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Variation in Regeneration Density and Population Structure of *Prunus africana* Across Human Disturbance Gradient in South West Mau Forest, Kenya

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Abstract: *Prunus africana* has been severely exploited for its valuable products rendering it unstable and at risk of extinction. Studies were therefore carried out on its regeneration density and population structure across different human disturbance gradients in South West Mau Forest (SWMF) Kenya. Four study sites with {undisturbed, low, moderate and high} human disturbances were identified in SWMF. In each study site three line transects, 100 m apart and running up to 1 km inside the forest were established. Four sample plots 20 m x 50 m were laid at 250 m intervals along each line transect then divided further into 10 subplots each 10 m x 10 m and nested 5m x 5 m sub-subplots. At the centre of each sub-subplot, a 1 m x 1 m quadrant was laid. In each sub plot Diameter at Breast Height (DBH) of all adult trees and poles were measured while the number of saplings in each sub-subplot and seedlings in each quadrant were counted. Light screening efficiency was evaluated in all study sites as an indicator of canopy openings. One way Analysis of Variance (ANOVA) was used to test for significant differences of the studied variables, Tukey Post Hoc test was used in pairwise mean comparison and parametric Pearson correlation analysis was used to test for relationship between variables. Bar graphs and line graphs were used to depict trends in population structure and diameter-size distribution respectively. Animal trails, old charcoal production sites, tree harvesting and debarking of *P. africana* were found as significant human forest disturbances ($p < 0.05$) that negatively influenced its relative abundance ($r = -0.077$). Canopy openings as consequence of disturbance negatively influenced its regeneration density ($r = -0.089$). The relatively undisturbed site of the forest had a stable population structure for *P. africana* that followed reverse-J curve irrespective of the high debarking rate (90%) that decreased across the disturbance gradient. These findings suggest a need for designing sustainable management strategies that will lead to rehabilitation, restoration and monitoring of *P. africana* population dynamics in SWMF.

Keywords: Human Forest Disturbance, *Prunus africana*, South West Mau Forest, Population Structure

1. Introduction

Natural forests are important for watershed protection, biodiversity conservation and carbon sink [1] while trees are selectively harvested for timber and medicine [2, 3]. Valuable tree species such as *Prunus africana* tend to be overexploited, threatening their survival and the very source of the needed products [4, 5]. Prolonged human forest disturbances such as continued clearance of forests for agriculture, tree products and grazing lead to ecological succession and biodiversity loss [6, 7, 5].

During the past two decades (1990-2010) the demand for forest products to meet people's livelihood needs in Kenya increased and resulted in considerable pressure on forest resources in Mau forest [8]. High value closed canopy tree species such as *P. africana* known to grow in this forest ecosystem are harvested for valuable products [9] hence may affect their population structure and abundance [10]. In South West Mau Forest (SWMF) continuous over extraction of high value mature trees and non-wood forest products for the last three decades (1983-2013) [1] may have created gaps in an otherwise continuous closed canopy forest which if unchecked could lead to alteration of ecological functions and habitats processes hence loss of species. Indeed parts of SWMF such as Maramara and Itare forest blocks have experienced different levels of human disturbance [8, 11, 12].

Prunus africana is a high value closed canopy, endangered and threatened tree species [9, 13, 14, 5, 15]. It is a tree species with maximum action priority in Africa [16] since it has been declining over much of its geographical range in Sub-Saharan Africa [17]. The seeds of *P. africana* germinate well under shady conditions but require light gaps to survive beyond sapling stage [18, 19]. The population of mature *P. africana* in Sub-Sahara Africa has declined due to exploitation for large scale bark harvest [20]. Harvesting of *P. africana* from natural forests in Kenya has raised concern that the regeneration and population structure of the species may be negatively affected in future [10]. Indeed the negative effect of logging on population status of *P. africana* has been observed in parts of Mt. Elgon forest [21]. The species is neither shade tolerant nor pioneer [17, 22] thus their regeneration performance in disturbed and undisturbed sites is useful for prediction and management purposes in relation to human activities.

