ABSTRACT

Title: MANAGEMENT MATTER? EFFECTS OF CHARCOAL PRODUCTION MANAGEMENT ON WOODLAND REGENERATION IN SENEGAL

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In Senegal, as in many parts of Africa, nearly 95% of its growing urban population depends on charcoal as their primary cooking energy. Extraction of wood for charcoal production is perceived to drive forest degradation. The Senegalese government and international donor agencies have created different forest management types with the ultimate goal of sustainably managing forests. This research combines local ecological knowledge, ecological surveys and remote sensing analysis to better understand questions related to how extraction for charcoal production and forest management affect Senegalese forests. Information derived from 36 semi-structured interviews suggests that the forests are degrading, but are depended on for income, grazing and energy. Interviewees understand the rules governing forest management types, but felt they had limited power or responsibility to enforce forest regulations. Ecological survey results confirmed that plots harvested for charcoal production are significantly different in forest structure and tree species composition than undisturbed sites. Across harvested and

undisturbed and within forest management types the Combretum glutinosum species dominated (53% of all individuals and the primary species used for charcoal production) and demonstrated robust regenerative capacity. Few large, hardwood or fruiting trees were observed and had insufficient regenerative capacity to replace current populations. Species diversity was higher in co-managed areas, but declined after wood was harvested for charcoal production. Proximity to villages, roads and park edges in harvested and undisturbed plots and within forest management types had little impact on forest structure and tree diversity patterns with the harvesting of trees for charcoal spread consistently throughout the landscape. Remote sensing analysis with the MISR derived k(red) parameter demonstrated its ability to accurately classify broad land classes and showed potential when differentiating between pre- and post-harvest conditions over a three year time period, but could not accurately detect subtle changes in forest cover of known harvest time since last harvest in a single MISR scene. This research demonstrated the utility of multidisciplinary research in assessing the effects of charcoal production and forest management types on Senegalese forests; concluding that the effects of charcoal production on forest characteristics and regenerative capacity are consistent throughout all forest management types.

MANAGEMENT MATTER? EFFECTS OF CHARCOAL PRODUCTION MANAGEMENT ON WOODLAND REGENERATION IN SENEGAL

By

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Dedication

To Olivia

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Chapter 1 - Introduction and Literature Review

In Senegal, 95% of a rapidly growing urban population depends on charcoal as their primary source of energy for cooking. The high demand for charcoal in urban environments has led to conclusions that charcoal harvesting is catalyzing widespread deforestation (Post and Snel 2003, Tappan et al. 2004, Mwampamba 2007). To address deforestation, the Senegalese government and international donors have initiated projects within new and previously existing protected areas to combat deforestation and create forest management plans aimed at a sustainable harvesting rotation for the production of charcoal.

How do varying forest management strategies affect forest sustainability after charcoal harvesting? To date, the effects of forest management techniques on forest regeneration are still in question. This research uses a multiphase approach integrating satellite analysis with field surveys to assess the effect of varying forest management strategies on forest regeneration and sustainability after harvesting of trees for charcoal production.

The following chapter serves as a literature review and introduction to the research. The chapter first takes a broad look at fuelwood and forests from both a historical and technical perspective. First presenting the historical perspective and subsequent evolution of research related to fuelwood use and the effects of fuelwood harvesting and consumption on forest environments in the developing world. Second, it discusses how the development of remote sensing technology has allowed researchers more accurately and frequently to assess change in forest cover and structure. Finally, a description of the Senegal study area is presented with a discussion of environmental change in Senegal, a detailed description of how charcoal is produced, how charcoal consumption might contribute to forest changes in the region, and the management measures being taken by the Senegalese government and international donors to mitigate these perceived changes.

"Fuelwood crisis" – Thesis and Anti-thesis

Over the course of the last 30 years, assessments of fuelwood consumption, both firewood and charcoal, in developing countries have changed substantially (Arnold and Persson 2003). In the mid-1970s to early 1980s, recognition that huge and growing numbers of people depended on fuelwood as their principal domestic fuel led to predictions of a potentially devastating depletion of forest resources (DeMontalembert and Clement 1983, O'keefe 1985, Leach and Mearns 1988). Many believed serious negative livelihood consequences would be felt by the rural poor, unless action was taken to address this "fuelwood crisis" (Clarke 1983a, Eckholm et al. 1984, Timberlake 1985, Harrison 1987). By the mid to late 1980s, it was argued that the nature and impact of the crisis had been significantly overestimated due to inaccurate estimates of forest stocks, the dependence of rural populations on wood from non-forest lands and the ability of harvested tree to naturally regenerate (Dewees 1989, Benjaminsen 1993, Top et al. 2004), and that it was not a crisis requiring interventions just to maintain fuelwood supplies. Consequently, during the 1990s, most of the fuelwood-oriented forestry programs put in place in the 1970s and 1980s were terminated or significantly reduced (Arnold, Kohlin and Persson 2006).

Today, potentially due again to rising energy prices (Bruinsma 2003, Maconachie, Tanko and Zakariya 2009), the negative consequences of fuelwood extraction by billions of people throughout the developing world is returning to the center of forestry and political debates (Arnold et al. 2006). The thesis and anti-thesis fuelwood discussion has gone full circle. Climate, culture, environment, and income all play an important role in determining fuelwood consumption rates and environmental impact in the developing world.

Thesis

> "Dwindling reserves of petroleum and artful tampering with its distribution are the stuff of which headlines are made. Yet for more than a third of the world's people, the real energy crisis is a daily scramble to find the wood they need to cook dinner. Their search for wood, once a simple chore and now, as forests recede, a day's labor in some places, has been strangely neglected by diplomats, economists, and the media; But the firewood crisis will be making news – one way or another – for the rest of the century."
>
> *Opening paragraph from "The Other Energy Crisis" by Eric Eckholm 1975*

For the remainder of the 20th century and into the first part of the 21st century the ideas presented by Eric Eckholm in his 1975 *Worldwatch* paper helped make the issue of fuelwood shortages in developing regions of Africa, Asia, and Latin America a major development priority. Throughout the 70's and 80's loud voices from scientists and government agencies were heard (Eckholm et al. 1984, Timberlake 1985, Harrison 1987, Leach 1988, Cline-Cole, Main and Nichol 1990) shouting that the increasing demands of the world coupled with rapid population growth and dwindling biomass supply would lead to widespread deforestation and a developing world-wide "fuelwood crisis".

The general perception was that cutting for fuelwood was a major factor leading to forest degradation and destruction. It was argued that, as the poor often had no alternative to fuelwood or other locally available organic materials, "on consequence of growing rural populations is…an inexorable growth in the pressures on locally available forest resources and the other sources of woody material. The source of fuelwoods extends progressively from collecting deadwood to the lopping of live trees, the felling of trees, the total destruction of tree cover, the loss of organic matter to the soil and eventually to the uprooting of stumps and removal of shrubs" (FAO 1978).

The theory of a fuelwood crisis goes as follows: First, wood energy is believed to be used by poor populations who cannot afford, or have access to, the energy alternatives of gas, LPG and electricity (DeMontalembert and Clement 1983, Allen and Barnes 1985, Leach 1988, Soussan, Okeefe and Munslow 1990, Leach 1992, Dang 1993, Shackleton 1993, Boahene 1998). Fuelwood is collected on foot, by bike or using livestock (Gill 1987, Foley, Kerkhof and Madougou 2002). Second, because of the restrictions of the fuelwood collectors options and mobility, the harvest pressure is perceived to be nearest to population centers; thus allowing traveling distance to be used as a proxy measurement of wood scarcity (Arnold et al. 2006). Third, these limitations combined with a general lack of "environmental awareness" (Ogunkunle and Oladele 2004) results in unsustainable harvesting (Shackleton 1993, Soussan et al. 1990, Boahene 1998), creating rings of degradation and deforestation surrounding population centers (Eckholm 1975, DeMontalembert and Clement 1983, Anderson 1986, Soussan et al. 1990, Leach 1992, Dang 1993).

Finally, the growing scarcity of fuelwood around urban zones is hypothesized to drive commercialization of fuelwood, putting increased pressure on rural zones to produce and therefore extending deforestation into rural areas. Commercialization of fuelwood is seen to only occur after wood has been exhausted in the immediate vicinity of the population centers (Anderson 1986, Leach 1988). The presence of a fuelwood market is also perceived as a level of wood scarcity (Dewees 1989). Additionally, commercialization of fuelwood has a negative influence on deforestation because it extends and amplifies land use change (Anderson 1986, Soussan et al. 1990, Kersten et al. 1998). After the most accessible stocks are depleted the commercial harvesters move further and further into the bush until all the forest stock is depleted (Dang 1993).

A study prepared for the 1981 UN Conference on New and Renewable Sources of Energy which estimated that 2 billion people depended on fuelwood and other biomass fuel in 1980. More than half were unable to meet their energy needs without cutting from forests, and that the over-harvesting of land would result in fuelwood scarcity for up to 2.4 billion people by the year 2000 (DeMontalembert and Clement 1983).

Fuelwood shortages were predicted to result in a whole range of negative social and environmental outcomes, including: increased wood collection times (especially for women and children) (Cecelski 1987), increased use of agricultural residues for fuel with subsequent loss of soil fertility, less frequent cooking with corresponding nutritional consequences (Carruthers and Chambers 1981, O'keefe 1985), and greater monetization of fuelwood supplies requiring more cash outlay from poor households (Timberlake 1985, Arnold and Persson 2003).

Estimates of fuelwood demand in various regions of the developing world were compared with the rates of annual growth in biomass from existing forest resources, and in those cases where demand exceeded growth it was assumed that the difference was being met by over-cutting and depletion of forests (Laarman and Wohlgement 1984, Cline-Cole et al. 1990). In addition, fuelwood demand was projected to grow at roughly the same rate as population, with many studies predicting a growing ‘gap’ between declining fuelwood supply and rising demand (O'keefe 1985, Mearns 1989, Cline-Cole et al. 1990).

The need to address this catastrophic environmental change was one of the driving forces behind leading early strategies by government and international donor agencies to restructure approaches to forestry and make them more effective in meeting fuelwood demands (Arnold and Persson 2003). This led to many proposals and plans to encourage ways to use fuelwood more economically, the more efficient management of existing wood resources, and the planting of trees to increase fuelwood (Dang 1993, Bruinsma 2003). The gap between fuelwood supply and demand was estimated and translated into planting targets and attracted substantial donor and government funding, resulting in significant increases in these types of forestry programs (Arnold et al. 2006).

Anti-thesis

A picture emerged by the end of the 1980s that was very different from the one presented in the 1970s. According to the revised view, fuelwood use seldom posed a serious threat of deforestation (Cecelski 1987, Norman 1984), reduced access to fuelwood was fairly easily managed by households through a number of alternative energy possibilities (e.g. Dewees 1989), and therefore interventions such as fuelwood plantations or improved stoves were not a high priority for the target groups and consequently had limited potential for success (Arnold and Persson 2003). By the 1990s, these results and arguments had become generally accepted, leading to a significant reduction in programs designed to encourage planting of trees primarily to produce fuelwood.

The initial announcement of the fuelwood crisis and analysis of wood supply was seriously constrained by a lack of accurate and reliable data. Very few countries had rough estimates of the extent and degree of fuelwood production or use, and there was inadequate data on sources of supply and the interactions between supply and demand (Arnold et al. 2006). By the mid 1980's, the understanding of the adequacy of fuelwood supplies and the environmental impacts of their harvest and use had undergone substantial change. Earlier predictions of widespread fuelwood shortages based on a combination of rising populations and shrinking forest areas had not materialized (Bhattarai 2001).

Many authors have since concluded that the policy and program interventions initiated during the early years of the crisis failed to solve the problems they were designed to address. Most projects were based on an imperfect link between fuelwood use and deforestation, exaggerated the extent of existing or impending fuelwood shortages, and failed to recognize that targeted populations had already begun to adapt to impending fuelwood shortages through their own methods (Cline-Cole 1998, Arnold and Persson 2003, Bensel 2008). In particular, many fuelwood policy interventions failed to recognize that much of the fuelwood consumed in developing regions was originating from trees and shrubs growing outside of forest areas, and that farmers were often already responding to forest product scarcities through increased tree planting (Rudel et al. 2005).

These trees were meeting much of the local populations demand for wood and also regenerating naturally (Foley 1985, Dewees 1989). Additionally, fuelwood is also taken from deadwood collection, pruning, lopping and other forms of harvesting other than the felling of live trees (Arnold et al. 2006, Norman 1984).

A more nuanced view of the situation was beginning to take shape; acknowledging the general factors influencing energy consumption and the use of fuelwood vary from place to place and are all subject to change over time. Differences in culture, climate, the availability of alternative fuels and income and economic development are the main explanations for this variation (Agarwal 1986).

Changes in Fuelwood Consumption

Today, more than 30 years after the crisis began, over two billion people in developing countries still rely on biomass energy in the form of firewood, charcoal, crop residues, and animal wastes to meet their cooking and heating requirements (MEA 2005). The broad claims of links between fuelwood (firewood and charcoal) use and deforestation, as well as forecasts of widespread fuelwood shortages still persist (Schulte-Bisping, Bredemeier and Beese 1999, Kauppi et al. 2006).

The overall quantities involved, and the numbers still relying on fuelwood will continue to be very large. The International Energy Agency recently estimated that in 2030, biomass energy will still account for an estimated three quarters of total residential energy in Africa. Additionally, due to population growth, the number of people using fuelwood and other biomass fuel in that region will rise by more than 40% during 2000–30 to about 700 million. In Asia, in spite of consumption declining, there will still be an estimated 1.7 billion users in 2030, and 70 million in Latin America 70 million (IEA 2002).

In 2001 the FAO began a significant effort to reassess their projections of fuelwood consumption. Although the final numbers were slightly less than the IEA predictions, the FAO study shows a growing consumption of fuelwood worldwide, particularly in Africa (Broadhead, Bahdon and Whiteman 2001) (Table 1-1).

Additional studies (Barnes, Krutilla and Hyde 2002) estimate that charcoal consumption is often growing faster than firewood consumption. Charcoal is becoming a much larger part of the fuelwood total in Africa and South America and, in Africa, growing close to the rate of population growth. Significant variations between countries exist, but the general trend of decreasing per capita consumption of both fuelwood and charcoal with increasing income remains (Broadhead et al. 2001).

There is a kind of ladder of energy sources in the urban areas: from firewood at the bottom, through charcoal, kerosene and gas, to electricity at the top. People generally climb this ladder as their income increases. Therefore charcoal, which is infrequently used in the rural areas because of availability of free wood, is quite popular in urban areas because of higher income and other factors such as its lightness and non-smoking nature (FAO 1993). As income rises, initially more fuelwood is consumed, but beyond a certain level its use decreases due to its substitution by other fuels (Laarman 1987). According to Foley (1985), price influences the amount of fuel that is consumed, but only minimally affects the choice between fuels.

Growing urban populations are relying on the more compact charcoal as the

Table 1-1 - FAO projections of fuelwood (firewood and charcoal) consumption to 2030 in the main developing regions

Year	1970	1980	1990	2000	2010	2020	2030
Firewood (million cubic meters)							
South Asia	234.5	286.6	336.4	359.9	372.5	361.5	338.6
Southeast Asia	294.6	263.1	221.7	178.0	139.1	107.5	81.3
East Asia	293.4	311.4	282.5	224.3	186.3	155.4	127.1
Africa	261.1	305.1	364.6	440.0	485.7	526.0	544.8
South America	88.6	92.0	96.4	100.2	107.1	114.9	122.0
Charcoal (million tons)							
South Asia	1.3	1.6	1.9	2.1	2.2	2.4	2.5
Southeast Asia	0.8	1.2	1.4	1.6	1.9	2.1	2.3
East Asia	2.1	2.3	2.3	2.2	2.1	2.0	1.8
Africa	8.1	11.0	16.1	23.0	30.2	38.4	46.1
South America	7.2	9.0	12.1	14.4	16.7	18.6	20.0

Source: (Broadhead et al. 2001).

primary source of urban cooking energy (Hosier, Mwandosya and Luhanga 1993, Bailis, Ezzati and Kammen 2005, Kammen and Lew 2005) with many transitioning from firewood to charcoal as the cost of wood increases in urban areas (Barnes et al. 2002, Bruinsma 2003, Madubansi and Shackleton 2007, Maconachie et al. 2009). The Charcoal Potential in Southern Africa (CHAPOSA) study estimated that consumption of charcoal grew during 1990–2000 by 80% in both Lusaka and Dar es Salaam. The proportion of households in Dar es Salaam using charcoal as their primary fuel increased from 50 to 70% over the same period (SEI 2002).

As African cities grow, they require more charcoal. It is estimated that for each 1% increase in urbanization there is a 14% increase in charcoal consumption (Hosier et al. 1993). The high rates of urbanization prevalent in the region suggest that by 2050, more than 50% of Africans will reside in cities (UNFPA 2009). High and ever-increasing demand for charcoal, coupled with improper forest management, and poor regulation of the trade present a solemn future for forests in Africa (Bruinsma 2003, Madubansi and Shackleton 2007, Mwampamba 2007, Maconachie et al. 2009). In places where this combination of factors exists, the fuelwood crisis needs to be revisited.

Environmental Impacts of Fuelwood Extraction

Removal of woody biomass for fuel can have far-reaching consequences for the structure and functioning of ecosystems. Fuelwood extraction has been cited in increasing soil erosion (Anderson 1986, Aweto 1995, Ogunkunle and Oladele 2004), reducing soil moisture content (Anderson 1986), and decreasing soil fertility as nutrient leaching is increased (Ogunkunle and Oladele 2004) while vegetative recycling of subsoil nutrients (Aweto 1995). These are then associated with more extensive effects including reservoir siltation, flooding, water shortages due to shifting ground water regimes (Anderson 1986, Oguntunde et al. 2004) and biological impacts such as reduced faunal abundance (Bellefontaine et al. 2002, Ogunkunle and Oladele 2004) and biodiversity (Clarke 1983b). Additionally, in extreme cases such changes are expected to culminate in changes in weather patterns (Anderson 1986) and, in drier regions, desertification (Eckholm 1975, Clarke 1983b, Anderson 1986, Aweto 1995, Kersten et al. 1998, Bellefontaine et al. 2002) thus making the increased utilization of fuelwood by urban populations one of the most critical environmental issues sub-Saharan Africa must address (Boahene 1998).

A study of a wide range of case studies in tropical countries also concluded that multiple causes of deforestation exist, with fuelwood harvesting being important in some situations in Africa where deforestation is associated with wood extraction (Geist and Lambin 2002). Additionally, economic models of tropical deforestation support the existence of multiple causes of deforestation and cite fuelwood extraction as an occasional cause in parts of Africa (Kaimowitz and Angelsen 1998). A World Bank study in six countries in West Africa also concluded that, in areas of intense utilization, charcoal production can represent a main source of tree loss (Ninnin 1994).

The cutting of trees does not necessarily have detrimental effects on an ecosystem. It is well known among scientists and foresters that coppiced stems grow faster than older stems and branches, knowledge which has been put to use for centuries in European woodland management (Rackham 2001). Often the removal of fuelwood has far less impact on ecosystems than other land uses, such as commercial logging or clearance for agriculture (Cecelski 1987, Kaimowitz and Angelsen 1998, Angelsen and Kaimowitz 1999, Geist and Lambin 2002). Overall, tree-cutting which does not completely remove or kill trees over wide areas is unlikely to have serious negative consequences for the environment (Belsky and Amundson 1998).

A long running regional program found that, in aggregate, 16 Asian countries had total potential physical fuelwood supplies that exceeded their fuelwood demand in 1994, and that this is likely to continue to be the case in all but two of the countries in 2010. Conclusions for these countries were broadly in line with what had been hypothesized in the late 1980s that the demand for fuelwood is unlikely to cause large scale depletion of forests, but due to imbalances between regional patterns of demand and availability local fuelwood scarcity may occur (RWEDP 1997).

