016). In the Congo Basin, the Democratic Republic of Congo (DR Congo) occupies an important place in terms of forest cover. Indeed, it is the African country with the best forestry potential with its 128 million hectares of dense rainforests, which represents 54% of the national territory, 47% of the continent's tropical forest and 6% of the world's remaining forests. In addition, the Congolese forests contain a great biological diversity (flora and fauna) and also offer important ecosystem services to the populations as they serve as sources of food, medicine or other services (Lescuyer & Cerutti, 2013). In addition, dense tropical rainforests abound in multiple resources of products and services that increasingly contribute to the improvement of social and economic well-being of households (Betti & Lejoly, 2010).

Prunus africana (Hook. F.) Kalkman (*Rosaceae*), commonly known as Pygeum, is a species of Afromontane forests at altitudes of 900 - 3000 m (Tassiamba et al., 2022; Ingram et al., 2009) and grows well on volcanic soil and in cool, high-altitude climates. Its range extends from Ivory Coast, Bioko Island, Sao Tome, Ethiopia, Kenya, Uganda, Burundi, Rwanda, Republic of Congo, Cameroon, and the Democratic Republic of Congo to South Africa and Madagascar (Betti, 2008). In the Democratic Republic of Congo, *Prunus africana* has been reported in four provinces namely: the Eastern Province, Katanga, North Kivu and South Kivu (Muhesi & Mate, 2018). Considering its range, *Prunus africana* populations are discontinuous and fragmented (Kembelo, 2008). Furthermore, the importance of *P. africana* lies in the medicinal virtues of its bark extracts used for the manufacture of more than 19 drugs, sold on the European and American markets and intended for the treatment of benign prostatic hypertrophy (Cunningham et al., 2002).

Traditionally, *P. africana* has multiple uses (Ingram et al., 2009). It produces lumber used to make tool handles and poles for house and fence construction, as well as firewood, especially for charcoal (Fashing, 2004; Stewart, 2003). The major importance of *Prunus africana* is related to its bark. Indeed, the bark of the tree is used by traditional medicine in the treatment of prostate problems, traditional products derived from it are used as medicines against gastritis disorders and infusions of the bark treat inappetence, urinary and bladder disorders, chest pain, malaria, microbial infections and kidney diseases (Betti, 2008; Bii et al., 2010; Jeruto et al., 2011; Otieno & Analo, 2012; Mwitari et al., 2013; Koros et al., 2016). Internationally, *P. africana* bark extracts are used medicinally to treat benign adenoma and benign prostatic hyperplasia which is common in elderly men (Cunningham et al., 2002; Fashing, 2004; Betti, & Ambara, 2013; Betti et al., 2014).

Despite its multiple uses, the distribution of *Prunus africana* is very vulnerable and this variability is becoming increasingly noticeable in the face of global warming. This situation sufficiently demonstrates that in situ and ex situ conservation of this species will be a solution to global warming (Mbatudde et al., 2011). For several decades, timber exploitation has been the only source of income from forests. As a result, other forest resources such as non-timber forest products (NTFPs) have been of less concern to stakeholders. Currently, the importance of NTFPs in household incomes and even in the accumulation of wealth at the national level can no longer be denied. Among these NTFPs, the bark of *Prunus africana* ranks high and is produced in about twenty countries in sub-Saharan Africa (ICCN, 2021). However, Africa remains the third largest exporter of this bark after Cameroon and Kenya with an annual average of 1600 tons in the years 1995-2004 (Cunningham et al., 2002).

In this context, the demand for *Prunus africana* bark as well as wood from other species is of concern to scientists, civil society actors and environmental non-governmental organizations. Several authors such as (Muhesi & Mate, 2018) have already reported the lack of natural regeneration and low levels of recruitment of *Prunus africana* under a dense canopy of forests in its range. In the face of this situation marked by excessive harvesting of bark for commercial purposes, the natural population of *P. africana* has seriously declined and the species has found itself listed in Appendix II of the Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES) (Tonye et al., 2000). In practical terms, the listing of this species in Appendix II means that its trade is authorized but remains under control and is carried out in strict compliance with the rules of exploitation and sustainable management in force.

As such, this study on the knowledge of the dynamics of the regeneration of post-debarking of *Prunus africana* in North Kivu Province is essential. This paper has two specific objectives: 1) to study the regeneration dynamics of *Prunus africana* bark after exploitation in two sites in North Kivu and 2) to study the influence of altitude on growth parameters (tree diameter, bark diameter, tree height etc.) and regeneration of *Prunus africana*. The results of this study are of major importance. They will help raise awareness among stakeholders in the *P. africana* production chain (local actors, members of civil society, local and international non-governmental organizations, etc.) about the rational and responsible management of this species. This study will also help guide the Ministry of the Environment and Sustainable Management in developing effective and dynamic strategies to manage the resource and ensure the application of prescribed harvesting techniques in the field. Ultimately, the study will contribute to the improvement of forest governance rules and the consideration of the regeneration of this endangered species in sustainable management policies.

2. Study Area and Methods

2.1. Study Area

The study was conducted at two *Prunus africana* harvesting sites in North Kivu Province (**Figure 1**). A dense network of in situ measurements would constitute the most reliable set of these data; however, East Africa suffers from a shortage of rain gauges. This shortage of rain gauges is even more prevalent in mountainous regions such as the Ruwenzori Mountains, where the complex topography makes it difficult to install and maintain measuring stations (Nakulopa et al., 2022). Therefore, for these regions, precipitation estimates from satellites or climate model simulations are often used as alternative sources of precipitation data (Jacobs et al., 2016; Nakulopa et al., 2022). That's why these two sites are described using climate data from the National Aeronautics and Space Administration (NASA) POWER database (https://power.larc.nasa.gov/data-access-viewer/). Five parameters whose monthly data cover a period from 1981 to 2021 were directly via this site: precipitation or rainfall (P), mean temperature (Tme), minimum temperature (Tmin), maximum temperature (Tmax), and relative humidity (RH).

2.1.1. Ruwenzori-Lume Site

This site is located in the Ruwenzori Sector in Beni Territory at latitude 0.49661 North and longitude 29.45314 East. **Figure 2** shows the umbrothermal diagram for the Ruwenzori-Lume site.