Studies on ecological disturbances have been reported in the upper regions of SWMF that had experienced human settlement in the past [8, 9, 11, 23]. This study evaluated the regeneration density and population structure of *P. africana* across human disturbance gradient in lower SWMF Forest, Kenya.

2. Materials and Method

2.1. Study Area

This study was conducted in the Western part of SWMF, Kenya which lies between latitudes 00° 22' 46.77" S - 00° 38' 51.25" S and longitudes 035° 17' 28.22" E - 035° 35' 06.75" E [24]. SWMF is characterized by a bimodal rainfall (2000-3000 mm per annum) with peaks in April and August [8]. Mean annual temperature ranges between 12-16°C [8, 11, 12] and potential evapo-transpiration between 1,400 and 1,800 mm [11]. The forest is relatively closed canopy, has high biodiversity and hosts indigenous tree species such as *P. africana* [11, 1].

2.2. Study Sites

The study was done in four forest sites of SWMF, each representing different level of forest-human interactions and disturbance gradients. The forest site bordered by large scale multinational tea estates was described as of low disturbance (LD) while the site bordered by tea belt of 100 m width that stretched between farmlands and the forest boundary represented moderate disturbance (MD). The forest site bordered by farmlands and homesteads was described as highly disturbed (HD) while the area next to Forest Station offices represents a relatively undisturbed site (RD). In each study site regeneration density and population structure of *P. africana* was determined.

2.3. Experimental Design

In each study site, three parallel line transects that ran from the forest edge up to 1 km into the forest were established such that the distance from one transect to the next was 100 m. Ground Positioning System (GPS) coordinates of the starting points of the established transects were recorded. Sample plots measuring 20 m x 50 m (0.1 ha) were laid at 250 m intervals along each transect and further sub-divided into 10 subplots of 10 m x 10 m. A quadrat of 1 m x 1 m was laid at the centre of 5 m x 5 m sub subplots nested in each of the 10 m x 10 m subplots.

2.3.1. Indicators of Human Forest Disturbances

In every 20 m x 50 m (0.1 ha) sample plot, lengths and widths of all the foot paths, animal trails and roads, their areas (m^2) calculated and expressed in ha^{-1} while charcoal kiln sites were counted and expressed in number ha^{-1}. In situations where animal trails were present with human footpaths, the most visible category was quantified. The relative value of each human disturbance indicator in every site was calculated and the mean obtained as a disturbance index for that particular site. The disturbance indices (1) were used to establish a disturbance gradient across the study sites (Equation 1).

$$\text{Disturbance index (\%)} = \left\{\frac{\text{Relative value }(1+2+\cdots+6)\%}{6}\right\}\% \quad (1)$$

All standardized values obtained were subjected to one way ANOVA at $\alpha = 0.05$ and Tukey HSD Post Hoc test to determine significant differences between the four disturbed sites.

2.3.2. Debarking of P. africana

The debarked stems of *P. africana* in each study site were identified, counted and at Diameters at Breast Height (DBH) were measured and categorized as regenerations (<10 cm), poles (10-20 cm) and adult trees (>20 cm). The obtained number of the debarked stems in each study site were then used to compute the density (debarking level per hectare) (Equation 2) and the DBH to determine the category in which it was mostly exploited. The significant differences in debarked the in the sites were determined by One way ANOVA at $\alpha = 0.05$ and Tukey HSD Post Hoc test.

$$\text{Density(Stems ha}^{-1}) = \frac{\text{Number of stems of individual species}}{\text{Area in ha}} \quad (2)$$

2.3.3. Regeneration and Relative Density of P. africana

In each 10 m x 10 m sub plot, the number and DBH of all adult *P. africana* trees and poles were counted and measured respectively. DBH was used to segregate *P. africana* into size classes as follows: seedlings (DBH <5 cm or 1.3 m in height), saplings (DBH 5-9.9 cm), poles (DBH 10-19.9 cm) and adult trees (DBH >20 cm). In each (5 m x 5 m) nested sub subplot *P. africana* saplings were counted while in each (1 m x 1 m) quadrat seedlings were counted. DBH of *P. africana* trees with buttresses were assessed at points just above the buttresses. Regeneration density (stems ha^{-1}) of *P. africana* (Equation 3) in each study site was obtained.

