Analyzing the Impact of Charcoal Harvest and Land Management Type on Vegetation Regeneration in the Tambacounda Region of Senegal

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Abstract

Households throughout Sub-Saharan Africa depend on fuelwood (firewood and charcoal) as their primary source of energy. In Senegal, increasing demands for charcoal by urban consumers has led to intensified harvesting of wood for charcoal production in the Tambacounda region. Forest management projects have been created in the region to reduce degradation caused by charcoal production. This study analyzes tree diversity and regeneration patterns in the Tambacounda region to determine the effect of tree harvesting for charcoal production on plot structure, tree species composition and forest regeneration and assess the effect of forest management types on forest composition and regeneration near charcoal production sites. Results from this study demonstrate that species composition and structure in harvested and undisturbed plots are significantly different. Regeneration of common species such as *Combretum glutinosum* (53% of the total surveyed population) is robust in all harvested plots. Large, hardwood tree species are rare in both harvested and undisturbed plots and lack sufficient populations replace the current population. Harvesting is spread throughout the regions and plots regardless of proximity to villages, roads and park edges are equally susceptible to changes in forest structure and composition. Forest management type also appears to have little impact on forest composition before and after harvesting with the exception of species diversity. Co-managed plots have higher species diversity values than government managed plots, but large declines of over 50% in species diversity values were observed between undisturbed and harvested plots. Steady growth rates of resilient species are occurring in all forest management types, but trees are still much smaller in height (4.5m) and diameter at breast height (dbh) (5.4cm) six years after cutting than undisturbed plots (7.7m and 17.5 cm, respectively). A new forest landscape is taking shape in the Tambacouda region, one dominated by fast growing and resilient species. Forest management could play an important role in slowing this change, but currently is having little influence on forest composition, structure and regeneration rates.

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*This research was conducted independently and may not reflect the views of the United States Government.

Introduction

In Senegal, as in most parts of Sub-Saharan Africa, households both rural and urban are largely dependent on fuelwood (charcoal and firewood) for their energy needs (Ribot 1995, Girard 2002, Post and Snel 2003). In the late 1980's, due to increase demands of urban consumers, a wave of charcoal production began to sweep through the woodlands (Post and Snel 2003). Currently the Tambacounda region of Senegal accounts for over 50% of the country's official charcoal quota (PROGEDE 2007). The influx of charcoal production has been perceived to cause severe degradation of over half of the wooded savannah altering the biology and habitat quality (Tappan et al. 2004). These noticeable changes in the remaining forests have raised concerns about the ability of local populations to manage lands in the face of expanding pressures likely caused from combined human and climatic influences (Gonzalez 2001, Wezel and Lykke 2006).

In present day Senegal, charcoal is legally produced in two regions, Tambacounda and Kolda, in southern Senegal. Because of the area's importance to the country's charcoal trade, it has become the focal point of the international forestry and natural resource management projects including the World Bank funded Programme de Gestion Durable et Participative Des Energies Traditionnelles et de Substitution (PROGEDE) and United States Agency for International Development (USAID) funded Wula Nafaa project. Due in part to the presence of these projects, much of the forests are classified as restricted access areas including a national park, classified forest reserves and co-managed forests.

Forests in these regions are categorized by the Senegalese Forestry Department as: Classified Forest (CF), PROGEDE co-managed forests (PRO), USAID/Wula Nafaa managed forests (WN) and a Rural Community forests (RCF). Rural Community forests are woodlands near to villages technically under local management, but the government actually remains in control of most forest access. This area is often utilized as grazing land, an important source of fuelwood and supplemental income through the collection and sale of deadwood, timber extraction and the harvesting of wood for the production of charcoal. Agricultural plots also exist within this zone. Land management types CF, PRO, and WN are all officially managed to exclude (in CF types) or limit the negative impacts of tree harvesting for timber or charcoal production (in PRO and WN types). Although no live wood cutting is officially allowed within the boundaries of a CF, much extraction takes place in these forests (Ribot 1995). PRO and WN land management types are jointly managed by local and government bodies. Harvesting of wood for charcoal production is limited to annually rotating harvesting zones. Effectiveness of this method often varies depending on community and government involvement.

While the social dynamics of the charcoal industry are well studied, (Ribot 1990, Lazarus, Diallo and Sokona 1994, Ribot 1995, Post and Snel 2003, Manga 2005, Ribot 2009), the effect of forest management and the harvesting of wood for charcoal production on regeneration and forest diversity are still in question. Previous studies have shown that land access rights and management style may impact forest composition and regeneration characteristics (Ribot 1993, Banda, Schwartz and Caro 2006); but little ecological information is available to confirm these results.

Objectives and Hypotheses

This research analyzes tree diversity and regeneration patterns in the Tambacounda region of southeastern Senegal. The specific objectives of this research are to: 1) determine the effect of the harvesting of trees for the production of charcoal on plot structure, tree species composition and forest regeneration; and 2) assess the effect of varying forest management types on forest composition and regeneration near charcoal production sites.

To accomplish this, the following hypotheses are tested:

- Tree species diversity, forest plot structure (average plot tree height and diameter at breast height (dbh)), and estimated percent canopy cover (PCC) will be less in areas of charcoal production when compared to areas of no production;
- Plot species composition, tree species diversity, and vegetation structure characteristics are positively correlated with proximity to major roads, villages, and park edges;
- Forest management type will result in no significant variation in tree species composition and regeneration rate near charcoal production sites.

Study Area

The Tambacounda region of Senegal is part of the Eastern Transition Ecoregion (WWF 1998) and consists of land cover characterized by sandstone plateaus of the continental sedimentary basin with savannah woodlands, areas of agricultural parkland, and thin sections of gallery forest near river and stream beds. All of the sampled plots are located in the savannah woodlands cover type defined in Tappan et al. 2004.

Senegal has experienced four serious droughts during the 20th century, but in recent years rainfall has shown increasing trends with "good years" in 1994, 1999, 2003, and 2005 seen as a return of good rainfall years (Mbow et al. 2008). In the past ten years the region has received a relatively consistent rainfall of 500-800mm.

Fire is an important component in the ecoregion with dry season fires burning 60 to 90 percent of the land in the study area annually (Mbow, Nielsen and Rasmussen 2000, Mbow et al. 2008). The main objectives of human-started fires are to clear land for agriculture or grazing of livestock (Wurster 2010).

Methods

A four part methodology was derived to test the hypotheses.

1) Descriptive plot statistics (average dbh, average height, percent canopy cover, plot density, etc) were calculated for the entire data set, then disaggregated by harvested and undisturbed sites and by land management type.
2) Multiple regression analyses were performed to test for correlations between plot vegetation statistics and distances to villages, roads, and park edges.
3) Species count and size (diameter at breast height and height) information were used to create species density estimates and species size class distribution curves estimating regeneration within the entire data set, harvest/undisturbed, and different land management types.
4) Data collected during interviews and previous field data were used to estimate the rate of regeneration after harvesting for charcoal production.

Field Survey Methodology

Field work was conducted during January 2008 to May 2008. The effects of charcoal harvesting on tree diversity and regeneration were characterized over an area of 655 km^2 in the Tambacounda region of Senegal (Figure 3-1). The study area included 77 sample plots (61 charcoal, 15 undisturbed) belonging to four different forest management types (Rural Community forest (RCF), Classified Forest (CF), PROGEDE (PRO), Wula Nafaa (WN)).

High resolution Ikonos satellite imagery (scene size of 11.3 by 11.3 km) and GPS data from previously conducted surveys in 2003 and 2004 were used to identify historic charcoal production sites. In total, 500 historical charcoal locations were identified with 80 historical charcoal locations randomly selected for field sampling. Historic charcoal sites were categorized as RCF, CF, PRO, or WN. A stratified random sampling technique was used to select equal numbers of plots across the different land management types. Latitude and longitude coordinates for each selected plot were entered into a GPS. Eleven villages adjacent to the randomly selected set of plots were chosen to serve as regional field headquarters.

A total of 77 randomly selected 25mx25m plots were surveyed throughout the Tambacounda study area. 61 of the 77 were locations of historical charcoal production while 15 were designated as undisturbed sites. Much of the forest is altered by human activity, therefore areas completely lacking human disturbance were infrequently encountered. The selection of undisturbed sites was based only on the visual absence of disturbance (disturbance included wood removal for charcoal harvesting, timber collection, wood fuel collection, heavy grazing, or recent fire). Tree size and/or plot diversity were not taken into account. The visual lack of disturbance was the only criteria.

A total of 15 25m x 25m undisturbed plots were identified while in the field. Undisturbed plots were collected within each of the 11 regions and within each land management type allowing for comparisons to be drawn between regions and management types.

Plots ranged between 500 m and 10 km from villages. Sample plots were located 50m from the center of the charcoal kiln scar (Figure 3-2). This point served as the front-left corner of the plot. The direction that the 50m was measured was randomly determined by spinning a stick on an axis. The 25m x 25m plot was then measured from this point for which all living trees (defined as woody perennial species) of dbh >1cm were counted and measured. Plot size of 25m x 25m was used to match previous tree diversity field work in the region (Manga 2005). Plot variables including lat/long, land management type, presence/absence of fire, grazing, insects, charcoal harvest, timber harvest, other harvest, estimated percent tree cover (based on readings from a densitometer), and estimated slope and direction were collected for each plot (Appendix B - Forest plot form).

Diameters were measured at 1.3m above ground (diameter at breast height – dbh) for all trees with diameters larger than 2 cm. For trees that branched below 1.3m, had dbh <2cm, or had been cut below 1.3m, diameters were measured at 0.5m above ground. The species identity of each tree was established in the field. Tree species were identified using local knowledge and verified using "Tree, shrubs and lianas of West African dry zones" (Arbonnier 2002). All coppicing plants were counted, the average dbh of coppicing plants was measured, and the number of old stumps was counted. This information was used to assess the rates and factors of regeneration after charcoal production within the varying forest management types (Appendix C – Forest plot species forms).

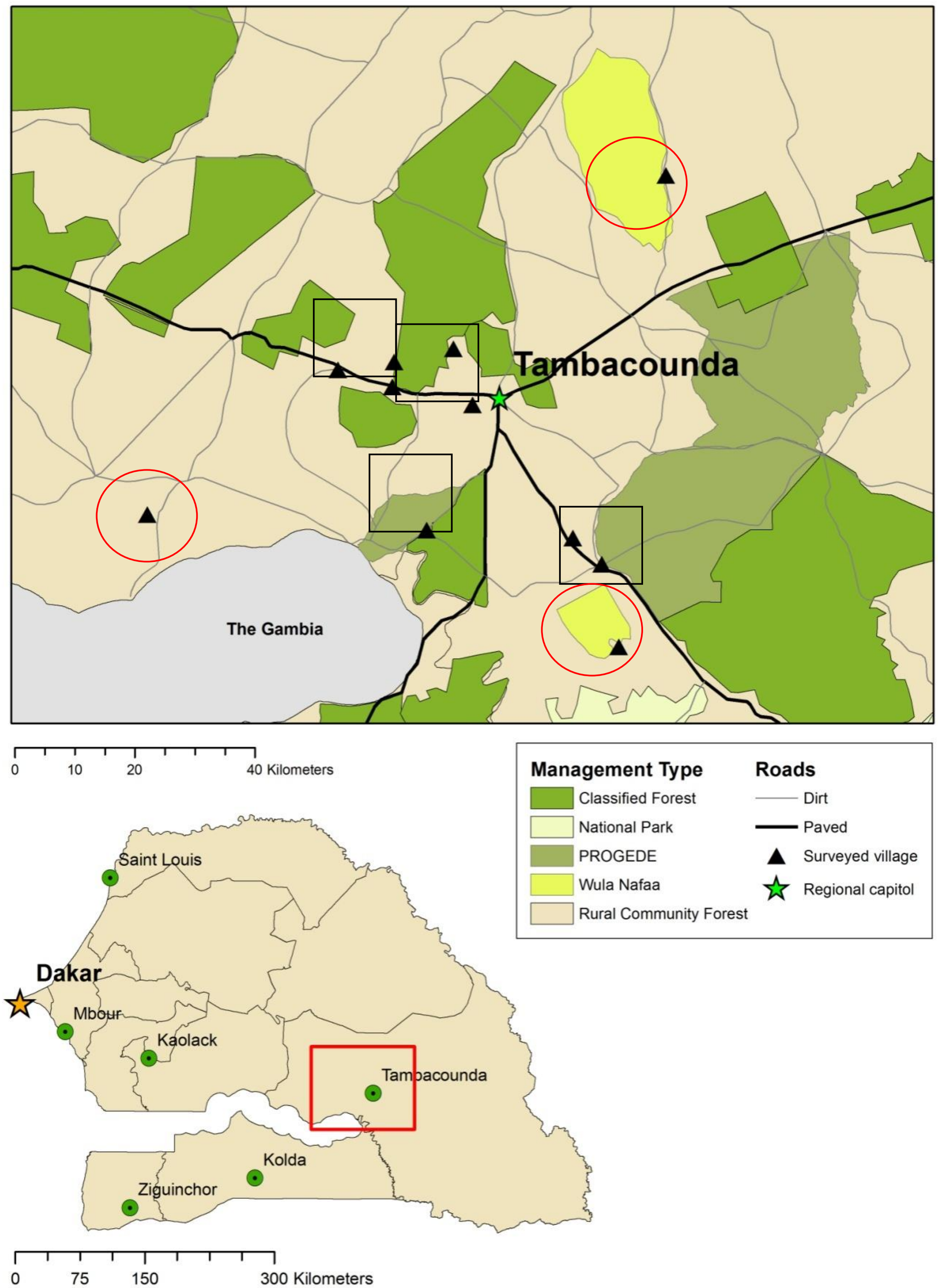


Figure 0-1 - Location of forest management types in the Tambacounda study area. Black boxes indicate where Ikonos satellite images were used to identify historic charcoal sites. Red circles identify areas were previous charcoal sites have been identified in the field.