Rainfall in Ruwenzori-Lume varies from 580 to 1713.9 mm per year with an average of 1085.7 ± 236.33 mm. The umbrothermal diagram shows the existence of four seasons, including two dry seasons (January-February and June-July) with total rainfall of less than 80 mm and two rainy seasons (March-May and August-December) with total rainfall of more than 80 mm (**Figure 2** and **Table 1**). Estimates obtained by previous work confirm the precipitation values obtained in this study. Indeed, the Ruwenzori Mountains like other regions of East Africa experience great rainfall variability, both in time and space (Nakulopa et al., 2022). In the Ruwenzori Mountains, the temporal variation of rainfall is characterized by a bimodal pattern with a rainy season from March to May and

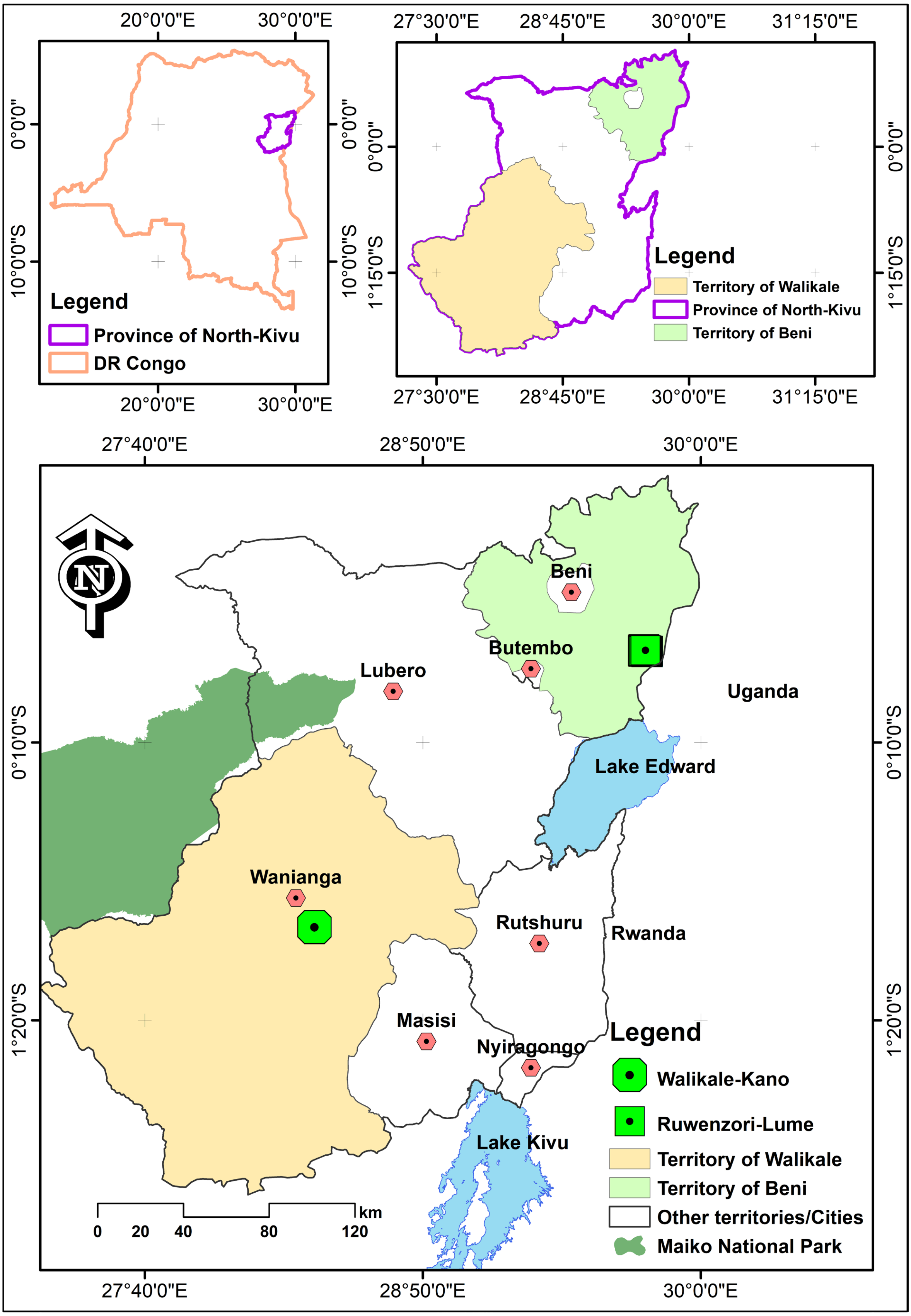

Figure 1. Localization of two exploitation sites (Ruwenzori-Lume and Walikale-Kano) in eastern DR Congo.

Table 1. Average values of climatic parameters according to the months of the year (period 1981-2021) in Ruwenzori-Lume.

Months	P (mm)	Tme	Tmin	Tmax	RH
January	53.76 ±44.08	22.36 ± 0.84	15.74 ± 0.77	30.80 ± 1.77	67.77 ± 5.51
February	52.86 ± 32.13	23.21 ± 0.87	16.34 ± 0.77	32.12 ± 1.67	64.80 ± 6.01
March	104.44 ± 60.91	22.99 ± 0.82	16.85 ± 0.61	31.74 ± 1.72	69.49 ± 5.10
April	127.05 ± 50.36	21.94 ± 0.68	16.52 ± 0.57	29.54 ± 1.83	76.37 ± 3.89
May	113.03 ± 40.65	21.39 ± 0.59	15.90 ± 0.80	28.26 ± 1.45	77.63 ± 3.79
June	44.83 ± 35.55	21.53 ± 0.75	15.58 ± 1.14	28.96 ± 1.43	70.50 ± 4.87
July	47.02 ± 36.89	21.76 ± 0.75	15.06 ± 1.07	29.49 ± 1.24	65.30 ± 5.16
August	78.64 ± 33.25	22.06 ± 0.56	16.00 ± 0.85	30.01 ± 1.23	67.36 ± 4.43
September	100.17 ± 42.85	22.07 ± 0.58	16.44 ± 0.69	29.79 ± 1.25	70.64 ± 4.01
October	139.73 ± 56.60	21.63 ± 0.57	16.49 ± 0.53	29.10 ± 1.55	74.86 ± 3.58
November	138.47 ± 52.59	21.21 ± 0.46	16.13 ± 0.48	27.70 ± 1.30	77.60 ± 3.26
December	85.72 ± 41.15	21.61 ± 0.69	15.63 ± 0.55	29.02 ± 1.60	73.29 ± 5.27

Legend: P is the average monthly precipitation (mm), Tme is the average temperature, Tmin is the minimum temperature and Tmax is the maximum temperature (in ˚C) and RH is the relative air humidity (%) for the period 1981 to 2021.

