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The Influence of Soil Characteristics on Plant Species Diversity and their Distribution Patterns in Western Serengeti, Tanzania

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Abstract: This study was conducted in Western Serengeti with an objective of exploring how plant diversity changes along a gradient of different human influences, starting from a public land (open area), through a game reserve and into a national park. In terms of human influence, there is no legislation governing utilization of public land, whereas game reserve areas enjoy partial protection where prescribed human activities are allowed. For the case of national parks, apart from tourism, human activities are totally prohibited. Three sites were selected for this study namely Mihale, Robanda and Sodeko. The study further aimed to identify plant indicator species associated with different soil characteristics. Species diversity and evenness increased from the public land through the game reserve and maximum diversity was observed in the national park zone, although such results were not statistically significant ($p>0.5$). Canonical Correspondence Analysis (CCA) results indicated that floristic composition in any study site was dependent on its conservation status as well as its historical background. This was quite obvious for Mihale site but not for Robanda and Sodeko (also known as Tabora B) where much of the game reserve was annexed recently from the public land. Texturally, the soils of Western Serengeti are highly variable, comprising of 11 textural classes, dominated mainly by clay fractions. The chemical and physical characteristics of the soils in Western Serengeti were directly linked to different vegetation typologies occurring in Serengeti with exchangeable bases overriding other factors as determinants of the vegetation. The decline in available phosphorus concentration detected along the soil profiles accumulation of the same in the top soil was an indication that soil phosphorus was chiefly derived from frequent fires that sweep the Serengeti grasslands annually and not from weathering of the parent material. A number of indicator plant species of various ecological conditions conforming to those reported in various literatures were encountered. These included indicators of fallow land; indicators of disturbed and poor soils; indicators of water logged soils and indicators of phosphate and nitrogen rich soils.

Key words: Conservation, fire, grassland, human influence, indicators, nutrients, overgrazing, plant diversity, Serengeti ecosystem, soils

INTRODUCTION

Serengeti National Park (SNP) covers an area of 13 250 km^2 and is located between latitudes 01°30' and 03°30' and longitudes 33°80' and 35°30', in the North-Eastern Tanzania (Fig. 1). The park consists of Serengeti plains which are confined to the lower altitudes and the Serengeti woodlands in the higher altitudes. The altitude ranges from 1135-2090 m above the sea level (De Wit, 1978). Geologically, SNP is very diverse and consists of very old rocks of pre-Nyanzian gneisses, Nyanzian quartizites, metamorphosed volcanics and granites which are a common feature throughout the park (Jaeger, 1982). The Serengeti ecosystem has unique habitat and landscape diversity which support a mosaic of distinct vegetation associations and large herds of migratory herbivores such as wildebeest, zebra and Thomson gazelle. The large herbivore community of Serengeti ecosystem plays an important role in nutrient cycling. In addition to grazing, the frequent fires that sweep the ecosystem contribute to the rapid nutrient cycling (Norton-Griffiths, 1979). Depending on the abundance of grazers and their movement patterns, perennial grasslands may eventually be converted into annual grasslands and this can be regarded as a manifestation of land degradation. In very dry grasslands, annual species may dominate even in the absence of grazers while wetter sites will be dominated by perennial grasses. Grazing may affect the primary productivity of grasslands by removing the photosynthesizing surface area. McNaughton (1979) observed that low to moderate grazing increases net productivity in grazing ecosystems. The East African ungulates harvest nutrients over a fairly broad area and concentrate them in ecological hotspots where those resources limiting plant growth can be found in relatively high abundance (Young *et al*., 1995). This has been