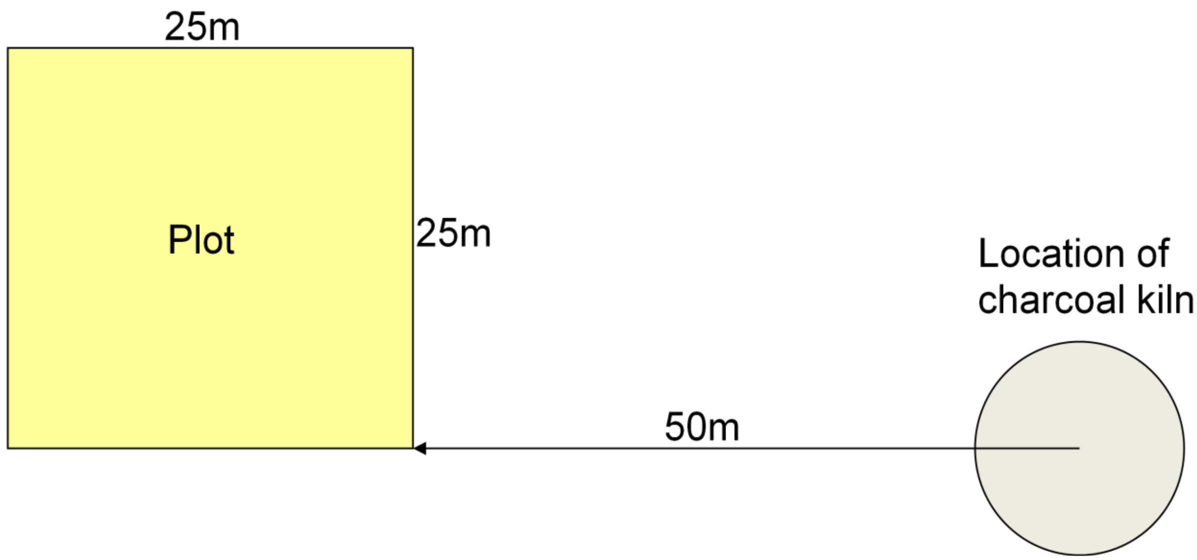


Figure 0-2 - Plot locations – Sample plot layout in relation to the location of a charcoal kiln.

Analysis Methodology

1) How do sites vary in structure and diversity?

Plot structure, diversity and tree characteristics for each sample plot were used to analyze the differences between harvested and undisturbed sites and within forest management type categories.

Plot structure and individual tree characteristics

Percent tree cover, plot tree density, average diameter at breast height (dbh), and average tree height were used to assess plot structure across all categories. Percent tree cover was estimated using a densiometer with reading taken in 25 points throughout the plot (one reading every five meters). Tree plot density was calculated by dividing the total number of individuals by the total area of an individual plot (625 m^2). Average tree height and dbh were calculated using individual tree height and dbh from the plot and dividing by the total number of individuals.

Species Diversity Index

Diversity indices provide a summary of richness (number of species per sample) and evenness (relative abundance of the different species) by combining these two facets of diversity into a single statistic. There are many ways by which richness and evenness can be combined, and this has resulted in many different diversity indices. Some of the common diversity indices are the Shannon, Simpson, and log series alpha diversity indices (Begon, Townsend and Harper 2005).

For this study the Simpson's diversity reciprocal index (1/D) were used to compare tree diversity between sites and forest management types. This index is based on the Simpson's index (Simpson 1949) developed to account for species frequency and evenness measuring the probability that two randomly selected individuals from a sample will belong to the same species. The Simpson's index is expressed as:

$$\sum_{i=1}^{S} \frac{n_i(n_i - 1)}{N(N - 1)}$$

Where n_i is the number of individuals in species *i* and N is the total sample size. The reciprocal form (Williams 1964) has additional desirable mathematical qualities (MacAurthor 1972), often used in ecological research (Hill 1973, Milchunas et al. 1989, Gimaret-Carpentier et al. 1998, Yoccoz, Nichols and Boulinier 2001) and more intuitive to understand. Simpson's diversity reciprocal index (1/D) values are always between one and the total number of species with higher values suggesting greater species diversity.

2) How does proximity to villages, roads and park edges influence plot composition?

Multiple regression analysis

In many environments, plot distance to villages, roads and park edges have been hypothesized to positively correlate with deforestation (Geist and Lambin 2002). Frequently, forests near to human settlements or roads are more accessible and therefore more susceptible to deforestation (Serneels and Lambin 2001, Overmars and Verburg 2005). In areas where protected areas have higher levels of tree cover, park edges are often highly susceptible to deforestation and ecological changes resulting from anthropogenic and natural causes (Skole and Tucker 1993, Laurance et al. 2002).

Individual plots were located within varying distances from villages, roads, and protected area boundaries and characterized into harvested and undisturbed and forest management type categories. Plot composition, diversity, and structural characteristics such as average dbh, average height, species diversity and percent cover were regressed against potential causes of variation (distance to road, village, or park boundary). Multiple regression analyses were calculated for all 77 plots and compared across harvested and undisturbed categories and within the harvested forest management type category.

3) Is the forest regrowing?

Size Class Distribution Analysis

A size class distribution (SCD) analysis was used to describe tree regeneration through an analysis of static vegetation data. Size class distributions of trees have traditionally been described in studies of tropical forest systems and used as indicators of species composition change (Lykke 1998, Obiri, Lawes and Mukolwe 2002, Mwavu and Witkowski 2009, Jones 1956, Poorter et al. 1996, McLaren et al. 2005). A SCD curve that drops exponentially with increasing dbh, often referred to as reverse-J shape, is characteristic for species with good rejuvenation and continuous replacement of themselves, whereas other distribution curves indicate a lack of recruitment and maybe species composition change (Hall and Bawa 1993).

SCD analysis was used to assess tree regeneration patterns at the family and species level for the entire data set, harvest/undisturbed, and across the varying land utilization categories. For this study, a method of SCD analysis first proposed by Condit et al (1998) and later used by Lykke (1998) and Mwavu and Witkowski (2009) is used. Size classes are defined so they accommodate more individuals with increasing size thus balancing the sample across size classes since the number of individuals generally declines with size (Condit et al. 1998, Mwavu and Witkowski 2009). The following dbh size classes are used: 1-4.9, 5-9.9, 10-19.9, 20-39.9, 40-79.9, 80-120 cm (no trees were identified with a diameter larger than 100 cm).

The number of individuals in each size class is divided by the width of the class. This average number of individuals (Ni) is used as an estimate for the class midpoint. For each taxon a regression is calculated with class midpoint as the independent variable and the average number of individuals in that class (Ni) as the dependent variable. Slopes of these regressions are here-after referred to as SCD slopes. The size class variable is ln-transformed, and the average number of individuals (Ni) is transformed by ln(Ni+1) (1 is added because some size classes have 0 individuals). Size classes up to the largest size class with individuals present are included in regressions; larger size classes are omitted (Lykke 1998, Obiri et al. 2002, Mwavu and Witkowski 2009, McLaren et al. 2005). A regression is calculated for each of the 37 tree species and SCD slopes are used as indicators of population structure. Size class distribution of all 13 tree families and 37 tree species were analyzed.

SCD was assessed within each forest management type to determine how charcoal harvesting and forest management variations alter plot composition and regeneration.

4) How is regrowth affected by charcoal harvesting and management?

The final question to be addressed assesses how all coppiced trees are regenerating after harvest. A dataset of 26 plots of known harvest dates were analyzed to assess regrowth rate within harvested and forest management type plots. Fifteen of the sites' dates are known through previous sampling while 12 harvest dates were determined via knowledge obtained from local charcoal producers during field work and semi-structured interviews (Wurster 2010).

An uneven distribution of plots across forest management type and time since last harvest was collected due to the random selection of sites prior to having access to the local producers. To analyze the effect of forest management type, plots were grouped into two categories: government managed and co-managed. The government managed category consisted of plots from the CF and RCF forest management types, while the co-managed category consisted of PRO and WN forest management types.

Within these sites, average coppicing shoot diameter, height, percent canopy cover and plot species diversity were used to estimate the rate of regeneration and plot recovery after harvesting. Study sites were divided into 4 different age classes: sites where it was less than 1 year, between 1 and 2 years, between 2 and 4 years, and between 4 and 6 years since the last harvest.

Results

Plots were categorized by harvested or undisturbed and land management type. Results are presented by first analyzing the differences between undisturbed and harvested plots, then assessing the variation between plots within the harvested plots of the land management type.

1) How do sites vary in structure and diversity?

A total of 77 (16 undisturbed and 61 harvested) plots were surveyed across four unique forest management types. 2,432 individual trees were measured with 36 species identified in 11 families (Table 3-1). 17 of the 36 species were sampled on more than 15 instances and 11 species were found in all forest management types. The three most abundant species for the entire survey area were *Combretum glutinosum* (53% of total), *Hexalobus monopetalus* (9% of total), and *Strychnos innocua* (8% of total).

Estimated tree and coppiced individual density were compared across harvested and undisturbed plot categories. Insignificant differences were found between undisturbed and harvested plot density. Significant differences in average plot height, average plot dbh, and estimated canopy cover between undisturbed and harvested sites were observed (Table 3-2).

When harvested plots were disaggregated to individual land management types, estimated PCC, average dbh, average plot height, and estimated tree plot density all lacked significant differences between the different forest land management types ($P>0.05$) (Table 3-3, Figure 3-3).

Species diversity using the Simpson's diversity reciprocal index demonstrated significant variation between harvested and undisturbed plots ($P<0.001$) and between harvested and undisturbed plots within forest management types ($P<0.001$) (Figure 3-4).