The subtler impacts of tree-cutting for fuelwood are much more relevant when discussing the ecological impact of cutting. The most important perhaps is change in species compositions as cutting influences the survival and reproduction of preferred fuel species relative to less preferred species. Studies in Nigeria, Burkina Faso, Mali, Niger and Senegal found substantially different species compositions in farmed parkland and a nearby ecologically equivalent forest reserves (Nichol 1989, Kindt et al. 2008). Tree species which do not coppice may disappear altogether. A study in Senegal noted that many tree species, particularly large trees have very few seedlings and therefore very low probabilities of regenerating naturally (Lykke 1998). Another study in Ghana found that an important fuelwood species used by 80 % of households in two villages during the past decade was no longer available (Osei 1993).

Increasing scarcity of fuelwood can exacerbate tensions between fuelwood collection and competing land-uses. Trees can and often are cut at high intensities in certain protected areas for sale on a local market (Ribot 1993), but little empirical information has been collected about the actual ecological impacts of such cutting.

The CHAPOSA studies of the charcoal supply systems around three cities in southern Africa demonstrated that harvesting can alter the wood resources in regions of intense pressure. Areas of closed woodland diminished during the 10 year study with sections being converted to agriculture and degraded bush, but if areas were left idle, regeneration would occur (SEI 2002). Studies in the charcoal systems of West Africa show that harvesting is within sustainable limits (Ribot 1998). Problems surface when there is a failure to manage the fuelwood production in a way that allows for regeneration and sustainable production.

Remote Sensing Estimates of Forests

Remote sensing tools have been used to estimate the current state of the environment, particularly forests and woodlands, globally (i.e. DeFries et al. 2002) and locally in Senegal (Tappan et al. 2004, Mbow et al. 2008). Many of these studies estimate that forests are declining worldwide and that a variety of human induced and natural causes are driving the changes (Skole and Tucker 1993, Asner et al. 2005, Asner et al. 2009). In the last 20 years, large strides have been made in the mapping and detection of broad-scale deforestation and land degradation (DeFries et al. 2002, Hansen et al. 2005) . Satellite remote sensing has become an important resource for conservation and natural resource management, providing highly accurate data for mapping ecosystems and assessing ecosystem change (Lefsky et al. 2002, Justice et al. 1998).

The number of satellite sensors available for analysis has dramatically increased, along with computation tools, hardware, and software used to analyze the data. The advancement of computer workstations has also accelerated this expansion (Leimgruber, Christen and Laborderie 2005, Craglia et al. 2008). The introduction of software packages like Google Earth brought satellite imagery and geographic information systems into common culture and dramatically increased the public's knowledge, understanding and appreciation of geospatial information (Craglia et al. 2008).

Satellite imagery for mapping forests is not only a standard tool for researchers and geographers, but also policy makers, land managers, and environmental institutions

(Wilkie and Finn 1996). Remote sensing of tropical rainforest has clearly demonstrated the wide extent of deforestation in these vital ecosystems (Skole and Tucker 1993, Achard et al. 2002, DeFries et al. 2002, Curran et al. 2004).

In other parts of the world, much of the changes are not widespread deforestation such as in the Amazon, but more subtle changes caused by human impacts such as extraction of wood for fuelwood, charcoal and timber. Land change in the Senegal and much of West Africa is generally classified as land degradation. Within these countries little information is available on deforestation or land degradation. Conflicting reports of the extent, and even existence of desertification and severe land degradation in West Africa exist (Prince, De Colstoun and Kravitz 1998, Nicholson 2000, Tappan et al. 2000, Hein and de Ridder 2006, Prince et al. 2007, Wood, Tappan and Hadj 2004).

The limitations of remote sensing might help explain some of these inconsistencies. The biophysical characteristics of many of the forests and woodlands in region are not conducive to standard remote sensing analysis. Some aspects of degradation, such as species change and degradation in areas with high spatial heterogeneity in their canopy structure are difficult to monitor with coarse resolution satellite data (Wessels et al. 2007). Species and vegetative structure/cover changes in the region are sometimes detectable with remote sensing technology (Pickup and Chewings 1994, Prince et al. 1998, Tappan et al. 2004), but this is not always the case (Diouf and Lambin 2001, Stringer and Reed 2007). In spite of the limitations in the woodland environment, remotely sensed estimates of vegetative cover in the region might be the most useful method of detecting land degradation at regional and decadal scales (Pickup and Chewings 1994, Prince et al. 2007).

It is commonly accepted that the most accurate way to estimate local variations in vegetative structure via remote sensing would be to use high resolution (Quickbird or Ikonos) and/or LiDAR (Light Detection And Ranging) technology (Dubayah and Drake 2000, Drake et al. 2002, Lefsky et al. 2002). Unfortunately, due to high cost and the lack of global or even regional coverage at standard time increments, regional ecosystem analysis is difficult.

The spectral and temporal information available from wide-swath moderate resolution remote sensing, such as Moderate Resolution Imaging SpectroRadiometer (MODIS) derived Vegetative Continuous Fields (VCF) (global product with multiple layers at a spatial resolution of 500m) has proved extremely valuable in constructing new maps of forest attributes over regional or global areas that could not be produced in any other way (Hansen et al. 2002), some limitations have been recognized.

First, estimating canopy structure via remote sensing is not a straightforward process. Structural effects are captured indirectly since spectral remote sensing data rely on the optical properties of vegetation and soil elements (i.e. spectral reflectance, absorption and transmittance) (Chopping 2008). Additionally, there are limits on how well empirical regression tree methods can predict tree cover given spectral confusion of varying cover types (White, Shaw and Ramsey 2005). An alternative approach to both high resolution and/or MODIS approaches may be the use of spectral radiance measurements by a multi-angle instrument such as the NASA/Jet Propulsion Laboratory Multi-angle Imaging SpectroRadiometer (MISR).

Launched in 2000, NASA’s Multi-angle Imaging SpectroRadiometer (MISR) collects data across 4 spectral bands and 9 view angles at a spatial resolution of 275m.

The utility of MISR to detect variations in canopy heterogeneity has been demonstrated most notably by (Pinty et al. 2002, Gobron et al. 2002, Chopping et al. 2003, Widlowski et al. 2005, Widlowski et al. 2004, Armston et al. 2007, Su et al. 2007b) and summarized by Diner et al (2005). These studies have argued that the directional reflectance characteristics are diagnostic of surface cover heterogeneity. MISR provides data sets of these angular reflectance "signatures" for many classes of surface cover. MISR's inclusion of vertical structure through its unique multi-angle approach provides it with a distinct advantage over single angle sensors such as MODIS in detecting variations in canopy and subcanopy structure (Pinty et al. 2002, Diner et al. 2005).

Environmental Change in Senegal

Environmental change is an important challenge in natural resource dependent s[illegible]eties of sub-Saharan Africa, and land managers in developing countries are facing rapid and erratic modification of the bio-physical environment driven by a range of human and natural factors.

In 1997 a National Environmental Action Plan (NEAP) for Senegal spoke of an environmental and social crisis accelerated by the degradation of natural resources, a decline in agricultural productivity, a rapid population growth, and a general deterioration in the quality of life in Senegal (MEPN/CONSERE 1997). The National Action Program to Combat Desertification casts a similar scenario of environmental deterioration: 'the process of natural resource degradation seems to be increasing and accelerating under the combined effect of a worsening climate and human pressures' (MEPN/CONSERE 1998).

This perception continues today within United Nations Convention to Combat Desertification (UNCCD) and other government and donor reports (MEPN/CONSERE

2004, USAID 2008a). It is difficult to dispute that countries in West Africa, including Senegal, are experiencing rapid change at climatic, environmental, agricultural, demographic, political, and socio-economic levels. Senegal's population has grown tenfold since 1900 placing unprecedented pressure on its limited land resources while agricultural statistics show only modest increases in the primary food crops in recent decades (Bucknall and Livingston 1997), but estimating the current state of environment and projecting the outcomes are still very difficult.

An example of this is demonstrated with rainfall data. Studies indicate that the West African Sahel has experienced one of the most substantial and sustained declines in rainfall in the world (Nicholson 2000). 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). Future patterns are still rather uncertain with many models projecting rainfall trends showing an overall drying of Senegal with high inter annual variability (Boko et al. 2007), but there is no clear cut answer as to whether the climate in Senegal will become more arid or humid (Christensen et al. 2007).

A few studies have examined the state of Senegal's natural resources over time, but are limited to local or sub-national scales (Tappan et al. 2000, Gonzalez 2001, Tappan et al. 2004, Tappan and McGahuey 2007, Mbow et al. 2008). The rates and magnitudes of change are still very much debated, including whether these changes are related to short-term climate perturbations or longer-term anthropogenic impacts (Wardlaw, Hulme and Stuck 1996, Nicholson 2000, Diouf and Lambin 2001, Mbow et al. 2008).

Charcoal in Senegal – Production and Management

In Senegal, as in most parts of Sub-Saharan Africa, both rural and urban households are largely dependent on fuelwood (charcoal and firewood) for their energy needs (Ribot 1995, Girard 2002, Post and Snel 2003). Over the last 20 years in Senegal, a change is being documented by scientists, government officials and local people – fuelwood is becoming scarcer around charcoal consuming urban centers causing charcoal producers to travel greater distances away from these centers to collect charcoal (Post and Snel 2003). In 1985, nearly all of Senegal had adequate forest cover allowing for most regions to produce and export charcoal. As population increased and demand for charcoal grew in urban centers, particularly around Dakar, forest resources became degraded to the point where there were too few trees in existence to produce charcoal (Tappan et al. 2004). In present day Senegal, government quotas allow for the production of charcoal to take place in only two regions: Tambacounda and Kolda.

Study Area – Description of the Environment

The Tambacounda region of Senegal (Figure 1-1) produces much of the country's charcoal for urban consumers (Ribot 1995, Manga 2005). The area belongs to the West Sudanian Savanna ecoregion (WWF 1998). This ecoregion, stretches across West Africa just south of the Sahel, from Senegal and Gambia to the eastern border of Nigeria. Vegetation in the region is mapped as undifferentiated woodland and is comprised of woody trees (typically Combretaceae and Terminalia species) normally under 10m and an understory of long grasses, locally known as "elephant grass", shrubs and herbs. The woodland is also mixed with areas of agricultural parkland and thin sections of forest near to stream beds (White 1983, Wood et al. 2004).

The region is heavily used by local populations and principally threatened by agricultural, grazing, cutting of trees and bushes for fuelwood and charcoal, and from wild fires (Wood et al. 2004). The ecoregion also has pronounced seasonality and interannual variability of productivity resulting from climate variations, making it a challenge to distinguish changes related to climatic variations from those resulting from human impacts. Climate variability is a further threat, exacerbating human pressures, as the ability of the ecosystem to recover from human utilization is reduced when there is limited rainfall. The climate is characterized by a rainy season from June to October and a dry season from November to May (Wood et al. 2004).

How is Charcoal Produced?

Charcoal has been produced in the Tambacounda region for at least 50 years (Manga 2005). The method in which charcoal is produced has remained relatively constant over time. Charcoal is produced in a three step process. First select trees are cut. Second, the cut wood is stacked into a kiln and covered with a layer of grass and sand. Finally, the kiln is lit and left to burn slowly for up to three weeks. At this point the charcoal is ready to be collected into bags and sold either to charcoal merchants or individually along the roadside.

Kiln Preparation and the Harvesting of Trees

Charcoal is produced in a kiln (Figure 1-2b). Kiln locations require enormous amounts of work to prepare. The ground directly underneath the kiln must be loosened approximately 12 inches below the surface. This is a large amount of work because the laterite soil in the region is very hard and rocky. Because of the workload associated with preparing a kiln for charcoal production, many charcoal producers prefer to use the

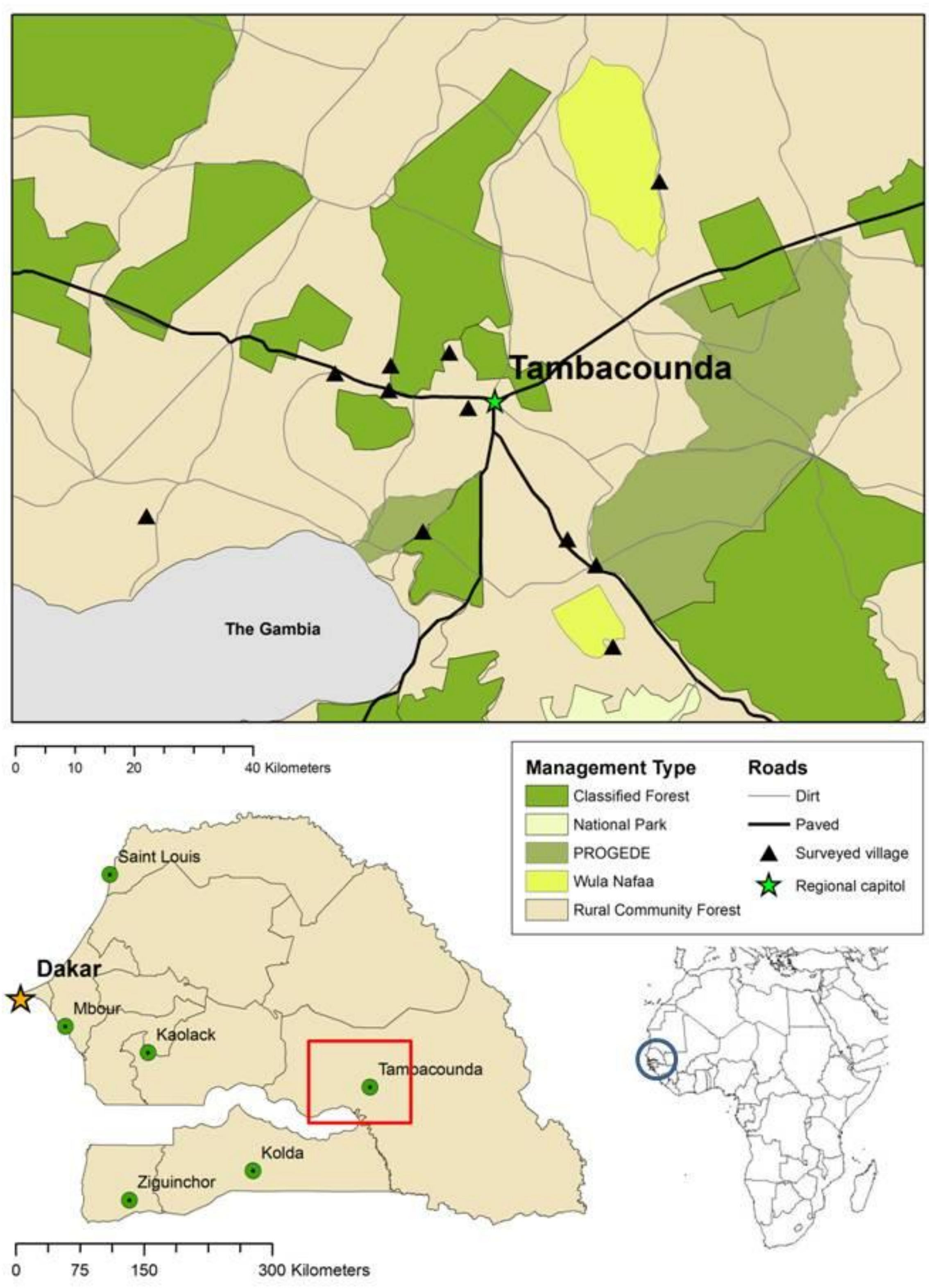

Figure 1-1 - Location of Senegal on the continent of Africa (circled in blue). Location of Tambacounda study area (red box).

same location repeatedly bringing wood from up to 500 meters away. After the first kiln is prepared, during subsequent periods of charcoal production, the charcoal producers must only do a quick tilling of the soil in order for it to be ready for a new kiln to be constructed in the same location (Manga 2005, Bah 2007) .

Once the kiln site is prepared, or often during preparation, charcoal workers harvest wood from the nearby forest. In the region, trees in the Combretaceae family (locally known as dooki in Pulaar) are preferred for the production of charcoal. This is also the most dominant family of trees in the woodland. Because a majority of the species are from the Combretaceae family the harvesting of wood for charcoal production selectively harvests the surrounding forest (Ribot 1990, Manga 2005). Experienced charcoal workers will harvest the trees at ground level to maximize the amount of wood collected, stimulate regeneration, and limit the potential impact from fire (further discussed in chapter 2). Kiln preparation and wood cutting takes between one to three months depending on the numbers of workers.

Building of the Kiln

Once a location is prepared and wood has been harvested, the cut wood is sorted by diameter and stacked next to the kiln site (Figure 1-2a). Once all of the wood is stacked the kiln will then be built (Figure 1-2b). In most locations a traditional method of stacking is used, while in PROGEDE or Wula Nafaa managed sites an alternative method using a chimney made of 4 welded together 50-gallon drums is required. Kilns can be built in as little as one day or more than a week, depending on the number of people working on the site.

After the wood is stacked the charcoal worker will cover the stack with leaves and grass that are both cut as nearby to the kiln as possible. Dirt from a ring around the outside of the kiln is then used to seal the kiln.

Carbonizing

Finally the kiln is lit through a hole in the top. After the wood in the center of the kiln catches fire the hole is sealed with small sticks, grass, and dirt. The kiln is then monitored numerous times during each day for 10-21 days while it is carbonizing (Figure 1-2c). A series of vents are present in each kiln allowing for proper ventilation and continued burning. If the kiln is not vented properly it can either smother the fire before carbonization takes place or burn too hot, causing the kiln to fully ignite, leaving only a pile of ashes.

The kiln is finished carbonizing when it stops smoking and cools. At this point, the charcoal worker begins raking and separating the dirt and debris from the newly formed charcoal (Figure 1-2d). Between one to two weeks is spent in this process with the time taken again varying depending on the size of the team.

At this point, charcoal is placed in sacks each weighing approximately 50 kg (110 lbs). These sacks are either collected by trucks hired by charcoal merchants or taken 1-5 at a time by donkey cart to the charcoal worker's village. Sacks of charcoal are also sold road-side or handled by charcoal merchants who collect the charcoal, load it into large trucks and transport 250-350 sacks at a time to urban centers, most frequently Dakar.

Senegal Forest Management

In the late 1980's, a wave of charcoal production began to sweep through the woodlands of Tambacounda. Currently this region accounts for over 50% of the official charcoal quota (PROGEDE 2007). The influx of charcoal production has been thought to cause severe degradation of over half of the wooded savannah and significantly altering the biology and habitat quality (Tappan et al. 2004).

Within the charcoal producing regions of Senegal a network of three government-regulated and one traditional forest management types are practiced; Rural Community forests (RCF), Classified Forests (CF), co-managed forests (CMF), and a large national park (NP). The sustainable management (forest extraction has been conducted in a way that allows its inherent regeneration and continued ongoing supply) of the forest resource is the ultimate goal within each zone. For complete regeneration to occur, harvested land should be left idle for at least 8 years (Arbonnier 1990). The varying management practices implemented in Senegal take this into account, but short of fencing off charcoal areas for regrowth it is nearly impossible to isolate harvested areas from any disturbance (human or natural) during the entire 8 year regeneration period.

At many sites a vast majority of the preferred species of a harvestable size are collected for charcoal production. Differing management plans call for selective logging to take place, leaving non-regenerating species and harvesting two-thirds of other species in the area, but in many instances well over 75% of the wood is harvested for charcoal production (USAID 2007, Bah 2007, PROGEDE 2007).