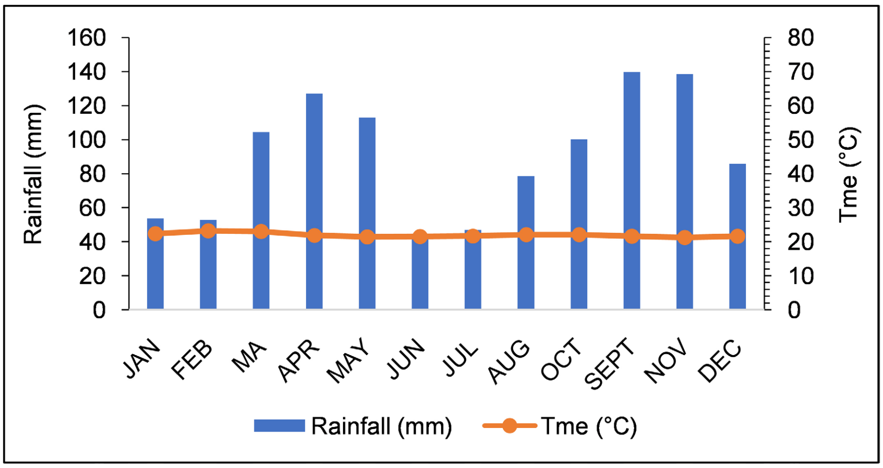

Figure 2. Umbrothermal diagram of the Ruwenzori-Lume region (period 1981-2021).

another from August to November (Jacobs et al., 2016; Taylor et al., 2009; Tibasiima et al., 2022), reflecting the twice-annual passage of the Intertropical Convergence Zone (ZCIT) in the region (Garelick et al., 2022; McGlynn et al., 2010; Russell et al., 2009; Taylor et al., 2009; Xue et al., 2017). Spatial distribution is controlled by orographic variation in mountain height (Jacobs et al., 2016; Nakulopa et al., 2022; Taylor et al., 2009). According to Nakulopa et al. (2022), the average annual precipitation is around 1500 mm per year. However, Russell et al.

(2009) and Garelick et al. (2022) report an average annual rainfall of 2500 mm per year, with monthly rainfall ranging from 80 to 100 mm/month during the dry seasons and up to 400 mm/month during the wet seasons. Furthermore, the orographic effect results in a general increase in mean annual precipitation from the foot of the Ruwenzori Mountains to the upper mean altitude (~3000 m) of the mountains. These factors justify the average values and their deviations obtained in this study. Furthermore, Taylor et al. (2006) found that due to the orographic effect, the mean annual precipitation fluctuates around 1540 mm at an altitude of about 1370 m and drops to 890 mm at an altitude of about 960 m. Similarly, Xue et al. (2017) indicate that mean annual precipitation increases from 1150 mm at ~1250 m altitude to 2500 mm at 3290 m altitude.

The minimum temperature (Tmin) during the year varies from 12.08˚C to 18.24˚C with an average of 16.06˚C. On the other hand the maximum temperature (Tmax) varies from 26.07˚C to 35.65˚C with an average of 29.71˚C. The average annual temperature (Tme) in the Ruwenzori-Lume area varies from 20.08˚C to 25.85˚C. The temperature values of our study site are similar to those reported by other research which indicates average temperatures of 23.3˚C in March-May and 22.9˚C in August-November (Tibasiima et al., 2022). As a function of the months of the year, the average temperature remains relatively stable although the averages of the dry seasons are slightly higher than the averages of the wet months (**Table 1**). The relative humidity of the air in the Ruwenzori-Lume region varies from 44.12% to 83.79%, with an average of 71.25% ± 6.37%. The presence of mountains in this region explains this high relative humidity. The altitude of the area where the inventory was conducted varies from 1888 to 2286 m with an average of 2119.5 m.

2.1.2. Walikale-Kano Site

This site is located at low altitude in the Wanianga sector in Walikale territory between −1.42970 South latitude and 28.0742 East longitude. **Figure 3** shows the umbrothermal diagram for the Walikale-Kano site.

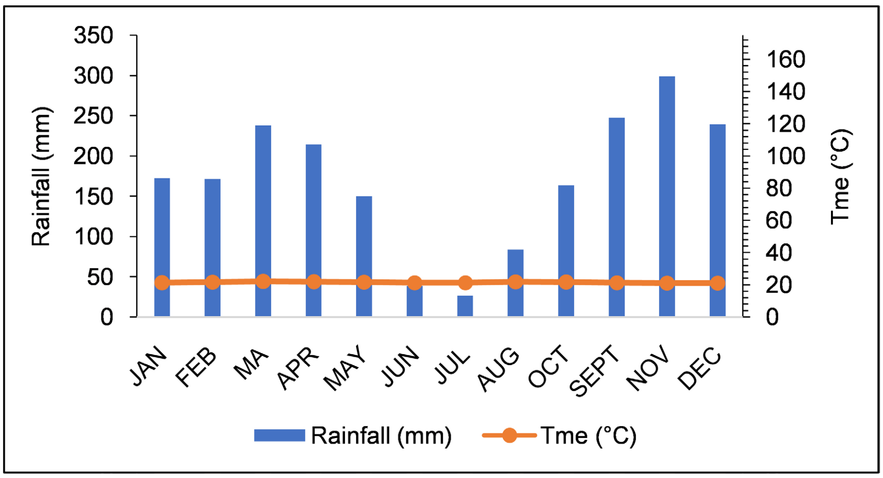

Figure 3. Umbrothermal diagram of the Walikale-Kano region (data from 1981-2021).

Unlike the Ruwenzori-Lume region, in the Walikale-Kane area, rainfall is abundant throughout the year and varies from 1271 to 3001 mm per year with an average of 2047 ± 426.55 mm per year. The average temperature (Tme) varies from 20˚C to 23.65˚C with an annual average of 21.66˚C. The maximum temperature (Tmax) varies between 26.44˚C and 33.76˚C with an annual average of 29.63˚C. Finally, the minimum temperature varies from 12.89˚C to 18.72˚C with an average of 16.17˚C. The seasons are not well marked compared to the Ruwenzori region. The umbrothermal diagram for the Walikale-Kano region shows a dry season (total monthly rainfall of less than 100 mm) between June and August, and two wet seasons (January-May and September-December) (**Figure 3**). The months of March-April-October-November-December have more water during the year (total monthly rainfall over 200 mm) (**Table 2**). Due to the high rainfall, the relative humidity remains high throughout the year and varies from 67.12% to 89.31% with an average of 82.75%. The altitude of the area where the species *Prunus africana* is distributed in Walikale-Kano varies from 1328 to 1580 m with an average of 1450 m.

The soils of two areas are kaolisols derived from parent rock that is predominantly clay (Eloge et al., 2022; Moïse et al., 2022a; Moïse et al., 2022b). Indeed, these soils in the highlands of extreme North Kivu are essentially crystalline clayey and weakly ferralitic and probably date from the Lower Cambrian (Achille et al., 2021).