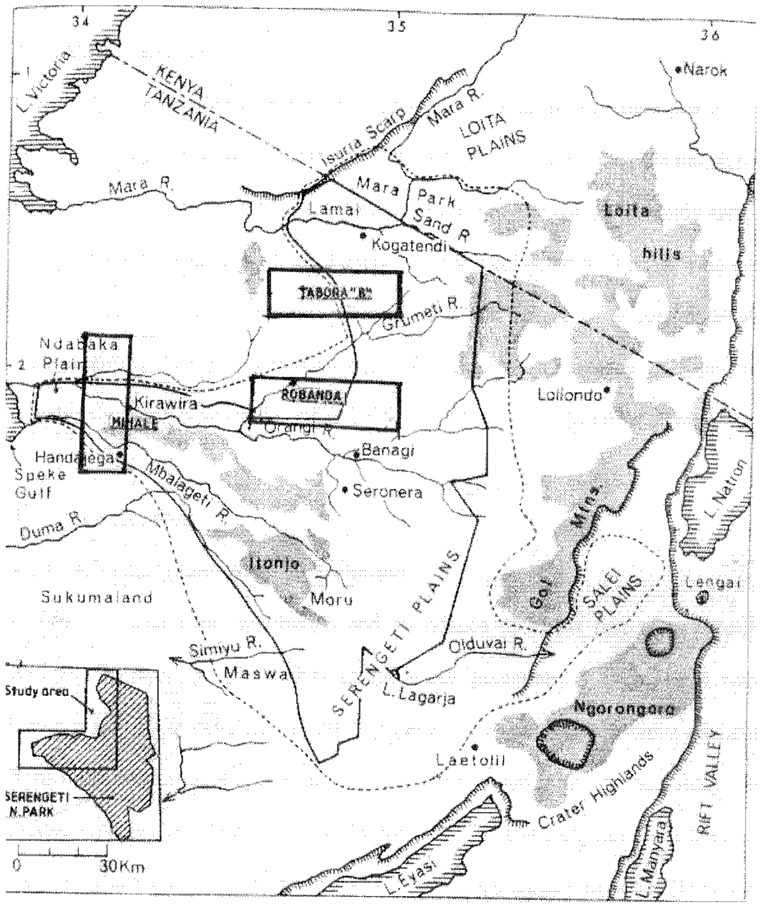

Fig. 1: A map of Serengeti ecosystem depicting the location of the study sites (Nkya, 2004)

observed in southern Turkana where a concentration of nutrients has been shown to be accompanied by a concentration of viable seeds of *Acacia tortilis* which have passed through digestive tracts of corralled animals, making abandoned corrals to be miniature thickets of *Acacia tortilis* (Reid, 1992).

The vegetation and soils of Serengeti have been studied extensively (Anderson and Talbot, 1965; Braun, 1973; Herlocker, 1976; Gerresheim, 1974; Kreulen, 1975; Banyikwa, 1976; De Wit, 1978; Jaeger, 1982; Metzger *et al*., 2005). However, these studies concentrated mainly on the geological aspect with little emphasis on the soil physical and chemical properties which are considered to be crucial determinants of plant diversity and the vegetation distribution pattern.

Moreover, most of the research concentrated on the easily accessible parts of the Serengeti ecosystem and not much attention was given to Western Serengeti. The Western Serengeti corridor is an important route of the migratory wildlife and therefore, this justify the need to undertake research in this area in order to explore the relationship between the vegetation and the soils of Western Serengeti. This main objective of the study was to assess changes in plant diversity in areas exhibiting different levels of conservation and link the trends to the soil properties.

In this aspect, public land (open area) was regarded as having no conservation status (i.e., not protected by any legislation on human use) game reserve had partial protection whereas the national park zone enjoyed fully protection and strict conservation measures. Plant bio-indicator species of various soil conditions were also investigated in this study.

The study hypothesis was that biodiversity increases along a gradient from the area with High Human Influence (HHI), i.e., the public land, through the game reserve with Intermediate Human Influence (IHI) and maximum plant diversity was expected to occur in the national park where there was Low Human Influence (LHI). Also it was hypothesized that soil properties strongly influenced plant species diversity and distribution patterns in Western Serengeti.

MATERIALS AND METHODS

The study area: This study was conducted in Western Serengeti which is comparatively less studied than any other area in the Serengeti. The Serengeti ecosystem constitutes the last of the great migratory systems in Africa which supports the largest herds of migratory ungulates and probably the highest concentrations of large predators of the world. The annual migration of the white-bearded wildebeest and to a lesser extent zebra and Thomson's gazelle is one of the most ecologically significant features of the Serengeti ecosystem (McNaughton, 1979). It is due to unique abundance and diversity of wildlife that the ecosystem was designated a national park in 1959 and the first to be declared a biosphere reserve in 1991.