In the community regulated landscape, wood is intensely harvested for charcoal production in very compact intense zones, closer to clear cutting (Manga 2005). On land managed by the Senegalese government and international development project, selective harvesting is required along with the use of the Casamance kiln, an alternative to the

Figure 1-2 - Steps in charcoal production. A) Collection of fuel for carbonization; B) Piling of wood into kiln structure; C) Lit kiln actively carbonizing wood; D) Removal of charcoal from outside of kiln.

traditional kiln used outside these managed area. The Casamance kiln is believed more efficiently carbonize the wood therefore increasing the output of the kiln by 10 – 30% (Girard 2002, Kammen and Lew 2005). This increase in efficiency combined with selective logging could result in a slightly larger extraction area, but a lesser degree of environmental impact. Areas classified as Classified Forest are theoretically off limits to charcoal production, but are often times used for charcoal production (Ribot 1995). These areas exhibit the same extraction methods as the community regulated region. In national parks, no charcoal harvesting or production is allowed (Table 1-2).

Rural Community Forest

Rural Community Forests are all areas that fall out of government managed land. Most of the land is agricultural with some stretches of woodland and forests along river beds. Although this area is theoretically owned and controlled by local communities, more specifically by rural councils, the reality is that the harvesting of wood is controlled and enforced by the Senegalese Forest Service.

By law, local community leaders must grant access to individuals to farm, graze, or remove timber from the areas. On paper they have this authority, but in reality a coalition between the charcoal patrons and the Forest Service force the hand of the local leaders and control who and where wood can be harvested for charcoal production. A thorough discussion of the Senegalese Decentralization policy can be found in Ribot (1999), Faye (2006a) and Ribot (2009).

Table 1-2 – Charcoal harvesting and production methods

	Charcoal harvesting – theoretical	Charcoal harvesting - actual-based on field work	Carbonization method
National Park (NP)	None allowed	Very little	n/a
Classified Forest (CF)	None allowed	Some – land clearing	Traditional kiln
Co-Managed Forest (CMF)	Selective harvest (~60-75% cut)	Selective harvest (~60-75% cut)	Casamance kiln
Rural Community Forest (RCF)	Land clearing	Land clearing	Traditional kiln

Before 1998, forests in Senegal were managed solely by the central government, i.e. Forest Service. Rural communities played no part in determining what areas in their jurisdiction could be harvested and the amount of wood that could be extracted. This power was controlled directly by the Forest Service and indirectly by the charcoal patrons whose influence could persuade the Forest Service.

This changed with Senegal's 1996 Decentralization Law that gave rural communities authority over the extraction of forest goods falling within their geographic boundaries. The 1998 code additionally placed a requirement on the Forest Service to gain permission from the rural council before any commercial production could take place in the forest and who would have access to produce (Ribot 2009). To date, the Forest Service continues to allocate access to the local land via the old methods.

Classified Forests

Classified Forests are present in all regions of Senegal (Table 1-3). Between 1932 and 1960 under French colonial rule, 87 forest areas were classified. Between independence in 1960 and present day over 120 additional forests were classified bring the present day total to around 213 forests (MEPN/CONSERE 1998). These forests can be grouped in three categories: Fuelwood reserves, soil conservation areas and "dense vegetation" (focused on the protection of vegetation and biodiversity). The limits of these forest areas are not well defined and control measures are insufficient to prevent illegal exploitation (USAID 2008b). These factors, combined with insufficient rainfall in some areas have led to severe degradation of vegetation in some classified forests (Tappan et al. 2004).

Populations in the buffer zones of these classified forests have use rights covered by the previously discussed 1996 Decentralization Law and 1998 code. Under the decentralization framework, rural councils can approach the Forest Service regarding the joint management of the adjacent classified forest. The Forest Service and rural councils then must create management plans based on key issues such as management objectives and the determination of zones for specific uses (e.g., charcoal, firewood, wood for construction or furniture and non-timber products) or for outright protection.

Table 1-3 - Classified Areas of Senegal

Region	**Region surface area (ha)**	**Number of classified forests**	**Area of classified forests (ha)**
Dakar	55,000	10	6,064
Diourbel	435,900	0	0
Fatick	793,500	15	187,676
Kaolack	1,601,100	23	528,240
Kolda	2,101,100	26	505,383
Louga	2,918,800	19	1,216,688
St. Louis	4,412,700	61	1,889,432
Tambacounda	5,960,200	17	1,635,819
Thies	660,100	13	98,926
Ziguinchor	733,900	29	119,420
TOTAL	**19,672,200**	**213**	**6,237,648**

Source - Plan d'Action Forestier du Sénégal, 1993

Co-managed Forests

Because of the Tambacounda region's importance to the countries charcoal trade it has become the focal point of the international forestry and natural resource management projects including the World Bank funded Sustainable and Participatory Energy Management Project (le 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. One of the main objectives of both programs is to increase the involvement of rural communities in the active management of their natural resources. The decentralization laws and forest code were used as starting points for both programs hoping to address some of the difficulties rural communities had faced in attempting to create natural resource management plans.

PROGEDE Overview

PROGEDE was initiated by the Senegal Forest Service in 1997 to address the perceived negative impacts of charcoal production on the forest cover, biodiversity, degradation of the soil, impoverishment of rural areas, and the acceleration of the rural exodus of the Tambacounda and Kolda regions. This World Bank funded project focuses on 1) helping rural communities develop and implement participatory natural resource management plans; 2) the promotion of inter-fuel substitution and improved stoves; and 3) capacity improvement activities to the rural communities involved in the management of the forests (PROGEDE 2005).

Regarding charcoal extraction, rural communities work with the PROGEDE/Forest Service officials to develop and implement management plans for the utilization of the protected forest. Focus is put on income generation for the rural communities via taxes and fees charged to individuals or groups wishing to produce charcoal in the PROGEDE managed forest. In most forests, management zones were created specifically for charcoal, grazing, timber extraction, etc. Rotation periods were also established allowing areas previously harvested a recovery period before being re-harvested. Additionally, significant efforts were made to create fire breaks throughout the forest.

A 2006 World Bank report highlights the sustainable community-management of 378,161 ha and the creation of a sustainable incremental income generation base of approximately $40,000 per participating village (PROGEDE 2005).

Wula Nafaa Overview

Initiated in 2003, the US Agency for International Development (USAID)/Senegal funded Wula Nafaa project focused on a similar goal as PROGEDE relating to the improved and decentralized management of forests in Eastern Senegal.

The objective of Wula Nafaa was to “contribute to the fight against poverty and to the rational, sustainable management of natural resources in targeted zones.” The central idea was to get communities to effectively exercise their rights to utilize natural resources as stipulated by the Senegalese decentralization law. Once local participants began to generate income from these resources then there would be more incentives for local communities to sustainably use and manage their natural resources (USAID 2008a).

In 2008, USAID/Senegal reported that the project resulted in the preparation and adoption of co-management plans between local communities and the Forest Service for dozens of forests in three regions (Tambacounda, Kolda and Ziguinchor) covering 350,000 hectares (USAID 2008a).

Research Goals and Objectives

This research uses a combination of remote sensing, forestry surveys, semi-structured interviews to assess the effects of forest management types on forest structure, tree species composition and forest regeneration around charcoal production sites. To accomplish this, the following set of questions and hypotheses are addressed:

How does charcoal production affect forest structure and species composition?

Hypothesis 1: Forest structure and tree species composition and richness will be less in areas of charcoal production when compared to areas of no production.

What are the factors that influence forest composition and structure after charcoal production?

Hypothesis 2: Forest composition and structure are positively correlated with proximity to villages, roads and park edges.

Do regeneration rates around charcoal production areas differ depending on forest management type?

Hypothesis 3: Forest management type will result in no significant variation in regeneration rates near charcoal production sites.

Understanding the effect of varying types of forest management on regeneration after charcoal production is vital to the development of forestry and energy policy in Senegal and throughout Sub-Saharan Africa. A method integrating freely available remote sensing data with detailed field surveys will provide forestry officials with the capability to efficiently assess and monitor regeneration within forest management types.

Dissertation Organization

Because the impacts of the harvesting of wood for charcoal production cannot be understood from a single angle, a multidisciplinary approach was developed to untangle some of the questions related to how extraction affects the forest and why varying management styles may or may not have an impact on this. This research is organized moving from a local scale social and ecological analysis to first understand the details of the potential impacts to a broader scale analysis in an attempt to extrapolate the local results to a regional level.

In Chapter 2 a case study was performed in nine villages within the study area. This chapter uses data collected through 36 semi-structured interviews of forest users in the Tambacounda study area to answer questions related to how the immediate forest environment is used, how it is changing, and the local impression of forest management types. Chapter 3 uses data collected from 77 forestry surveys to assess the state of the forests in the study area comparing harvested and non-harvested plots from four different forest management types. Detailed data on species richness and size-class distributions are used to assess forest diversity, degradation and regeneration rates. In Chapter 4 the utility of the Multiangle Imaging SpectroRadiometer (MISR) satellite in detecting subtle changes in forest cover is assessed over a three year period from 2001 to 2003. The chapter includes an extensive assessment of the capabilities of MISR to classify woodland cover types in the study area. In Chapter 5 the local analysis from Chapters 2 and 3 are combined with the broader scale remote sensing analysis of Chapter 4 to validate MISR's utility in detecting changes in woodland cover due to harvesting for charcoal production. Chapter 6 draws conclusions from local ecological knowledge, ecological surveys and remote sensing data regarding the stated research objectives and discusses how the research can be expanded on in the future to better inform forest management.

Chapters 2 through 5 have been written so that they may stand alone for publication in separate journals; each with an introduction, methods, results, and discussion. Chapter 4 has already been published in the October 2009 issue of the International Journal for Remote Sensing.

Chapter 2 - Local Perceptions of Forest Use, Change and Management – A Case Study in the Tambacounda Region of Senegal

Abstract

The addition of local ecological knowledge provides insights into ecological processes and adds value to ecosystem assessments and management plans. This chapter uses local ecological knowledge elicited through semi-structured interviews in nine villages from the Tambacounda region of Senegal to derive information about how the local forest is used, the processes that are driving forest change and the local impressions of forest management types. Based on the responses, forests are vital parts of the daily life supplying people with fuel, food for livestock and supplemental income. Wood cutting for timber extraction and charcoal production and fire are believed to drive much of the change in forests. Charcoal production is particularly divisive, people acknowledge both the positive (added income) and negative (increased negative ecological pressure) on the surrounding forests. Despite the pressures, forests are believed to regenerate after being cut for the production of charcoal. Forestry laws, created in the late 1990s aimed at decentralizing forest management, have not taken root. In both government and co-managed forests, people in the study feel that forest management is still the sole function of the Senegalese Forest Service. Illegal and legal harvesting of wood is said to occur in all forest management types creating a similar ecological environment regardless of government or co-management.

Introduction

Local ecological knowledge has long been recognized as providing far-reaching insights into ecological processes and in recent years has received increasing attention by academics and policy professionals when performing ecosystem assessments and drafting ecosystem management plans (Ellis and Swift 1988, Adams and McShane 1992, Heyd 1995, Berkes 1999, Illius and O'Connor 1999, Huntington 2000, Sullivan and Rohde 2002, Gadgil et al. 2003, Davis 2005, Fabricius, Scholes and Cundill 2006). Local societies harbor important information on valuable plants, vegetation dynamics, and land use practices that can yield insights into ecological processes and services that can then be used to help improve ecosystem management (Huntington 2000, Lykke 2000, Wezel and Lykke 2006, Roba and Oba 2008).

Local ecological knowledge takes a fine-scale, context-specific perspective (Berkes and Folke 2002) adding value to wider-scale conservation and management plans (Wezel and Lykke 2006). It can also increases the probability of success for management strategies (Ellis and Swift 1988), because people are often times more likely to abide by regulations influenced by themselves than those forced on societies from outside.

Many studies concerning local ecological knowledge have focused primarily on species, their distribution, techniques to harvest them, and their medicinal qualities (Trosper 2002, Lobe and Berkes 2004, Moller et al. 2004, Kaschula, Twine and Scholes 2005). In West Africa, local ecological knowledge has been used to understand the extent of recent vegetation changes (Wezel and Haigis 2000, Gonzalez 2001, Lykke, Kristensen and Ganaba 2004), but few studies have focused on the processes that drive changes and how different management types might influence these processes.

In this chapter I elicited local ecological knowledge to derive information about how the local forest is used, the processes that are driving forest change and the local impressions of forest management practices. To accomplish this, I collected and analyzed data from semi-structured interviews in nine villages in the Tambacounda Region of Senegal. This analysis of local ecological knowledge is used to supplement ecological and remote sensing data analysis (chapters 3 – 5) to improve the understanding of the effects of forest management and drivers of change in the study area. An identification of the most valuable land use practices, drivers of change, and management perceptions can provide a focus for future management strategies that allow a more sustainable use of forest resources and a better conservation of ecosystems.

Preface/Study Area

The research was carried out in nine villages in the Tambacounda region of Senegal. The description of the study area's ethnic composition, languages, and land use practices are based on the recent study as well as three years I spent living in Fulani and Mandinka villages while serving as a Peace Corps volunteer in the ecoregion.

Three ethnic groups dominate this region, Fulani, Wolof, and Mandinka. Small populations of the Bassari ethnic group are also found in a handful of villages. Villages with populations less than 300 are often dominated by one ethnic group with larger towns and villages in the region a mixture of ethnic groups. All ethnic groups depend heavily on agriculture as a major source of income. Ethnicities differ slightly in land use practices with Fulani communities associated with livestock and grazing activities while Wolof and Mandinka communities depend on agriculture as the primary source of income. In the following description I will describe the land use practices associated with each ethnicity and those shared across ethnicities.

Although the Fulani are traditionally known as nomadic or semi-nomadic pastoralists herding cattle, goats and sheep, many now farm (growing millet, peanuts for consumption and sale, and cotton as a cash crop) and live in villages or towns. Three sub-groups of Fulani are found in the region, dominated by the Fula Jeeri with smaller populations of Tukulor and Fula Jalon sub-groups. Major differences among the Fulani sub-groups arise from the geographic region of origin[1] and differences in the dialect of Pulaar spoken.

Both the Mandinka and Wolof ethnic groups are traditionally more sedentary than the Fulani and are known as skilled farmers; growing peanuts, millet and small amounts of rice near to larger rivers as staple crops. Most crops are grown for subsistence farming with small amounts sold at a local market. Cotton and peanut are also grown as cash crops. Most families also raise goats, sheep, bees, or poultry to supplement their diet and/or income.

A typical village in the region, Fulani[2], Mandinka, or Wolof, consists of people living in compounds grouped around a central village point, usually marked by a large tree such as a baobob, silk cotton, or African mahogany (Figure 2-1). A platform used

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[1] Fula Jeeri are indigenous to the Tambacounda region and make up the largest portion of the Fulani population. The Tukulor are a sub-group who traditionally farmed along the banks of the Senegal River and migrated to the Tambacounda region over the past 100 years. The Fula Jalon traditionally lived in the mountains of Guinea to the south, but some men seasonally migrate north to Senegal to participate in the harvesting of trees for the production of charcoal Lewis, M. P. 2009. *Ethnologue: Languages of the World, Sixteenth edition*. Dallas, Texas: SIL International..

[2] Small Fulani villages are more likely to be more isolated than small Mandinka or Wolof villages. This is most likely a result of their historical desire to remain separate from agricultural Wolof and Mandinka villages. These villages are noticeably lower on the economic ladder (lacking covered wells, few individuals with formal educations and a higher percentage of thatched-roof huts) than less isolated villages in the region.

for public gatherings is usually located beneath the tree. A mosque is often located near to the square. The compounds contain a number of small houses made of clay bricks or mud with thatch or corrugate roofs. Compounds are enclosed by a 1.5-2.5m fence made of elephant grass (Figure 2-2). During times not occupied by planting or harvesting much time is dedicated to maintaining the compound (repairing roofs, fences, walls, etc.). Many villages also have a community garden, most often managed by a group of women. These gardens generally produce a variety of vegetables including onions, cassava, lettuce, tomatoes, hot peppers, carrots, eggplant and/or potatoes. Vegetables and fruits that are not grown in the village are purchased at a local weekly market and some fruits are gathered from the forest.

Planting of crops coincides with the beginning of the rainy season usually in mid-June while harvesting time depends on the crop, but usually begins towards the end of the rainy season in September and could continue until February. During planting and harvesting seasons people work in the fields during the cooler periods of the day, between approximately 6 AM to 11 AM and then again between 4 PM and 7 PM. At other times, the men often temporarily migrate to the regional capital of Tambacounda or national capital of Dakar (approximately 500 km from Tambacounda) to look for part-time work to supplement their incomes. If they choose not to migrate, men often work in the woodlands harvesting and/or collecting timber or deadwood for sale or harvesting trees for the production and sale of charcoal (although this work is dominated by Fulani men from Fuuta Djallon). Additionally, many Fulani men migrate from Guinea, working in the region as laborers in the charcoal trade.

Land immediately surrounding villages (usually less then 1km from the village edge) is used for farming (Figure 2-3). Trees and shrubs are scattered throughout the landscape, but most of the arable land is used for cultivation of peanuts, cotton, or millet. Most land outside of agricultural plots is used for grazing. Grazing of cattle, sheep and goats occurs throughout the region but varies in intensity from village to village (Figure 2-4).

The words forest and bush (laɗeh in Pulaar, ñaakoo in Mandinka, alaa in Wolof) are referred to interchangeably as land outside of the village not used for agriculture. Forests area depended on by the local population for cattle grazing, hunting, collecting firewood, deadwood, timber and non-timber forest products such as fruit, medicinal plants, and honey. Fuelwood used for cooking is the sole source of cooking energy for local populations. Local populations do not depend on any other source of energy because wood is accessible and free.

The abundance of wood resources in the region has made the forest an important source of supplement income for many in the area. Timber is harvested, deadwood is collected, and charcoal is produced and sold along the road or to large merchants who transport it for sale to Dakar. In the last 15 years this region has produced much of the country's charcoal for urban consumers (Ribot 1995, Manga 2005, PROGEDE 2007) and is currently one of two regions (Kolda being the other) in Senegal were it is legal to produce charcoal.

The cutting of any live tree is illegal and people wishing to produce charcoal must first obtain a permit from the Forest Service. Authority to actively manage and controlling access to all forests are the main points of tension between local villagers and the Forest Service. The forests are depended on by local people, but management authority is controlled mainly by the forestry department with some shared responsibilities distributed to local rural councils in the last 10 years.

Historically, village chiefs functioned as regulatory bodies implementing and enforcing laws and resolving conflicts among villages. In some areas, villages also had forestry chiefs responsible for the management of the forest adjacent to the forest (Thiaw and Ribot 2005). Throughout the 20th century, control of the forests was centralized in the Forest Service. Until 1998, no forestry codes in Senegal transferred management authority to local communities (Ribot 2001). When "participatory" codes were first put in place in 1993, there was hope that decentralization would allocate more power to local communities, but little changed (Kanté 2006). But in practice it did no (Ribot 1995). Up to 1998, charcoal merchants and their workers would arrive in a village accompanied by foresters and harvest wood without input from the rural councils or any other local leaders (Faye 2006b). This would often lead to conflicts between the local communities, foresters, and charcoal laborers and merchants since many villages were against the harvesting of wood for charcoal production around their villages because of the negative effects it had on the forest and the feeling that others were benefiting from the forest while they were not allowed.

The forest code of 1998 promised to change this by allocating power to the rural councils over the management of a forest pending an approved forest management plan. The law gave the council jurisdiction over the cutting of wood and required the Forest Service to obtain the signature of the president of the rural council before any commercial production (i.e. charcoal production) could take place in their forests. The code also gave the council the authority to decide who could produce in their forest. Finally, the law required a majority vote of the rural council approving production before anyone could produce in the Rural Community forests (Faye 2006).

Due to the area's importance to the country's charcoal trade and the 1998 forest code it became the focal point of 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. These projects used the new forest code as a foundation for the development of community managed forests (Figure 2-5). Components of the projects assisted local communities to develop management plans thus gaining authority to manage their Rural Community forests. These projects created seven co-managed forests in the region, but a large majority of the forests are still under official governmental control as classified forests or unofficial government control as Rural Community forests lacking community designed co-management plans.