Table 2. Average values of climatic parameters in the Walikale-Kano region according to the months of the year (period 1981-2021).

Months	P (mm)	Tme	Tmin	Tmax	RH
January	172.48 ± 87.97	21.40 ± 0.58	16.21 ± 0.60	28.62 ± 1.09	84.83 ± 2.17
February	171.45 ± 72.16	21.88 ± 0.72	16.26 ± 0.74	29.35 ± 1.16	83.64 ± 2.52
March	238.08 ± 86.79	22.13 ± 0.62	16.61 ± 0.50	29.63 ± 1.07	84.17 ± 2.20
April	214.81 ± 81.27	21.94 ± 0.61	16.67 ± 0.74	28.88 ± 0.80	85.25 ± 1.97
May	150.41 ± 72.26	21.83 ± 0.45	16.66 ± 0.61	28.39 ± 0.56	83.91 ± 2.25
June	38.77 ± 38.53	21.46 ± 0.43	15.33 ± 0.92	28.36 ± 0.63	79.68 ± 2.50
July	26.78 ± 27.67	21.45 ± 0.50	14.88 ± 0.76	29.02 ± 0.88	75.70 ± 2.54
August	84.07 ± 53.12	22.03 ± 0.41	15.59 ± 0.78	29.92 ± 0.86	76.59 ± 2.66
October	163.86 ± 75.69	21.81 ± 0.44	16.31 ± 0.52	29.94 ± 0.86	81.50 ± 2.14
September	247.48 ± 100.16	21.45 ± 0.47	16.57 ± 0.51	29.48 ± 0.90	85.08 ± 1.85
November	299.19 ± 110.11	21.27 ± 0.38	16.53 ± 0.52	28.37 ± 0.66	86.46 ± 1.27
December	239.59 ± 85.24	21.30 ± 0.42	16.41 ± 0.69	28.29 ± 0.81	86.17 ± 1.67

Legend: P is the average monthly precipitation (mm), Tme is the average temperature, Tmin is the minimum temperature and Tmax is the maximum temperature (in ˚C) and RH is the relative humidity (%) for the period 1981 to 2021.

2.2. Methods

2.2.1. Data Collection

The study was conducted from August 10 to 30, 2022, at two *Prunus africana* harvesting sites in North Kivu province. Harvesting in these two sites was done in 2016. In this paper, the method consisted first of identifying for each site, the *Prunus africana* stems that had been logged by debarking. This exercise was made possible and easy thanks to the support of harvesters working for PLAVUMA and KAHINDO MUVUNGA, two companies that hold CITES permits in the country. For each stem identified, the geographical coordinates (longitude, latitude and altitude) were recorded using a GARMIN GPS. The inventory was conducted on 16 plots of 25 hectares each, with 8 plots per site. During the inventory runs, dendrometric data were collected: diameter at breast height (DBP), total tree height, year of harvesting, and stem bark thickness of the unharvested and harvested portion (restorative bark). For bark thickness, a square piece of bark was taken and the thicknesses on all four sides were measured with a caliper, the diameter of the trees at breast height (DBH) was obtained with a forestry compass and a diameter tape and the total height with a SUUNTO dendrometer. The purpose of collecting bark thickness data was to assess the influence of the debarking technique adopted on trees at the two opposite quarters (Wete et al., 2020; Mpouam et al., 2022).

2.2.2. Observed Parameters

Tree reconstitution rate (Trec), bark regeneration rate (Treg), and average annual increment of reconstituted bark (TAM) were estimated for each previously harvested tree and calculated according to the following mathematical expressions (Equations (1), (2), and (3), respectively) (Mpouam et al., 2022; Wete et al, 2020):

$$TRec = \frac{Nr*100}{Ne} \tag{1}$$

With *Trec* the tree recovery rate, *Nr* the number of trees recovered and *Ne* the total number of trees debarked.

$$Treg = \frac{TAM*t}{BT2} \tag{2}$$

With *Treg* the bark regeneration rate, *TAM* the average annual growth rate of the reconstructed bark, *t* the number of years elapsed after exploitation (5 years) and *TB2* is the thickness of the unlogged bark.

$$TAM = \frac{TB1}{t} \tag{3}$$

In Equation (3), *TAM* represents the average annual bark growth rate, *TB1* represents the average post-exploitation reconstructed bark, and *t* represents the number of years elapsed after exploitation.

2.2.3. Data Processing and Statistical Analysis

The data on growth parameters of *P. africana* were first subjected to the Shapiro-Wilk normality test and Bartlett's equality of variances test. These two tests showed that the data do not follow a normal distribution and the variances between the different sites considered are not equal. Therefore, the effect of altitude on the different parameters of growth and regeneration of *Prunus africana* was highlighted using the Wilcoxon rank test at a significance level of 5%. Boxplots and error bars with p-values indicating the level of significance were obtained using the package *ggpubr* (Kassambara, 2020). The correlation matrix between the different parameters was obtained using the *GGally* package (Schloerke et al., 2021). All statistical analyses of the data were performed using R 4.1.2 software (R Core Team, 2021) under the Rstudio 1.2.5003 script editor.

3. Results

3.1. Stem Density of *P. africana*

The results show an average density of 2.38 trees per ha in both study areas. High tree density was observed at lower elevations (Walikale-Kano) (**Table 3**).

3.2. Effect of Altitude on Growth Parameters of *Prunus africana*

Sites did not influence diameter at breast height (DBH) of *P. africana* trees ($p > 0.05$) (**Figure 4(a)**) or total tree height. In contrast, bark diameter of logged trees and bark diameter of unlogged trees varied significantly among sites ($p < 0.05$) (**Figure 4(c)** and **Figure 4(d)**). Bark diameter of harvested trees averaged 14.88 ± 4.53 mm at high elevation (Ruwenzori-Lume) and 11.17 ± 3.71 cm at low elevation (Walikale-Kano) (**Table 4**). This trend is similar if we also consider the bark diameter of unharvested trees. On the other hand, the average DBH of the trees is high at the Walikale-Kano site (79.12 ± 24.39 cm) compared to an average of 76.82 ± 24.19 cm for the trees at the Ruwenzori-Lume site (**Table 4**).

Table 3. Number of *Prunus africana* stems per ha.

Sites	Total number of stems (DBH > 30 cm)	Area inventoried (ha)	Density (stems/ha)
Ruwenzori-Lume	311	150	2.07
Walikale-Kano	405	150	2.7
Total	716	300	2.38

Table 4. Distribution of growth parameter values for *P. africana* at the two study sites.