A matrix of one-way analysis of variance (ANOVA) tests was established to test all combinations of forest management types (Table 3-4). These tests identified the dominance of WN values on both the undisturbed and harvested samples. When undisturbed Wula Nafaa values were removed from the test no significant relationships between the remaining forest management types (CF, RCF, PRO) remained. When harvested WN were removed, significant differences remained between forest

		Undisturbed				Harvested			
		total number individuals	number of individuals per hectare			total number individuals	number of individuals per hectare		
			>20 cm dbh	>5 cm dbh	regeneration (<5 cm dbh)		>20 cm dbh	>5 cm dbh	regeneration (<5 cm dbh)
Species name	Family								
Acacia macrostachya	Mimosaceae	15	-	7.2	8.2	65	-	7.5	6.0
Annona senegalensis	Annonaceae	-	-	-	-	2	-	0.2	0.2
Anogeissus leiocarpus	Combretaceae	1	1.0	1.0	-	-	-	-	-
Bombax costatum	Bombacaceae	8	6.2	8.2	-	17	1.7	3.5	-
Cassia sieberiana	Caesalpiniaceae	-	-	-	-	1	-	0.2	-
Combretum glutinosum	Combretaceae	218	13.3	166.2	57.4	1082	1.7	78.1	146.7
Combretum lecardii	Combretaceae	26	-	18.5	8.2	41		2.7	5.8
Combretum micranthum	Combretaceae	1	-	1.0	-	23		2.5	2.3
Combretum molle	Combretaceae	18	-	10.3	8.2	1	-	0.2	-
Combretum nigricans	Combretaceae	76	2.1	53.3	24.6	80	-	3.7	12.9
Cordyla pinnata	Caesalpiniaceae	20	15.4	20.5	0.0	30	5.6	6.0	0.2
Ficus dicranostyla	Moraceae	1	1.0	1.0	-	-	-	-	-
Grewia bicolor	Tiliaceae	-	-	-	-	1	-	0.2	-
Grewia flavescens	Tiliaceae	-	-	-	-	10	-	1.9	0.2
Hannoa undulata	Simaroubaceae	-	-	-	-	1	-	0.2	-
Hexalobus monopetalus	Annonaceae	59	-	44.1	16.4	171	0.4	14.1	21.4
Lannea acida	Anacardiaceae	7	3.1	7.2	-	29	3.1	4.4	1.7
Ostryoderris stuhlmannii	Papilionaceae	1	-	1.0	-	4		0.4	0.4
Piliostigma thonningii	Caesalpiniaceae	-	-	-	-	1	-	0.2	-
Pterocarpus erinaceus	Papilionaceae	5	4.1	5.1	-	20	3.3	4.2	-
Sclerocarya birrea	Anacardiaceae	1	1.0	1.0	-	1	0.2	0.2	-
Sterculia setigera	Sterculiaceae	2	2.1	2.1	-	17	1.9	3.5	-
Strychnos innocua	Loganiaceae	33	-	1.0	32.8	162	-	7.5	26.2
Strychnos spinosa	Loganiaceae	-	-	-	-	1	-	0.2	-
Terminalia avicennoides	Combretaceae	28	1.0	4.1	24.6	11	1.0	1.9	0.4
Terminalia macroptera	Combretaceae	1	-	1.0	-	2	0.2	0.4	-
Unknown 1	Unknown	32	-	-	32.8	-	-	-	-
Unknown 2	Unknown	1	1.0	1.0	-	1	0.2	0.2	-
Unknown 3	Unknown	9	-	1.0	8.2	16	-	-	3.3
Unknown 4	Unknown	-	-	-	-	8	-	-	1.7
Unknown 5	Unknown	-	-	-	-	8	-	-	1.7
Unknown 6	Unknown	1	-	1.0	-	-	-	-	-
Unknown 7	Unknown	-	-	-	-	2	-	0.4	-
Unknown 8	Unknown	-	-	-	-	1	-	-	0.2
Unknown 9	Unknown	-	-	-	-	1	-	-	0.2
Vitex madiensis	Verbenaceae	-	-	-	-	57	-	3.5	8.3
Ziziphus mauritiana	Rhamnaceae	1	-	1.0	-	-	-	-	-

Table 0-1 - Identified species and estimated size distributions in undisturbed and harvested plots

Table 0-2 - Plot characteristics within all undisturbed and harvested plots

Plot characteristics	Undisturbed		Harvested		
	Mean	SD	Mean	SD	P-value
Plot density (trees/hectare)	246.67	69.73	270.77	134.92	NS
dbh (cm)	18.02	3.54	8.75	5.37	***
Height (m)	7.78	1.24	4.17	1.48	***
Estimated Canopy Cover (%)	48.13	15.71	19.17	12.45	***
Simpson's diversity (1/D)	3.99	1.84	1.98	1.07	***

Plot density, diameter at breast height (dbh), estimated tree height, and Simpson's diversity index (1/D) values were calculated for trees and coppiced trees.
*** P<0.001, NS not significant based on two-tailed test assuming equal variance

Table 0-3 - Plot characteristics within different forest management types plots

	Undisturbed								
Plot characteristics	CF		RCF		PRO		WN		p-value
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Estimated Canopy Cover (%)	0.52	0.17	0.28	0.04	0.48	0.13	0.60	0.00	NS
dbh (cm)	19.75	2.85	17.22	2.82	14.40	3.17	19.37	5.36	NS
Height (m)	7.99	0.93	7.19	1.04	7.15	1.41	7.47	2.36	NS
Plot density (trees/hectare)	288.00	50.60	144.00	45.25	200.00	122.90	272.00	67.88	NS
Simpson's diversity (1/D)	3.24	1.10	2.36	0.37	2.97	1.34	7.30	0.42	**

	Harvested								
Plot characteristics	CF		RCF		PRO		WN		p-value
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Estimated Canopy Cover (%)	0.18	0.10	0.12	0.08	0.21	0.11	0.24	0.11	NS
dbh (cm)	9.26	5.58	5.77	3.65	9.24	5.22	8.42	5.58	NS
Height (m)	4.58	1.34	3.27	1.14	4.07	1.49	3.98	1.44	NS
Plot density (trees/hectare)	268.80	103.37	269.71	161.22	228.92	100.64	348.00	138.84	NS
Simpson's diversity (1/D)	1.38	0.31	1.32	0.73	2.08	1.20	3.55	1.11	***

Note: p-values - NS = not significant, * < 0.05, ** < 0.01, *** < 0.001

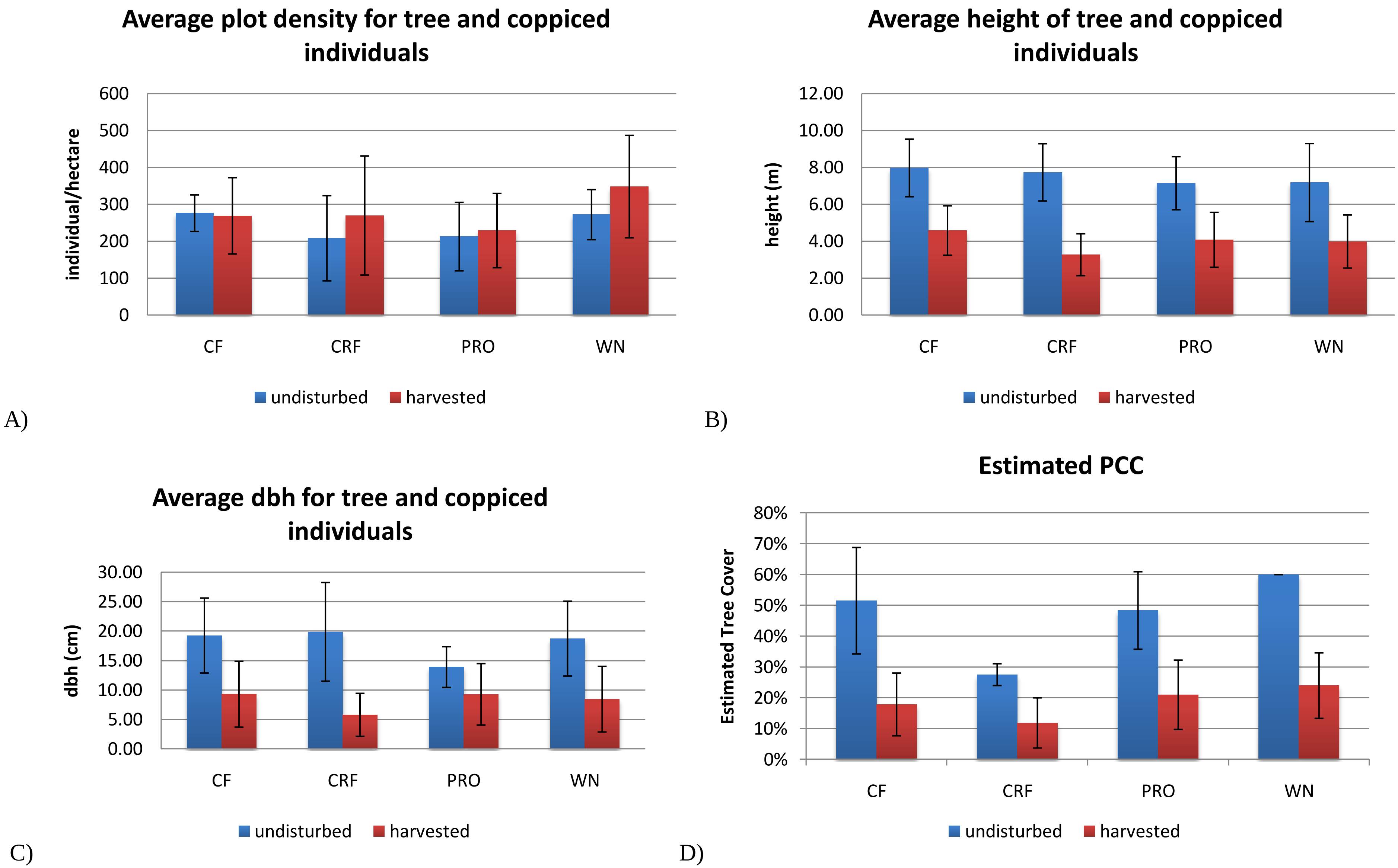


Figure 0-3 - Plot characteristics (plot density, height, dbh and PCC) of undisturbed and harvested plots within Classified Forest (CF), Rural Community forest (RCF), PROGEDE (PRO) and Wula Nafaa (WN) forests. All p-values based on a one-way analysis of variance (ANOVA). See table 3.4 for related p-values between all harvested forest management type plots and all undisturbed forest management type plots.

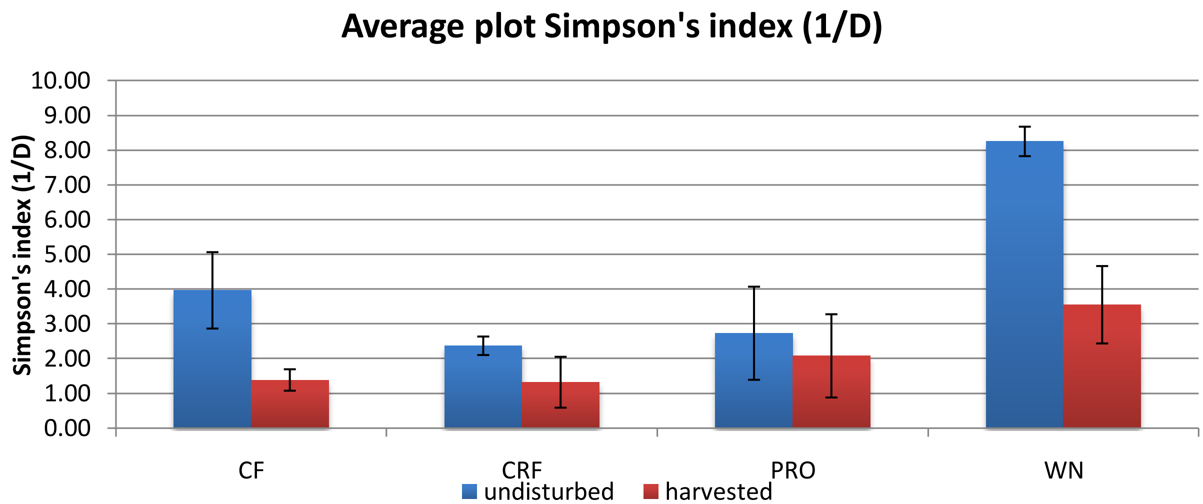


Figure 0-4 - Average plot Simpson's diversity index value for undisturbed and harvested plots within each forest management type. See table 3.4 for related p-values between all harvested forest management type plots and all undisturbed forest management type plots.

Table 0-4 - Simpson's diversity index analysis within all combinations of forest management types

Undisturbed				Harvested			
	CF	RCF	PRO		CF	RCF	PRO
CF				CF			
RCF	NS			RCF	NS		
PRO	NS	NS		PRO	**	*	
WN	**	**	**	WN	***	***	NS
CF-RCF-PRO	NS			CF-RCF-PRO	**		
CF-PRO-WN	**			CF-PRO-WN	***		
CF-RCF-WN	**			CF-RCF-WN	***		
RCF-PRO-WN	**			RCF-PRO-WN	***		
CF-RCF-PRO-WN	**			CF-RCF-PRO-WN	***		

Note: p-values * < 0.05, ** < 0.01, *** < 0.001

Table 0-5 - Percent change within each forest management type between undisturbed and harvested plots

1/D	Undisturbed		Harvested		Percent change
	Mean	SD	Mean	SD	
CF	3.24	1.10	1.38	0.31	-57.29%
RCF	2.36	0.37	1.32	0.73	-44.15%
PRO	2.97	1.34	2.08	1.20	-30.17%
WN	7.30	0.42	3.55	1.11	-51.39%

management types. Non-significant differences were found between WN-PRO and CF-RCF plots.