Figure 2-1 - Satellite image of village highlighting village center/meeting area (red arrow) and an example of the perimeter of a typical compound (yellow arrow).

Figure 2-2 - Field outside of a traditional compound. Elephant grass fencing encompasses the compound with thatch- roofed huts.

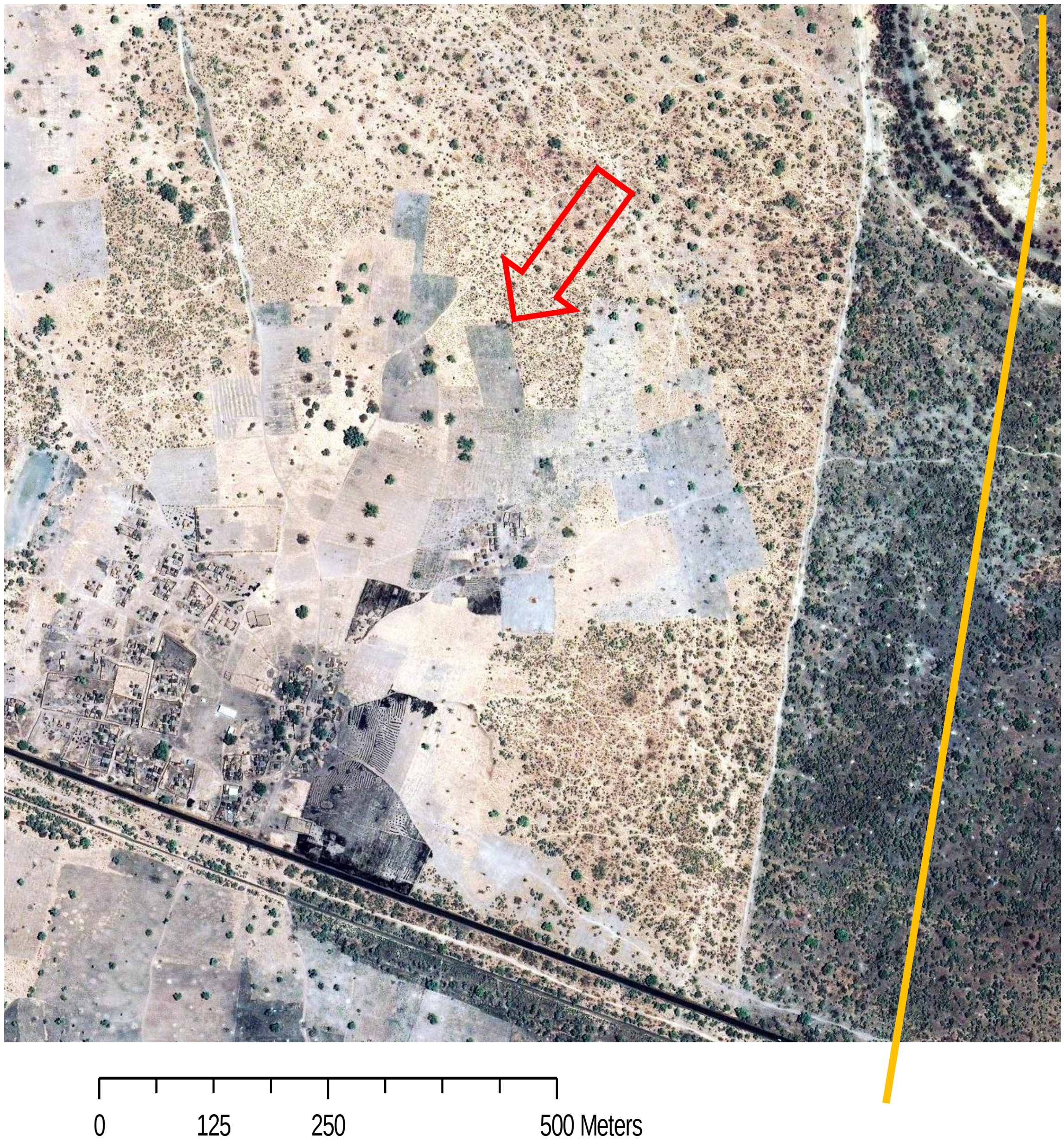

Figure 2-3 - Satellite image of landscape around village and leading up to the classified forest. The red arrow illustrates an example of the edge of a field approximately 1.5 km from the center of the village. The yellow line demarcates the edge of the adjacent Classified Forest. The area to the right of the line is inside the Classified Forest.

Figure 2-4 - Two Fulani boys herding sheep.

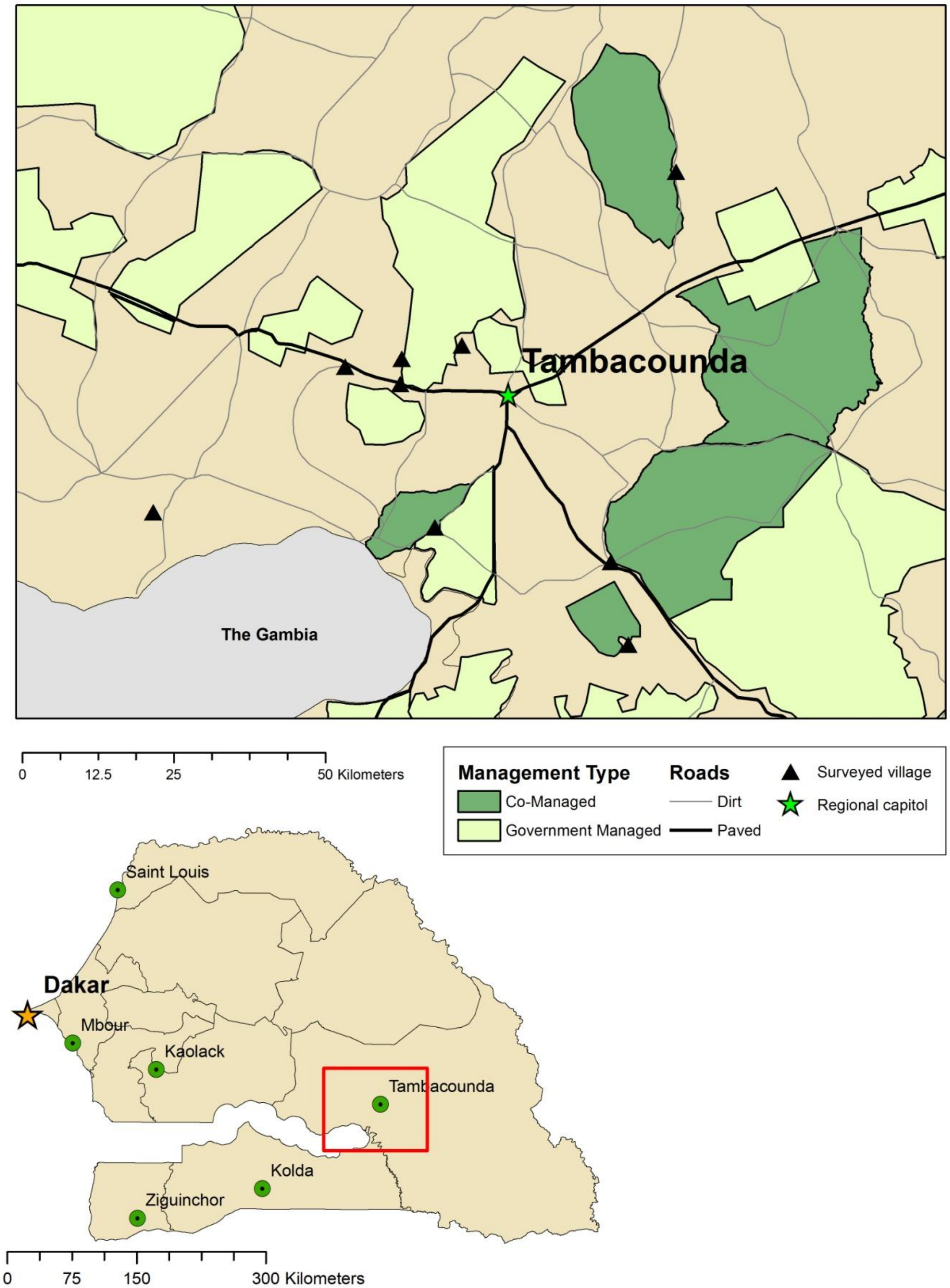

Figure 2-5 - The top map illustrates the locations of surveyed villages and government and co-managed forests. The bottom map shows the location of the study region (red box) to other large towns in Senegal.

Methods of Semi-Structured Interviews

In each village, upon arrival, we would hold a brief meeting with village elders, explaining who we were (that we were only students interested in learning about the local forest), why we were there and what we would be doing. We would present the village chief with a kilogram of cola nuts and sugar, who would then distribute the gift to each compound head. At this point the village chief identified a compound in which we could spend the length of our stay. Because we were a group of three researchers staying 3-4 days in each village, we contributed enough money and fresh produce to our local host compound to off-set the cost of our stay. Throughout our fieldwork we were never turned away from a village. In all villages we were given a hut to sleep in and provided with breakfast and dinner.

Semi-structured interviews were conducted in nine villages. Villages were identified via the random selection of previously know charcoal production points, generally one to ten kilometers from an old charcoal production point located in Rural Community forests, classified forests or co-managed forests. In total, 36 people were interviewed (Figure 2-6). Nine of the interviewees were identified by the village chief as someone who is very knowledgeable of the forest and harvesting for charcoal production. As discussed previously, nearly all of the people in the region who live in small villages, regardless of ethnicity, are farmers who supplement their income with activities in the forest. Individuals nominated for interview by the chief were often village elders and although they had a rich understanding of the forest and its uses, they frequently appeared to lack information on the present day condition of the forest and activities that went on in the forest. Because these individuals would create a highly skewed sample of respondents (they were often also friends of the village chief and/or possibly beholden to

	# Villages	# Interviews
Government managed	5	21
Co-managed	4	15
Total	9	36

Table 2-1 - Villages were classified into government managed (GM) forest or co-managed (CM) forest villages based. This classification was based on the designation of forests around each village. GM forests included Classified Forests and Rural Community Forests that did not have a government acknowledged management plan and CM forests included PROGEDE and Wula Nafaa supported forests. Semi-structured interviews were conducted in nine villages (five nearest to GM forests and four nearest to CM forests) and with 36 interviewees (21 in GM villages and 15 in CM villages; 11 in the village and 23 in the field).

him in some way) 25 of the interviews were conducted opportunistically in the forest en route to or while regeneration surveys were being conducted. This approach allowed for the targeting of individuals who were actively collecting fuelwood and/or in the process of harvesting wood for charcoal production.

Conditions for the each interview were attempted to be conserved from interview to interview. Interviews were carried out under two general conditions: within a person's compound or at the person's work in the forest. The first condition included meeting a person in his or her compound (home), speaking at a time convenient to them and not taking more than an hour of the person's time. The second condition included an opportunistic meeting in the field.

A digital recorder was used to record the entire conversation. Before initiating the interview, we asked permission to digitally record the interview. No one refused to be recorded. Discussions usually lasted approximately 40 minutes. Prior to beginning the interview, the interviewer stated that he received permission to record the interview, the date, time, location (in a village or in the forest), ethnicity of the interviewee, and forest type in which the interview was taken place, but each person was informed that their names or village's name would not be attached to a particular statement. If the interview was done opportunistically in the forest, the activity the interviewee was conducting immediately prior to the interview (cutting grass, cutting live wood, building a kiln, etc.) was noted.

Interviews were conducted by a Senegalese field assistant who has spent most of his life (28 years) in the region; only leaving to attend the University of Cheikh Anta Diop where he received a degree in linguistics. During the time of field work, he was living and working as a teacher in Kedougou, the regional capital of the Kedougou region. His native languages were Pulaar and Bassari, second Wolof and third Mandinka. He also spoke fluent French and English. Because of his exceptional language skills, each semi-structured interview was therefore conducted in the first language of the interviewee (Pulaar, Mandinka or Wolof) and later the same day translated into English.

An additional field assistant was hired to help perform forestry surveys and did not participate in conducting or translating the semi-structured interviews. This assistant was a Fulaani from The Gambia and had not previously visited any of the surveyed villages.

Although the semi-structured interviews ranged over topics in a flexible discussion, 8 questions (four leading questions each with a follow-up question) were used as a guide for the semi-structured interviews. Interviewees were allowed to give as little or as much information as they desired. In most instances, interviews conducted in the forest, away from the ears of other locals, were more free-flowing. The questions that guided each interview were as follows:

1. How is the forest around this village used?
    a. Does this degrade the forest?

2. Has the forest around this village changed over time?
    a. If so, how has it changed?
3. Is charcoal produced in the forest around this village?
    a. Does harvesting for charcoal production degrade the forest?
4. Who manages the forest around this village?
    a. Has this changed over time?

Afterwards, in the village setting and during our 3-4 days in the village, in order to have a sense of the social and economic status of the interviewees, we observed personal characteristics, including family size, the number of wives, types of illnesses for people who were sick, diet, and personal possessions. Also, we observed and noted the presence or absence of economic indicators including, horse, horse-cart, cement house, household member overseas, and television set. These indicators serve as a proxy for annual income. Finally, for each interview we noted a subjective impression of the quality of responses.

Because the issue of forest management and charcoal production is sensitive in the study region, some people appeared to shape answers concerning management strategies into something that we might want to hear. When this occurred we reiterated that we just wanted to hear what they think, not what they think will please us. The presence of outsiders made some interviewees noticeably nervous and appeared skeptical of our true intentions. In the village, when the chief or other villages knew they were talking with us, discussions were much more generic than discussions in the forest. Discussions in the forest appeared more frank and had more depth.

Importance of Forest to Local Users

Interviewees proved to be very knowledgeable about the surrounding forest. A single question usually opened up the conversation that continued for upwards of 45 minutes. People seemed genuinely concerned about the state of the environment surrounding their village and the overall state of the environment in the region.

When asked about the importance of the forest, all of the 36 respondents emphasized the importance of the forest in everyday life. All participants strongly expressed that the forest is an important component of their livelihoods. The forest is used for fuelwood for local consumption, the collection of non-timber forest products such as fruits and honey along with bark and sap for medical uses, grazing of livestock, timber and grass to make roofs, timber and charcoal.

Statements similar to this were heard in all villages regardless of the type of management around the village:

> "Many of our activities are done in the bush. We need the bush even more when there is a poor rainy season. If we have short rains we must try to make money from the bush. We cut deadwood and make charcoal. We do this only out of need.
>
> It is not only us rural people who depend on the bush, town dwellers need it too. They buy the deadwood and charcoal and use them for cooking. Gas is too expensive so they too are forced to - buy from us.
>
> If the rains are good, then we do not have to go to the bush as much, but only if the rainy season is good and we have enough harvest to feed our families. **Since we live here, we have nothing but the bush.**"

All respondents emphasized they use the forest out of necessity. Interviewees described the necessity to make some money so they can by rice, peanuts, or other food to survive. If given the choice, they would much prefer not to make the daily trips to the forest to collect forest products.

In many cases people expressed that the forest was used like a bank, although, generally more like a bank that only supplied money and received no reinvestment. People would draw from the forest savings every year in which they cannot produce enough of a gain from agriculture to buy staple products like rice and peanuts. If the agricultural yield is sufficient then they will not have to enter the forest to make charcoal or extract deadwood or timber for sale.

Within co-managed and government managed forest villages people used the forest for the same products (Fig 2.7). Interviewees within each forest management type knew of legal and illegal activities occurring on the daily basis in the forest. Activity within the co-managed forests appeared to be less than in the government managed forests, but harvesting of products such as honey, bark, roots, and timber was observed during field interviews and forestry surveys. The after effects of charcoal production and current charcoal production were also observed in both management types. Current charcoal preparation and/or active kilns were also found in all management zones and around all villages.

Every interviewee mentioned that the forest was an important source of energy for the people in the village. Eight of the nine villages had no access to electricity, and the single electrified village had very minimal access in only a handful of government


Figure 2-6 - Typical interview conducted in the forest with a local charcoal producer.

offices, businesses, and a few rooms in the local middle school. Gas was mentioned as too expensive and very difficult to find reliably. These factors make fuelwood the dominate source of cooking energy in the village. Charcoal is occasionally used in small quantities for the preparation of tea.

> "Most people in this area take something from the forest. Some make charcoal. Some sell deadwood for sale. Some people cut live trees for timber. These are very sensitive subject for us. We will listen to the government's ideas. We know the forest is degrading, but we need to do this so we can make money. We have no choice. We need to make money to survive."

In two of the four villages near to co-managed forests interviewees mentioned that some fruit trees are still present in the forest, while interviewees from five of seven villages near to classified forests mentioned that fruit collection was no longer possible. Field observations confirmed that fruit trees were not abundant in any forest, but trees such as Ziziphus Mauritania (an acacia species producing small round edible fruits) were found in the woodlands near to all villages (discussed further in Chapter 3).

Grazing was also mentioned as an important forest output in all villages and by 28 of the 36 interviewees. The Fulaani ethnic group was most often noted as the people who used the forest for these purposes. Livestock (cattle, sheep or goats) or the presence of livestock was observed in all forest management types.

Income generation was mentioned in all villages and by 32 of 36 interviewees. Income generation included collecting deadwood for sale, producing charcoal, and harvesting timber and non-timber products for sale. The collection and sale of deadwood was mentioned as an important source of income for 15 of 36 interviewees and in seven of nine villages. When mentioned, it was referred to as a way to supplement a family's income because of a poor agricultural yield. Deadwood[3]collection was more important for people near to GM then to PROGEDE or WN managed forests (14 of the 21 respondents and four of five villages).

Charcoal production[4] was also a very important source of income for all villages and was mentioned as a source of income by 32 of 36 interviewees. In villages near to government managed forests people usually stated that they themselves did not make charcoal, but know of people in the past and/or present that made charcoal near to the village. This was done because the harvesting of wood for charcoal production is illegal in many government managed forests. 13 of 15 participants from the co-managed forests mentioned income generation (for the individual and community) via charcoal production as a primary use of the forest.

The harvesting of timber for sale in neighboring large towns was mentioned in eight of nine villages and by 30 of 36 respondents. Whenever it was mentioned it was always followed by a statement acknowledging that it is illegal and that it is not done by people from the village, but by carpenters, or people working for carpenters, from larger

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[3] In many cases deadwood is something that is created by people, not wood that is found dead in the forest.
The word for deadwood, when translated from the local languages, is closer to dry wood (*kaina laiɗeh* in Pulaar, *ndeh looninola* in Mandinka, and *tahani mata* in Wolof) than deadwood. Generally speaking, when collecting firewood, people will go to the bush, cut or lop a tree and then leave it for a period of time to dry, thus becoming dry wood. This is done because dry wood is lighter and easier to transport than wet wood (*sopa laiɗeh* in Pulaar literally meaning cut wood). Additionally this limits the amount space a family needs use for the storage of firewood.
Trees that have been cut or have fallen due to illness or other means, are cut in the forest and brought to the village piece-by-piece in donkey carts or carried on top of the head. Often times, timber species such as dooki and bani are killed either by digging deep enough to expose the roots at the base of the trunk and either chopping or burning the roots to kill the tree or by chopping deep into the trunk of the tree on two sides (Fig 2.9). Trees are left standing until they are dead. Once the tree has lost all of its leaves or falls over on its own the timber harvesters will come to fell it and chop it into pieces for sale.
[4] Refer to chapter 1 for a complete discussion of how charcoal is produced.

