Journal of Applied Biosciences 99:9478 – 9493

ISSN 1997–5902

Tree response to bark harvest: the case of a medicinal species, *Garcinia lucida*, as source of raw materials for plant-based drug development

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Original submitted in on 11th January 2016. Published online at www.m.elewa.org on 31st March 2016 http://dx.doi.org/10.4314/jab.v99i1.13

ABSTRACT

Objectives: There is a huge demand for medicinal bark in developing countries and this demand is growing fast due to it high market values. To assess the effects of bark functions and tree capacities to recover from various debarking practices, a two-year experiment was conducted and several local harvest practices were tested on *Garcinia lucida*.

Methodology and Results: For each practice, 20 healthy trees were selected and harvested. Tree health was monitored every month and the total bark regrowth was calculated using planimetric techniques. In response to bark removal, *G. lucida* trees produced stilt-roots, sprouts and bark. Re-growth of bark was the most common strategy developed, with mean values ranging from 80 to 100% of trees. All stumps have developed sprouts, with an average number of 6 shoots per stump. The percentage of bark regrowth varies from 45 to 62% of the initial surface debarked for small trees and from 24 to 37% for large trees. A high rate of bark regeneration was found if narrow strips of bark remained on trees, from which bark was hardly removed from wood during harvest, probably characterized physiologically by a downward sap flow due to poor water supply in trees.

Conclusions and application of findings: The study has discussed main findings on the experimental debarking of *G. lucida* and management implications, which would also apply to other species with the same response to bark stripping as source of raw materials for plant-based drug prospects in developing countries. Bark strip harvesting requires species-specific parameters to make it sustainable, taking into account : (i) the bark regeneration capacity (edge growth), which may allow repeated harvest on the same tree; and (ii) the physiological status (downward sap flow) of the tree at the time of harvest, as decisive factor triggering bark regrowth. Partial bark strip harvesting show good prospects for the implementation of long-term sustainable strip harvesting prescriptions, while sustainable stripping through ring-barking practice is unsuitable. Shoot growth and stilt-root development in *G. lucida* species allows for other management options than strip harvesting, including coppice management and domestication. However, there are major limitations in using regenerated bark, as the time required to re-attain preharvest bark thickness, as well as the chemical composition due to stress-releasing mechanisms remain unknown.

Key words: medicinal bark regrowth, harvest practices, plant-based drug prospects, species recovering capacity, sprouting capacity.

INTRODUCTION

Tropical forests in developing countries have been traditionally exploited for a wide array of natural resources by billions of people for their livelihood. One of these resources is the bark of tree species, most commonly employed for many purposes such as medicines, dyes, food spice, wine flavour, and a range of other uses (Tshisikhawe *et al*., 2012; Cunningham, 2014a; Senkoro *et al*., 2014). The global demand for medicinal bark is steadily growing and has caused some valued indigenous plant species, very sensitive to high levels of harvest, to become threatened (Ndoye *et al*., 2000; 2001; Djaligue, 2007; Tshisikhawe *et al*., 2012; Cunningham, 2014a,b; Bodeker *et al*., 2014). Therefore, there is an increasing concern about the management of medicinal bark harvesting (Pandey & Das, 2013; Baldauf & dos Santos, 2014; Mariot *et al*., 2014; van Andel *et al*., 2015; Pandey, 2015). The term bark refers to all tissues outside the vascular cambium, comprising dead and live tissue (Camefort, 1977; Romero, 2014; Senkoro *et al.,* 2014). The dead tissue (rhytidome) corresponds to the outer layer of bark, functioning as a physical barrier that protects trees against desiccation, fire, insects, herbivores and diseases. The live tissue (phloem) constitutes the inner bark, playing a key role in nutrient transport. In contrast to leaves or fruits that can be replaced after being damaged or harvested, bark are not ephemeral and thus benefit from avoiding or recovering efficiently from removal. Despite these bark fundamental importance to tree survival and growth, issues such as bark responses to damage have been the subject of comparatively few studies, compared to leaves (Romero, 2014; Costa *et al*., 2015). Valuable efforts have been made to establish good quality assurance and standardization, as well as specific guidelines for good collection practices for medicinal plant parts (WHO, 2004; Kunle *et al*., 2012; van Damme & Delvaux, 2012; Pandey & Das, 2013). Despite these efforts, lack of sufficient knowledge about structure and functional ecology of the bark, as well as sustainable harvest rates and practices remain some of the major challenges to ensure that the necessary raw materials will be readily available for the development, according to WHO recommendations, of local plant-based industries. Few studies have assessed the ability of trees to regenerate bark following harvesting (Cunningham & Mbenkum 1993; Geldenhuys *et al*., 2007; Delvaux *et al*., 2009; Vermeulen *et al*., 2012; Baldauf & dos Santos 2014; Ngubeni, 2015) and have clearly demonstrated that this ability to regenerate bark is species-specific. Such large-scale field or case studies on tree responses after bark harvesting are scarce, but essential to define the maximum sustainable harvesting limit for the bark and to ensure the persistence of a species. To design approaches of sustained sourcing of bark as raw materials for plant-based drug prospects, the present investigation aimed at assessing tree response and abilities to recover from various intensities and techniques of debarking. The approach was illustrated on *Garcinia lucida* Vesque (Clusiaceae) species, one of the most valued wild medicinal resources in South Cameroon (Guedje, 2014).

MATERIALS AND METHODS

Study site: The study was carried out within an area located in the South Cameroonian Atlantic humid forests, near the village Nyangong (2°56.04' N, 10°49.62' E) in the Bipindi - Lolodorf - Akom II region (Fig. 1). The climate is humid tropical with two rainy and two drier seasons, with a yearly rainfall of about 2000 mm, and with an average annual temperature of around 25°C. Biodiversity in this part of Cameroon ranks among the highest in Africa. The forest cover is still largely intact, but due to human influence, it is alternated with a mosaic of fields, fallow lands, secondary forest and logged-over forest.