Further, the densities per site for every life form (seedlings, saplings, poles and adult trees) for all tree species and shrubs identified according to [25, 26]) were calculated and used to determine relative density of *P. africana* (Equation 3).

$$\text{Relative density (RD)\% for species } i = \frac{\text{Density of species } i}{\sum \text{Densities of all species}} \text{ x } 100 \tag{3}$$

The two densities were subjected to One way ANOVA at $\alpha = 0.05$ and Tukey HSD Post Hoc test to determine significant differences of each across the disturbance gradient. Pearson correlation analysis was used to establish a relationship between the relative density of *P. africana* and disturbance indices of the sites. The relative densities gave an insight on the abundance of the species in relation to other species.

2.3.4. Canopy Openings

Canopy openings indicated through Light Screening Efficiency (LSE) in every study site and plot were measured using light screening grid tool as described by [27] as follows: A 1 m x 1 m plastic sheet with small grid holes marked at 10 cm x 10 cm was fastened to a wooden frame. The tool was then held directly overhead up to at least 2 m above the ground then the number of grid holes not concealed from visible sky counted. This was done at four points along the middle of each study plot. Light screening efficiency as the proportion of the grid holes not concealed was then calculated in percentage at every point (Equation 4).

$$\text{Screening efficiency (SE)} = \frac{\text{Number of holes not concealed}}{100} \text{ x } 100 \tag{4}$$

Pearson correlation analysis was used to determine the relationships between regeneration density and of *P. africana* and canopy openings.

2.3.5. Population Structure of P. africana

The number of the seedlings, saplings, poles and adult trees in each DBH class was evaluated to arrive at the population structure of *P. africana*. The results obtained were compared to an inverse-J shape curve which reflects population structure of a tree species in typical undisturbed forests. The population structures were interpreted according to the system as described in [28, 29] as good, if seedlings > saplings > poles > adults; fair, if seedlings > saplings > poles ≤ adults; and poor, if sapling stage is present but no seedlings or any other imbalance in the structure.

3. Results and Discussion

3.1. Human Forest Disturbances

Table 1 presents human forest disturbances across the established disturbance gradient indices LD (10%) < RU < (19%) < MD (34%) < HD (37%). Footpaths, animal trails, abandoned roads, old charcoal production sites, tree harvesting and debarking were the major disturbances in SWMF.

Table 1. *Disturbance gradient, indices and indicators of forest disturbances in SWMF.*

Disturbance gradient	Disturbance index (Scale: 100%)	Animal trails (m^2 ha^{-1})	Roads (m^2 ha^{-1})	Old charcoal sites (No. ha^{-1})
LD	10	0.00a	0.00a	0.00a
RU	19	251.83b	0.00a	0.00a
MD	34	147.33ab	91.67a	0.00a
HD	37	186.93b	0.00a	6.67b
∑	100	586.09	91.67	6.67

Table 1. *Continued.*

Disturbance gradient	Trees harvested (Stems ha^{-1})	Trees debarked (Stems ha^{-1})	Disturbance index (Scale: 100%)
LD	8.33a	8.33a	10
RU	43.33a	4.17a	19
MD	19.17a	6.67a	34
HD	95.00b	1.67a	37
∑	166.33	20.84	100

Values followed by same letter in a column are not statistically different at $\alpha = 0.05$.