The percent change of Simpson's diversity index values were also calculated between undisturbed to harvested plots (Table 3-5). In all cases, index values decrease by over 30% suggesting substantial declines in species diversity after tree have been harvested for charcoal production.

2) How does proximity to villages, roads and park edges influence plot composition?

Dependent variables of percent tree cover, average plot tree dbh and Simpson's diversity index values were regressed against the explanatory variables of distance to nearest village, road, and park edge. To ensure collinearity between explanatory variables does not introduce bias, variance inflationary factor (VIF) statistics were calculated. Recent publications (Graham 2003, O'Brien 2007, Smith et al. 2009) have argued that VIF values of 20 or even higher to do not themselves discount the results of a regression analysis, but a more conservative VIF threshold of less than 5 (Snee 1973, Marquardt 1980) was used for this analysis. Results from these diagnostics procedures demonstrated VIF statistics ranging from 1.7 to 2.9 for all harvested and undisturbed plots and from 1.2 to greater than 10 for harvested plots within different forest management types. VIF values less than five suggest that these data sets are not confounded by collinearity. VIF values were calculated to be greater than 5 within the PRO and WN data sets. In these instances explanatory variables of distance to park edge and distance to road were removed from respective PRO and WN models producing models with significant coefficients.

Table 3-6a shows the outcomes of regression results harvested and undisturbed sites and harvested plots within each forest management types. As hypothesized there are few significant relationships between forest structure and composition variables for all categories.

The multiple regression model for all harvested sites with PCC as the dependent variable and all explanatory variables produced Adjusted $R^2 = 0.112$ and $p<0.05$. As noted in Table 3-6a, the distance to village values had weak significant positive regression weights ($p<0.05$), suggesting that plot PCC increases slightly with increasing distance to village. The species diversity index model produced a Adjusted $R^2 = 0.105$ and $p<0.05$ with weak significant regression weights with distance to nearest road, suggesting plot species diversity increases slightly as distance to road increases. Although the trees/hectare model produced Adjusted $R^2 = 0.061$ and $p<0.1$ no significant regression weights were produced.

Within all undisturbed plots model results for dbh regressed with all explanatory variables produced Adjusted $R^2 = 0.251$ and $p<0.05$. The distance to village values had a significant negative relationship suggesting decreasing tree dbh as distance from villages increases.

When harvested plot were disaggregated into forest management type similar weak relationships were produced (Table 3-6b). As previously mentioned, collinearity was present in the PRO and WN data sets. Distance to park edge and distance to road values were dropped from PRO and WN models respectively to remove collinearity. Three models produced significant results. Within Rural Community Forests, tree plot height regressed with all explanatory variables produced $R^2 = 0.238$ and $p<0.1$. Distance to road values had a significant positive relationship ($p<0.1$) with tree plot height, suggesting tree plot height

Table 0-6 - Harvested and Undisturbed plot multiple regression results. Table 3-6a are regression results for all harvested and undisturbed plots. Table 3-6b are regression results for harvested plots within in forest management type.

	Harvested					Undisturbed				
	PCC	dbh (cm)	height (m)	trees/ha	1/D	PCC	dbh (cm)	height (m)	trees/ha	1/D
village	0.004	0.002	0.000	-0.012	0.000	0.003	-0.003	-0.001	-0.011	0.001
	(0.00)**	(0.00)	(0.00)	(0.03)	(0.00)	(0.01)	(0.00)**	(0.00)	(0.04)	(0.00)
road	0.000	0.000	0.000	0.034	0.000	-0.005	0.001	0.000	-0.008	0.000
	(0.00)	(0.00)	(0.00)	(0.02)	(0.00)*	(0.01)	(0.00)	(0.00)	(0.03)	(0.00)
park edge	-0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.001	0.000
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)
Adjusted R^2	0.11	0.02	0.02	0.06	0.10	-0.05	0.25	-0.01	-0.13	0.01
Observations	61	61	61	61	61	16	16	16	16	16
p-value	**	NS	NS	*	**	NS	*	NS	NS	NS

Standard errors are reported in parenthesis

p-values *p<0.1, **p<0.05, ***p<0.01, NS –not significant

Table 3.6b – Harvested plot forest management type results

	Rural Community Forest					Classified Forest				
	PCC	dbh (cm)	height (m)	trees/ha	1/D	PCC	dbh (cm)	height (m)	trees/ha	1/D
village	0.000	0.000	0.000	-0.049	0.000	0.001	0.001	0.000	0.024	0.000
	(0.00)	(0.01	(0.00)	(0.05)	(0.00	(0.00	(0.00	(0.00)	(0.05)	(0.00)
road	0.005	0.001	0.001	-0.005	0.000	0.001	0.001	0.000	0.026	0.000
	(0.01)***	(0.00	(0.00)	(0.04)	(0.00	(0.00	(0.00	(0.00)	(0.03)	(0.00)
park edge	0.000	0.000	0.000	0.004	0.000	0.007	0.000	0.000	-0.046	0.000
	(0.00)	(0.00	(0.00)	(0.01)	(0.00	(0.01	(0.00	(0.00)	(0.06)	(0.00)
Adjusted R^2	0.59	0.13	0.23	-0.03	0.17	0.27	0.04	-0.19	-0.01	-0.23
Observations	21	21	21	21	21	15	15	15	15	15
p-value	NS	NS	*	NS	NS	NS	NS	NS	NS	NS

	PROGEDE					Wula Nafaa				
	PCC	dbh (cm)	height (m)	trees/ha	1/D	PCC	dbh (cm)	height (m)	trees/ha	1/D
village	0.007	0.016	0.003	-0.037	0.000	0.000	0.000	0.000	0.019	0.000
	(0.01	(0.01)**	(0.01)***	(0.07)	(0.01)	(0.00)	(0.00)	(0.00)	(0.05)	(0.00)
road	0.003	-0.006	-0.001	0.042	0.000					
	(0.00	(0.01)*	(0.00)	(0.03)	(0.00)					
park edge						0.000	0.000	0.000	0.022	0.000
						(0.00)	(0.00)	(0.00)	(0.02)	(0.00)
Adjusted R^2	0.21	0.43	0.43	0.01	-0.17	-0.21	-0.21	-0.15	0.01	0.07
Observations	13	13	13	13	13	12	12	12	12	12
p-value	NS	*	*	NS	NS	NS	NS	NS	NS	NS

Standard errors are reported in parenthesis
p-values *p<0.1, **p<0.05, ***p<0.01, NS – not significant

increases in RCF with increasing distance to roads. Additionally, the RCF PCC model produced insignificant results, but did show a positive significant relationship ($p<0.01$) with distance to road.

Within PROGEDE plots, dbh regressed against distance to villages and roads produced Adjusted $R^2 = 0.43$ and $p<0.1$. Slight increases in dbh had a significant negative relationship with distances to roads ($p<0.1$), suggesting larger dbh trees further from roads, and significant positive relationship with distance to villages ($p<0.01$), suggesting larger dbh values closer to villages. Tree plot height regressed against distance to village and distance to road produced a model with a similar fit (Adjusted $R^2 = 0.44$ and $p<0.1$). In this model, tree plot height had a positive significant relationship ($p<0.01$) with distance to village, suggesting increasing tree plot height with increasing distance from village.

Null hypotheses are accepted for a six of the ten harvested and undisturbed models and 17 of 20 forest management type models. The estimated coefficients within the remaining significant models indicate that forest plot characteristics are weakly and inconsistently related to variations in distance to villages, roads and park edges across harvested and undisturbed plots and within forest management types.

3) Is the forest regrowing?

Species Density Estimates

Results of an analysis of species density within harvested and undisturbed plots and across the different harvested forest management types demonstrate that the *Combretum glutinosum* species dominates the forest by a wide margin in all land management types and within harvested and undisturbed sites. *Combretum glutinosum* is a small tree and generally does not exceed 20 cm in dbh. Because of this other species such as *Cordyla pinnata* dominate the size class, but at much lower densities.

Species density estimates of the 37 tree species (26 identified with 9 unique unknown species) (Table 3-1 and 3-7) ranged from 0.21 per hectare to 270.13 per hectare (20 species with less than 15 individuals observed and 11 species with only 1 individual observed). *Combretum glutinosum* was the dominant species for all sized individuals within the Tambacounda study area. Density estimates for species with dbh <5cm ranged from 0.21 to 158.34 individuals per hectare, *Combretum glutinosum* as the dominant species. Density estimates for individuals >5cm ranged from 0.21 to 111.50 for 32 tree species with *Combretum glutinosum* again as the dominant species. Density estimates for individual species >20cm ranged from 0.21 to 8.73 for 13 tree species with *Cordyla pinnata* as the dominant species.

Within harvested plots across the different forest management types *Combretum* species again dominated. In all dbh sizes, species density range from 0.21 to 285.33 with *Combretum glutinosum* as the dominant species across all management types (227.37, 285.33, 185.60, and 173.71 individuals per hectare for CF, RCF, PRO, and WN respectively). Species density estimates for individuals with dbh <5cm ranged from 0.84 to 202.00. *Combretum glutinosum* was the dominant species type across all management types (106.11, 202.00, 143.20, and 112.00 individuals per hectare for CF, RCF, PRO, and WN respectively). Species density estimates for individuals with dbh greater than 5 ranged from 0.84 to 121.26. Across all management types *Combretum glutinosum* was again the dominant species type (121.26, 83.33, 42.40, and 61.71 for for CF, RCF, PRO, and WN respectively). Species density estimates for dbh>20 cm ranged from 0.67 to 8.00 with *Cordyla pinnata* dominate in CF, RCF, and PRO (7.58, 6.00 and 5.60 individuals per hectare, respectively) and *Pterocarpus erinaceus* in WN (8.00 individuals/ha).