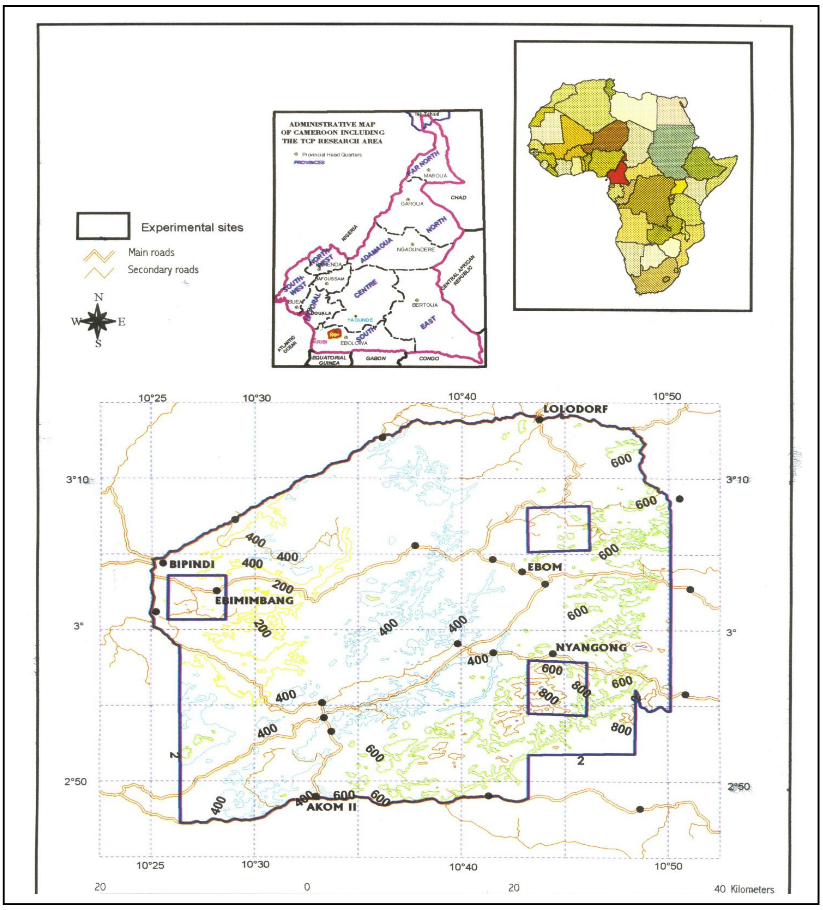

Fig. 1: Location of the Bipindi – Akom II – Lolodorf area in the South Cameroonian Atlantic humid forests.

Study species – *Garcinia lucida* Vesque (Clusiaceae): *G. lucida* is a small understory dioecious tree, standing sometimes on stilt roots, reaching 25 - 30 cm in diameter at breast height (DBH), with yellow and resinous sap exuded after bark tranche. It grows in high-density stands in hilly moist forests sides. It is well-known in South Cameroun as "Essok" in the Boulou and Ewondo local languages. The bark is one of the most valued and sold non-timber forest products for its multipurpose properties in Cameroon, Gabon and Equatorial Guinea. The bark and the seeds are used as flavour in raphia and palm wine production, as well as in traditional liquor distillery. It is used for medicinal purposes as an antidote against poison or to prevent food poisoning, to cure diarrhoeas, stomach and gynaecological pains, as well as to cure snake bites. It is also believed to possess some aphrodisiac properties and that it could be used to chase away ghosts (van Dijk, 1999; Chikamai *et al*., 2009). Many active compounds with bioactivities such as antibacterial, antimicrobial, anti-inflammatory, antacids, curare antidote or inhibitory effect, β-lactamase inhibition have been found in its diverse plant parts (Kamanyi *et al*., 1990; Nyemba *et al*., 1990; Fotie *et al*., 2007; Gangoué-Piéboji *et al*., 2009; Momo *et al*., 2011; Lacmata *et al*., 2012). Bark harvesting has been intensified due to the steadily increasing demand for palm wine and traditional liquor (Ndoye *et al*., 2001; Djaligue, 2007; Chikamai *et al*., 2009). Usually, before debarking, a machete is used to test the thickness of the bark and if the bark will be easily detached from the wood. Consequently, many standing trees are covered with scars causing stress and making the tree more susceptible to further damage. Local harvesters apply various bark harvesting practices. This includes, debarking by hammering the stem with a stick (if bark is easily removed from wood) or peeling off the bark with a machete (if bark is thick but hardly removed from wood) one side of reproductive individuals. Very often, though, the bark is removed over almost the entire circumference of the stem, especially when the bark is thick and can be easily detached from the wood, and regardless of whether it is a young or an old mature tree. This practice leads to a high mortality of trees (Guedje *et al*., 2007). A practice, less frequently used, is felling the tree at approximately 1 m height and harvesting the bark of the felled part.

Experimental design, data collection and analysis: From the above harvesting practices, the following treatments, illustrating the local bark harvesting system, were applied:

(i) Control (**C**) : no debarking;

(ii) Partial debarking of the stem, with three sub-treatments: **(a)** peeling off pieces of bark with a machete and debarking over 1/3 of the tree circumference at breast height (**P 1/3**), **(b)** hammering on the tree with a stick and debarking over 1/3 of the tree circumference at breast height (**H 1/3**), and **(c)** hammering with a stick and debarking over 2/3 of the tree circumference at breast height (**H 2/3**);

(iii) Ring-barking of the stem (**R 3/3**);

(iv) Felling the tree at approximately 1 m height above the ground and thereafter harvesting the bark on the felled tree part (**F**).

For each treatment and each sub-treatment, 20 healthy trees (no scars and previous bark harvest) were selected, marked with numbers, equally distributed in two size classes : [10 - 17[cm diameter at breast height (DBH) for small trees and [17 – 26[cm DBH for large trees. The sample was restricted to this number of trees and size classes as healthy trees were scarce, and as many *G. lucida* forest stands in the area mostly composed of harvested trees or unharvested trees but covered with many scars. Bark was extracted from 0.3 m from the ground (or above stilt roots) in a vertical strip up to 1.5 m stem height. For each treated tree, "bark easiness" to be removed from wood like "cassava peel", or "bark hardness" to be removed from wood were noted. Health parameters (survival, sprouting, bark re-growth, stilt-root development) were monitored every month over a period of two years. Insect holes were noted, new sprouts and shoots around the wound was counted. Re-growth of bark was monitored, and at 6, 12 and 24 months, tracing papers were used to copy the surface area of edge growth on the wound. The total bark area regrowth was calculated using planimetric techniques. Variance (ANOVA) and regression analysis techniques using SPSS have been used to compare the different treatments. At the start of the research, a total of 120 trees were bark stripped. Over the two-year study period, 16 trees (13.33%) were illegally stripped again by unknown local community members and struck out from the sample (Table 1).