Parameters	Ruwenzori-Lume			Walikale-Kano		
	Min	Average ± SD	Max	Min	Average ± SD	Max
DBH (cm)	35.70	76.82 ± 24.19	125.10	35.70	79.12 ± 24.39	128.70
Total height (m)	5	7.43 ± 3.01	17	6	7.54 ± 3.10	15.30
BT1 (mm)	6	14.88 ± 4.52	23	5	11.17 ± 3.71	20
BT2 (mm)	9	15.2 ± 4.57	26	8	13.08 ± 3.82	23

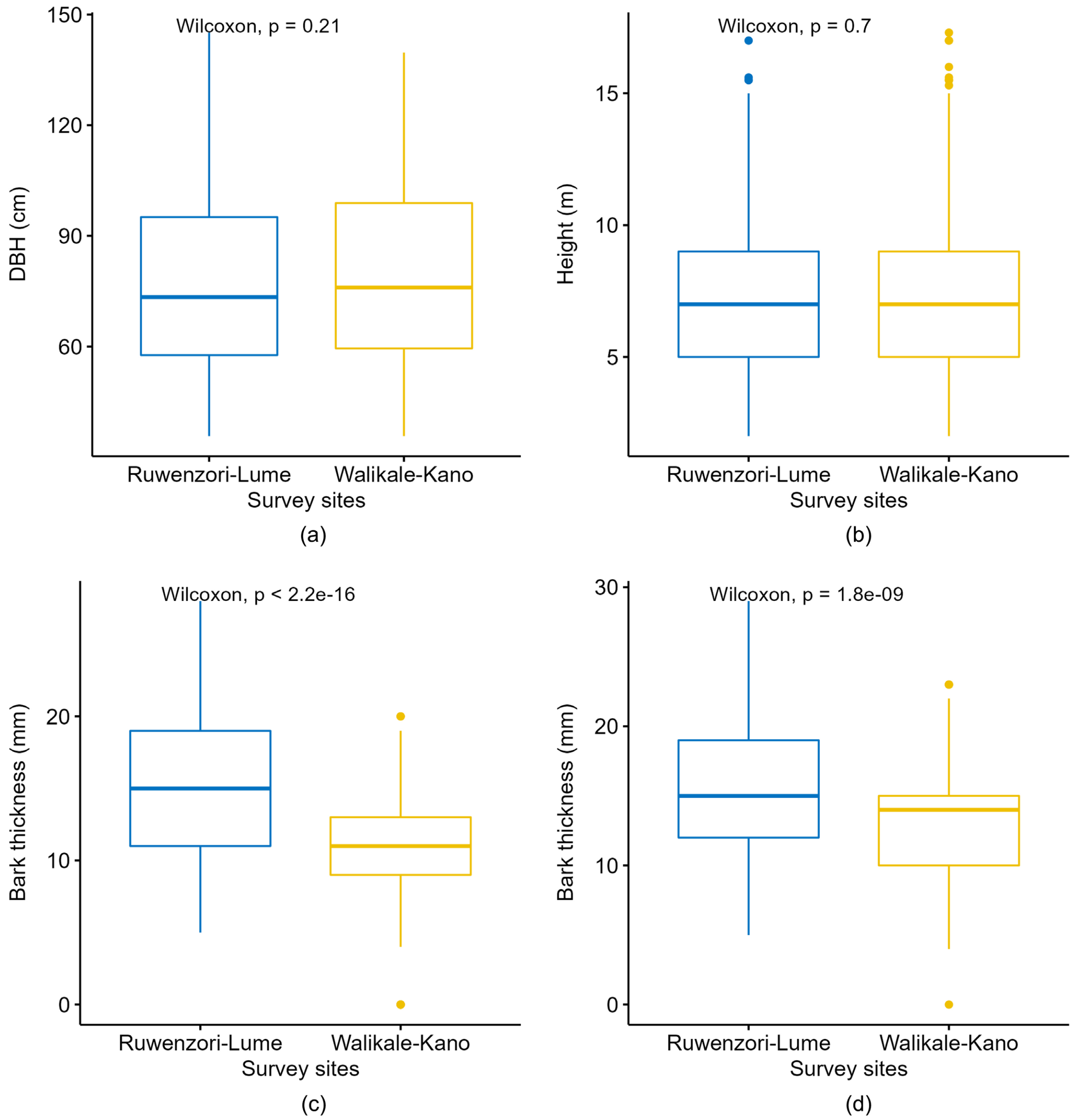

Figure 4. Comparison of means of growth parameters of *P. africana* across sites.

3.3. Effect of Altitude on Tree Recovery Rate, Bark Regeneration Rate and Mean Annual Increment of Recovered Bark

The inventory data at both sites show high rates of tree regeneration. At the Ruwenzori-Lume site, 304 trees out of 311 barked trees have recovered between 2016 and 2022, i.e. a recovery rate of 97.75%. Similarly, 396 trees out of 405 debarked trees have recovered in the Walikale-Kano site, i.e. a recovery rate of 97.77%. The Wilcoxon test shows that there is no statistically significant difference between the rate of regeneration and the two sites ($p > 0.05$). In contrast, bark regeneration rate (W = 122169, $p = 2.2*10^{-16}$) and average annual bark growth rate after 6 years (W = 91136, $p = 2.2*10^{-16}$) differed between the study sites (Table 5). Figure 5(a) and Figure 5(b) show the means and standard deviations of bark regeneration rate and mean annual bark growth rate.

Table 5. Bark regeneration rate and average annual growth rate based on the two study sites.

Parameters	Ruwenzori-Lume			Walikale-Kano		
	Min	Average ± SD	Max	Min	Average ± SD	Max
TReg (%)	85.71	97.87 ± 3.1	100	0	85.57 ± 11.90	100
TAM (mm)	1	2.97 ± 0.90	5.60	0	2.23 ± 0.74	4