			Number of individuals per hectare															
			All Harvested plots				>20 cm dbh				> 5cm dbh				regeneration (<5cm dbh)			
Species name	Family	Total number individuals	CF	CRZ	PRO	WN	CF	CRZ	PRO	WN	CF	CRZ	PRO	WN	CF	CRZ	PRO	WN
Acacia macrostachya	Mimosaceae	65	0.8	5.3	1.6	61.7	-	-	-	-	0.8	5.3	1.6	28.6	-	-	-	33.1
Annona senegalensis	Annonaceae	2	-	-	-	2.3	-	-	-	-	-	-	-	1.1	-	-	-	1.1
Bombax costatum	Bombacaceae	17	8.4	0.7	0.8	5.7	0.8	0.7	0.8	5.7	8.4	0.7	0.8	5.7	-	-	-	
Cassia sieberiana	Caesalpiniaceae	1	-	-	0.8	-	-	-	-	-	-	-	0.8	-	-	-	-	-
Combretum glutinosum	Combretaceae	1082	227.4	285.3	185.6	173.7	1.7	0.7	3.2	1.1	121.3	83.3	42.4	61.7	106.1	202.0	143.2	112.0
Combretum lecardii	Combretaceae	41	4.2	4.7	4.0	27.4	-	-	-	-	2.5	3.3	2.4	2.3	1.7	1.3	1.6	25.1
Combretum micranthum	Combretaceae	23	0.8	-	10.4	10.3	-	-	-	-	0.8	-	1.6	10.3	-	-	8.8	-
Combretum molle	Combretaceae	1	-	0.7	-	-	-	-	-	-	-	0.7	-	-	-	-	-	-
Combretum nigricans	Combretaceae	80	-	0.7	48.8	20.6	-	-	-	-	-	-	12.0	3.4		0.7	36.8	17.1
Cordyla pinnata	Caesalpiniaceae	30	8.4	6.0	6.4	3.4	7.6	6.0	5.6	2.3	8.4	6.0	6.4	2.3	-	-	-	1.1
Grewia bicolor	Tiliaceae	1	-	-	0.8	-	-	-	-	-	-	-	0.8	-	-	-	-	-
Grewia flavescens	Tiliaceae	10	1.7	5.3	-	-		-	-	-	0.8	5.3	-	-	0.8	-	-	0.0
Hannoa undulata	Simaroubaceae	1	-	-	0.8	-	-	-	-	-	-	-	0.8	-	-	-	-	-
Hexalobus monopetalus	Annonaceae	171	26.1	32.7	8.8	91.4	0.8	0.7	-	-	16.8	14.7	8.8	17.1	9.3	18.0	-	74.3
Lannea acida	Anacardiaceae	29	5.1	2.0	4.0	17.1	4.2	2.0	1.6	5.7	5.1	2.0	4.0	8.0	-	-	-	9.1
Ostryoderris stuhlmannii	Papilionaceae	4	-	-	-	4.6	-	-	-	-	-	-	-	2.3	-	-	-	2.3
Piliostigma thonningii	Caesalpiniaceae	1	-	-	-	1.1	-	-	-	-	-	-	-	1.1	-	-	-	-
Pterocarpus erinaceus	Papilionaceae	20	0.8	4.0	2.4	11.4	-	4.0	2.4	8.0	0.8	4.0	2.4	11.4	-	-	-	-
Sclerocarya birrea	Anacardiaceae	1	-	-	0.8	-	-	-	0.8	-	-	-	0.8	-	-	-	-	-
Sterculia setigera	Sterculiaceae	17	3.4	-	6.4	5.7	3.4	-	-	5.7	3.4	-	6.4	5.7	-	-	-	
Strychnos innocua	Loganiaceae	162	41.3	21.3	19.2	65.1	-	-	-	-	7.6	10.7	6.4	3.4	33.7	10.7	12.8	61.7
Strychnos spinosa	Loganiaceae	1	-	0.7	-	-	-	-	4.0	-	-	0.7	-	-	-	-	-	-
Terminalia avicennoides	Combretaceae	11	-	-	4.8	5.7	-	-	0.8	-	-	-	4.8	3.4	-	-	-	2.3
Terminalia macroptera	Combretaceae	2	0.8	-	0.8	-	-	-	-	-	0.8	-	0.8	-	-	-	-	-
Unknown 2	Unknown	1	0.8	-	-	-	0.8	-	-	-	0.8	-	-	-	-	-	-	-
Unknown 3	Unknown	16	-	-	-	18.3	-	-	-	-	-	-	-	-	-	-	-	18.3
Unknown 4	Unknown	8	-	-	-	9.1	-	-	-	-	-	-	-	-	-	-	-	9.1
Unknown 5	Unknown	8	-	-	-	9.1	-	-	-	-	-	-	-	-	-	-	-	9.1
Unknown 7	Unknown	2	-	-	1.6	-	-	-	-	-	-	-	1.6	-	-	-	-	-
Unknown 8	Unknown	1	-	-	0.8	-	-	-	-	-	-	-	-	-	-	-	0.8	-
Unknown 9	Unknown	1	0.8	-	-	-		-	-	-		-	-	-	0.8	-	-	-
Vitex madiensis	Verbenaceae	57	-	-	-	65.1	-	-	-	-	-	-	-	19.4	-	-	-	45.7

Table 0-7 - Estimated species density per hectare within all harvested plots disaggregated by forest management type.

Size Class Distribution (SCD) Results

Within the entire sample and when broken into harvest/undisturbed and forest management type categories, 24 of 37 species have SCDs that are highly scattered around the regression line with SCD slopes close to zero or positive. SCD slopes range from -2.21 to 0.18 for 37 tree species identified for the entire data set. For harvested and undisturbed areas, SCD slopes range from -1.06 to 0.18 for undisturbed areas (24 tree species) and from -1.64 to 0.19 for harvested areas (32 tree species) (Table 3.8 and 3.9). The different land management type SCDs range from -1.18 to 0.22 for CF (15 tree species), -1.51 to 0.96 for RCF (13 tree species), -1.16 to 0.13 for PRO (20 tree species), and -1.26 to 0.05 for WN (20 tree species) (Table 3.10 and 3.11).

It is convenient to describe the tree species as three types based on SCD slope values and density of the tree species and family, although there will be an overlap between types. Type 1, *Grewia bicolor, Unknown 7, Cordyla pinnata, Pterocarpus erinaceus, Cassia sieberiana, Hannoa undulata, Piliostigma thonningii, Strychnos spinosa, Unknown 6, Ziziphus mauritiana,Unknown 2, Anogeissus leiocarpus, Sclerocarya birrea, Ficus dicranostyla, Terminalia macroptera, Bombax costatum, Sterculia setigera, Annona senegalensis,* and *Ostryoderris stuhlmannii* have extremely flat distributions (SCD slope from -0.07 to 0.18), sometimes positive meaning that only larger individuals were sampled. This group is composed of rare species with poor regeneration. Many are often used for timber production and are noticed to be declining by local populations. They are characterized by being large, mainly single trunked trees with the exception of *Grewia bicolor, Piliostigma thonningii, Annona senegalensis* which are small trees or large shrubs.

Type 2, the next 5 species, *Grewia flavescens, Lannea acida, Combretum molle, Unknown 8,* and *Unknown 9* , have less flat distributions (SCD slopes from -0.23 to -0.11), but are far from having reverse J-shaped distributions. *Combretum molle* are sometimes used by people for charcoal production and *Lannea acida* are often desired for timber. This type is also characterized by large single-trunked trees (except for *Grewia flavescens*), but in contrast to the former type most are common in the study area and have a relatively healthy rates of regeneration (SCD slopes are all negative therefore weak reverse J-curves).

Type 3, the final 13 species, *Combretum micranthum, Terminalia avicennoides, Combretum lecardii*, *Acacia macrostachya, Unknown 3, Combretum nigricans, Unknown 4, Unknown 5, Hexalobus monopetalus, Vitex madiensis, Strychnos innocua*, *Combretum glutinosum,* and *Unknown 1,* have the largest negative SCD slopes (-2.21 to -0.50). Most of the species in this group are common in the study area and the strong negative SCD slopes (strong reverse J-curves) translate into good regeneration rates. Most species in this group are characterized as small trees, many with multiple trunks. Many of these species (5 most frequently used species) are harvested for charcoal production.

SCDs in Harvested and Undisturbed Areas

As previously stated the presence of a species in type 1 suggests the species has poor regenerative capacity and the long-term viability of the species is in doubt. Type 2 species demonstrate a slightly better regenerative capacity, but the species is still lacking sufficient numbers of young seedlings/saplings to replace the mature population. Type 3 species have strong regenerative capacity due to high numbers of seedlings/saplings. The shifting of species from undisturbed type 2 to harvested type 3 could be translated into species with a higher regenerative capacity in harvested verses undisturbed plots. While the shifting between undisturbed type 3, or type 2, to harvested type 1 could translate into species with less regenerative capacity in harvested verses undisturbed plots.

Two species, *Acacia macrostachya*, *Hexalobus monopetalus* were sampled in undisturbed type 2 and also in harvested type 3; this suggests that these two species regenerating more in the harvested sites. Two species, *Combretum micranthum* and *Combretum lecardii* were found in undisturbed type 1, but in harvested type 2; one species, *Vitex madiensis,* was not present in undisturbed plots, but present in harvested type 3 also suggesting a better rate of regeneration in harvested plots. *Terminalia avicennoides* was located in undisturbed type 3, but in harvested type 1 while *Combretum molle* was located in undisturbed type 2 and in harvest type 1 suggesting a decline in regenerative capacity from undisturbed to harvested plots (Tables 3-8 and 3-9).

SCDs Across Forest Management Types

Within the four forest management types, SCDs were developed for all individuals recorded in harvested plots. Species were separated again into the same three SCD types (Table 3-10 and 3-11). Two species, *Combretum glutinosum and Strychnos innocua* were present in type 3 within all forest management types. Both of these species are small trees and are harvested for charcoal production. *Hexalobus monopetalus* was in type 3 for CF, RCF and WN forest management types, but was present in type 1 for PRO plots suggesting that the species is regenerating poorly within PRO areas.

Large tree species such as *Bombax costatum, Pterocarpus erinaceus, Sterculia setigera* and *Cordyla pinnata* are found only in type 1 or in very low numbers (fewer than five per forest management type) suggesting that regenerative capacity of non-coppicing tree species is very low in all forest management types.

4) How is regrowth affected by charcoal harvesting and management?

Regeneration after tree harvesting for charcoal production was assessed using average coppicing species plot dbh, average coppicing species plot height, plot PCC and plot tree diversity from 26 plots where harvest year was known via previous research or obtained by the semi-structured interviews. Within these sites, 366 coppicing individuals from 10 different species were sampled.

Coppiced tree dbh values for all known harvested plots ranged from 2.7cm in plots harvested in the last year to 5.4cm in plots harvested between 2 and 4 years previous. (Figure 3-5a). Coppiced tree heights ranged from a low of 2.2m in <1yr class to a high of 4.5m in 2-4yr class (Figure 3-6a). PCC values for the different time-steps ranged from 15% at <1 year to 23% at 4 to 6 years, but the plots are far from returning to the undisturbed PCC average of 36% (Figure 3-7a). Known harvested plot tree diversity also varies depending on time since harvest with Simpson's diversity index values ranging from 1.17 at <1 year since cutting to 2.87 from 4 to 6 years since cutting. Although diversity values are increasing over time at the 6 year mark they are still much lower than the undisturbed value of 3.52 (Figure 3-8a).

Within the government category the second time-step (1 to 2 years after cutting) was missing, while within the co-managed category the third time-step (2 to 4 years after cutting) was absent. The regeneration patterns for both suggest slow regrowth from the time of cutting to 4 to 6 years after cutting (Figure 3-5b). Coppiced tree dbh for government managed plots ranged from a low of 2.9cm at less than 1 year after cutting to a high of 8.4cm 4 to 6 years after cutting. Coppiced tree dbh for co-managed plots demonstrates less pronounced, yet similar trend with a low of 2.5cm at less than 1 year after cutting to a high of 3.8 4 to 6 years after cutting. The average dbh at 4 to 6 years is still much lower than the undisturbed dbh value of 19.0cm and 15.5cm for GM and CM, respectively.

Coppiced tree heights averaged lows of 1.8m for GM and 2.5m for CM at less than 1 year since cutting and increased to highs of 4.6m for GM and 2.8m for CM at 4 to 6 years since cutting (Figure 3-6b). Again, these values are much smaller than the undisturbed tree height averages of 7.9m for GM and 7.5m for CM.

Average plot PCC also average lows at less than 1 year since cutting, 9% for GM and 17% for CM and highs at 4 to 6 years after cutting, 22% for GM and 24% for CM (Figure 3-7b). These values again are still much lower than the average PCC of 29% for GM and 48% for CM in undisturbed plots.

Undisturbed plots

Botanical	*Slope*	*R^2*	*Type*
Terminalia macroptera*	0.1857	1.0000	1
Lannea acida	0.0761	0.3740	1
Pterocarpus erinaceus	0.0646	0.8950	1
Combretum micranthum	0.0481	0.7500	1
Ostryoderris stuhlmannii*	0.0481	0.7500	1
Unknown 6*	0.0481	0.7500	1
Ziziphus mauritiana*	0.0481	0.0642	1
Cordyla pinnata	0.0445	0.0785	1
Bombax costatum	0.0287	0.3430	1
Anogeissus leiocarpus*	0.0147	0.6000	1
Unknown 2*	0.0147	0.6000	1
Sterculia setigera	0.0091	0.6915	1
Ficus dicranostyla*	0.0070	0.4286	1
Sclerocarya birrea*	0.0050	0.5000	1
Combretum lecardii	-0.0966	0.0872	1
Combretum molle	-0.2345	0.2543	2
Acacia macrostachya	-0.2904	0.2709	2
Hexalobus monopetalus	-0.4413	0.4586	2
Terminalia avicennoides	-0.5491	0.5704	3
Unknown 3	-0.5578	0.8708	3
Combretum glutinosum	-0.6813	0.7386	3
Combretum nigricans	-0.7133	0.8250	3
Strychnos innocua	-1.0618	0.7161	3
Unknown 1	-1.1099	0.7500	3

*less than 15 observations

Table 0-8 - Classification of species sampled in undisturbed plots into SCD types. Type 1 consists of species with extremely flat or sometimes positive SCD slopes meaning that only larger individuals were sampled. This group is composed of rare species with poor regeneration. Type 2 have slightly negative SCD slopes (weak reverse J-curves). Type 2 is also generally characterized by large single-trunked trees, but in contrast to Type 1, most are common in the study area and have relatively healthy rates of regeneration. Type 3 species have large, negative SCD slopes (strong reverse J-curves) translating into good regeneration rates. Most species in this group are common and are characterized as small trees, many with multiple trunks.