Table 1: Number of sample trees selected per treatment and number of trees struck out after illegal stripping.

Treatment	Initial Sample	**Number of treated trees illegally stripped again and struck out**	
		N	**%**
C	20	4	20
P 1/3	20	4	20
H1/3	20	4	20
H2/3	20	3	15
R3/3	20	1	5
F	20	0	0
Total	**120**	16	13,33

RESULTS

Harvest practices impact on tree survival: Damage to and removal of bark has serious effects on plant survival. According to the criteria of bark easiness to be removed from wood like "cassava peel" or bark hardness to be removed, treated trees were distributed as shown in table 2. The proportion of trees where bark was easily removed like "cassava peel" was only 7.5%, while trees that bark was more or less easily removed counted for 51.25%, and trees where bark was hardly removed counted for 41.25%. During the experiment, it was observed that the yellow and resinous sap exudates were abundantly produced along the sides of wounds, regardless of the harvest practices applied. It was also observed that, when bark was easily removed from wood like "cassava peel", trees were entirely stripped of its protective and conducting bark tissues, leading consequently to "clean-stripped" trees. On the contrary, when bark was hardly or very hardly removed from wood, narrow strips of bark tissues always remained on stem wood, together with more yellow and resinous sap exudates produced. When trees were also peeling off with machete, narrow strips of bark tissues always remained on stem wood. During the monitoring of treated trees, it was observed that, trees where bark was easily removed like "cassava peel" have undergone rapid and severe dehydration after stripping than those that bark was hardly removed, resulting in the exhibition of external signs of tree die-back six months later after stripping (Fig. 2). The six months' time interval seems to be the time spans needed by trees to overcome the internal stress that may compromise trees fitness and survival. For ring-barked trees, the percentage of mortality increased over time, which a peak between 12 and 15 months. For other treatments, the percent of mortality has remained more or less constant after the first six months.

Table 2: Distribution of *G. lucida* trees per bark removal easiness categories after stripping.

		Number of treated trees					
		P 1/3	**H 1/3**	**H 2/3**	**R 3/3**	**Total**	
						N	%
Bark removal easiness category	**Very easy**	3	1	1	1	6	7.5
	More or less easy	11	13	8	9	41	51.25
	Very difficult	6	6	11	10	33	41.25
	Total	20	20	20	20	80	100

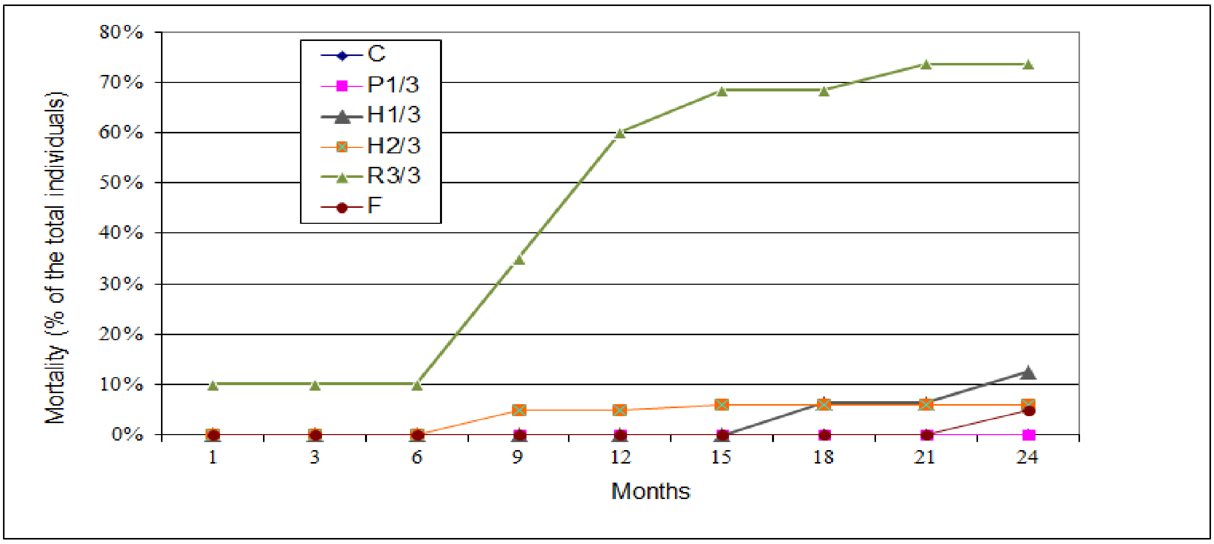

Fig. 2: Characterization of stages of tree fitness and survival in *G. lucida* over 2 years following bark harvesting, for all size classes. N= 20 for each treatment; P1/3 = peeling with a machete and debarking over 1/3 of the circumference, H1/3 = hammering on tree and debarking over 1/3 of the circumference, H2/3 = hammering on tree and debarking over 2/3 of the circumference, R3/3 = Ring-barking tree by peeling with a machete or hammering on tree.

The survival of treated trees was highly influenced by harvesting treatments. Ring-barking of stem was the most destructive, leading to 0% of surviving large trees, compared to 50% survival probability for small trees (Fig. 3). In contrast, trees were remarkably tolerant to partial debarking practice, especially in trees peeled with a machete P 1/3 (100% surviving trees) compared to trees debarked by hammering with a stick. Concerning felling tree practice, tree survival probability was 100% for small trees and 90% for large trees. Although survival probabilities of small ring-barked trees was significantly lower ($p < 0.001$) than those partially debarked, as well as those felled at 1 m height above the ground and the control, no significant difference was recorded between size-classes in overall practices (variance analysis with LSD at 5%), suggesting that tree survival is very sensitive to harvest intensity and practice, regardless of whether it is a young or mature tree.