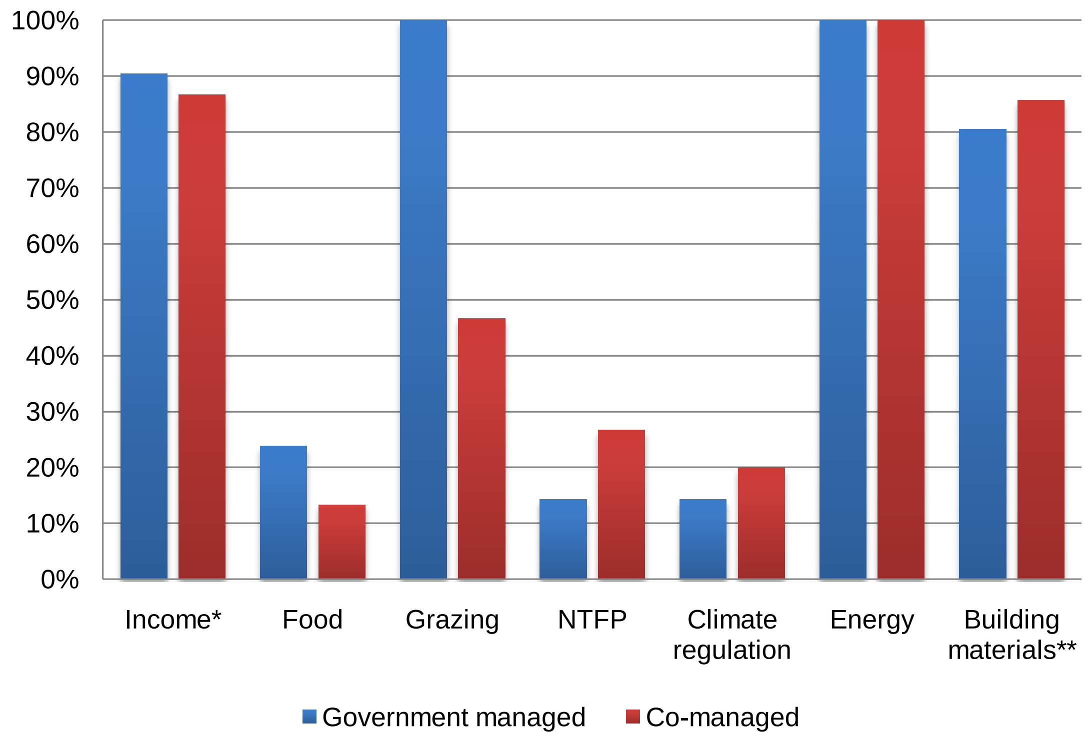

Figure 2-7 - Percentage of interviewees stating the above variables of forest services and uses within government and co-managed types. In most cases respondents listed more than one use/service of the forest. The results are not prioritized. *includes the collection and selling of deadwood, charcoal production, timber, and NTFP (non-timber forest products). **includes the collection of grass, pole timber, and soil for the building and repair of houses and fencing.

towns (most often citing Tambacounda). People cutting live trees for timber were observed around by us in seven of nine villages. Stumps of large trees were observed around all villages regardless of forest management type.

In addition to the physical products the forest provides, many individuals also expressed that the trees and forest are very important for climate regulation. In 6 instances interviewees made direct reference to local climate and rainfall. It is a common belief among local people that large trees attract rain, so if large trees are abundant, rain will be plentiful, tree regeneration good, and vegetation dense. If on the contrary, trees

a)  b) 

c)

Figure 2-8 – Examples of how large trees (this photo is of a Pterocarpus erinaceus) are partially cut and left to dry (photos a and b) before being felled and cut into smaller pieces (photo c) for timber extraction.

are logged, then rain becomes deficient and trees sparse. According to most people, low rainfall of the last 20 to 30 years is a major reason for vegetation changes, but the vegetation changes also reinforce the poor rainfall.

Is the forest changing and what is causing this change?

Nearly every respondent (35 of 36) in both forest types acknowledged that the forest around them was degrading. The drivers of change (fire, grazing, charcoal activity, deadwood collection, timber cutting and clearing for agriculture) were the same within co-managed and government managed forests (Figure 2-9).

When questions were asked about the previous status of the forest interviewees would talk about the past when large trees like *Pterocarpus erinaceus*, *Adansonia digitata* and *Cordyla pinnata* were abundant; times when antelopes and other wildlife were present; times when it wasn't safe to venture into the forest because of the abundance of predators. Statements such as this were common:

> "When we were young, we dare not travel far from the village because we know there were dangerous animals in the bush like lions and buffalo. Now they are no longer here. No one is scared of the bush anymore. There are no animals. I even want to say that the bush has disappeared. What we have now cannot be truly called the bush. This is nothing. This is no longer the bush[5]."

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[5] The image an adult in the village has of the forest is often much different than the one they had as a child or teenager. Children are often told stories of spirits and dangerous animals living in the forest that make it a terrifying environment. Generally, as people grow older, they lose this fear. The decreases in wildlife populations might be at least in part, due to this loss of fear. Additionally, some people in the study area are born in more forested areas and might be drawing comparisons between their place of birth and present location.

Interviewees also spoke of the lack of large, harder wood trees in the current forest. In the past, these trees were abundant producing lots of shade, fodder for livestock, timber for roofs, and fruit. Presently, people felt that most of these were missing from surrounding government and co-managed forests. There was an abundance of smaller trees that re-grew well, but the bush lacked the larger trees that do not regrow after cutting. A point reiterated by nearly all of the respondents (33 of 36) was that people know which trees can regrow (mainly the Combretum species) after cutting and which species die. Timber harvesters from outside the community were blamed in many cases for the decline of large species.

> "You can easily see that lots of big trees are disappearing – bani, duuki, kelleyh. Another tree that we used to use to make the roofs of houses, much like cane that can be up to 10 meters long and we used to make flutes out of the smaller portions of it, but it is no longer here. It is those who cut the trees for timber who reduce the forest." – Statement made by a person living near to co-managed forests.
>
> "Kahi, bani, duuki, bori – carpenters cut these trees not charcoal workers. They cut these trees to make beds and chairs to sell in town. We (charcoal workers) see them in the bush all the time. We cut trees we know will regrow like dooki gorko. We do this hoping they will regrow so we can make charcoal here again. If you cut a tree that you know does not regrow you are killing the forest. It is those who cut those trees who hurt the forest to make beds and doors. Charcoal makers aren't cutting these trees." – Statement made by a person living near to government managed forests.

The cutting of trees for timber (Figure 2-8), as mentioned when earlier discussing deadwood, is difficult to place on any one group of individuals. Since this is illegal in all forests, no one confessed to cutting large trees for timber, but instead blamed outsiders, most frequently, carpenters from Tambacounda for this practice.

Local participants also mentioned that the clearing of land for agriculture was leading to the degradation of the forest immediately adjacent to villages. People often cited the need for more land to produce cash crops like cotton. In most areas, the land immediately surrounding the village is used for agriculture. In some cases, field can extend up to the boundary of a demarcated classified or co-managed forest.

Fire is known as one of the main drivers of ecosystem change around the world (Higgins, Bond and Trollope 2000, Roques, O'Connor and Watkinson 2001, van Langevelde et al. 2003), particularly in the woodlands of Africa (Sankaran et al. 2005). Fires were mentioned as a major driver of forest degradation and change by 34 of 36 interviewees stating that reoccurring fires throughout the year never give the forest time to recover and regrow.

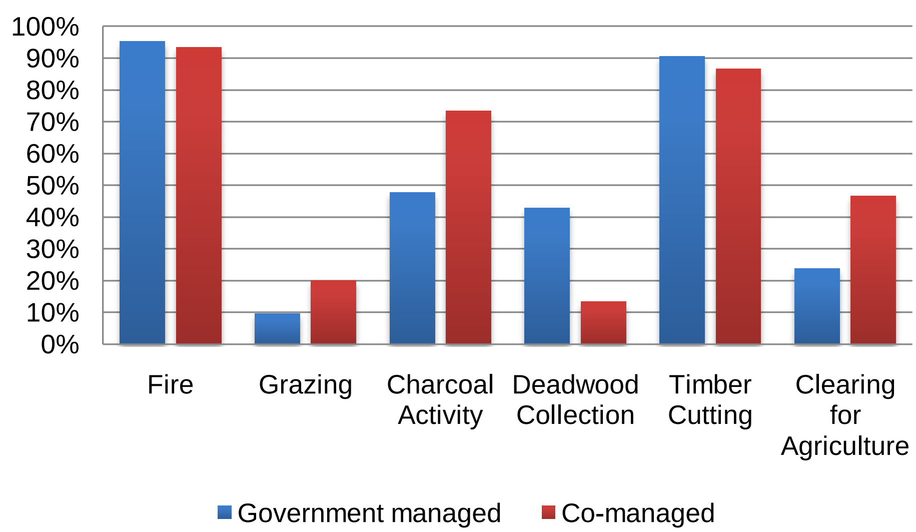

Figure 2-9 - The perceived causes of forest cover change as stated by interviewees who were living nearest to government managed forests and co-managed forests.

Interviewees cited a number of causes for fires including: cattle herders and farmers starting them to clear land for grazing and farming, charcoal producers accidentally starting them because a kiln burned too hot, traffic from the main road (via cigarettes being flicked in to the bush or over-heating engines catching fire to the grass along the roadside), timber harvesters lighting small fires around the bottom of trees which can burn out of control, and hunters setting fires to find animals.

Cattle herders blamed charcoal producers, charcoal producers blamed timber producers and cattle herders, and timber producers blamed the others. Frequently people acknowledged their role in the fire regime, but preferred to place a majority of the blame on other groups as the primary culprits.

> "Who starts fires? It is smokers, cattle herders, timber harvesters, people walking from one village to another. They start fires (as he takes a long drag from his cigarette)."
>
> I ask, "What about charcoal producers? They smoke."
>
> He smiles at me as he flicks his cigarette butt onto the ground and says sarcastically, "We never do that." Then laughs and says, "Smokers are the problem, people should avoid this activity."

Forest degradation caused by fire was obvious to all interviewees. Because Combretum glutinosum was the primary species harvested for charcoal production specific questions were asked when possible about the length of time it would take for a tree to become resistant to fire. Answers varied and ranged from two to eight years. A young tree of only two years, could resist a weak fire (one that passes quickly at low heat), but would be killed by a more intense fire. It was generally believed that regenerated saplings of over four years could resist most fires, while at eight or more years trees were considered fire resistant (Figure 2-10).

The charcoal producers interviewed in the forest mentioned specific methods to minimize the impact of fire on the forest. First, the clearing of grass would greatly reduce the intensity and frequency of fires. Interviewees mentioned that grass should be cleared, at minimum, around the freshly cut tree stumps after cutting to minimize the impact of a potential fire (reducing the fuel load and subsequent fire intensity nearest to the newly regenerating shoots). Also, Combretaceae species should be cut as close to the ground as possible. This significantly decreases the proportion of the cut tree exposed to potential fire greatly increasing the probability of survival.

Charcoal was also mentioned by as a driver of forest change by 21 of 36 interviewees. People in villages where co-management occurred often cited the uncontrolled harvesting of trees for charcoal production as a cause of forest degradation while respondents in villages depending on illegal harvesting downplayed the impacts. Charcoal harvesting frequency was observed consistently across the study area (Figure 2-11).

> "It is easy to see that the forest is degrading. Look around. You see lots of trees that were cut. When you walk around the forest you see and hear people cutting trees for charcoal and timber. Some years ago there used to be many fruit trees in the bush, but they are no longer here. Nothing is here. We used to spend all day in the bush. We could feed ourselves from the bush. Now you cannot bring anything back. There is nothing left to bring back."

Harvesting of trees for charcoal production does not necessarily predetermine a region for rapid deforestation. Interviewees differentiated between trees that naturally regenerated and trees that died after cutting.

> "The bush is degrading because of the cutting of live trees like bobori and bani, trees that cannot regrow after cutting. Look how big this tree was (pointing to a large bani stump). This was cut for timber and now it will take many many years for a tree like it to be here again. Dooki is different. If you cut one, many branches will grow back quickly. This is why people only cut dooki for charcoal."

Previous research and interviews noted that charcoal workers and fuelwood collectors also return re-cut areas that were previously harvested (Bergeret and Ribot 1990). The existence of re-cutting of Combretaceae species indicates that regeneration is taking place. This information is consistent with regeneration data for the area collected since the beginning of the 20th century (Arbonnier 1990).

The time between harvesting varied with interviewees estimating the earliest a Combretum tree could be reharvested ranged from 3 to 8 years. In many cases, 5 to 6 years was stated to be an optimal time interval to re-cut trees from the same locations[6]. Regeneration after cutting of Combreteceae species (locally generally referred to as dooki in Pulaar (individual species were *Combretum glutinosum* (dooki gorko), *Combretum*

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[6] Interviews conducted in Senegal, Mali, Niger and Burkino Faso stated that charcoal workers return to harvest the same area after 9 to 12 years Ribot, J. C. 1999. A history of fear: imagining deforestation in the West African dryland forests. 291-300. while other studies have estimated that woodcutters could return to re-cut at 8 years for optimal return Jensen, A. M. 1995. Evaluation des données sur les ressources ligneuses au Burkina Faso, Gambie, Mali, Niger et Sénégal. In *Examen des politiques, stratégies et programmes au secteur des énergies traditionnelles*. World Bank.. It is this data that led the co-managed projects to require an 8 year rotation between harvests Heermans, J. March 2008..

lecardii (dooki debbo), *Combretum molle* (ngañaka), and *Combretum nigricans* (busti)) was observed in all co-managed and government managed forest types. Interviewees said that the regeneration of these trees allows for the repeated cutting of forests.

Interviewees stated that saplings or small trees less than three years of age were generally not cut. Charcoal producers stated that small trees, usually less than 3 years in age (approximately 5 centimeters in diameter 1 meter off the ground), were unprofitable because they did not make good charcoal, and therefore were left unharvested. These trees would be left to grow for a number of years until they would eventually be large enough to produce good charcoal.

Impacts of Village Economic Status and Power

Across the study area the apparent economic status of surveyed villages varied. In developing countries, the assets that households have acquired, such as consumer goods, housing quality, water and sanitary facilities and other amenities are a good indicator of their long-term economic status (Groenewold and Tilahun 1990, Morris et al. 2000, Filmer and Pritchett 2001, Mweemba and Webb 2008, Somi et al. 2008).

Although specific household or village incomes were not asked or discussed during our time in each village, we did observe and discuss proxies such as diet, apparent health of children and elders, states of compounds (presence or absence of corrugate roofing material and cement vs. mud floors) and the presence or absence of motorized vehicles.

a)  b) 

c)

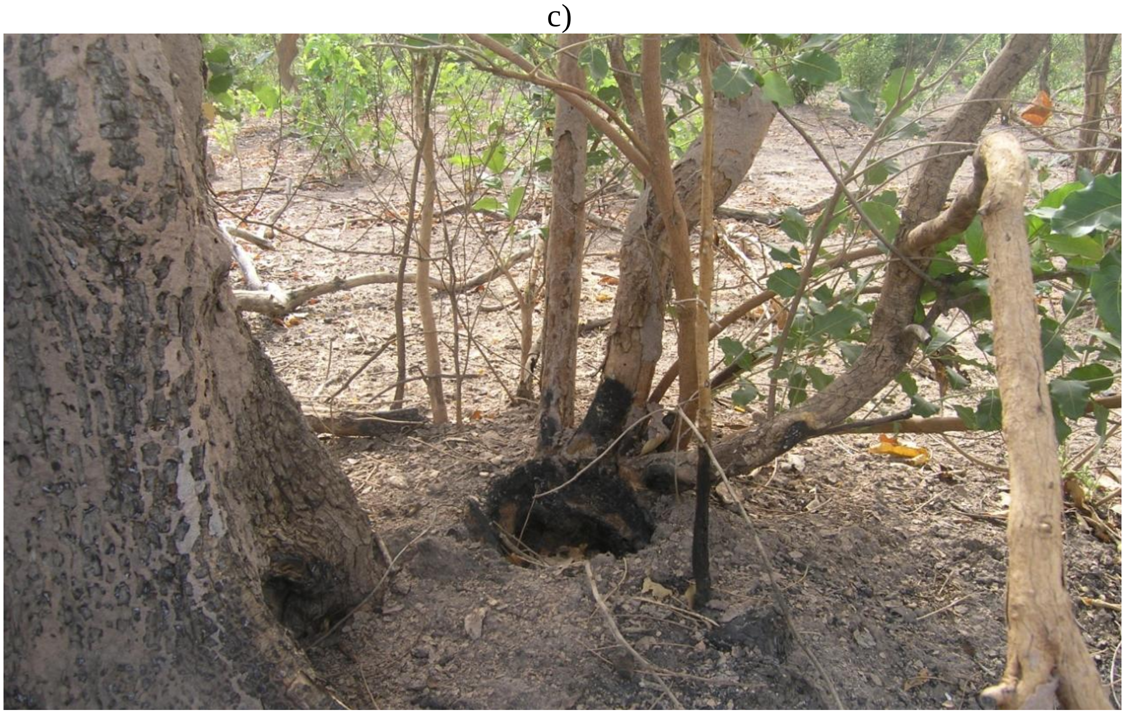


Figure 2-10 Examples of effects of fire and regeneration: A) Three saplings less than 2 inches in diameter killed by recent fire. B) Demonstrates regeneration of *Combretum glutinosum* after recent fire. Shoots are less than ½ inch in diameter. C) Demonstrating the resiliency of *Combretum glutinosum* with at least 5 years growth to fire. In this case, a large stump was burned adjacent to a group of established *Combretum glutinosum* leaving them slightly scared, but continuing to grow.

Figure 2-11 - Charcoal kiln preparation

A typical village falling onto the poor end of the spectrum would have no community garden or access to vegetables, eat only millet (occasionally rice) with a light peanut-based sauce, a majority of infants would have distended stomachs(Groenewold and Tilahun 1990), homes would be constructed of mud with thatch roofs (Morris et al. 2000, Mweemba and Webb 2008) (Figure 2-12a), and no motorized vehicles would be present in the village (Morris et al. 2000).

A village falling into the other end of the economic spectrum would have a working community garden, a wider, more balanced diet, and therefore healthier children. Most compounds would have at least one or two houses with a corrugate/tin roof (Figure 2-12b) and most homes would have cement floors.

Often, poorer villages stated a stronger dependence on the forest for income and daily energy. Some of these villages were also located on major roads and voiced strong levels of frustration with government led forest management.

In one of the apparently wealthier villages (nearest to a PROGEDE forest) the traditional leader and elected leader were from the same family. This family was obviously the wealthiest in the community and had a number of children and relatives working in Europe. An additional family was also the former owner of one of the largest hotels in Tambacounda. People in this village were very content with the state of the forest and management.

If a successful management campaign is measured by minimal visible human impact in a forest, then this would be one of the best in the area. Very few people were seen working in the forest and there was very little sign of livestock grazing. One man was found preparing wood for charcoal production. He was aware of the rules and

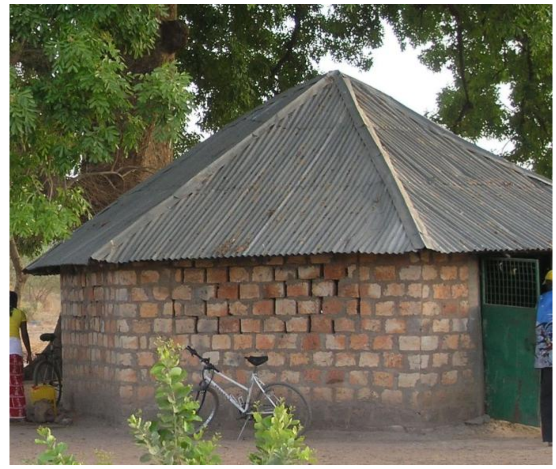
a)  b) 

Figure 2-12 – Typical huts from different socioeconomic levels; a) thatch-roofed hut with mud floors, b) corrugate-roofed hut with cement floors.

necessary paperwork needed to produce charcoal in the forest and showed us documentation proving that he was there legally.