Highest density of footpaths was observed in moderately disturbed forest, bordering tea zone buffer. However, there was no statistical significant difference, $F_{(3, 44)} = 0.773$, $p = 0.515$, $\eta^2 = 0.050$ across the gradient. Footpaths indicate unauthorized human access into the forest that lead to seedlings trampling, charcoal production, tree harvesting, fuel wood extraction and tree debarking [30, 31, 21, 32]. Animal trails differed significantly across the disturbance gradient $F_{(3, 44)} = 4.88$, $p =$

0.005, $\eta^2 = 0.250$ and were attributed to livestock grazing that negatively affect regeneration of vegetation in forest [33, 34]. According to [35, 11, 36], animal trails impact soil hence impede regeneration of some tree species. This creates persistent light gaps that will prevent forest succession by facilitating pioneer plants and tree species and preventing the emergence of secondary tree species [17]. In California forest, [37] attributed nutrient enrichment from cattle manure and urine as factors that could favor invasion of weedy species along animal trails hence decreased diversity. Such changes in an otherwise natural ecosystem like SWMF may alter the microclimate of the sites hence ecosystem malfunction that could give rise to undesirable plant species. Disturbance due to roads was not significant across the gradient, $F_{(3, 44)} = 1$, $p = 0.402$, $\eta^2 = 0.064$. Lack of *P. africana* in close proximity to road suggest that the road could have been used in extracting them and its regeneration out competed by pioneer tree species which are shade tolerant.

Charcoal production differed significantly, $F_{(3, 44)} = 4.63$, $p = 0.007$, $\eta^2 = 0.24$ across the gradients. Charcoal production leads to the removal of preferred species, cause forest fires hence unsustainable harvesting and loss of species [38, 39]. Fire leads to changes in soil pH (from acidic to alkaline), reduction in bulk density and increase in porosity [40]. This may explain the observed changes in regenerations of *P. africana* and colonization by the invasive species *S. mauritianum* in SWMF hence a negative shift in biodiversity and a compromised ecosystem health as described by [40].

Disturbance due to tree harvesting was significantly different $F_{(3, 44)} = 10.25$, $p < 0.001$, $\eta^2 = 0.411$ across the gradients. High density of trees harvested in the porous site bordered by farmlands directly could be due to ease of access into the forest by the adjacent community. Harvesting particular tree species and size classes leads to changes in species composition hence diversity of the forest [41, 42]. It will also affect forest composition and structure, leading to alteration in the forest ecosystem functions and succession collapse as observed in SWMF [43].

3.2. Debarking Levels of *P. africana*

Table 2 shows debarking levels and regeneration density of *P. africana* (seedlings and saplings combined) across the disturbance gradient. Rate of *P. africana* debarking was high in the low disturbed site bordering multinational tea company and at the site bordering tea zone belt, however there was significantly different, $F_{(3, 44)} = 4.06$, $p = 0.012$, $\eta^2 = 0.217$ across the disturbance gradient. High rate of debarking *P. africana* (90%) may substantially deteriorate the health of this species and put it under potential risk of extermination from SWMF in the near future, suggesting the need for an ecological intervention.

Table 2. *Debarking levels of P. africana in SWMF.*

Disturbance gradient	Disturbance index (Scale: 100%)	Debarked stems (Stems ha^{-1})	Undebarked stems (Stems ha^{-1})	Total stems (Stems ha^{-1})	Debarking percentage (%)
LD	10	7.50a	0.83	8.33	90
RU	19	0.00b	29.17	29.17	0
MD	34	0.83a	6.67	7.50	11
HD	37	0.00ab	20.83	20.83	0
∑	100	8.33	57.50	65.83	

Values followed by same letter in a column are not statistically different at $\alpha = 0.05$.

The debarking trends of this species may be a slow continuation of the past authorized trade of its barks in Kenya [44, 45]. The significant difference in debarking across the disturbance gradient is attributed to the continued exploitation of adult *P. africana* despite protection by CITES and IUCN [46, 47]. Quality concoction is obtained from the bark of adult *P. africana*; however if uncontrolled will severely diminish its population [48, 46, 49, 50]. This may explains why only adult trees are exploited for the barks, even though *P. africana* is more resilient to a high percentage of ring-barking and could recover through callus development on the debarked wound [51]; however unsustainable harvesting of the barks could lead to death of the trees.

3.3. Regeneration and Relative Density of *P. africana* in Different Canopy Openings

Table 3 presents the regeneration densities (seedlings and saplings combined) and relative densities and canopy openings of *P. africana* across the disturbance gradient. The regeneration densities were significantly different across the disturbance gradient $F_{(3, 44)} = 2.95$, $p = 0.043$, $\eta^2 = 0.168$, with site factors as the consequences.