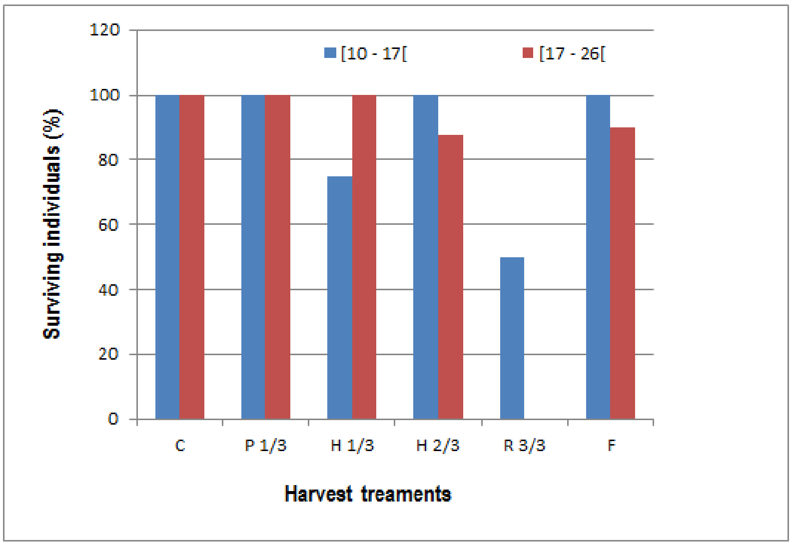

Fig. 3: Comparison of tree survival rate between the harvest treatments for small and large trees 24 months after treatment. P1/3 = peeling with a machete and debarking over 1/3 of the circumference, H1/3 = hammering on tree and debarking over 1/3 of the circumference, H2/3 = hammering on tree and debarking over 2/3 of the circumference, R3/3 = Ring-barking tree by peeling with a machete or hammering on tree.

Tree response capacities after debarking: Three types of plant tissue development in response to bark removal were recorded on surviving trees (Fig. 4): stilt-roots, sprouts and bark. Re-growth of bark was the most common strategy developed, with mean values over 90% of trees partially debarked. The recruitment of new stilt-roots from the extreme treatments occurred most frequently in the remained 50% sample of small trees ring-barked and in the H 2/3 debarked trees (33%), while only 6% and 7% of trees have developed stilt-roots in P 1/3 and H 1/3 respectively.

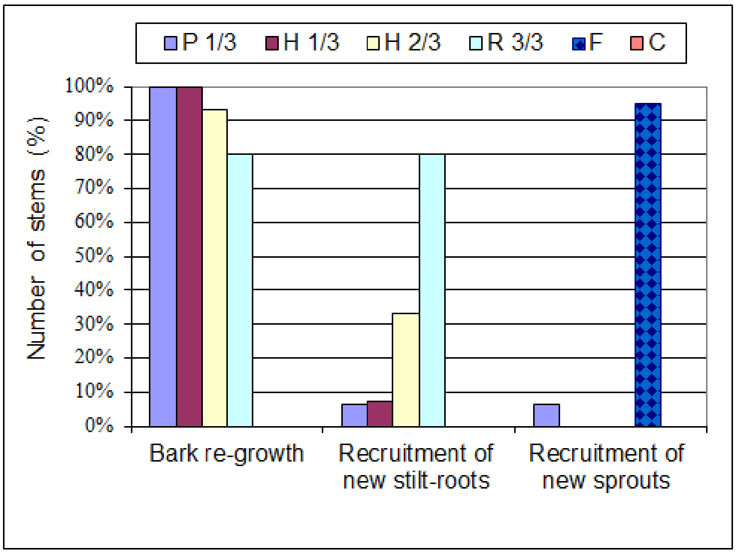

Fig. 4: Frequency of the three types of response to bark stripping in *Garcinia lucida*, for surviving trees 24 months after treatment (n = 86). C = Control (n = 16), P1/3 = Peeling with a machete and debarking over 1/3 of the circumference (n = 16), H1/3 = Hammering on tree and debarking over 1/3 of the circumference (n = 14), H2/3 = Hammering on tree and debarking over 2/3 of the circumference (n = 16), R3/3 = Ring-barking tree by peeling with a machete or hammering on tree (n = 5), F = Felling the tree at 1m height (n = 19).

The development of new sprouts or shoots around the wound was observed only for a few trees in the P 1/3 treatment (6% of trees), with a mean of only one or two shoots per tree. Comparatively, 95% of felled trees have developed shoots, with a mean number of shoots varying from 0 to 12 per stump (Fig. 5) and an average number of 6 new shoots per stump. After 12 months, the length of shoots varied between 1 and 65 cm, with an average of 18.3 cm and an annual growth rate of 14.6 cm.

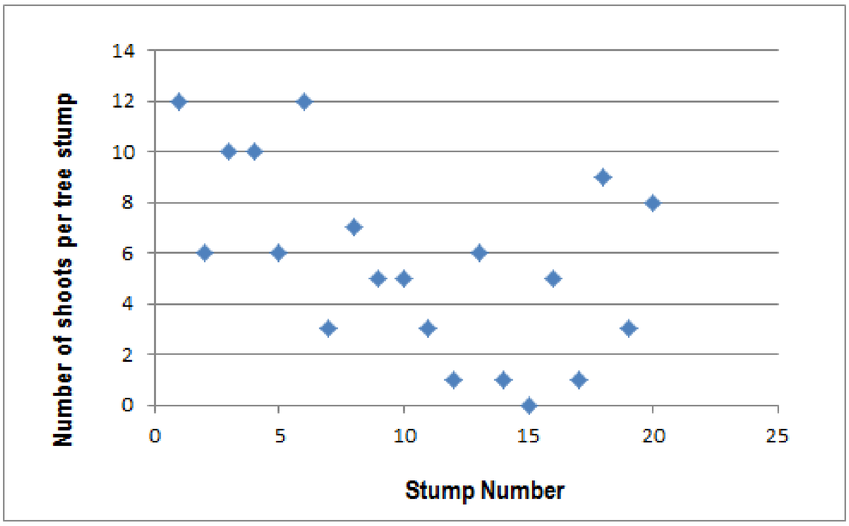

Fig. 5: Vegetative growth of *G. lucida* stumps in response to felling trees at 1m height, 12 months after treatment.