Harvested plots

Botanical	*Slope*	*R^2*	*Type*
Grewia bicolor*	0.1857	1.0000	1
Unknown 7*	0.0920	0.7500	1
Pterocarpus erinaceus	0.0611	0.1438	1
Cordyla pinnata	0.0562	0.1156	1
Cassia sieberiana*	0.0481	0.7500	1
Combretum molle	0.0481	0.7500	1
Hannoa undulata*	0.0481	0.7500	1
Piliostigma thonningii*	0.0481	0.7500	1
Strychnos spinosa*	0.0481	0.7500	1
Terminalia macroptera*	0.0243	0.4633	1
Sclerocarya birrea*	0.0147	0.6000	1
Unknown 2*	0.0147	0.6000	1
Terminalia avicennoides	-0.0491	0.4017	1
Sterculia setigera	-0.0603	0.0869	1
Bombax costatum	-0.0617	0.0585	1
Annona senegalensis*	-0.0660	0.3319	1
Grewia flavescens*	-0.1141	0.0434	2
Unknown 8*	-0.1141	0.7500	2
Unknown 9*	-0.1141	0.7500	2
Ostryoderris stuhlmannii*	-0.1150	0.3073	2
Lannea acida	-0.1649	0.3270	2
Combretum micranthum	-0.5378	0.9377	3
Unknown 4*	-0.5578	0.7500	3
Unknown 5*	-0.5578	0.7500	3
Acacia macrostachya	-0.5854	0.9940	3
Combretum lecardii	-0.7547	0.8049	3
Unknown 3	-0.8149	0.7500	3
Hexalobus monopetalus	-1.1100	0.9894	3
Vitex madiensis	-1.1624	0.9910	3
Combretum nigricans	-1.2092	0.9768	3
Strychnos innocua	-1.3793	0.9826	3
Combretum glutinosum	-1.6357	0.9870	3

*less than 15 observations

Table 0-9 - Classification of species sampled in harvested plots into SCD types. Type 1 consists of species with extremely flat or sometimes positive SCD slopes meaning that only larger individuals were sampled. This group is composed of rare species with poor regeneration. Type 2 have slightly negative SCD slopes (weak reverse J-curves). Type 2 is also generally characterized by large single-trunked trees, but in contrast to Type 1, most are common in the study area and have relatively healthy rates of regeneration. Type 3 species have large, negative SCD slopes (strong reverse J-curves) translating into good regeneration rates. Most species in this group are common and are characterized as small trees, many with multiple trunks.

Harvested plots disaggregated by forest management type

CF	*Botanical*	*Slope*	*R^2*	*Type*
	Lannea acida*	0.2236	0.8730	1
	Cordyla pinnata	0.0387	0.1832	1
	Bombax costatum	-0.0725	0.0411	1
	Combretum lecardii*	-0.1589	0.9088	1
	Hexalobus monopetalus	-0.5060	0.8188	3
	Strychnos innocua	-1.1624	0.9796	3
	Combretum glutinosum	-1.1816	0.9500	3
	Acacia macrostachya**			
	Combretum micranthum**			
	Grewia flavescens**			
	Pterocarpus erinaceus**			
	Sterculia setigera**			
	Terminalia macroptera**			
	Unknown 2**			
	Unknown 9**			

RCF	*Botanical*	*Slope*	*R^2*	*Type*
	Grewia flavescens*	0.9680	1.0000	1
	Acacia macrostachya*	0.2961	0.7500	1
	Pterocarpus erinaceus*	0.0791	0.6000	1
	Cordyla pinnata*	0.0409	0.3202	1
	Combretum lecardii*	-0.0373	0.1028	1
	Strychnos innocua	-0.5187	0.9753	3
	Hexalobus monopetalus	-0.7592	0.8865	3
	Combretum glutinosum	-1.5078	0.9798	3
	Bombax costatum**			
	Combretum molle**			
	Combretum nigricans**			
	Lannea acida**			
	Strychnos spinosa**			

*between 5 and 9 individuals
**fewer than 5 individuals

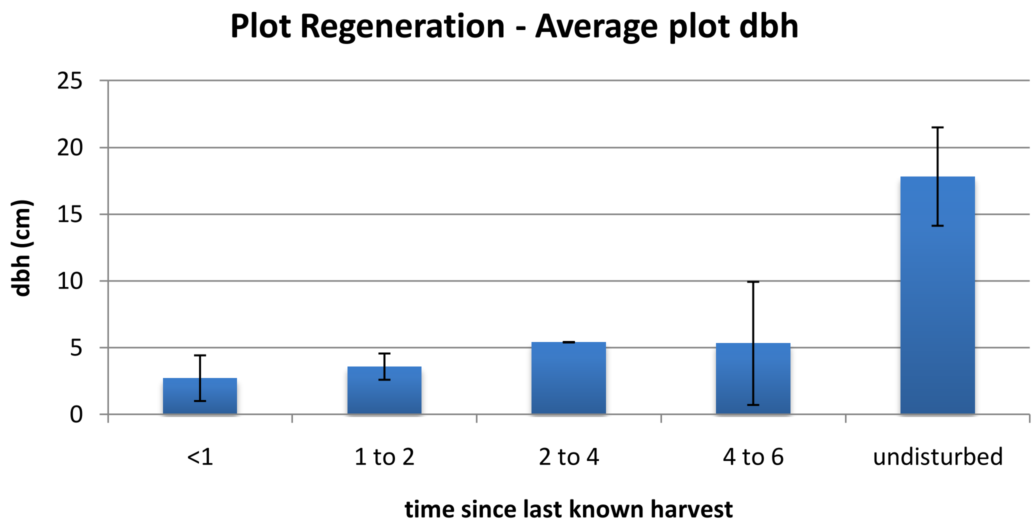
Table 0-10- Classification of species sampled in harvested plots into SCD types. Type 1 consists of species with extremely flat or sometimes positive SCD slopes meaning that only larger individuals were sampled. This group is composed of rare species with poor regeneration. Type 2 have slightly negative SCD slopes (weak reverse J-curves). Type 2 is also generally characterized by large single-trunked trees, but in contrast to Type 1, most are common in the study area and have relatively healthy rates of regeneration. Type 3 species have large, negative SCD slopes (strong reverse J-curves) translating into good regeneration rates. Most species in this group are common and are characterized as small trees, many with multiple trunks.

PRO	*Botanical*	*Slope*	*R^2*	*Type*
	Hexalobus monopetalus	0.132	0.07	1
	Terminalia avicennoides*	0.077	0.87	1
	Lannea acida*	0.055	0.33	1
	Cordyla pinnata*	0.032	0.30	1
	Sterculia setigera*	0.000	0.00	1
	Combretum lecardii*	-0.075	0.13	1
	Combretum micranthum	-0.622	0.80	3
	Strychnos innocua	-0.815	0.98	3
	Combretum nigricans	-1.070	0.96	3
	Combretum glutinosum	-1.164	0.95	3
	Acacia macrostachya**			
	Bombax costatum**			
	Cassia sieberiana**			
	Grewia bicolor**			
	Hannoa undulata**			
	Pterocarpus erinaceus**			
	Sclerocarya birrea**			
	Terminalia macroptera**			
	Unknown 7**			
	Unknown 8**			

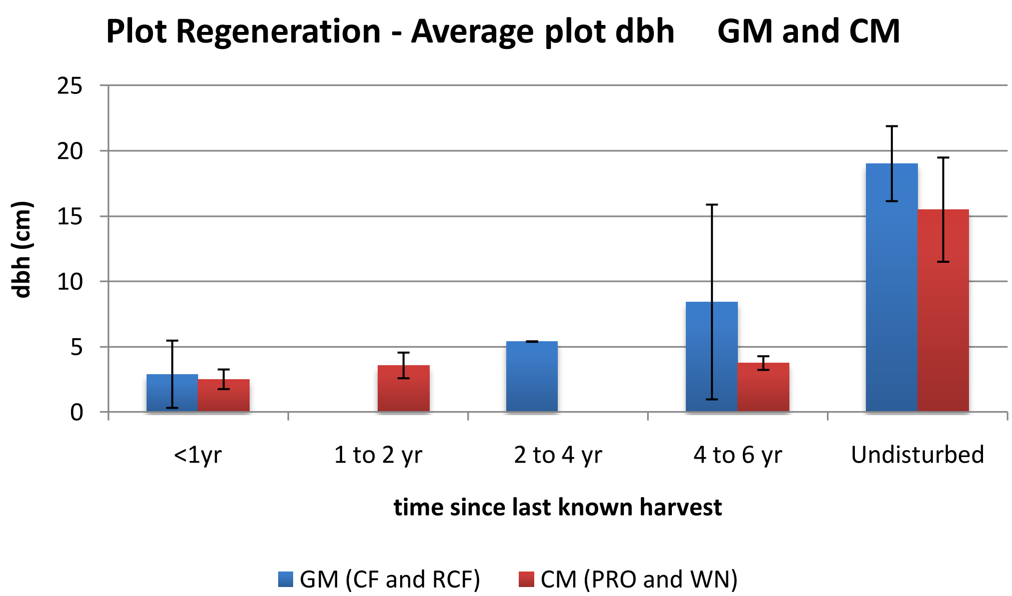
WN	*Botanical*	*Slope*	*R^2*	*Type*
	Combretum micranthum	0.048	0.01	1
	Pterocarpus erinaceus	0.031	0.12	1
	Sterculia setigera	0.024	0.50	1
	Bombax costatum	0.023	0.21	1
	Terminalia avicennoides	-0.115	0.76	2
	Lannea acida	-0.199	0.47	2
	Unknown 4	-0.558	0.75	3
	Unknown 5	-0.558	0.75	3
	Combretum nigricans	-0.789	0.95	3
	Unknown 3	-0.815	0.75	3
	Acacia macrostachya	-0.862	0.94	3
	Combretum lecardii	-0.947	0.88	3
	Combretum glutinosum	-1.102	0.99	3
	Hexalobus monopetalus	-1.113	0.80	3
	Vitex madiensis	-1.162	0.99	3
	Strychnos innocua	-1.257	0.75	3
	Annona senegalensis			
	Cordyla pinnata			
	Ostryoderris stuhlmannii			
	Piliostigma thonningii			

Table 0-11 - Classification of species sampled in PRO and WN harvested plots into SCD types. Type 1 consists of species with extremely flat or sometimes positive SCD slopes meaning that only larger individuals were sampled. This group is composed of rare species with poor regeneration. Type 2 have slightly negative SCD slopes (weak reverse J-curves). Type 2 is also generally characterized by large single-trunked trees, but in contrast to Type 1, most are common in the study area and have relatively healthy rates of regeneration. Type 3 species have large, negative SCD slopes (strong reverse J-curves) translating into good regeneration rates. Most species in this group are common and are characterized as small trees, many with multiple trunks.