Table 3. *Regeneration and relative density of P. africana in SWMF.*

Disturbance Gradient	Disturbance Index (Scale: 100%)	Regeneration Density of *P. africana* (Seedlings + saplings) (Stems ha^{-1})	Relative Density of *P. africana* (%)	Canopy Openings (Light%)
LD	10	1.67a	1.45a	23.90a
RU	19	25.83ab	2.85a	31.31a
MD	34	3.33a	1.06a	18.57ab
HD	37	20.00a	2.44a	21.83a
∑	100	50.83	0.57	95.61

Values followed by same letter in a column are not statistically different at $\alpha = 0.05$.

Disturbance leads to an impairment in the overall regeneration potential of the forest ecosystem [52]. *Prunus africana* in natural forests is sensitive to disturbances such as harvesting and grazing which influence trees and seedlings growth, mortality and reproduction [53]. Least disturbed site was characterized by multi-storey tree species such as *Albizia gummifera, Polyscias fulva* and *Tabernaemontana stapfiana*, pioneer shrubs such as *Solanum mauritianum* and very thick undergrowth of herbs such as *Acanthas eminens.* This could explain the low regeneration hence relative abundance of *P. africana* in the site.

The negative correlation r (46) = -0.089, p = 0.548 between the canopy openings and regenerations of *P. africana* implied that the species is not a pure secondary species (requires light for survival at later stages of its life). Shade could have nursed its regenerations at initial stages to some extend but later on outcompeted by the stiff competitors. *Prunus africana* regeneration in highly and relatively undisturbed sites could have been nursed by shade at initial stages to some extent but later on outcompeted by the stiff competitors as it requires light for survival at later stages of its life. These findings concurred with [18] who grouped *P. africana* among non pioneer tree light demanders whose seedlings are nursed by shade. Human disturbances are associated to light gaps [54] which promote successful regeneration and recruitment of pioneer species such as invasive *S. mauritianum*. In South West Mau forest, disturbance due to exploitation of *P. africana* barks leading to deaths coupled with stiff competition from pioneer, invasive species and herbaceous plants could have impeded its regeneration and lead to low densities in the study sites.

The relative densities did not differ significantly, $F_{(3, 44)}$ = 1.93, p = 0.139, η^2 = 0.116 across the disturbance gradient. The negative correlation between the disturbance and the relative density of *P. africana*, r (46) = -0.077, p = 0.603 indicates that disturbance has had negative effects on its population in SW M forest suggesting that the conditions for proper regeneration and recruitment were not met. Despite this, there was still very low relative abundance of the saplings, a situation that may suggest that the seedlings of *P. africana* were not being recruited to sapling stage. The seedlings of this species were found to succumb to competition at their early stages resulting in poor recruitment across the sites. Such imbalances in the life stages of a tree population may lead to disappearance of this species from these sites in future.

3.4. Population Structure of P. africana in SWMF

Figure 1 presents the population structure of *P. africana* species forms across the disturbance gradient. The relatively undisturbed site had all the life forms of *P. africana*, with more adult trees than saplings and poles hence fairly reverse-J shaped structure. Despite absence of poles in the moderately disturbed site the low densities of seedlings, saplings and adult trees almost displayed reverse J-curve. Least and highly disturbed sites failed to show specific shapes in relation to J-curve, pointing to a possible disappearance of adult *P. africana* which seeds every year [55].