The increase of human population around the Serengeti ecosystem has caused considerable stress and impacts of various kinds on the ecology, despite the high ecological diversity and conservation status. The rapid population growth, resulting from migration of herders into the area resulting into huge influx of domestic livestock, compounded with poverty as well as increasing demand of arable land and bio-resources are major threats to the Serengeti ecosystem. Research has shown that depending on the season, the density of grazers influences both species diversity, spatial heterogeneity and the vegetation structure (Adler *et al*., 2001; Metzger *et al*., 2005). The area exhibits a bi-modal rainfall pattern of 400-1200 mm annum^{-1} with peaks occurring in December and April (Norton-Griffiths *et al*., 1975). Rainfall and topographic relief are the major contributors to the distribution of woodlands and grasslands in the Serengeti ecosystem (Reed *et al*., 2008). The climate of Serengeti ecosystem is influenced by the Ngorongoro Crater highlands which create a rain shadow in the area. The hydrologic cycles of Lake Victoria account for temperate fluctuations between the lake and the surroundings (Jaeger, 1982).

The experimental design: Three study sites were selected for this research viz. Mihale in the West, Sodeko (Tabora B) in the North-West and Robanda between Mihale and Sodeko (Fig. 1). Using a Global Positioning System (GPS), a total of 5 transects each 15 km long and spaced 1 km apart were established along a gradient of human use influence from a public land, through a game reserve into the national park for each study site. In total, five sampling points spaced 1 km apart (i.e., a total of 15 sampling points per transect), forming a grid of 75 km^2 for each of the three study sites were selected. Nested quadrat sampling technique (Stohlgen *et al*., 1995) was adopted in this study. Three-level sampling was employed whereby trees were sampled in 225 quadrats measuring 50×20 m and shrubs and juvenile trees in 225 measuring 5×2 m quadrats nested into the big quadrat. Grasses and herbs which were the predominant vegetation cover of the study area were sampled in 900 quadrats measuring 2×0.5 m taken from each corner of the big quadrat.

The information recorded for trees included specie's names, Diameter at Breast Height (DBH), crown cover, phenology and browsing intensity. For shrubs and juvenile trees, frequency was recorded in addition to relative cover, height, browsing intensity and their phenology. For grasses and herbs, information on specie's identity, relative cover, grazing intensity, average height and the overall vegetation cover of the quadrat was estimated. The average height was obtained by measuring randomly four heights of grasses in a quadrat. Grazing and browsing intensities were scored as 0 for no grazing/browsing; 1 for low; 2 for moderate; 3 for high and 4 for very high. For grass cover, a modified Braun-Blanquet (Mueller-Dombois and Ellenberg, 1974) scale was adopted where vegetation cover <25% scored 1; cover 25-50% = 2; 50-75% = 3 and above 75% = 4. Species difficult to identify in the field were collected, pressed, dried and taken to the Herbarium of the University of Dar es Salaam (DSM) for proper identification by matching with dried herbarium specimens or by using the available floras. The nomenclature used follows that of Turril and Milne-Redhead (1952) and Exell and Wild (1960).

Soil sampling: Soil samples were collected in plastic bags during the dry season and transported to Dar es Salaam for laboratory analysis. For each of the selected sampling point (45 for each study site and 15 from each area with different human influence or conservation status), soil was sampled using soil auger at three different depths viz. 0-10, 10-20 and 20-40 cm.

The soils were air dried and analyzed for seven physical parameters and 10 chemical parameters using standard procedures for soil analysis as outlined by Allen (1989).

The samples were coded to indicate the study site, the area in terms of conservation status and transect number for ease of identification. The three study sites Mihale, Robanda and Sodeko were coded M, R and R, respectively. Transects (5 in each site) were coded as T1, T2, T3, T4 and T5. Thus, a sample collected from Robanda in the game reserve area in transect number 5 with a plot number 25 was coded RGT525. For the open (public) area and the national reserve, samples were coded as ROT and RNP, respectively for Robanda samples, MOT and MNP for Mihale samples and SOT and SNP for Sodeko samples.

Data analysis: The data sets were tested for normality using Kolmogorov-Smirnov Test. The data that were not normally distributed were square root transformed, followed by one way Analysis of Variance (ANOVA) and multiple comparison done using Least Square Differences (LSD) test. In order to identify the indicator species and explore the relationship between the soil characters and the vegetation of Western Serengeti, multivariate analysis using the program PC-ORD version 4.20 (McCune and Mefford, 1999) was used. Canonical Correspondence Analysis (CCA) was employed where two files, one with species data x plots as one matrix and the other with environmental data x plots matrix were employed. For species, only qualitative data was used.