Bark regeneration patterns: Bark-regrowth occurred on trees three months later after stripping in overall treatments, with a peak of the maximum number of trees exhibiting the process observed between 9 and 12 months; and after 12 months, a decline, due to the number of trees die-back and struck out after illegal stripping (Fig. 6).

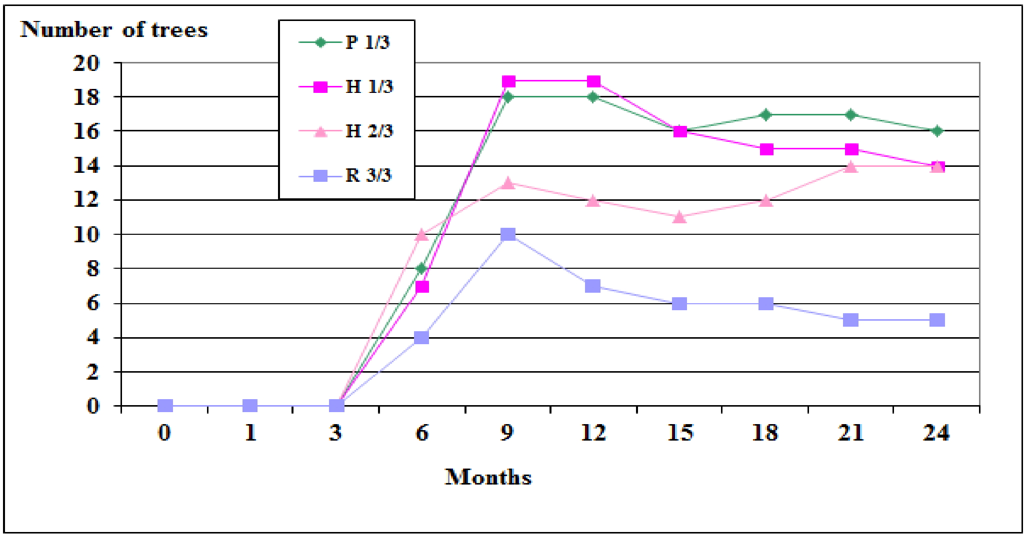

Fig. 6: Characterization of bark-regrowth process in *G. lucida* over 2 years following bark stripping for all size classes. P1/3 = Peeling with a machete and debarking over 1/3 of the circumference (n = 16), H1/3 = Hammering on tree and debarking over 1/3 of the circumference (n = 14), H2/3 = Hammering on tree and debarking over 2/3 of the circumference (n = 16), R3/3 = Ring-barking tree by peeling with a machete or hammering on tree (n = 5).

For each treatment, the average percentage of re-growth area is presented in Fig. 7. For small trees an average comprised between 30 and 50% of the initial surface debarked was covered by regrowth for the different treatments, compared to 14 and 28% for large trees, six months after treatment. Bark re-growth started from the sides of wounds toward the center, regardless of the harvest practices applied. After two years, the percentage covered varied from 45 to 62% for small size trees and from 24 to 37% for large size trees, indicating that bark regeneration was faster in younger trees. Amongst all these trees, five (9% of trees) have recovered more than 90% of the surface initially debarked, while 31 trees (58.5% of trees) have recovered less than 50% of the total surface debarked.