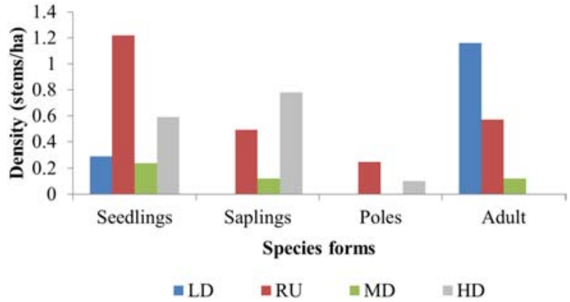

Figure 1. *Population structure of P. africana in SWMF.*

An imbalance in *P. africana* life forms means the success of non-pioneers' survival of the juveniles and their subsequent recruitment to upper age classes is not possible [28, 29]. Indeed adult trees of *P. africana* were few and scattered in all sites and may not provide adequate seeds to subdue its competitors [56]. Excessive debarking including ring barking of the stems lead to death of the tree in two years [57], increased canopy openings and subsequent invasion of *S. mauritianum* weed. Indeed [58] observed that *S. mauritianum* had established itself in Mau forest hence could have provided stiff competition to *P. africana* regenerations resulting in their poor establishment.

3.5. Diameter-Size Distribution of P. africana in SWMF

Figure 2 reports results on diameter-size distribution of *P. africana* across the disturbance gradient. The results indicates presence of higher number of regenerations, very low number of poles sizes and absence of adult trees of between 20 cm and 49.9 cm.

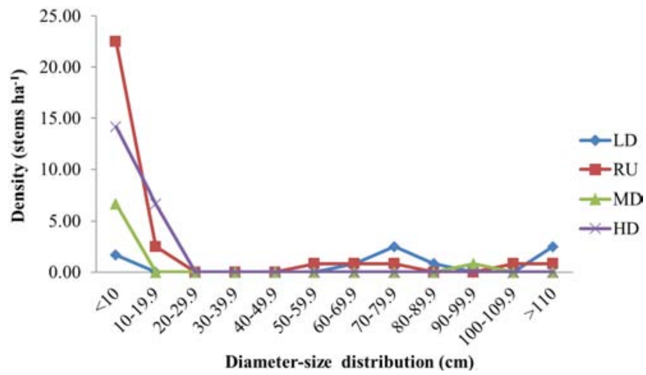

Figure 2. *Diameter-size distribution structure of P. africana in SWMF.*

According to [58], disturbance is a cause of modification of natural regeneration patterns, thus recruitment in the Mau forest ecosystem. The observed recruitment of *P. africana* in South West Mau forest was poor indicating a modified natural regeneration pattern. The erratic recruitment potential indicates unstable population that might cause local extermination of the species [29, 43].

The higher density of stems < 10 cm and very low densities or lack of stems of diameter classes beyond 10-19.9

cm indicates high seedling mortality. Very few adult trees means inadequate seeds production, a situation coupled with seedling mortality may endanger the survival of the species in the wild. Poor diameter-size distribution could be due to harvesting of the species for timber and medicines in the past leaving only few scattered stems whose seedlings succumb to competition by herbs and other invasive species.

Conservation of SWMF as opined by [58] should be enhanced to enable early successional species to give way to late successional non-pioneers. A study by [59] stated that enrichment planting is the preferred method of assisting natural regeneration of degraded forests when desirable species are absent or at low densities. Similarly, [60] suggested enrichment planting as a way of restoring the under-populated tree species.

4. Conclusions

Prunus africana in South West Mau forest has experienced significant human disturbance due to debarking. The regeneration density of *P. africana* was highest in a lesser disturbed site near Forest Station office. The population structure of *P. africana* near Forest Station office was fair as it was close to reverse-J curve. The structures were poor in the rest of the sites indicating the species is at potential risk of disappearing from these study sites in future. There is need for immediate conservation strategies for *P. africana* and training of law enforcement personnel on the importance of conservation of these species as a supplementary to forest protection laws which seem not to provide an effective conservation of the species. There is also need to involve the community fully in conservation of the species through writing of appropriate management plans to avoid uncontrolled debarking of *P. africana*. Policies of domestication of *P. africana* may be introduced to reduce disturbance and exploitation of those in the wild. Protection of seedlings in the wild may as well be improved through minimization of human disturbances particularly in areas where *P. africana* is abundant. The results suggested that both natural and human disturbances reduced species richness and diversity. The observed poor population structures of *P. africana* in South West Mau forest may be due to both natural and human factors. The vulnerability of *P. africana* to both natural and human threats [48] implied the need to highly prioritize areas for conservation [61].

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