Large fire breaks created by large bulldozers divided the forest into varying zones of use (rotating charcoal production zones along with access to deadwood, fuelwood collection and grazing) and two large community gardens for women were also created as part of the project. These large initial investments could be interpreted as a successful means of getting buy-in from the local community in assisting with the management and control of the forest. On the other hand, the perceived relative wealth, high level of education and employment in cities within and outside Senegal probably played an important role in determining the dependence of the community on the surrounding forest. In reality it is most likely a combination of all factors including political connectivity, wealth, education, management, and initial investment that allowed for the visibly successful management and conservation of resources within the nearby forest.

Who is responsible for the management of the forest?

When asked their impressions of forest management mixtures of opinions were heard. Nearly half of the respondents were content with how the forest was managed (16 of 36), although there was a noted difference between respondents who lived near to co-managed forests and government managed forests (11 of 16 lived near to co-managed forests). The relative contentedness with management appeared to stem from communities being more tied to potential profits collected via charcoal production and inclusion in determining how the forest should be managed. In villages near to government managed forests, 16 of 21 respondents thought management of the forest needed improvement (Figure 2-13). Improvement usually meant increasing local involvement in decision making and receiving a greater cut of profits from charcoal production.

The opinions of forest management by the Forest Service and co-managed projects of Wula Nafaa and PROGEDE varied by individual; some were very happy with government control:

> "The government chose to work in this village and make it a co-managed area. As a community we are now involved in the management of the forest. Our task is to look for and stop bush fires. We are also supposed to report illegal harvesting and activity in the forest. In the forest the government does a good job of controlling the area. Because they are here, the forest is not decreasing like it is in other areas. They are doing a good job.
>
> The government also created a garden for the women of the village. The women manage it themselves and receive a good profit from what they produce." – the perspective of a local forest manager.

Others felt the management of the forest by government entities as a façade:

> "This area is a classified forest (government managed forest), but there is really no management here. The Forest Service only comes here and walks the road around the edge of the forest. It is very easy to cut illegally because they never go into the forest. Who would work next to the road? They waste their time thinking they are working while driving around the forest. This is all they are paid to do. They "hire" young people from the villages to go into the forest for them, but they never pay them for the work. They do not pay local people or give them bikes to go into the forest to enforce the rules. We would not work cotton for free. We need to earn a living." – quoted by a charcoal producer in the bush 3-4 kilometers from the edge of the Classified Forest.

Others perceived the Forest Service as a government entity who only appeared in the village to take forest products from people that had no choice but to use the forest. In many instances, people spoke of how they had to produce charcoal, with or without the correct paperwork, and how Forest Service workers waited until the charcoal was ready for sale to confiscate the charcoal and tools. Many people stated that local ecological knowledge should be used to create management that would benefit the local populations while OF should be used as an enforcing agent.

> "We are the ones who live in the bush. We know the bush. We know what is going on in the bush. We need the bush. Before the Forest Service came we had local committees who took care of the bush. We still have these committees. The Forest Service is working here for us and they need our help to keep the bush healthy."

But when it came to enforcing laws…

> "The local people have no power. People fear the Forest Service. If local people only managed, we do not fear each other. A civilian cannot enforce a rule on another civilian. Neither owns the forest. Each has no right to stop the other. We should keep the Forest Service managing because they are feared. The management of the forest is for our own interest, but we need the Forest Service to manage the forest for us."

When asked about who actually managed the forest 24 of 36 respondents said that the Forest Service was in control of the management process (Figure 2-14). In areas of co-management, the Forest Service was still perceived by a third of the respondents (Five of 15) to be in control and responsible for the management of the forest. Wula Nafaa managed forests appear to be sharing the conceived responsibilities of management (six of seven respondents believed the forest was truly co-managed) better than PROGEDE managed forests (four of eight respondents believed the forest was still mostly managed by the Forest Service).

All communities have Rural Community forests surrounding them, in most cases this land is also controlled by the Forest Service. The cutting of any live tree, inside or outside demarcated forest parks and within Rural Community forests, is illegal and people wishing to produce charcoal must first obtain a permit from the Forest Service. These regulations probably helped lead 19 of 21 respondents nearest to government managed forests to feel that the Forest Service was the sole manager of the forest, inside and outside park boundaries.

Impacts of Management on the Forest

The forests in both co-managed and government managed areas looked quite similar. Some areas were thickly wooded while others were sparse. Activity was observed in all forests. Grazing was apparent, fires occurred, and illegal timber harvesting was happening. During the interviews people exhibited a high level of understanding of the current forest management and rules and regulations that they placed on individuals who used the forest. The rules were known, but were they actively applied?

In government managed forests, people generally stated that in order to avoid contact with Forest Service officials they worked in areas where they knew Forest Service officials would not go. As long as harvesting was done at least one-half kilometer from the forest edge or road the Forest Service used to patrol they were generally safe from Forest Service officials. A majority of local people felt they had no responsibility to confront illegal harvesters because it was not there job. It is the responsibility of the Forest Service to enforce.

In Co-managed forests the situation was different. Illegal harvesting was observed and noted by people in the community. The methods of confronting, documenting and charging people with illegal forest extraction was thoroughly discussed, but when illegal harvesting was encountered during two field visits forest patrollers expressed great hesitation in confronting people illegally harvesting timber. They reiterated statements made by people in government managed lands saying that confrontation of illegal harvesters is best handled by Wula Nafaa or Forest Service officials.

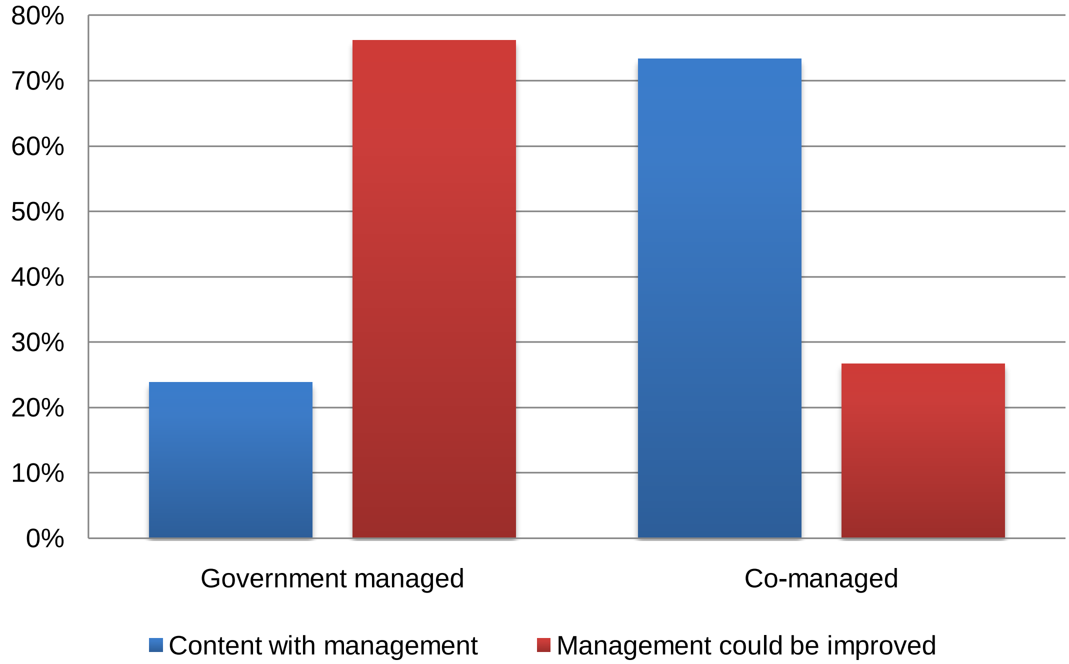


Figure 2-13 – Percentage of interviewees in government and co-managed forest type villages expressing that they were content with how the forest was managed or that forest management should be improved.

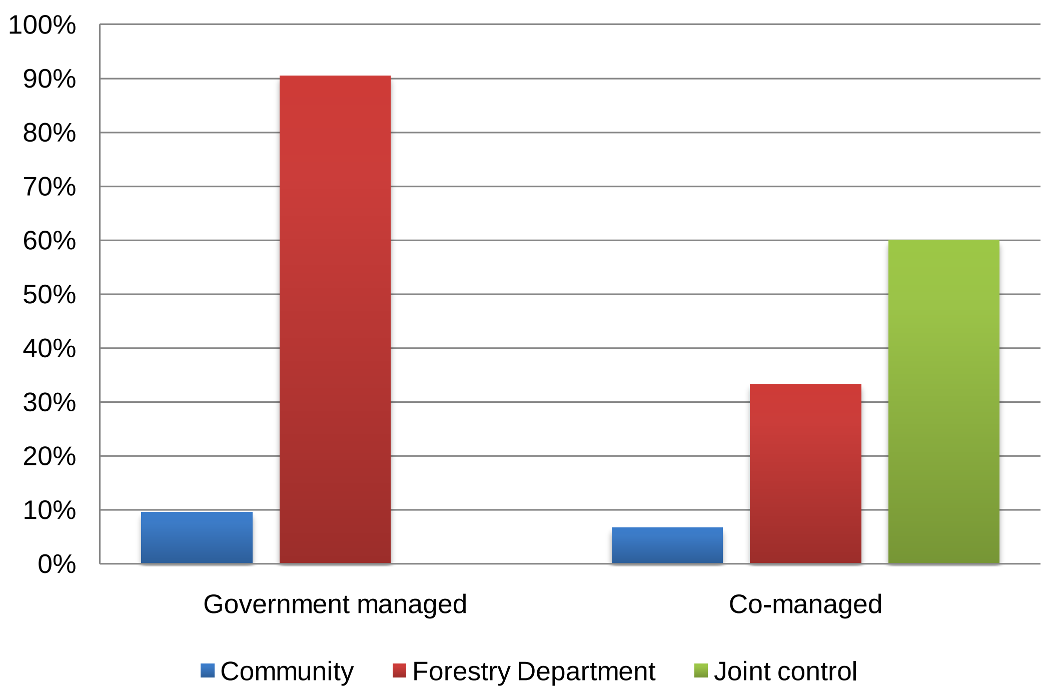


Figure 2-14 - Percentage of interviewees in government and co-managed forest villages who felt the management and access to the forests surrounding their village were controlled by the government, the community, or jointly by both the government and community.

They were theoretically “empowered”, but did not act. Why? Often regional representatives, prefecture reps, and village chiefs feel powerless when addressing forest extraction and harvest issues (Ribot 2009). Forest laws that were intended to decentralize power, share the profits of charcoal production and limit the negative perceived impact resulting from charcoal production never materialized (Faye 2006, Ribot 2009). Previous research looking at power dynamics throughout the 1990s and into the early 2000s demonstrated that power was held by a handful of patrons and the OF (Ribot 2009). To date, the people outside of GM and CM lands still lack the power, and therefore lack the will, to confidently enforce forest access regulations. Local awareness was raised through some campaigns (Faye 2006), but awareness is little without action. People gave the impression that action would not be taken unless the people in the forests have the power to enforce laws and restrict access to the forests surrounding their villages.

In some villages young men were hired through the Wula Nafaa, PROGEDE or the Forest Service to patrol the forest. When people were hired by the Forest Service they were promised monetary compensation, but that promise was rarely kept and if it was it was not for long. After a period of a couple months, many interviewees stated that the Forest Service would only demand information without paying the individual for their efforts. People saw this type of enforcement not as beneficial to the village by giving some men small jobs, but instead negative in that they saw the Forest Service officers as lazy and corrupt, not wanting to do the work they are hired to do.

In Co-managed forests young men spoke freely about how the projects had given them jobs and how the community was benefiting from the charcoal that was being produced in their village. They said they did the work for their community, but also stated repeatedly that if they were not getting paid for their time they would not be patrolling the forest. The focus was on charcoal activity, not illegal timber harvesting. Because of this, the perceived impact of management on forest and forest regeneration by local people was minimal. People said they knew the bush as degrading and knew what was causing the changes, but felt powerless to act.

Conclusion

The answers provided by interviewees only scratch the surface of the important economic, political and ecological issues of how forest resources are controlled and managed. The information gathered serves as a good starting point for future discussions and is valuable information to compare ecological data against.

The local ecological knowledge derived from semi-structured interviews demonstrated that local people have extensive knowledge of forest uses, the drivers of forest change and thoroughly understand the realities of government and co-managed forests. This research emphasized the extent to which local villages in the Tambacounda region of Senegal depend on the surrounding forest for energy, food, and income. The forest products harvested and income generated by the forest often helps supplement their diets and frequently offset the income lost due to a bad agricultural year.

The uneven distribution of power over forest resources and management is believed to minimize the influence of management type on forest ecology. Local people believe that forest are changing in both government and co-managed areas; large, hardwood species are disappearing, animals are sparse or are locally absent, illegal harvesting of timber is throughout, fires burn, and wood is harvested (legally or illegally) for charcoal production. Charcoal was often a divisive topic with people acknowledging the positive and negative effects it brings; supplemental income, but also increasing pressure on the environment.

Many interviewees believe that in spite of the many pressures on the environment, the forest is regenerating in both government and co-managed areas. Many people who use the forest on the daily basis understand that certain species (mostly trees in the Combretaceae family) regenerate after being cut for fuelwood or the production of charcoal.

In many respects, in spite of efforts to decentralize power, management of the forest is believed to be sole function of the Forest Service. This is even the belief of some interviewees in communities that are signed into co-management plans. The decentralization forest code of 1998 raised the interest level of local communities by potentially allocating increased power and decision making to rural councils, but in the opinion of interviewees, the Forest Service still maintains much of the authority to determine where, when and what is harvested within forested areas. People are willing to participate in management, but the lack of resources and an incomplete transfer of authority to local rural communities are limiting people's willingness to participate in forest management.

Chapter 3 - Analyzing the Impact of Charcoal Harvest and Land Management Type on Vegetation Regeneration in the Tambacounda Region of Senegal

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.

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 chapter analyzes tree diversity and regeneration patterns in the Tambacounda region of southeastern Senegal. The specific objectives of this chapter 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

As discussed in chapter 1, 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). As discussed in Chapter 2, the main objectives of human-started fires are to clear land for agriculture or grazing of livestock.

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).

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.

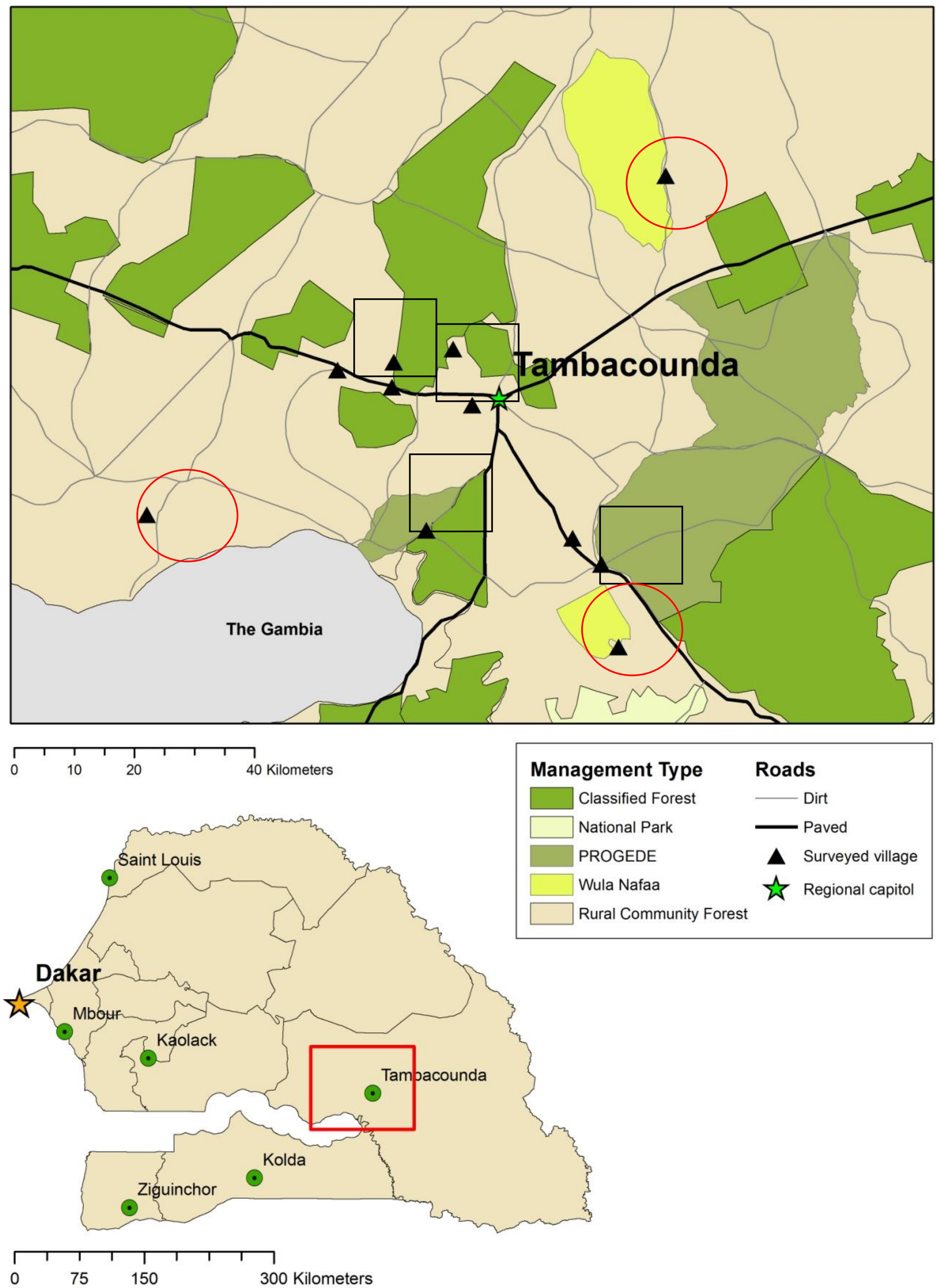


Figure 3-1 - Location of forest management types in the Tambacounda study area. Black boxes indicate where Ikonos satellite images were used to identify historic charcoal sites. Red circles identify areas were previous charcoal sites have been identified in the field.

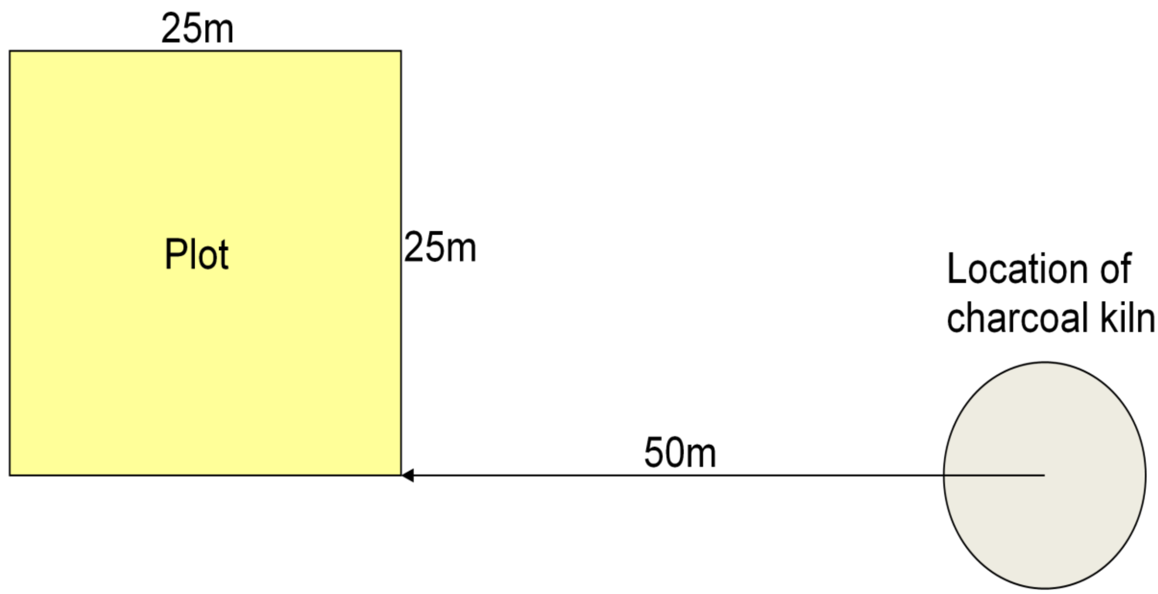


Figure 3-2 - Plot locations – Sample plot layout in relation to the location of a charcoal kiln.