*between 5 and 9 individuals
**fewer than 5 individuals

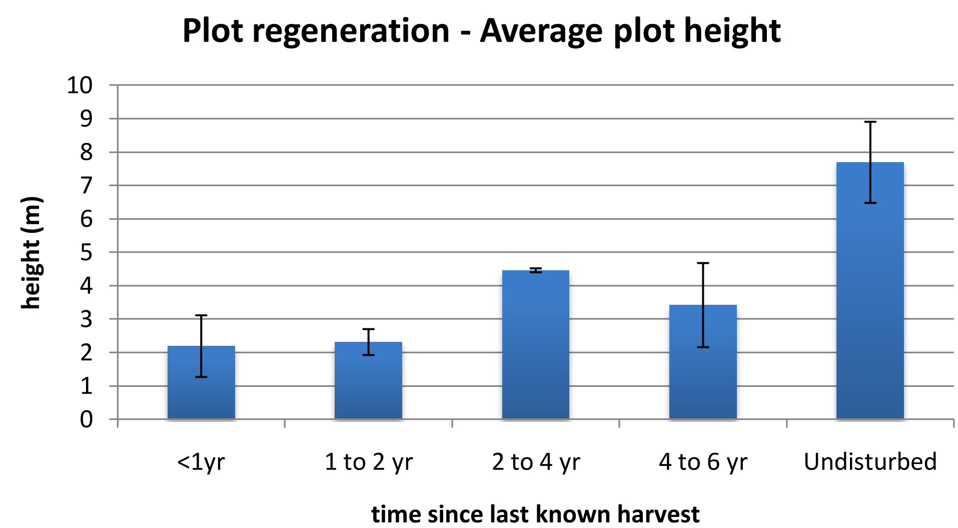


a)

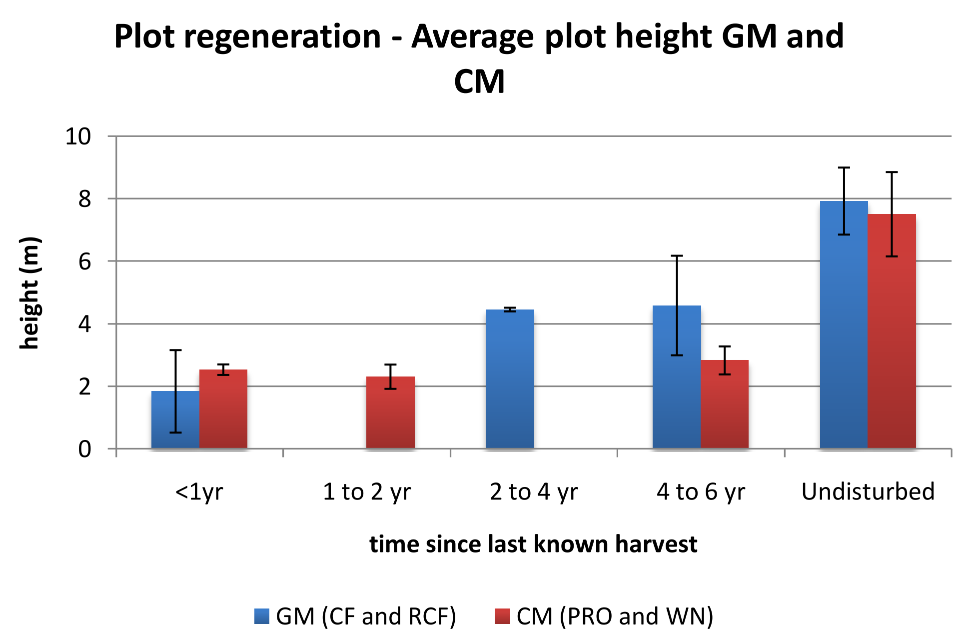


b)

Figure 0-5 - A) Average plot dbh (cm) in each time-step category since time of last known harvest for charcoal production. Based on a sample of 26 plots in all known forest management types. Undisturbed dbh values are from all undisturbed sites sampled in the study area (16 plots). B) Average plot dbh (cm) since time of last known harvest disaggregated by GM (CF and RCF – 10 plots) and CM (PRO and WN – 16 plots). Undisturbed dbh values are from undisturbed plots within GM or CM classifications.

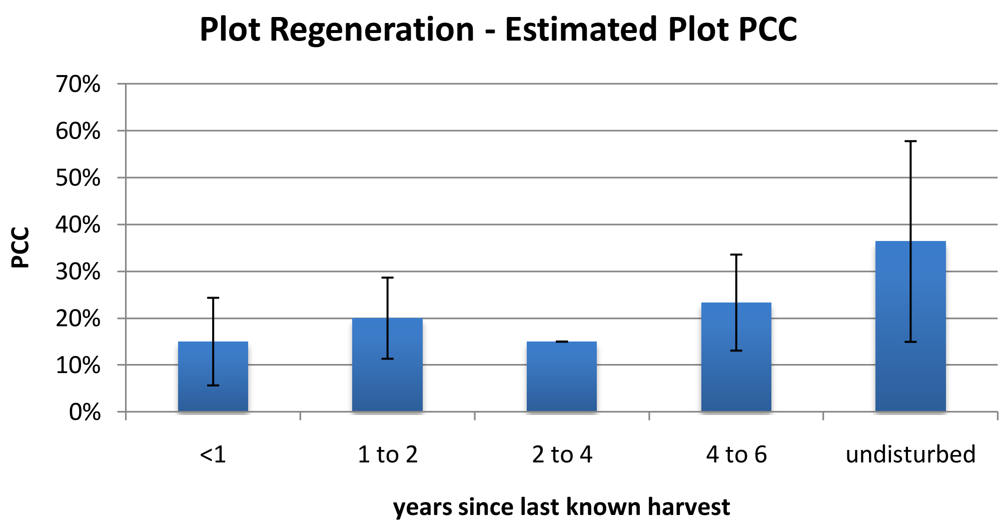


a)

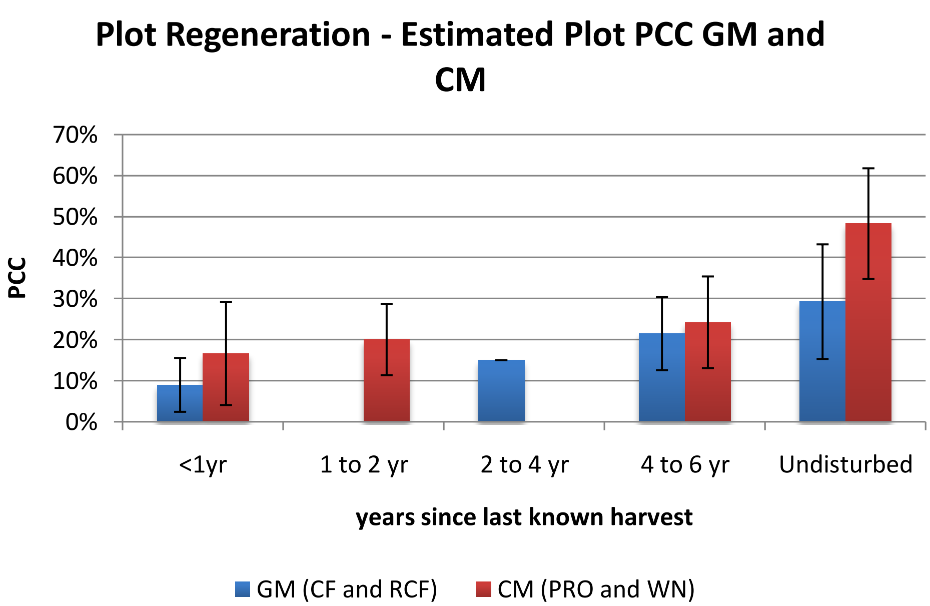


b)

Figure 0-6– A) Average plot height (m) in each time-step category since time of last known harvest for charcoal production. Based on a sample of 26 plots in all known forest management types. Undisturbed height values are from all undisturbed sites sampled in the study area (16 plots). B) Average plot height (m) since time of last known harvest disaggregated by GM (CF and RCF – 10 plots) and CM (PRO and WN – 16 plots). Undisturbed dbh values are from undisturbed plots within GM or CM classifications.

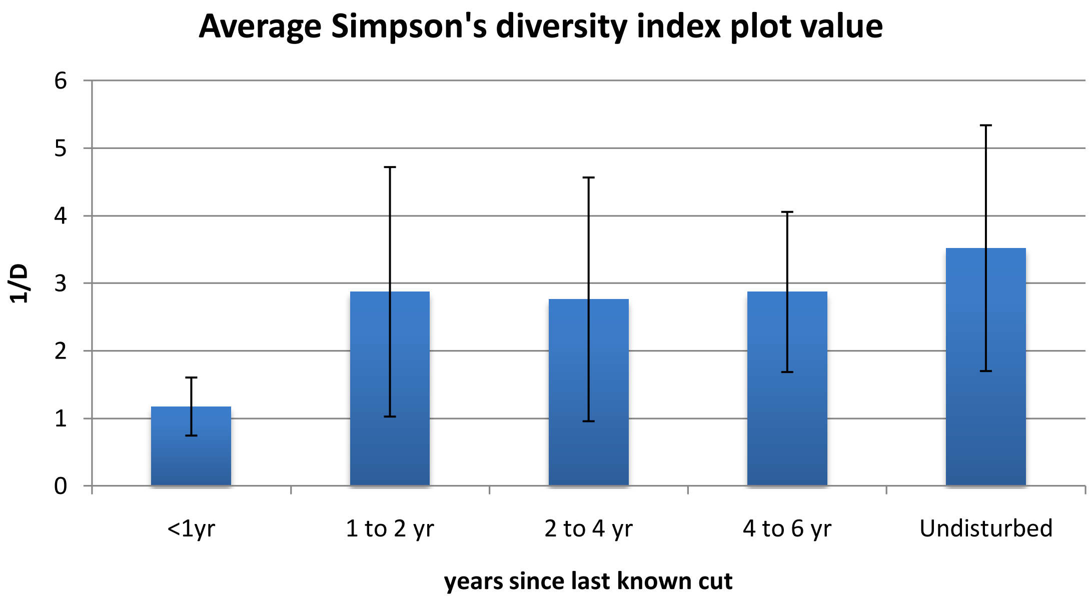


a)

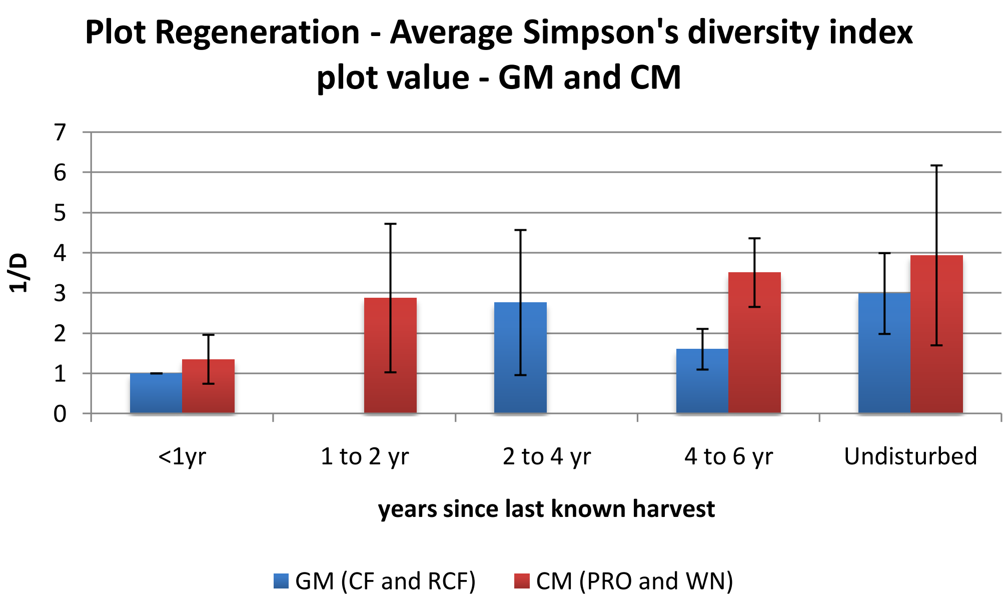


b)

Figure 0-7 - A) Estimated PCC in each time-step category since last known harvest for charcoal production. Based on a sample of 26 plots in all known forest management types. Undisturbed PCC values are from all undisturbed sites sampled in the study area (16 plots). B) Estimated PCC in each time-step category since time of last known harvest disaggregated by GM (CF and RCF – 10 plots) and CM (PRO and WN – 16 plots). Undisturbed PCC values are from undisturbed plots within GM or CM classifications.



a)



b)

Figure 0-8 – A) Average Simpson's diversity reciprocal index (1/D) value in each time-step category since last known harvest for charcoal production. Based on a sample of 26 plots in all known forest management types. Undisturbed 1/D values are from all undisturbed sites sampled in the study area (16 plots). B) Average 1/D values in each time-step category since time of last known harvest disaggregated by GM (CF and RCF – 10 plots) and CM (PRO and WN – 16 plots). Undisturbed 1/D values are from undisturbed plots within GM or CM classifications.

Finally, average plot Simpson's diversity index (1/D) values were calculated for GM and CM categories. Patterns were less pronounced with 1/D values starting at a low of 1 for GM and 1.4 for CM and highs of 2.7 at 2 to 4 years after cutting for GM and 3.5 at 4 to 6 years after cutting for CM (Figure 3-8b). The high values nearly reached the undisturbed 1/D values of 3 for GM and 3.9 for CM.

Discussion

Results suggest that charcoal harvesting has a large effect on forest structure and diversity. Within all harvested plots, forest management type has little impact on the rate of regeneration and forest structure. The following section discusses these results vis-à-vis the research objectives and corresponding hypotheses.