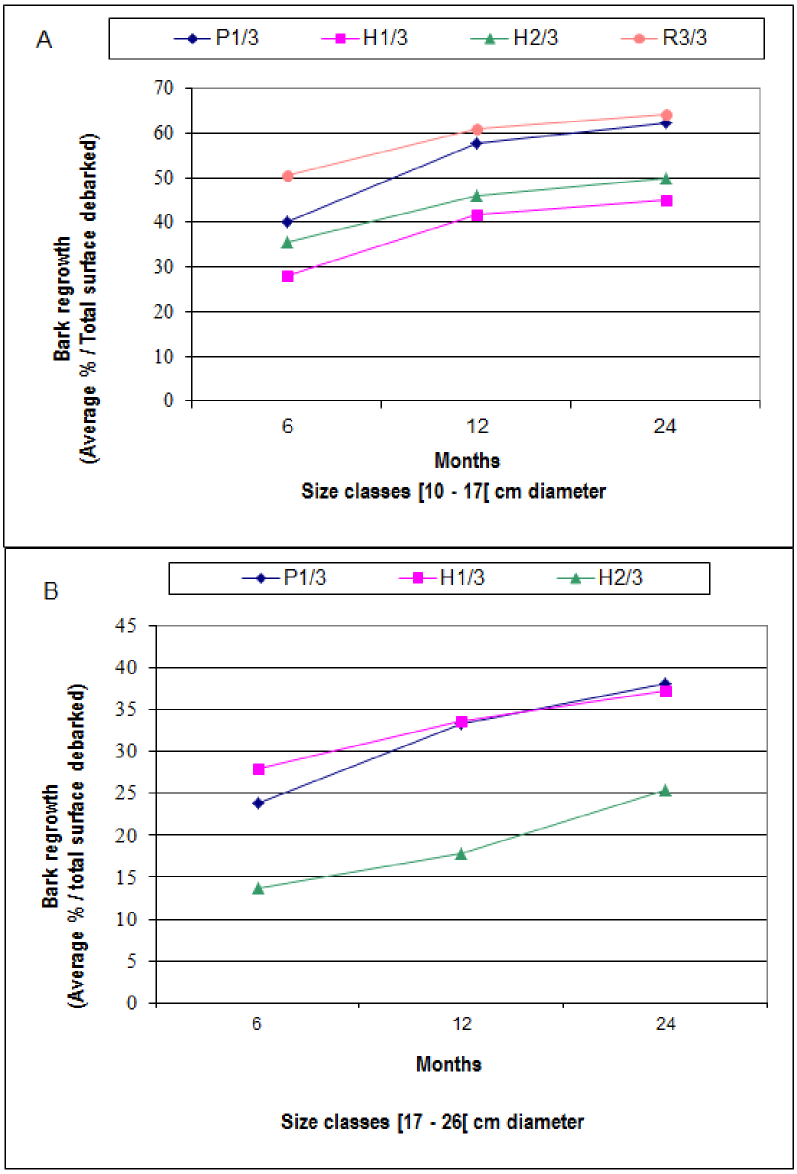

Fig. 7: Characterization of stages of bark regeneration in *G. lucida* over 2 years following bark harvesting**.** A= small size classes, B = large size classes; P1/3 = Peeling with a machete and debarking over 1/3 of the circumference (n = 16), H1/3 = Hammering on tree and debarking over 1/3 of the circumference (n = 14), H2/3 = Hammering on tree and debarking over 2/3 of the circumference (n = 16), R3/3 = Ring-barking tree by peeling with a machete or hammering on tree (n = 5).

A high rate of bark-regrowth was found for trees that bark was hardly removed and narrow strips of bark tissues remained on stem wood, as well as for trees that bark was more or less easily removed (Fig. 8). The differences observed in treatments H1/3 for smaller trees and P 1/3 for larger trees may be linked to the uneven distribution of trees in forests according to the criteria of bark easiness to be removed as shown in table 2, with higher percentages of trees where bark was more or less easily removed, and a very poor percentage of trees where bark was very easily removed like "cassava peel". In most cases, there were no pests or diseases present on the uncovered part of the wood. Variance analysis (with LSD at 5%) of the mean surface area recovered for each treatment shows no significant difference between size-classes in overall treatments. However, if the surviving sample ring-barked small trees (due to the number of trees die-back and struck out after illegal stripping) are take into consideration, therefore, there is a significant difference between treatment R 3/3 (ring-barked trees) and treatments P 1/3, H 1/3, H 2/3 ($P < 0.001$).

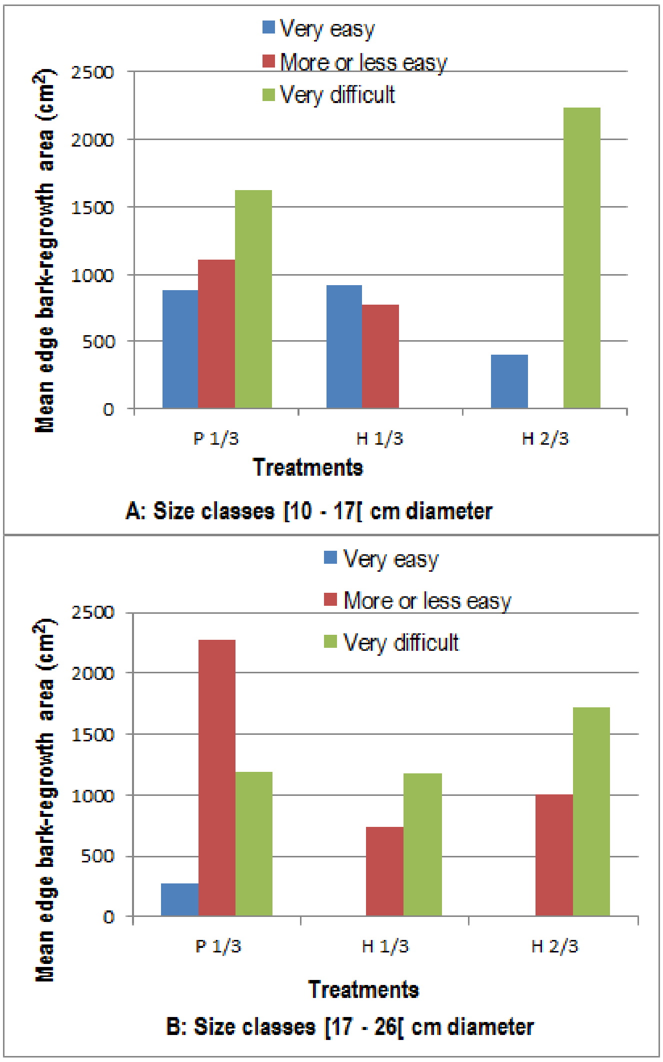

Fig. 8: Influence of bark stripping easiness on rate of edge bark re-growth on *Garcinia lucida* during 24 months following bark harvesting**.** P1/3 = Peeling with a machete and debarking over 1/3 of the circumference (n = 16), H1/3 = Hammering on tree and debarking over 1/3 of the circumference (n = 14), H2/3 = Hammering on tree and debarking over 2/3 of the circumference (n = 16).