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 discussed in chapter two.

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

Table 3-1 - Identified species and estimated size distributions in undisturbed and harvested plots

		Undisturbed				Harvested			
		total number individuals	number of individuals per hectare			total number individuals	number of individuals per hectare		
Species name	Family		>20 cm dbh	>5 cm dbh	regeneration (<5 cm dbh)		>20 cm dbh	>5 cm dbh	regeneration (<5 cm dbh)
Acacia macrostachya	Mimosaceae	15	-	7.2	8.2	65	-	7.5	6
Annona senegalensis	Annonaceae	-	-	-	-	2	-	0.2	0.2
Anogeissus leiocarpus	Combretaceae	1	1	1	-	-	-	-	-
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	-	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	30	5.6	6	0.2
Ficus dicranostyla	Moraceae	1	1	1	-	-	-	-	-
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	-	4		0.4	0.4

Table 3.1 continued - Identified species and estimated size distributions in undisturbed and harvested plots

		Undisturbed				Harvested			
		total number individuals	number of individuals per hectare			total number individuals	number of individuals per hectare		
Species name	Family		>20 cm dbh	>5 cm dbh	regeneration (<5 cm dbh)		>20 cm dbh	>5 cm dbh	regeneration (<5 cm dbh)
Piliostigma thonningii	Caesalpiniaceae	-	-	-	-	1	-	0.2	-
Pterocarpus erinaceus	Papilionaceae	5	4.1	5.1	-	20	3.3	4.2	-
Sclerocarya birrea	Anacardiaceae	1	1	1	-	1	0.2	0.2	-
Sterculia setigera	Sterculiaceae	2	2.1	2.1	-	17	1.9	3.5	-
Strychnos innocua	Loganiaceae	33	-	1	32.8	162	-	7.5	26.2
Strychnos spinosa	Loganiaceae	-	-	-	-	1	-	0.2	-
Terminalia avicennoides	Combretaceae	28	1	4.1	24.6	11	1	1.9	0.4
Terminalia macroptera	Combretaceae	1	-	1	-	2	0.2	0.4	-
Unknown 1	Unknown	32	-	-	32.8	-	-	-	-
Unknown 2	Unknown	1	1	1	-	1	0.2	0.2	-
Unknown 3	Unknown	9	-	1	8.2	16	-	-	3.3
Unknown 4	Unknown	-	-	-	-	8	-	-	1.7
Unknown 5	Unknown	-	-	-	-	8	-	-	1.7
Unknown 6	Unknown	1	-	1	-	-	-	-	-
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	-	-	-	-	-

Table 3-2 - 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 3-3 - 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

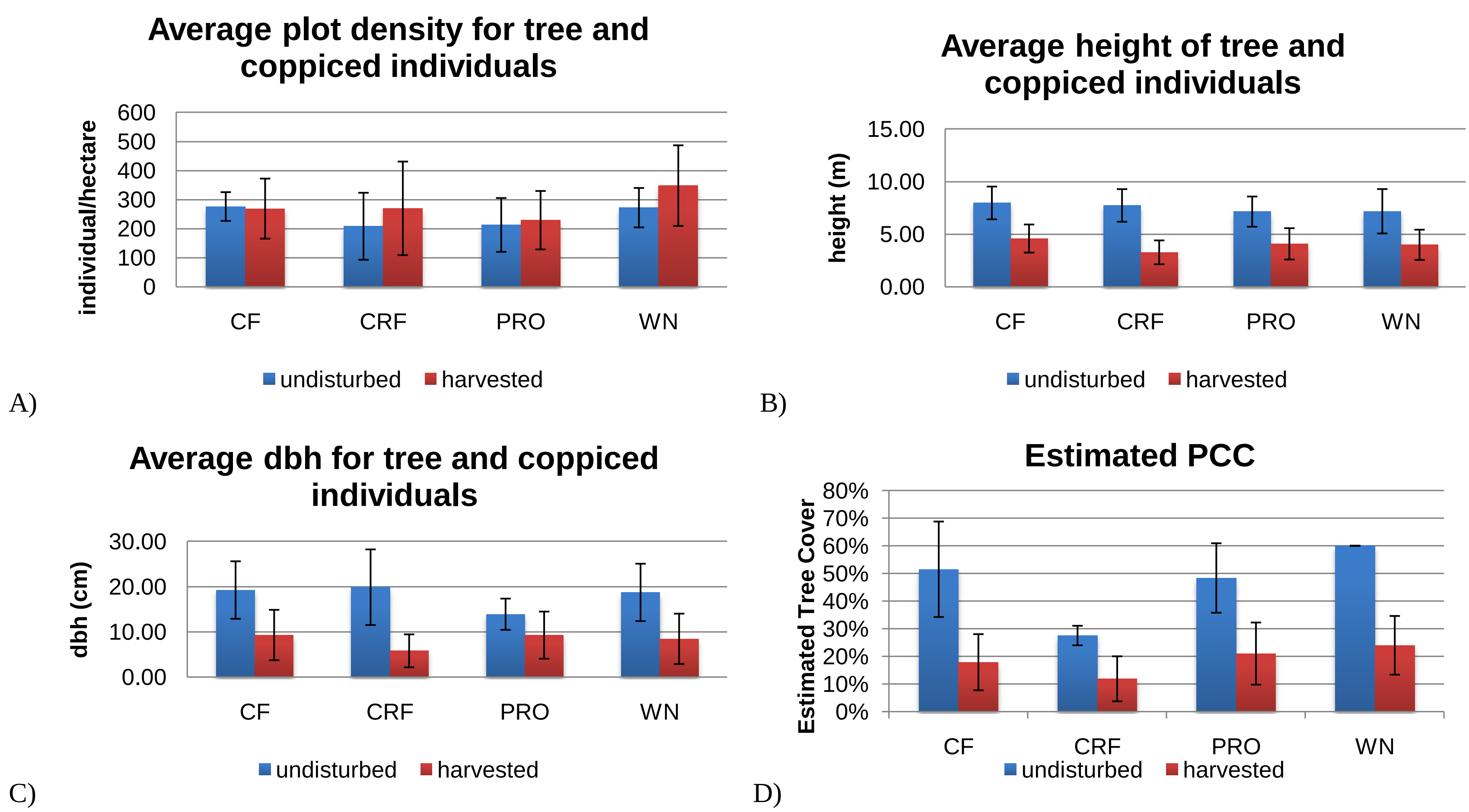


Figure 3-3 - Plot characteristics (plot density, height, dbh and PCC) of undisturbed and harvested plots within Classified Forest (CF), Rural Community forest (RCF), PROGEDE (PRO) and Wula Nafaa (WN) forests. All p-values based on a one-way analysis of variance (ANOVA). See table 3.4 for related p-values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

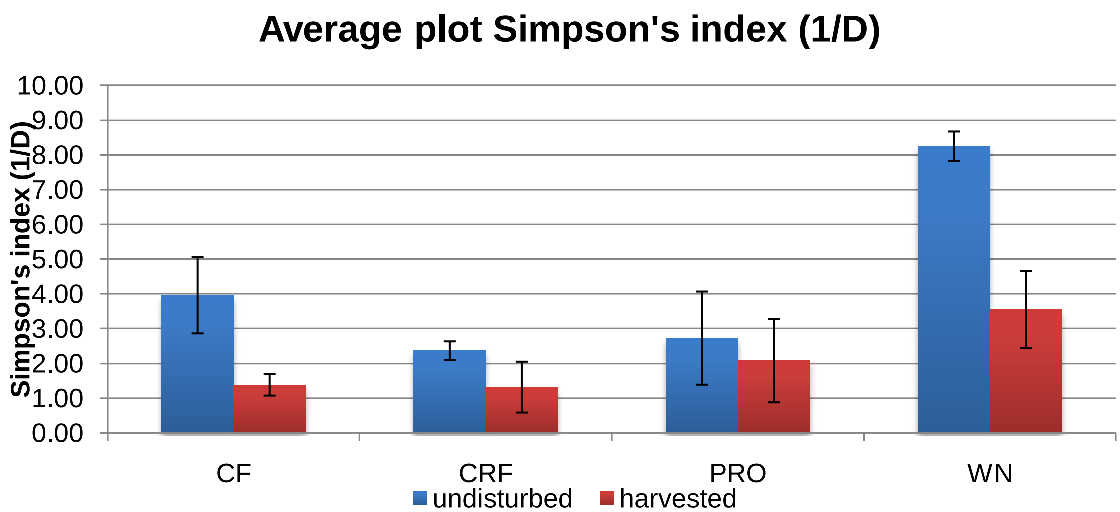


Figure 3-4 - Average plot Simpson's diversity index value for undisturbed and harvested plots within each forest management type. See table 3.4 for related p-values between all harvested forest management type plots and all undisturbed forest management type plots.

Table 3-4 - 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 3-5 - 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%

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 increases in RCF with increasing distance to roads.

Table 3-6 - 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					PROGEDE					Wula Nafaa				
	PCC	dbh (cm)	height (m)	trees /ha	1/D	PCC	dbh (cm)	height (m)	trees /ha	1/D	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	0.007	0.016	0.003	-0.037	0.000	0.000	0.000	0.000	0.019	0.000
	(0.00)	(0.01)	(0.00)	(0.05)	(0.00)	(0.00)	(0.00)	(0.00)	(0.05)	(0.00)	(0.01)	(0.01)***	(0.01)***	(0.07)	(0.01)	(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	0.003	-0.006	-0.001	0.042	0.000					
	(0.01)***	(0.00)	(0.00)*	(0.04)	(0.00)	(0.00)	(0.00)	(0.00)	(0.03)	(0.00)	(0.00)	(0.01)*	(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						0.000	0.000	0.000	0.022	0.000
	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.01)	(0.00)	(0.00)	(0.06)	(0.00)						(0.00)	(0.00)	(0.00)	(0.02)	(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	0.21	0.43	0.43	0.01	-0.17	-0.21	-0.21	-0.15	0.01	0.07
Observations	21	21	21	21	21	15	15	15	15	15	13	13	13	13	13	12	12	12	12	12
p-value	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	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

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)

Table 3-7 - Estimated species density per hectare within all harvested plots disaggregated by forest management type.

			Number of individuals per hectare															
		Total number individuals	All Harvested plots				>20 cm dbh				> 5cm dbh				regeneration (<5cm dbh)			
Species name	Family		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	143.2	112
Combretum lecardii	Combretaceae	41	4.2	4.7	4	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	3.4		0.7	36.8	17.1
Cordyla pinnata	Caesalpiniaceae	30	8.4	6	6.4	3.4	7.6	6	5.6	2.3	8.4	6	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
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	-	74.3
Lannea acida	Anacardiaceae	29	5.1	2	4	17.1	4.2	2	1.6	5.7	5.1	2	4	8	-	-	-	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	2.4	11.4	-	4	2.4	8	0.8	4	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	-	-	-	

Table 3.7 continued - Estimated species density per hectare within all harvested plots disaggregated by forest management type

			Number of individuals per hectare																
		Total number	All Harvested plots				>20 cm dbh				> 5cm dbh				regeneration (<5cm dbh)			
Species name	Family	individuals	CF	CRZ	PRO	WN	CF	CRZ	PRO	WN	CF	CRZ	PRO	WN	CF	CRZ	PRO	WN
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	-	-	0.7	-	-	-	-	-	-
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

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.

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.

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 3-8 - 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 3-9 - 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

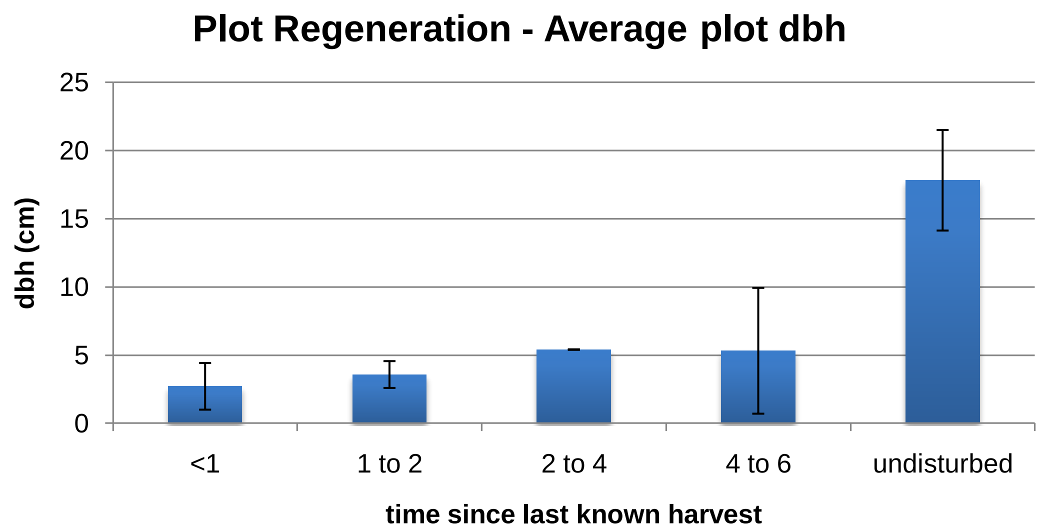
Table 3-10- Classification of species sampled in harvested plots into SCD types. Type 1 consists of species with extremely flat or sometimes positive SCD slopes meaning that only larger individuals were sampled. This group is composed of rare species with poor regeneration. Type 2 have slightly negative 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**			

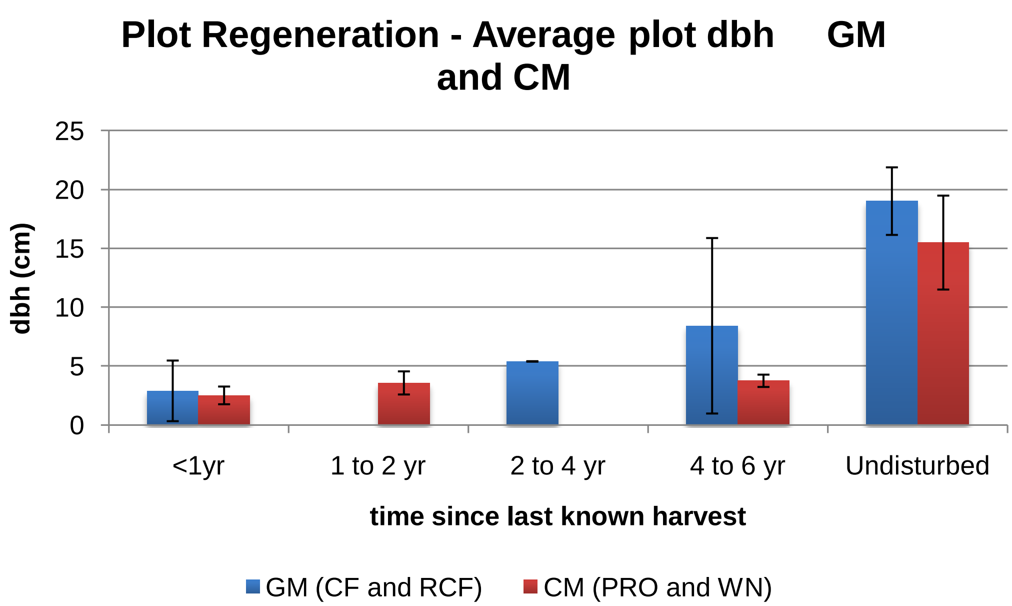
WN	Botanical	Slope	R^2	Type
	Combretum micranthum	0.048	0.01	1
	Pterocarpus erinaceus	0.031	0.12	1
	Sterculia setigera	0.024	0.50	1
	Bombax costatum	0.023	0.21	1
	Terminalia avicennoides	-0.115	0.76	2
	Lannea acida	-0.199	0.47	2
	Unknown 4	-0.558	0.75	3
	Unknown 5	-0.558	0.75	3
	Combretum nigricans	-0.789	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 3-11 - 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

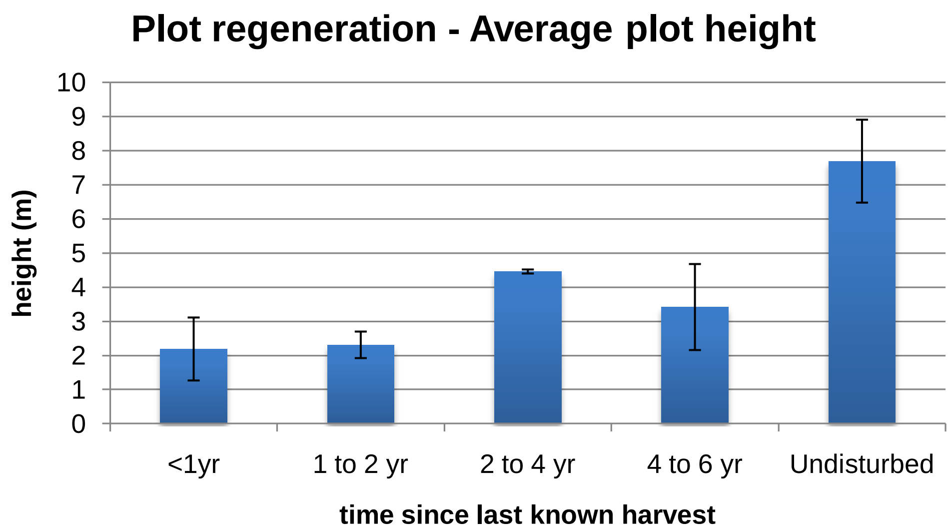


a)



b)

Figure 3-5 - 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.