RESULTS

Although, species diversity and evenness appeared to increase along the human influence gradient in the three study sites, (i.e., from the public land, through the game reserve and into the national park), the difference was not significant ($F_{(2, 42)}$ = 0.626, p>0.5 for Robanda ($F_{(2, 42)}$= 0.51, p>0.5 for Sodeko and ($F_{(2, 42)}$= 0.741, p>0.5 for Mihale). Species richness followed the opposite trend of decreasing towards the area with low human influence but again the difference was not statistically significant in the three study sites ($F_{(2, 42)}$ = 1.572, p>0.05).

Canonical Correspondence Analysis of species x environmental data matrices (only axes 1 with eigen value 0.413 and axis 2 with eigen value 0.346 considered) clearly separated areas with different human influences in the Mihale study site.

The sampled plots from the public land formed one cluster whereas those from the game reserve and the national park zones were inseparable. In Robanda and Sodeko, the distinction of different human influence zones was not obvious.

On a fine scale, the soils Western Serengeti can be divided into 11 textural classes, with clayey soils dominating by over 50% of the other classes. Others include sandy loams, loamy sand, clay loam, silt clay, clay, silt, silt loam, sand clay loam, sand and silt clay loam.

The public land in Robanda had significantly higher concentration of exchangeable sodium than the game reserve and the national park zones ($F_{(2, 42)}$= 7.29, p>0.002). Contrary to this observation, soils from Sodeko had significantly high levels of sodium in the national park ($F_{(2, 42)}$ = 7.22, p>0.002) than either the public land or the game reserve zones.

Most soil samples from Mihale and Robanda ranged from being neutral (pH 7) to slightly alkaline whereas Sodeko soils were slightly acidic. The observed difference is attributed to the levels of sodium in the soil in this case, Robanda and Mihale soils having a high concentration of sodium anions (i.e., more sodic) than Robanda soils.

Among the areas with different human influences, Potassium levels were significantly higher in the national park zone ($F_{(2, 42)}$ = 12.446, p>0.05) than was detected in the public land or the game reserve for all study sites. In Mihale there was higher concentration of Magnesium in the soil samples collected from the game reserve and the national park zones compared to those samples collected from the public land.

The same trend was observed with electro-conductivity. The levels of available phosphorus (P-PO_4^-) varied considerably across the three sites but there was general tendency to decrease with soil depth. Total nitrogen in soil samples collected in the national park zone was significantly higher ($F_{(2, 42)}$ = 4.943, p>0.05) than either those collected from the game reserve or public land in Robanda but was not so for Mihale and Sodeko.

CCA dendrograms revealed that specific soils characteristics were correlated with distribution patterns of different plant species in Western Serengeti (Fig. 2). With increasing bulky density, the soils favored predominantly the establishment of grasses and herbs that are shallow rooted, except for *Balanites aegyptica*, *Acacia tortilis*, *Lannea humilis*, *Lannea stuhlmannii* and *Acacia seyal* var. *seyal* which are trees.

Increasing grazing intensity greatly favored invasion of stoloniferous grasses such as *Cynodon dactylon*, *Dactyloctenium geminatum*, *Eustachys paspaloides*, *Urochloa mossambicensis* and *Digitaria milanjiana*. The number of unpalatable, spiny woody herbs such as *Tragia furialis*, *Crotalaria spinosa*, *Ocimum kilimandscharica*, *Melhania ovata*, *Lippia spicata*, *Corchorus aestuans* and *Tribulus terrestris* increased. Presence of dense thickets of *Dichrostachys cinerea* is a clear manifestation of overgrazing.

High soil pH and increased exchangeable sodium seen in cultivated land is regarded to be a result of alkaline volcanic depositions. Such sites in the cultivated land were associated with agricultural ruderal weeds which formed a distinct cluster in the ordination space. The weeds which were predominantly herbaceous, included *Trichodesma zeylanicum*, *Bidens schimperi*, *Oxygonum sinuatum*, *Crabbea velutina*, *Senecio abyssinica*, *Zornia setosa* and *Perotis hildebrandtii*.