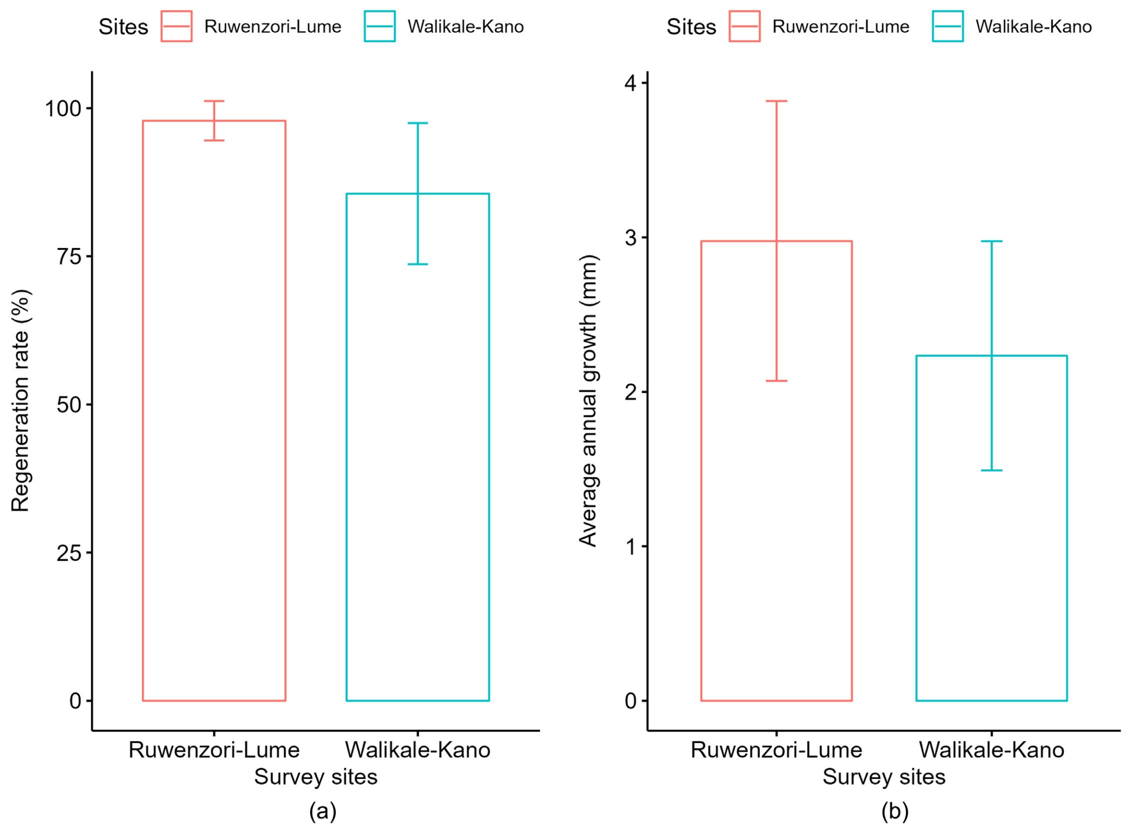

Figure 5. Average values of regeneration rate (a) and average annual bark growth rate (b) based on the two sites.

The high variations in the mean annual growth rate of the crust expressed in terms of standard deviations (**Figure 5(b)**) could be linked to strong variations in climatic conditions (precipitation) which fluctuate from one year to another at the level of two sites. These differences would then be impacted by the alternation of dry and wet seasons, especially since the physiological processes of the tree are dependent on the amount of water available.

3.4. Effect of Altitude and Diameter Classes on Post-Bark Mortality of *P. africana* Trees

The distribution of *P. africana* stems in diameter classes across sites show an inverted J-shaped curve. The number of trees decreases as the diameter increases. This is one of the characteristics of tropical forests where young and old trees are less numerous in the stands (**Figure 6**). Pearson's chi-squared test of independence shows that tree numbers within diameter classes do not differ between the two study sites (X-squared = 2.86, df = 5, p = 0.721).

Descriptive statistics (**Table 6**) show that the percentage of mortality is higher at low altitude (Walikale-Kano) than at high altitude (Ruwenzori-Lume). However, statistically, the chi-squared test shows that the difference in mortality percentages is not significant ($p = 1 > 0.05$). The high percentage of post-barking mortality was obtained for trees with a diameter between 90 and 120 cm. Statistically, mortality was different across diameter classes at the 5% threshold (**Table 6**).

3.5. Correlation between Growth Parameters of *P. africana* at the Two Sites

This study shows that the average annual bark growth rate of *P. africana* is positively correlated with the bark diameter of the logged tree (r = 1) and negatively correlated with total tree height (r = −0.053). Bark regeneration rate after debarking was also positively correlated with bark diameter of harvested trees (**Figure 7**).

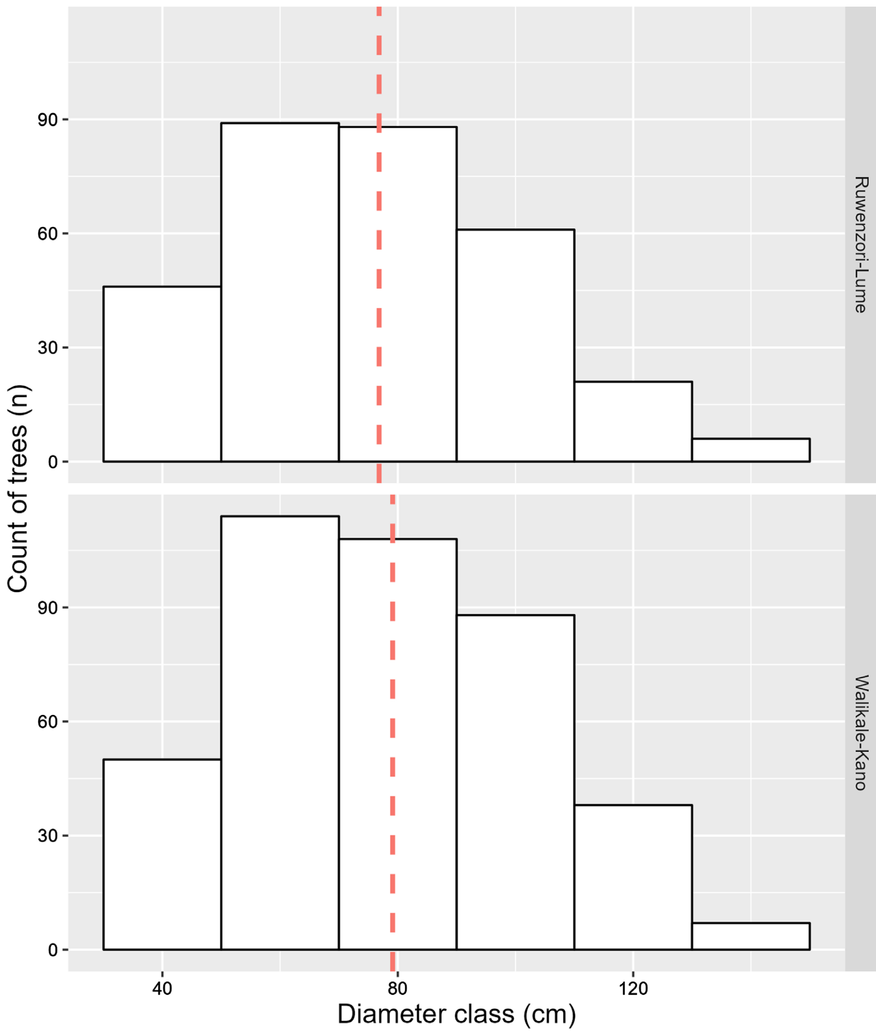

Figure 6. Distribution of *P. africana* stems in diameter classes for the two sites (red line indicates the position of the mean DBH of the trees).