DISCUSSION

During bark harvesting on *G. lucida* trees, tissues often (almost always) extracted are the outer bark (dead tissues) and the periderm (lives tissues conducting phloem) of the inner bark. Damage to the inner bark interrupts the transport of photosynthates, thereby bereaving roots from nutrients and leading to the exhibition of external signs of tree die-back six months later after stripping. Whereas damage to the phellogen reduces the ability of this vascular cambium to produce storage cells and tissues important for stem protection. This explain why damages due to partial peeling of bark with machete (P 1/3) may be superficial and affect only the outer bark and the old phloem and phellem, permitting trees treated by this way to survive (0% mortality) and to further recover from wounds. The results of this study shown that in response to bark removal, *G. lucida* trees produce stilt-roots, sprouts and bark, indicating a high resilience to bark removal. Re-growth of bark was recorded with all the different debarking treatments, while the 2/3 harvested trees responded by developing new silt-roots in addition to bark regrowth. The ability of a species to develop new roots after bark removal is reported for very few species, Delvaux *et al*. (2009) noticed that only one species (*Uapaca togoensis)* of 12 species studied produced roots around the wound area, but they did not investigate this phenomenon further. With this study the production of new shoots was observed on trees with bark peeled off over 1/3 of the tree's circumference (P1/3 treatment), and felled trees. According to Geldenhuys *et al*. (2007), the ability of a species to develop agony shoots around the wound after bark harvesting is related to the ability of that species to produce coppice shoots. Some other species have also been studied for their ability to coppice (Sawadogo *et al*., 2002; Ky-Dembele *et al*., 2007) or to re-sprout (Rietkerk *et al*., 1998; Delvaux *et al*., 2009). Coppices are a potential source of bark and better knowledge of the complex coppicing response of individual tree species could help in the designing specific strategies for the optimization of coppice management (Kaschula *et al*., 2005; Neke *et al*., 2006; Ky-Dembele *et al*., 2007; Delvaux *et al*., 2009). According to Cunningham (2014a), whether a tree reproduces from seed or by resprouting from vegetative shoots strongly influences its vulnerability to bark removal or stem cutting. Where stem harvesting occurs, resprounting adds resilience to individual plants and populations, so it is important to consider the use of seeds and sprouts in regeneration of harvested plants. Some trees tend to resprout, some very vigorously, some weakly, and a few not at all. Therefore, intensive harvesting of bark has very different effects on reseeder, or resprouter populations. Growth rates after coppicing are a key factor in determining rotation times if coppice rotations are proposed as a management strategy. The high number of buds and shoots produced by *G. lucida* stumps indicates it's higher resilience and sprouting capacities and the good prospects of a clonal multiplication in domestication strategies (with desirable "genetic" qualities such as bark thickness, organoleptic and chemical components). Bark regrowth patterns varied between harvest treatments with highest values, expressed as percentage to the total number of tree stems exhibiting bark regrowth, recorded in treatments P 1/3 and H 1/3 (Fig. 4). When expressed as a percentage of re-growth area, higher values were recorded for treatment P 1/3 (Fig. 7). Bark regrowth from the edges recorded for *G. lucida* trees was also found for *Drimys brasiliensis* (Mariot *et al*., 2014) and *Himatanthus drasticus* (Baldauf & dos Santos, 2014). However, over the two-year follow-up period, no tree was able to close the wound completely, suggesting a recovery time of more than two years. Geldenhuys *et al*. (2007) found that many species showed sheet growth, varying from poor to very good sheet growth. Delvaux *et al*. (2009) found that only four species, out of the 12 studied, showed a good recovery rate and that only *Khaya senegalensis* and *Lannea kerstingii* were able to close the wound completely over the two-year follow-up period. Baldauf & dos Santos (2014) have indicated that three years were not sufficient for a total recovery of the rhytidome of *Himatanthus drasticus*. There have been several studies to determine the limits of bark harvesting on species that survived ring barking such as *Prunus africana* (Cunningham and Mbenkum, 1993) and *Mangifera indica* (Delvaux, 2009). In other species, ring-barking resulted in the death of all ring-barked trees (Delvaux, 2009). The survival of *G. lucida* ring-barked smaller trees (5 over 10), as well as the relative higher percentage of re-growth area recorded for these trees (Fig. 7A) were due or linked to the fact that bark was more or less easily removed on one tree and was very hardly removed on 4 trees. This ability to easily recover bark by ring-barked small trees that bark was hardly stripped, however, does not provide conclusive evidence and is of limited value to evaluate the sustainability of ring-barking practice, as the analysis was based on a limited sample of trees. Furthermore, this practice has been proved by matrix models (Guedje *et al*., 2007) to induce a sharp drop in the amount of harvestable trees after the first extraction; and populations would not fully recover to the pre-harvest bark availability with this treatment. While in case of populations harvested by partial debarking, the models predicted that the amount of harvestable trees would gradually, decline and reach 50% of the initial size within the first two decades and that the population would start to recover after 30 years and would be back at initial values after 40 years. A high rate of bark-regrowth was found for trees that bark was hardly removed and narrow strips of bark tissues remained on stem wood, whereas little regeneration was observed if the bark was easily removed from wood, thereby living wood without strips of bark tissues. This trend was also found by Delvaux *et al*. (2009) and Baldaud & dos Santos (2014). The remained narrow strips of bark, which allowed for sap flow to the roots, may have contributed substantially to tree stability, as well as serving to protect the stem from insect or pathogen attack, and triggered bark regeneration. According to Kengue *et al*. (1998), bark is easily removed from wood like "cassava peel" when trees are characterized physiologically by the existence or predominance of an upward sap flow, due to good water supply in tree. These authors have highlighted the importance of this tree physiological status and considered it as a determining factor for the success of layering techniques for *Dacryodes edulis*. *G. lucida* grows along hilly moist forests versants where water supply is limited for uphill trees, explaining why bark was more or less hardly removed for the majority of trees, probably characterized by the existence of a downward sap flow. Therefore, the physiological status of trees, in term of upward or downward sap flow due to water supply, as it plays an important role in maintaining bark functioning, appears as a decisive factor in plant survival and bark re-growth process; thereby constituting a key element in designing sustainable harvesting practice. Several studies have shown that another important factor for successful recovery of bark was the humidity of the exposed surface immediately after wounding, which may be related to the occurrence of a rainy season (Stobbe *et al*., 2002; N'Koma Mwange *et al*., 2003; Juan *et al*., 2006). As *G. lucida* trees were harvested at the beginning of the rainy season, it is possible that rain has contributed favourably to bark regeneration. Thus, seasonality may be an important variable to be tested in future studies on the bark regeneration potential. However, Mariot *et al*. (2007) have tested the effect of different harvest seasons on the regenerative ability of *Drimys brasiliensis* (Winteraceae) in an Atlantic Forest area and found no seasonal differences in the speed of biomass regeneration. As *G. lucida* is also an Atlantic forest species, it is likely that the remaining narrow bark strips, as well as the yellow and resinous exudates produced along the sides of wounds after bark stripping, may have served to provide the necessary humidity to trigger the cellular division process that had culminated in the recovery of injured xylem and phloem. Romero & Bolker (2008) have studied the effects of debarking in seven species and found that species that produce some type of exudate showed more efficient bark recovery. Cunningham (2001) also found that plants of certain families, such as Apocynaceae, Euphorbiaceae, Moraceae and Canellaceae, show great resilience after debarking, in part because the cambium was protected by exudates after the bark removal. The yellow exudate that flowed and remained on *G. lucida* trees after debarking, containing secondary metabolites with antimicrobial properties (Fotié *et al*., 2007; Gangoué-Pieboji *et al*., 2007, 2009; Lacmata *et al*., 2012), may also have served as defensive compounds protecting the stem from insect or pathogen attack, explaining why no pests or diseases were present on the exposed part of the wood. For species with bark exudates, many insects and pathogens appear to be deterred as these defensive substances dry out on the exposed surfaces after damage. However, bark regeneration is a relatively slow process compared to the re-growth of other plant parts such as leaves (Borgtoft-Pedersen, 1996; Gaoue *et al*., 2013). As highlighted by previous studies (Guariguata & Gilbert, 1996; Schoonenberg *et al*., 2003; Romero & Bolker, 2008; Baldauf & dos Santos, 2014; Pandey & Das, 2013), responses to damage of the bark and, consequently, the formulation of criteria for sustainable management, depend on a number of factors, including the type of damaged tissue, the extent of damage, the tree physiology, morphology of the bark, and the presence of exudates. The outermost, conducting phloem tissues are the parts generally harvested, interrupting the translocation of photosynthates and bereaving roots from nutrients. Because of these multiple factors, the effect of bark removal and the sustainability of different harvesting practices are species-specific, as stated by Chungu *et al*. (2007) and Delvaux *et al*. (2009). Cunningham & Mbenkum (1993) indicated that *Prunus africana* in Cameroon can achieved complete bark re-growth after ring barking. In Nigeria, Fasola & Egunyomi (2005) indicated that *Alstonia boonei*, *Entandophragma angolense*, *Khaya grandifolia*, *Khaya senegalensis* and *Spondias mombin* belong to the fast re-growth group, whereas the bark of *Adansonia digitata*, *Gliricidia sepium, Newbouldia laevis* and *Theobroma cacao* have relatively slow re-growth. In South Africa, *Ocotea bullata* and *Warburgia salutaris* show good re-growth; in contrast, the bark of *Rapanea melanophloeos* shows no re-growth (Geldenhuys *et al*., 2007). This study indicates that *G. lucida* belongs to the fast re-growth group, according to its abilities to close the wound after partial debarking, it resistance to insect or pathogen attack, and the ability to develop shoots and stilt-roots. These findings constitute biological advantages in designing sustainable harvesting practices and management strategies for *G. lucida*, which is also characterized by effective resilience capacities to partial debarking and the possession of important bioactive compounds with great therapeutic potential for new drugs or improved plant medicines. This study has discussed findings on the experimental debarking of *G. lucida* and management implications, which would also apply to other species with the same response to bark stripping as source of raw materials for plant-based drug prospects in developing countries. The following species-specific characteristics need to be taken into account to make strip harvesting sustainable:

(i) the bark regeneration capacity (edge growth), which may allow repeated harvest on the same tree;

(ii) the physiological status (downward sap flow) of the tree at the time of harvest, as a key factor ensuring humidity, protection against pathogen attacks, and more moreover, influencing bark's capacity to regenerate after damage. With the good bark regrowth and higher survival rates recorded in *G. lucida* trees partially stripped (P 1/3, H 1/3 and H 2/3), especially in trees peeled with a machete (P 1/3), these treatments show potential for the implementation of long-term sustainable strip harvesting system and it integration with indigenous resource management. In contrast, ring-barking practice showed high mortality, especially in large trees where most of the trees died, rendering this practice unsuitable for bark stripping as a method of long-term bark harvesting. Nevertheless, there are also major limitations in using regenerated bark, as the time required to re-attain preharvest bark thickness and fibre quality, as well as the chemical composition for *G. lucida* as well as for many other species, are still unknown. Bark differs from all other plant parts in development and anatomy, as well as chemical composition (Pandey *et al*., 2011; Costa *et al*., 2014; Romero, 2014; Eich *et al*., 2015). Chemical compounds found dispersed in low concentrations throughout most of the plant are highly concentrated in bark than in other plant tissues (Young, 1971; Romero, 2014). Although inner bark and wood are derived from vascular cambium, they are fundamentally different in structure and function, but are more similar in chemical constituents than either is to outer bark. Unfortunately, with the study of bark chemistry, the bark tissues from which compounds were derived are rarely specified. In addition, the chemical composition of bark tissues varies as a function of ontogeny, history of disturbance, environmental conditions and even the height on the tree at which a sample is taken (Romero, 2014). Furthermore, in some conifers, chemical composition varies with stress level and other factors, and there can be chemical differences in the resin produced before and after wounding (Klepzip *et al*., 1996). To protect themselves from beetle larvae and their associated pathogenic fungi, some trees develop traumatic resin ducts and produce resin with a chemical composition different from that in resins produced before wounding, with more phenolic compounds in traumatic canals and in reaction tissue (Berg *et al*., 2013; Romero, 2014). Similarly, in response to bark removal *G. lucida* trees may also produce exudate and young bark tissues with a chemical composition different from that produced before wounding. Stress-releasing mechanisms remain to be tested and little formal studies are known on the long-term effects of frequent bark removal on regenerated bark chemical composition. Therefore, extensive research on rates of bark regeneration in relation to bark structure, physiology and chemical composition would further assist the implementation of sustainable strip to source raw bark materials for plant-based drug development. Shoot growth and stilt-root development in *G. lucida* species allows for other management options than strip harvesting, including coppice shoots management rotations and domestication. These alternative management options could easily be integrated into forest management planning and regulations as proposed by Guedje *et al*. (2010) or might be considered as a by-product of timber harvesting and could be integrated to the SCH (Senility Criteria Harvesting) timber yield regulation system, as practiced in the Southern Cape forests, basing on harvesting of dying trees equivalent to the natural mortality rates (Seydack *et al*., 1995; Ngubeni, 2015).

ACKNOWLEDGEMENTS

This work received financial support from the Ministry of Higher Education in Cameroon. We are grateful to the inhabitants of Nyangong village for their hospitality and participation during fieldwork. We also thank the anonymous reviewers for their precious comments.

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