High concentrations of exchangeable bases notably potassium, sodium and calcium together with high salinity resulting from poor drainage favors the establishment and domination of *Acacia drepanolobium*, *Acacia robusta*,

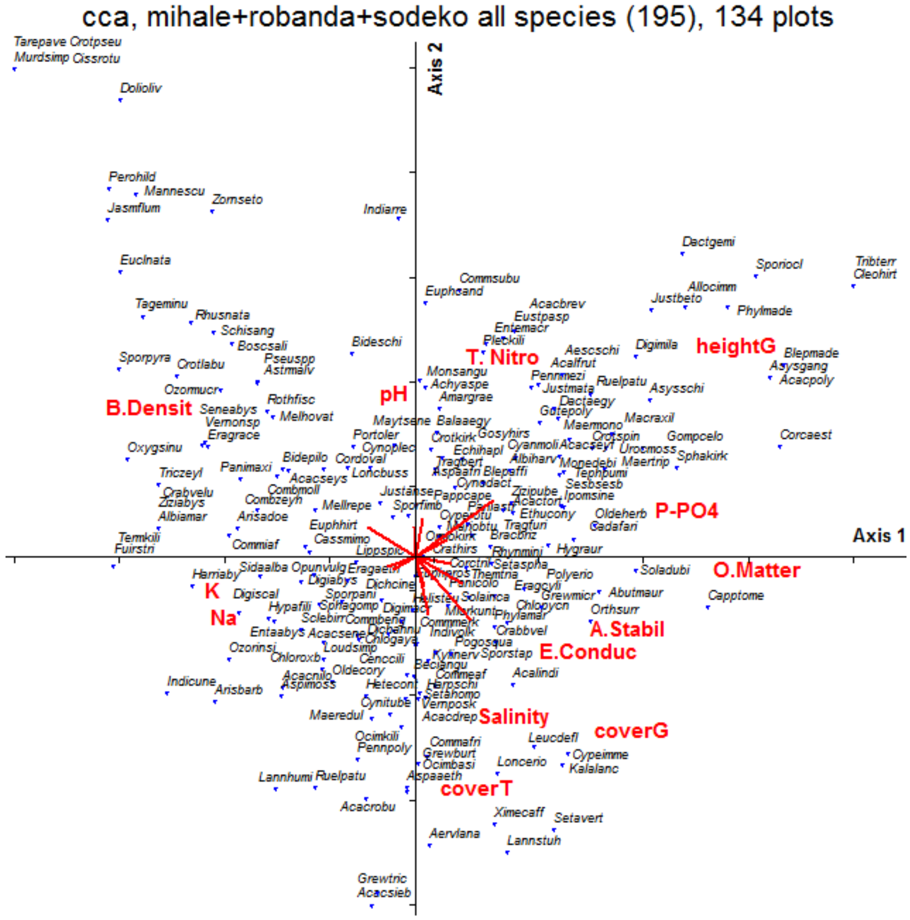

Fig. 2: Dendrogram showing the relationship between the environmental variables and plant species (all three sites combined)

Acacia tortilis, *Balanites aegyptica* and *Acacia seyal* var. *fistula* in many waterlogged areas of Western Serengeti.

DISCUSSION

The research findings reported in this study on the soil properties and their influence on species diversity and distribution patterns of plant species are concurrent with those reported in Anderson and Talbot (1965), Banyikwa (1976), De Wit (1978) and Jaeger (1982). Most soils of Western Serengeti are derived from volcanic depositions and weathering of pre-Cambrian basement rocks (De Wit, 1978). Whereas volcanic soils mainly support grassland vegetation, soils derived from parent rock support predominantly woodland vegetation.

The dynamics of vegetation in a rangeland are determined by array of factors which include fire frequency and intensity, grazing regime, climatic fluctuations and to some extent the soil characteristics. Intensive grazing is known to increase species diversity, species richness and the total amount of crude protein in plants (McNaughton, 1979; Western and Gichohi, 1995; Vesk and Westoby, 2001). Removing grazers in a protected ecosystem may have a number of consequences such as increase of the above ground biomass and dominance of herbaceous vegetation (Vesk and Westoby, 2001). Some grass species were directly associated with high grazing intensity.