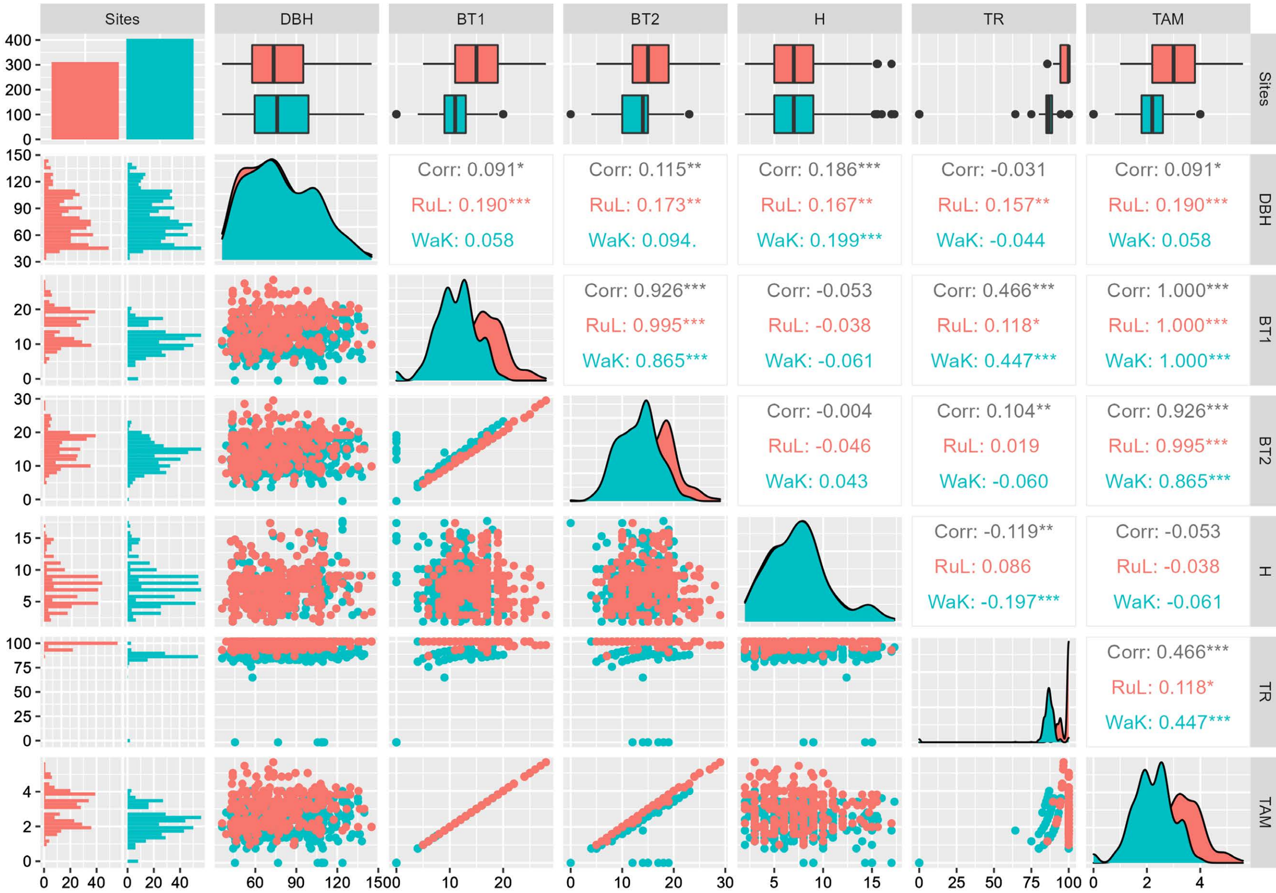

Figure 7. Correlation matrix between parameters. Legend: RuL = Ruwenzori-Lume site, WaK = Walikale-Kano site, DBH = Diameter at breast height (cm), H = Total tree height (m), TR = Bark regeneration rate of harvested trees, TAM = Average annual bark increment rate, BT1 = Bark diameter of harvested trees, BT2 = Bark diameter of unharvested trees.

Table 6. Numbers and proportions of trees alive or dead after debarking.

Variables	Modalities	Trees mortality status		p-value
		Dead trees	Living trees	
Sites	Ruwenzori-Lume	7 (43.8)	304 (43.4)	1
	Walikale-Kano	9 (56.2)	396 (56.6)	
Diameter class (cm)	]30 - 60]	3 (18.8)	186 (26.6)	0.050
	]60 - 90]	4 (25)	302 (43.1)	
	]90 - 120]	6 (37.5)	176 (25.1)	
	>120	3 (18.8)	36 (5.1)	

4. Discussion

4.1. Stem Density

The results show an average density of 1.79 trees per ha in the two study areas. This density is similar to the values obtained by many authors. After a five-year rotation, Wete et al. (2020) observed that out of a total of 170 trees harvested by both methods, of which 86 (56%) trees were harvested by the 2/4 technique and 84 trees (54%) by the 4/8 technique, tree density decreased from 1.7 to 1.28 stems/ha (Wete et al., 2020). In a paper that aimed to assess the potential of *P. africana* in the 25,671 ha Tchabal Mbabo Forest in Cameroon, Wilfried et al. (2022) counted three hundred and fifty-eight (358) stems of *P. africana* over an area of 57.5 ha, giving a density of 6.23 stems/ha. This value is higher than the average density of this paper.