Charcoal Harvest as an Indicator of Degraded Landscape

- *Hypothesis 1 - Tree species diversity, forest plot structure (tree height and dbh averages), and estimated percent canopy cover will be less in areas of charcoal production when compared to undisturbed areas.*

Many studies of ecological resilience and regrowth capabilities of African woodlands have shown that undisturbed areas have a greater ability to recover from disturbance because they have greater ecological resilience (ability of the plot to respond to disturbance and maintain or return to its current physical and species composition) than a frequently disturbed site (Chidumayo 2002, Jansen, Bagnoli and Focacci 2008, Kindt et al. 2008).

In this study, sites harvested for the production of charcoal were found to have lower average plot structure, estimated PCC and lower tree species diversity than undisturbed sites thus creating a more degraded forest environment. Species composition and diversity are lowered making it very difficult for natural regeneration and succession return harvested plots to undisturbed tree species diversity levels. The post-harvest environments are dominated by highly resilient coppicing tree species such as *Combretum glutinosum*.

All large trees identified in harvested and undisturbed sites have flat SCD curves indicating few young individuals, a lack of rejuvenation and declining populations (Condit et al. 1998, Lykke 1998, Nezerkova-Hejcmanova et al. 2005, Kindt et al. 2008). Extremely few young individuals make it unlikely that species populations can be maintained at the present level, because for a population to maintain a relatively constant population, more individuals are required in the smaller classes than in the larger ones. Some individuals will inevitably die before maturity due to cutting, disease or other disturbances.

Although harvested sites are degraded, some species are regenerating. A closer look at the size class distribution (SCD) of each species in both harvested and undisturbed sites shows that some tree species are regenerating at a rate needed to replace individuals that are harvested or die. Within undisturbed plots, 6 of 24 species have a strong reverse J-curve (high regenerative capacity) while harvested plots show 11 of 32 species with a reverse J-curve. All identified species with reverse J-curves are common, small trees (many in the Combrataceae family harvested for charcoal production).

When analyzing average plot tree dbh and height over time, values are greatest 2 to 4 years after harvest then decline the next time-step of 4 to 6 years since cutting. Interviews with local charcoal producers revealed that many kilns are used repeatedly, sometimes every year. Based on the interviews, this does not mean the immediate area near to the kiln is harvested each year, but that wood is harvested and brought to that spot frequently.

Frequently revisiting the same site for charcoal production brings higher foot-traffic to the area. When Combrataceae species regenerate, a large number of shoots coppice from the original stump. Re-growth is often uneven with one shoot growing quicker than the others. In this case, when charcoal producers return to the area in year 4 they might harvest the largest shoot (now with a potential dbh of 5 to 7cm) and leave the other smaller shoots. This selective harvest method was noted during many visits with charcoal producers in the field. When field surveys were conducted with the individual/s who harvested the plot this data was noted when possible. The question asked to producers was when was the last time this site was harvested for the production of charcoal. Even if it is known that charcoal was harvested in 2003 it would be difficult for the producer to remember or know if a selective harvest of the area was done in subsequent years.

The strongly negative SCDs of Combrateceae species is aided by its resistance to fire. The capacity to resist fire is often cited as one of the most important factors for high survival rates in the region (Lykke 1998, Wood, Tappan and Hadj 2004) and the strongly negative SCDs of Combrateceae species is aided by its resistance to fire. Semi-structured interviews indicated that fire was a perceived driver of forest change in all forest management types (Wurster 2010). In high-frequency fire environments such as this, species with good fire-insulating bark or with the capacity to resprout after fire will have the highest survival rates (Pinard and Huffman 1997, Otterstrom, Schwartz and Velazquez-Rocha 2006, Nefabas and Gambiza 2007).

Proximity to Potential Disturbance Factors as Indicator of Degraded Landscape after Charcoal Production

- *Hypothesis 2 - Plot species* composition and vegetative structure characteristics are positively correlated with proximity to major roads, villages, and park boundaries.

In most environments a single proximate cause very rarely leads to environmental degradation. Instead, degradation most often occurs when multiple proximate causes (Hosier 1993, Geist and Lambin 2002, Mbow et al. 2008) are combined with underlying causes in a particular environment. Policy actions and management methods are generally classified as underlying causes of deforestation and land degradation (Geist and Lambin 2002) and are believed to significantly alter the environment in Senegal (Ribot 2002, Mbow et al. 2008).

Previous studies have shown that forests near to human settlements or roads are more accessible and therefore more susceptible to deforestation (Serneels and Lambin 2001, Overmars and Verburg 2005). In areas where protected areas have higher levels of tree cover, park edges are often highly susceptible to deforestation and ecological changes resulting from anthropogenic and natural causes (Skole and Tucker 1993, Laurance et al. 2002).

It was hypothesized that distance to the nearest road and village should positively correlate with presence of charcoal activity and plot degradation since large quantities of charcoal (up to 50 large bags per kiln) need to be transported to either main roads or larger town. Transporting a large quantity of charcoal would be theoretically difficult from remote points of production.

In this study, in all harvested sites and within all forest management types few combinations of distance to village, road and park edge correlates significantly with forest plot characteristics. In instances where relationships were suggested the estimated significant coefficients were very weak indicating that forest plot characteristics changed very slightly when proximity to roads, villages and park edges varied.

Models also did not produce consistent results across forest characteristic variables demonstrating little explanatory power. For instance, if the explanatory variable of roads had a large impact on forest characteristics it would produce significant coefficients across more than one of the plot characteristic variables; within harvested and undisturbed plots and across forest management types, only distance to villages had significant positive coefficients in two (plot tree dbh and height) of the five forest characteristics variables.

In each area surveyed active harvesting for charcoal production and charcoal production was seen throughout the landscape. Charcoal was produced where the desired tree species were large enough (greater than 5cm) to yield good pieces of charcoal regardless the proximity to roads, villages or park edges. Degraded plots were equally found within hundreds or thousands of meters from villages, roads and park edges.

Numerous interviewees noted that illegal charcoal production needed only be “far enough” into the forest; out of site of infrequently patrolling Forest Service employees. Interviewees also stated that frequently authorities knew where charcoal was produced, but only infrequently confiscated charcoal and equipment.

Forest Management Type and Its Influence on Forest Composition and Regeneration after Charcoal Production

- *Hypothesis 3: Land management type will result in no significant variation in tree species composition and regeneration rate near charcoal production.*

Results suggest plot compositions throughout all harvested forest management type plots are not statistically different when comparing average plot tree dbh, average plot tree height, PCC and estimated tree plot density, but significant differences do exist between harvested plot tree species diversity values. Although the values are different the basic species composition with the different forest management types are very similar.

Combretum glutinosum and other species within the Combrataceae family dominated each forest management type plot and were the only species found with strongly negative SCD curves (robust regenerative capacity) throughout the study area. The dominance of this species and a lack of other species in the type 3 SCD class suggest that all forest management types are at a high risk of significant species diversity loss in the near future. Large trees are found within each forest management type, but all have flat SCDs making it unlikely that they will be able to maintain current species levels. Within each harvested plot, regardless of forest management type, fewer than 20 trees of greater than 20cm are found per hectare. WN plots exhibited the largest number of species in the type 3 class for all forest management types, but still lacked any large trees showing the potential for continued presence into the future.

Repeated forest harvesting by humans and has been shown to decrease species diversity (Uhl et al. 1997, Smith et al. 1999, Naughton-Treves, Kammen and Chapman 2007, Klanderud et al. 2010) and could explain the differences in diversity index values between recently established WN and PRO types compared to CF and RCF types. In all parts of the study area people use the forest frequently for the collection of fuelwood, grazing of livestock and harvesting of non-timber forest products. Interviewees in the sample CF and RCF locations stated that harvesting for charcoal production was occurring for over 50 years (Wurster 2010). On the other hand, harvesting for charcoal production in many PRO and WN forest management types has been taking place for a much shorter period of time, starting in the 1990's for many PRO sites (Lo 2007) and the early 2000's for most WN sites (Heermans 2008). The historical impact of charcoal due to repeated harvesting rotations is therefore much lower in PRO and WN sites.

Forest management types also have different extraction methods which could impact tree species diversity, plot composition and regenerative capacity. The WN and PRO types practice a selective harvest (Lo 2007, Heermans 2008), while harvesting is illegal in CF and by permit only in RCFs.

In practice, RCF and CF extraction methods are identical with desirable trees within a short distance of the kiln site (preferably less than a couple hundred meters) cut, stacked, and used to create charcoal. Interviewee stated that trees from the Combrateceae family (i.e. *Combretum glutinosum, Combretum lecardii*, *Combretum nigricans*) are preferred for charcoal production because of their clean burning and regenerative properties (Wurster 2010). This information was confirmed by reverse J-shaped SCD curves of all Combrateceae species.

Growth rates from less than one year after cutting to six years after cutting suggested that plots within CF and RCF forest management types are regenerating. In six years time they are not reaching the undisturbed plot characteristics, but are on a positive growth trend to reach them if left undisturbed for an extended period of time. In areas of charcoal production this is usually not the case with charcoal producers returning to areas previously cut every four to eight years (Jensen 1995, Ribot 1999). Based on the regeneration results, a rotation period of six years allows tree to grow sufficiently large for charcoal production (larger than the minimum dbh of 5cm mentioned by charcoal producers), but inadequate if the goal is a return to an undisturbed state. If rotation periods of less than eight years continue, the results of this research suggest that the forest will continue to exist in its present disturbed state with a high percentage of one or two Combretaceae species (most often *Combretum glutinosum*) and very few large trees.

In WN and PRO forest management types, harvesting of trees for charcoal production is accomplished through selective harvesting techniques. In general, if a tree selected for harvest has four shoots of adequate dbh, three of the four trunks would be cut. Based on stump size observations and discussions in the field, the three largest trunks were most often cut leaving the smallest of the four. Additionally, charcoal producers in the WN areas acknowledged cutting a wider variety of species when making charcoal. Some of these species, such as Lannea acida, were historically used for charcoal production and locally common in WN plots, but do not regenerate well (flat SCD curve) and could become locally rare if this practice is continued. A substantial decline (-51.4%) in tree species diversity is already observed between undisturbed and harvested WN plots and could decrease to the lower levels observed in CF and RCF types if such harvesting practices are continued.

Regeneration after cutting is occurring within WN and PRO sites, but at a slower growth rate (based on dbh and height values) than CF and RCF sites. Within the WN and PRO forest management types, areas designated for charcoal production are set to be cut every eight years. Based on the trends observed in this research, this rotation period might be too short for many coppicing trees to regrow to a dbh larger than 5cm. If rotations occur every eight years in these areas it is possible that harvested forest plots could decrease in plot composition and structure in addition to species diversity.

Conclusion

Plots that have been harvested for the production of charcoal are significantly different in species composition and structure than undisturbed plots. Information derived from SCDs concluded that few species are regenerating in harvested and undisturbed areas. The species that are regenerating are common, small trees in the Combretaceae family. These trees are preferred for charcoal production, but because of their strong regenerative capacity continue to dominate the forest landscape. Large, hard wood trees are sparse and are not regenerating at levels that needed to replace the current population. This information could lead to the eventual transition, at least in species diversity terms, to that closer to present day harvested plots rather than maintaining the characteristics of undisturbed plots.

Plots regardless of proximity to villages, roads and park edges are equally susceptible to changes in structure and composition. Illegal charcoal producers in the region understand enforcement patterns of the Forest Service and therefore harvest wood and create kilns at safe distances from enforcement, sometimes deep in forests or just far enough out of sight to decrease detection.

Forest management type also appears to have little influence on forest plot composition before and after harvesting with the exception of species diversity. WN and PRO harvested and undisturbed plots had significantly different (and higher) species diversity values than Classified Forest and Rural Community forests. This increased diversity could be due to the limited exposure these areas have had to charcoal production (usually one or two charcoal rotations in contrast to repeated cutting over the past 50 or more years for CF and RCF plots). When compared to CF and RCF plots, WN and PRO plots are not regenerating as quickly and also decreasing in tree species diversity at a rapid rate. This could be due to harvesting of non-coppicing trees not commonly found in many CF and RCF plots.

A new forest landscape is taking shape in the Tambacounda region of Senegal, one dominated by fast growing and resilient species with very few of the large, hardwood trees historically found in the region. Management of select regions might slow this transition, but it might not be able to stop it. Furthermore, if increased harvesting pressure is put on newly formed WN and PRO forest management types an even quicker decline in species composition and forest structure might be eminent.

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