Such species have evolved morphological plasticity as an ecological adaptation to cope up with increased grazing pressure. This explains the overwhelming dominance of stoloniferous grasses such as *Cynodon dactylon*, *Dactyloctenium geminatum*, *Eustachys paspaloides*, *Sporobolus iocladus* and *Urochloa mossambicensis* in intensively grazed areas. The association of specific tree species such as *Balanites aegyptica*, *Acacia tortilis* and *Acacia seyal* var *seyal* with soils of high bulky density (>2 g cm^{-3}) is interesting and requires an explanation. Throughout the range where these species dominate, the top soil (A-Horizon) is very shallow and this is followed by a restricting zone which has been referred to as petrocalcic horizon by De Wit (1978). In the A-Horizon, there is very high density of localized grass roots, since they can not penetrate the petrocalcic zone. It has been reported that most tropical soils have bulky density ranging from 1.0-1.7g cm^{-3} (Arshad *et al*., 1996) and that 1.7 g cm^{-3} was the maximum threshold needed to restrict root growth. A probable explanation to this observation could be linked to the presence of mycorrhiza in roots of such plants. The importance of the fungus rests on its ability to solubilize soil particles in the vicinity of the roots so that trees are able to send their roots past the petrocalcic zone into the B-Horizon.

Chemical characteristics of soils such as salinity, electro-conductivity and extremes of pH greatly determine the type of vegetation in an area as they directly influence nutrient uptake. However, frequent burning which is very common in the Serengeti ecosystem has two effects on soil nutrient economy. Firstly, it eliminates the trees and later may completely suppress regeneration of the same. Elimination of trees may consequently intensify leaching as a result of reduced dry season transpiration (Anonymous, 1979). Secondly, fire may cause a loss of soil nutrients such as nitrogen, sulphur and to a lesser extent phosphorus and potassium through volatilization (McNaughton *et al*., 1998). Loss of nutrients under extensive grazing conditions is minimal but is much pronounced under intensive grazing conditions (Anonymous, 1979; Proulx and Mazumder, 1998).

Presence of high concentrations of sodium cations in Robanda and Mihale soils account for their high electro-conductivity. Low electro-conductivity is detrimental to soil fertility as it negatively influences the available nitrate nitrogen (NO_3^-N). Soils with low electro-conductivity are mainly sandy loams in which soluble salts are constantly being lost through leaching. This is the case with the soils of Sodeko study site. Most nutrient elements are available to plants within a pH range of 6.0-7.5 (Emteryd, 1989). It is known that at pH values above 8.0, ammonium ion (NH_4^+) only exists in form of ammonia gas which evaporates easily from the soil. The activity of nitrite oxidizing bacteria is also inhibited by high pH values. The pH values obtained from this study are within the range which allows effective nutrient uptake from the soil.

This study revealed a pattern whereby the available phosphorus decreased with depth along the soil profile. The interpretation here could be that the available phosphorus is not a product of weathering of the parent material but a result of frequent fires that sweep the Serengeti grasslands and that is why it is localized in the top soil.

A number of indicator plant species of various ecological conditions were encountered in this study. These included indicators of fallow land; indicators of disturbed and poor soils; indicators of water loggedness and indicators of phosphate and nitrogen rich soils. Such species conform to those reported in literature (Dogal and Bogdan, 1960; Skerman and Riveros, 1990; Boonman, 1993). Other important palatable and heavily grazed rangeland grasses reported in this study that are tolerant to sodic soils included *Urochloa mosambicensis*, *Panicum coloratum*, *Chloris gayana* and *Cenchrus ciliaris* (Russell, 1976; Skerman and Riveros, 1990). Plants can be categorized as increasers or decreasers, corresponding to their shifts in relative abundancies in response to grazing but this will depend on the total amount of rainfall available in that rangeland (Vesk and Westoby, 2001). Other plant species and what they indicate in brackets were: *Digitaria abyssinica* and *Eragrostis aethiopica* (pioneers of disturbed and fallow land); *Setaria sphacelata*, *Panicum astrosanguienum* and *Digitaria scalarum* (notorious weed of arable land); *Cynodon dactylon* (pioneer and early successional colonizer); *Brachiaria brizantha* (free-draining sandy soils) and *Sporobolus fimbriatus* (poor dry soils and wastelands).

CONCLUSION

Deaths of extensive stands of *Acacia drepanolobium* seen in Robanda and in other places is explained by severe root damage caused by cracking clays and possibly not due to increased levels of exchangeable bases. During the dry season, the black cotton soils crack heavily and they close when the rainy season ensues. It is anticipated the process of contracting and expanding exhibited by clayey soils accounts much of the observed tree deaths. Alternatively, high concentrations of toxic soluble salts such as sodium chloride and sodium carbonate find their way to the roots through the cracks during the rains, thereby killing the roots.

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