4.2. Effect of Altitude on Growth Parameters

This paper showed that growth parameters (stem diameter and tree height) did not vary with altitude ($P > 0.05$), but bark parameters were significantly different with altitude ($P < 0.05$) (**Figure 4**). In both study areas, the average diameter of harvested trees was 76.82 ± 24.19 cm in Ruwenzori-Lume and 79.12 ± 24.39 cm in Walikale-Kano. The average thickness of unharvested bark was 15.2 ± 4.57 mm in Ruwenzori-Lume and 13.08 ± 3.82 mm in Walikale-Kano. For the logged portion, the bark thickness at the Ruwenzori-Lume site is 14.88 ± 4.52 mm and 11.17 ± 3.71 mm at the Walikale-Kano site (**Table 4**). These results are different from those reported by Mpouam et al. (2022) in terms of tree diameter and similar in terms of the thickness of the unmined bark. Indeed, these authors found that the average diameter of harvested trees was 47.60 ± 17.65 cm, the average thickness of the unharvested bark was 15.47 ± 4.32 mm, and that of the portion under reconstitution was 7.30 ± 2.32 mm (Mpouam et al., 2022). In the Tchabal Mbabo forest in Cameroon, mean values for tree diameter, height, and bark thickness of stems (unharvested and harvested sides) are 48.17 ± 19.8 cm; 7 ± 4.26 m; 14.1 ± 4.72 mm; and 10.39 ± 4.22 mm, respectively (Wilfried et al., 2022). These values are lower than those in that study. As in this study, Mpouam et al. (2022) found an influence of altitude on the parameters of *Prunus africana*. Overall, these authors found an overall mean stem diameter of 47.60 cm. This same study revealed that the highest average diameter (53.2 cm) at an altitude greater than or equal to 2100 m and the lowest average diameter (41 cm) at 1800 - 1900 m altitude (Mpouam et al., 2022). Mpouam et al. (2022) also found a variation in logged and unlogged bark thickness with altitude. These authors found average bark thicknesses of 7.54 mm, 7.30 mm, 7.23 mm, and 6.80 mm for the logged portion at elevations of 1800 - 1900 m, 1900 - 2000 m, 2000 - 2100 m, and above 2100 m, respectively. Considering these same altitudes, the average bark thickness values for the non-harvested portion are in the order of 16.75 mm, 15.40 mm, 15.18 mm and 14.20 mm respectively (Mpouam et al., 2022). These mean bark thicknesses of the unharvested portion are close to those of this study.

4.3. Regeneration, Recovery and Average Annual Bark Growth Rates

In this study, the average annual average bark growth rate (TAM) was 2.97 ±

0.90 mm for the Ruwenzori-Lume site and 2.23 ± 0.74 mm for the Walikale-Kano site after a 5-year rotation. For both sites studied, the rate of reconstitution was greater than 80% (**Table 5**). This rate is higher than that reported by Mpouam et al. (2022) who found an average annual rate of increase in bark thickness of 1.12 ± 0.47 mm/year. In the Tchabal Mbabo forest in Cameroon, Wilfried et al. (2022) report an average annual bark growth rate of 1.3 mm/year for a bark regeneration rate of 60% after a 7-year rotation. Mpouam et al. (2022) also found a variation in mean annual bark growth rate (MAPR) with elevation. These authors found that the mean TAM of 1.08 mm, 1.14 mm, 1.12 mm and 1.04 mm respectively at altitudes of 1800 - 1900 m, 1900 - 2000 m, 2000 - 2100 m and above 2100 m. The rate of increase in this study is higher than the average reported by Stewart (2009) who found a value of about 0.34 mm per year; a rate that is similar between the different diameter classes.

4.4. Post-Debarking Vulnerability of *P. africana* by Diameter Class

Based on the inventory data, across two study sites (Ruwenzori-Lume and Walikale-Kano), post-debarking tree mortality is 2.23% between 2017 and 2022. This rate is low compared to values reported in the literature. A study was conducted on Mount Cameroon on a 100 ha plot where two harvesting methods of *P. africana* (2/4 and 4/8) are practiced (Wete et al., 2020). These authors found that after a five-year rotation, out of a total of 170 trees harvested by both, only 128 (75.30%) trees were alive, 35 trees were dying (20.51%) and 7 (4.12%) trees were dead. This mortality is more attributed to the 4/8 debarking technique with 35.70% dying and dead trees compared to 14% for the 2/4 technique (Wete et al., 2020). Other research showing high mortality rates relative to the value of this study has also been reported from Mount Cameroon. One study indicates a survival rate of 70.53% and a mortality of 29.47%. Another conducted on a sample of 3058 harvested trees revealed 5 years later that 2134 trees (69.9%) were in good health compared to 924 (30.1%) in poor health and not harvestable (Wete et al., 2020). In Kenya, Gladys (2020) observed that more than 90% of the trees that died after debarking of which more were small in diameter (less than 30 cm) (Gladys, 2020). Another study was conducted in Isecheno (Kakamega Forest, Kenya), one of the locations where the species is experiencing rapid mortality. This study reveals that between 1997 and 2003, 21% of *P. africana* (10 cm DBH) at Isecheno died and an additional 9% experienced canopy dieback (Fashing, 2004). Other work provides further evidence of the detrimental effects of large-scale debarking on *P. africana* populations. In Equatorial Guinea, one study found that 68% of logged *P. africana* were either dead or undergoing canopy decline. However, not all declines of *P. africana* appeared to be related to unsustainable bark harvesting practices. In another study of *P. africana* near the southernmost end of its geographic distribution along the Bloukrans River Gorge in South Africa, Geldenhuys (1981) found that 47% of the 10 cm DBH standing stems were dead, but he did not mention the effect of bark removal

(Fashing, 2004).

The results of this study show that all diameter classes are sensitive to debarking, but the highest percentage of post-barking mortality was obtained for trees between 90 and 120 cm in diameter (**Table 6**). This observation is similar to Stewart (2009) who found that diameter class is not a significant predictor of tree death. Stewart (2009) found that diameter class was not a significant predictor of tree death. He suggested that other factors were involved in mortality, such as the location of the harvest. Trees that were harvested without disturbing the vascular cambium survived better and suffered a minimal crown loss. Thus, the fate of trees in a given plot may depend on the care taken by an individual harvester (Stewart, 2009).

5. Conclusion

The objectives of this work were to acquire data on the standards of exploitability in the field in the different sites of *P. africana* in North Kivu and to study the influence of altitude on growth parameters (tree diameter, bark diameter, tree height, etc.). The results show high tree recovery rates. At the Ruwenzori-Lume site, 304 trees out of 311 debarked trees have recovered between 2016 and 2022, i.e. a recovery rate of 97.75%. Similarly, 396 trees out of 405 debarked trees have recovered in the Walikale-Kano site, i.e., a rate of 97.77%. A high percentage of post-barking mortality was obtained for trees with a diameter between 90 and 120 cm. However, the diameter of the bark of harvested trees and that of the bark of unharvested trees varied significantly between sites ($p < 0.05$). The hypothesis that growth parameters vary with site and elevation is supported. Based on the average annual increment in bark thickness, a 7-year half-rotation can be used in North Kivu subject to more detailed studies on bark cover. As a prospect, future research should be focused on the influence of edaphic determinism (physicochemical and biological properties of soils) on the post-bark response of *Prunus africana*. In addition, understanding the effects of environmental factors (soil types, climate, altitude, etc.) on the chemical composition of bark is a domain of research that would contribute to the advancement of knowledge of the species in the region. Finally, socio-economic and ethnobotanical analyses of *Prunus africana* in North Kivu province should be conducted. These investigations will contribute to the development of sustainable management policies for this species, which is at risk due to its multiple usages.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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