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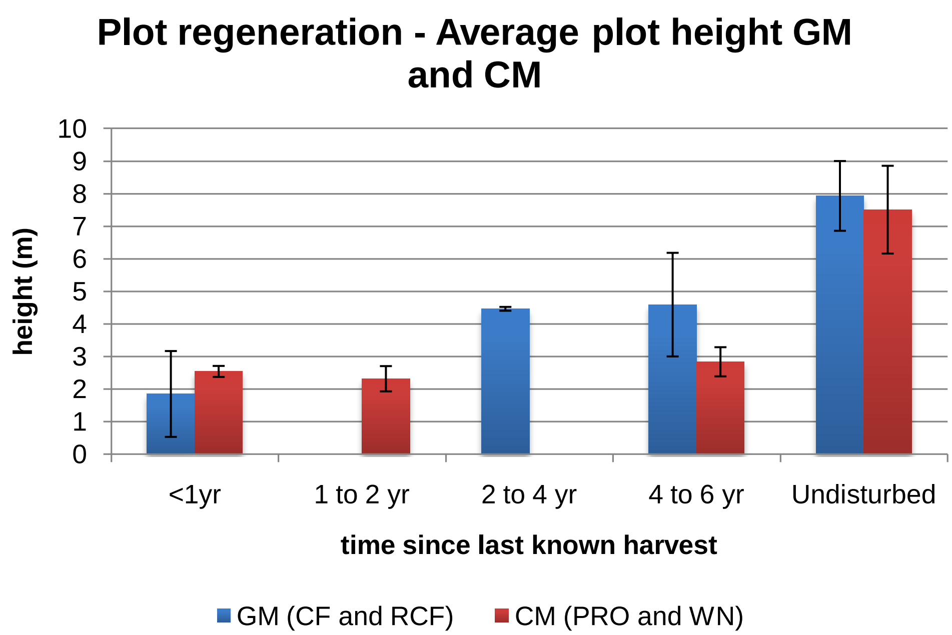
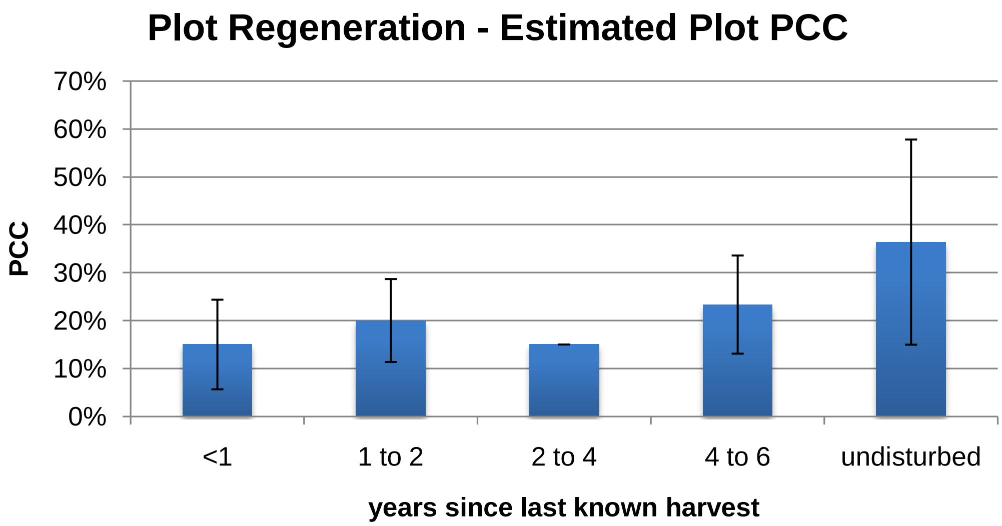
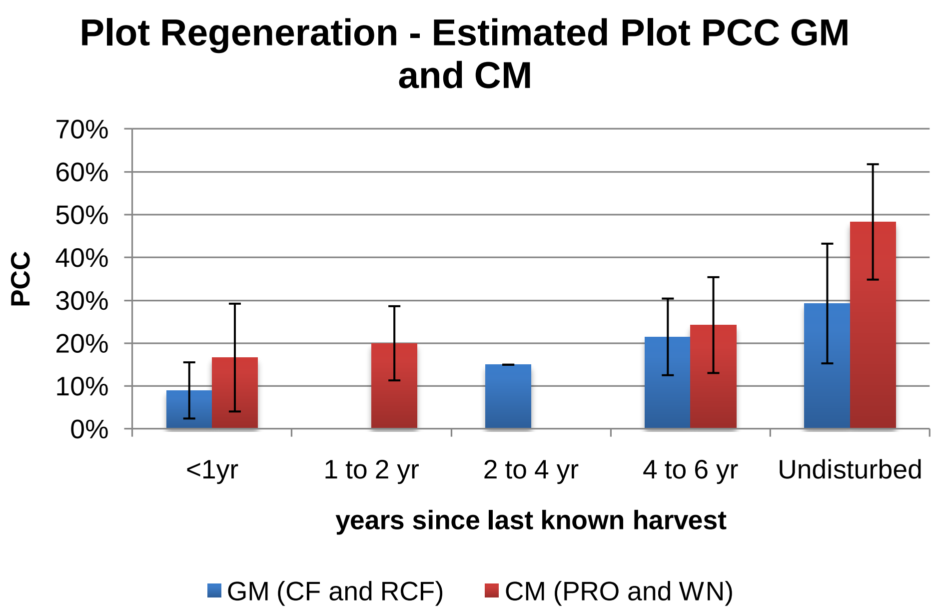


b)

Figure 3-6– 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.

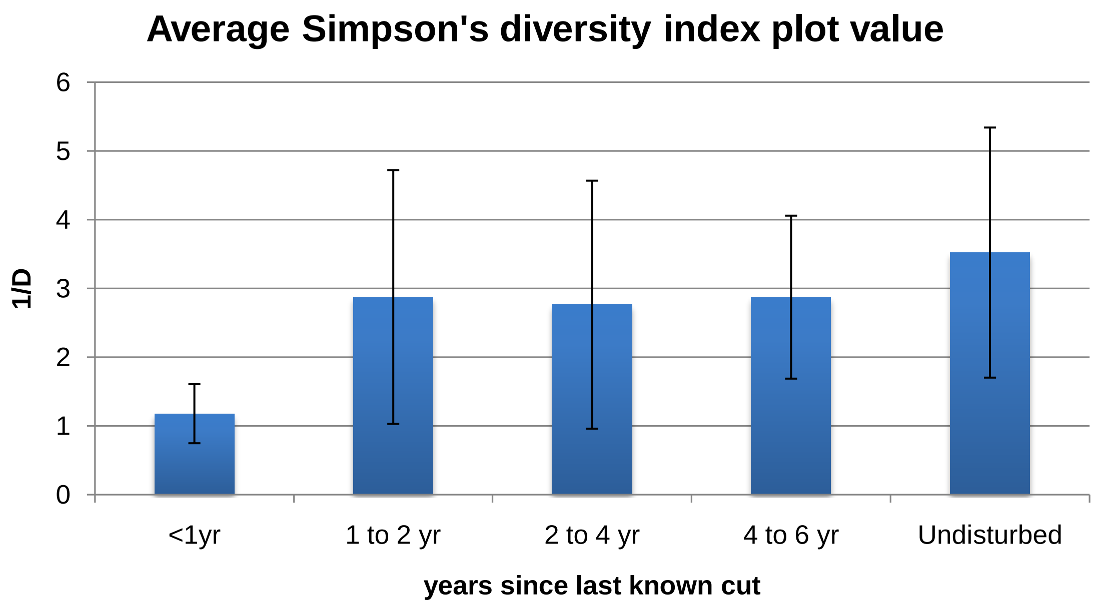


a)

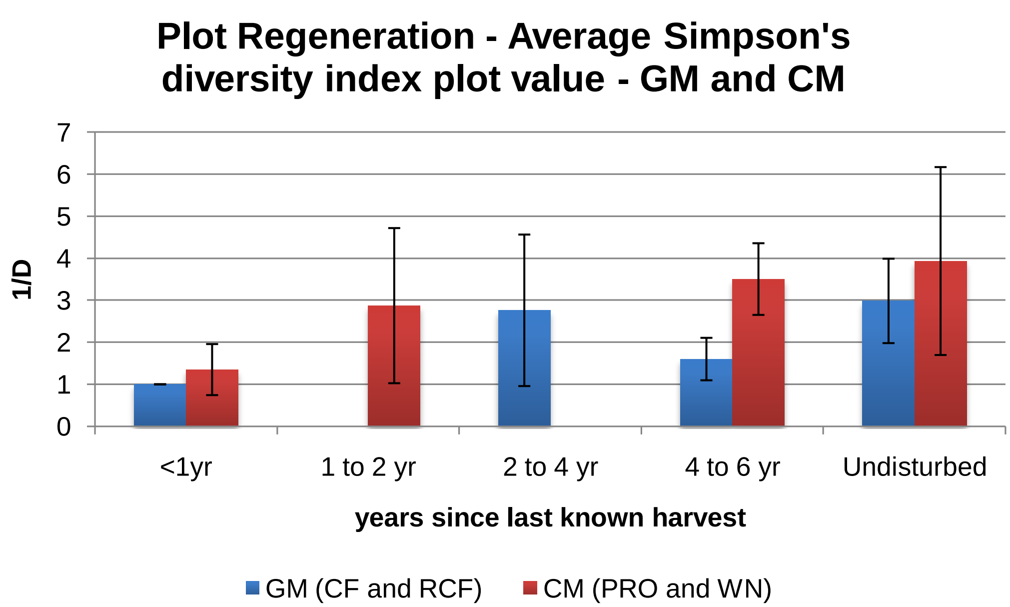


b)

Figure 3-7 - 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 3-8 – 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.

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 chapter 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 et al. 2004) and the strongly negative SCDs of Combrateceae species is aided by its resistance to fire. During the semi-structured interviews discussed in chapter 2, fire was a perceived driver of forest change in all forest management types. 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 (Chapter 2). 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 (Chapter 2). 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.

For forest managers to efficiently monitor changes in forest structure at regional and national levels, remote sensing technology must be combined with local level social and ecological analysis of the forests. The next two chapters will explore the utility of using the Multiangle Imaging SpectroRadiometer (MISR), a NASA multi-angle satellite, to accurately classify landcover types, differentiate between harvested and undisturbed forest areas, and detect subtle changes in forest structure due to harvesting and regeneration. The combination of local social and ecological analyses with regional level remote sensing analyses will create a more complete understanding of the extent, rate and drivers of forest change in the region.

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Chapter 4 - Testing the Capability of MISR in Detecting Forest Changes Caused by Charcoal Production in Senegal

Abstract

In Africa, urban households are largely dependent on charcoal for their energy needs. To date, the effect of charcoal production on forest regeneration rates is not well understood. The aim of this study was to use the Multi-angle Imaging SpectroRadiometer (MISR) to assess the relationship between MISR derived surface values and forest change resulting from charcoal extraction in Senegal. Remote sensing data from 2001 to 2003 and charcoal production field data from 2002 were used to test MISR's capability. This analysis shows the MISR derived k(red) parameter can consistently differentiate between forest cover types and can differentiate between woodland sites at pre- and post- charcoal harvest stages.

Introduction

In sub-Saharan Africa 750 million people consume almost 500 million tons of fuelwoods (charcoal and firewood) each year (Bailis et al. 2005). In urban environments over 75% of a rapidly growing population depends on charcoal as their primary source of energy for cooking (Ribot 1995, Post and Snel 2003, Bailis et al. 2005). The high demand for charcoal has led many to believe that charcoal harvesting is catalyzing widespread deforestation (Post and Snel 2003, Tappan et al. 2004, Mwampamba 2007). To date, the effect of charcoal production on long-term vegetation structure is not well understood.

Vegetation structure is here defined as the “the horizontal and vertical distribution of components within a plant community” (Jupp and Walker 1996). The extractive nature of charcoal production can drastically alter the vegetation structure of a forest or woodland environment. To produce charcoal, wood is harvested and taken to a central location where it is stacked into a large mound or kiln. This kiln is then lit, covered in dirt and allowed to smolder for 10-20 days (Ribot 1993, Manga 2005). Charcoal production requires the intensive cutting of the surrounding forest within a 100 to 300 meter radius of the kiln (Ribot 1990, Manga 2005). In many cases upwards of 75% of standing wood is harvested creating a loss is forest vertical and horizontal structural diversity (Manga 2005). Frequently, as many as 6 kilns are within 200m of one another simultaneously producing charcoal (Manga 2005). This intensity of harvest and overlap of areas can cause a decrease in vegetation structure over an area upwards of 30 ha (30,000 m^2).

To assess losses or gains in vegetation structure after charcoal harvesting using remote sensing, sub-pixel variation in canopy heterogeneity must be detected. Launched in 2000, NASA’s Multi-angle Imaging SpectroRadiometer (MISR) collects data across 4 spectral bands and 9 view angles at a spatial resolution of 275m. The utility of MISR to detect variations in canopy heterogeneity has been demonstrated most notably by Pinty et al., 2002, Chopping et al., 2003, Gobron et al., 2002, Widlowski et al., 2004, Armston et al., 2007, Su et al., 2007, and summarized by Diner et al., 2005. These studies argue that directional reflectance characteristics are diagnostic of surface cover heterogeneity. MISR provides data sets of these angular reflectance "signatures" for many classes of surface cover. MISR’s inclusion of vertical structure through its unique multi-angle approach provides it with a distinct advantage over single angle sensors in detecting variations in canopy and subcanopy structure.

The goal of this study was to assess the relationship between the bidirectional reflectance factor (BRF) land surface values and forest change resulting from charcoal harvesting. This study provides a preliminary assessment of the potential utility of MISR for assessing the impact of charcoal production on the surrounding vegetation structure.

The objectives of this study are to: 1) test the capability of MISR to differentiate between bare, woodland, and forest cover types and 2) test the capability of MISR to differentiate between unchanged woodland and woodland that has been disturbed by charcoal production.

Study Area

The Tambacounda region of Senegal produces much of the country's charcoal for urban consumers (Ribot 1995, Manga 2005). The area belongs to the Eastern Transition Ecoregion and consists of a homogeneous land cover characterized by lateritic plateaus of the continental sedimentary basin with wooded savannahs, small areas of agricultural parkland, and thin sections of gallery forest near river and stream beds. The climate is characterized by a rainy season from June to October and a dry season from November to May (Wood et al. 2004).

Data and Methodology

MISR Level 1B2 Terrain Projected Radiance (VersionF03_0022, VersionF03_0024), Level 1B Geometric Parameters (VersionF03_0012, VersionF03_0013, VersionF03_0014), and Level 2 Land Surface Products (VersionF04_0015, VersionF04_0017) covering the study area were acquired through the Earth Observing

System (EOS) Data Gateway at the National Aeronautics and Space Administration (NASA) Langley Research Center Atmospheric Science Data Centre. The Level 1B2 Terrain Projected Radiance data was acquired in Global mode.

Data used for this study were from January and February 2001, 2002, and 2003. These months were chosen because of the relative lack of cloud cover, smoke, and other atmospheric contaminants. Acquisitions contaminated by cloud or smoke or that were predominantly missing data in the Level 2 product were excluded.

To estimate surface cover heterogeneity for this study the Armston method of MISR RPV inversion was used (Armston et al. 2007). This process involves first calculating "at-sensor" radiance, followed by the calculation of surface bidirectional reflectance factor (BRF). Surface BRF analysis of all nine view angles are then fitted with the parametric Rahman Pinty Verstraete (RPV) model to retrieve the best set(s) of parameter combinations that explain the available data. Detailed descriptions of the RPV model are available in Gobron & Lajas, 2002, Pinty *et al*., 2002, Rahman *et al*., 1993, and Widlowski *et al*., 2001.

One of the outcomes of this model is the modified Minnaert function parameter, k. The k parameter at red wavelength (k(red)) has proven capable of revealing surface cover heterogeneity at the subpixel level (Pinty et al. 2002). In most vegetation cover types, spectral measurements in the red region maximize the contrast between the scattering/absorption properties over the vegetation stands and the underlying soil. K(red) parameter values are explained as follows:

• $k>1.0$ indicates a bowl-shape anisotropy curve where BRF values close to nadir are lower than larger exiting angles.

• k=1.0 means a Lambertian surface, rarely found in nature.

• k<1.0 indicates a bell-shape anisotropy curve where BRF values measured at large exiting angles are lower than those measured at angles close to nadir.

Most terrestrial surfaces display a bowl-shape anisotropy pattern. Examples include thick homogeneous plant canopies and bare soil. Some terrestrial surfaces will demonstrate a bell-shape anisotropy pattern. Bell-shaped curves are generally observed in a thin coniferous forest over a bright snow background or sparse bushes over a bright sandy surface at red wavelengths. In such cases, the high background reflectance dominates at small viewing zenith angles, while the absorbing properties of the dark objects control the reflectance of the entire scene at large view angles (Pinty et al. 2002).

K(red) values were extracted for known areas of bare, forested, and unchanged woodland. These areas were located using high resolution Ikonos images from 2005 and field observations in 2002 by Dr. Alla Manga of the University of Cheikh Anta Diop - Dakar. K(red) values were also extracted for GPS point locations of 175 charcoal production sites in 2002. Based on k(red) values, charcoal production site values were divided into pre- (2001 and 2002) and post- (2003) production values.

It is hypothesized that the forested and bare land areas will demonstrate bowl-shaped curves while woodland areas with thin canopy cover and bright sand background will create bell-shaped curves. When forest or woodland areas area harvested it will decrease the structural complexity of the site and therefore increase the sub-pixel homogeneity; creating a curve more similar to that of the bare land area.

Results

K(red) values from 2001 to 2003 are summarized in Figure 4-1. K(red) values for bare land, forest, and unchanged woodland averaged 0.86 (SD=0.008), 0.62 (SD=0.062), and 0.77 (SD=0.023), respectively. Values were relatively stable throughout the three year study period. The k(red) parameter does not show any values greater than 1.0 due to the lack of spectral contrast between the canopy and the laterite soil background. All combinations of land cover type were shown to be independent based on analysis of variance tests for independence ($P<0.001$ were calculated between all possible combinations of bare-woodland-forest land cover types). These results suggest that the MISR k(red) parameter can be used to accurately differentiate between bare land, woodland, and forest land types.

Changes in k(red) values were also observed between 2001 and 2003 around charcoal production sites (Figure 4-2). Plotting the k(red) values over time resulted in a sigmoid curve with k(red) values beginning low, then increasing over a short period of time. The jump in k(red) value may be related to the harvesting of charcoal in these locations. Analysis of variance of mean k(red) values from the Yoliboubou and Ndoussoua locations showed significant changes between pre and post harvest values ($P<0.01$), suggesting that pre-harvest and post-harvest stages can be observed. Individual charcoal production sites from Yoliboubou and Ndoussoua (57 unique sites) displayed significant differences in pre- and post- harvest values ($P<0.001$).

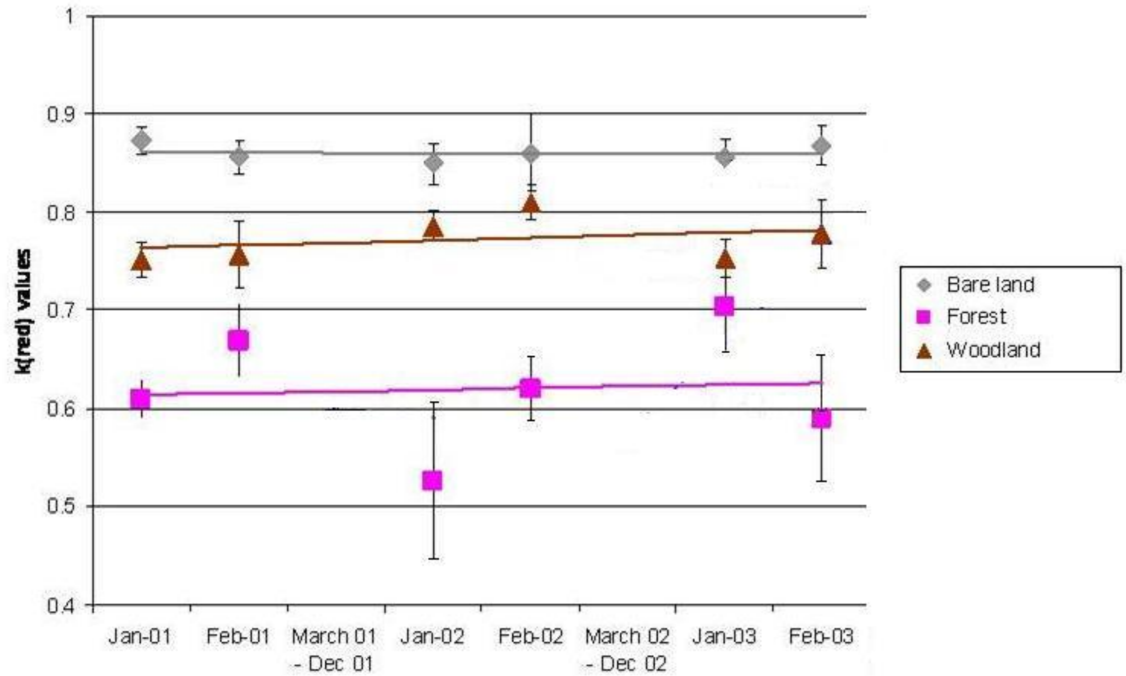

Figure 4-1 - Variation in mean k(red) values for bare, forest and unchanged woodland cover types over time (2001–3). Values were derived from the inversion of the RPV model. Vertical error bars represent the standard deviation from the mean. ANOVA tests concluded that all possible combinations of forest–woodland–bare land-cover types are independent of each other ($p<0.001$).

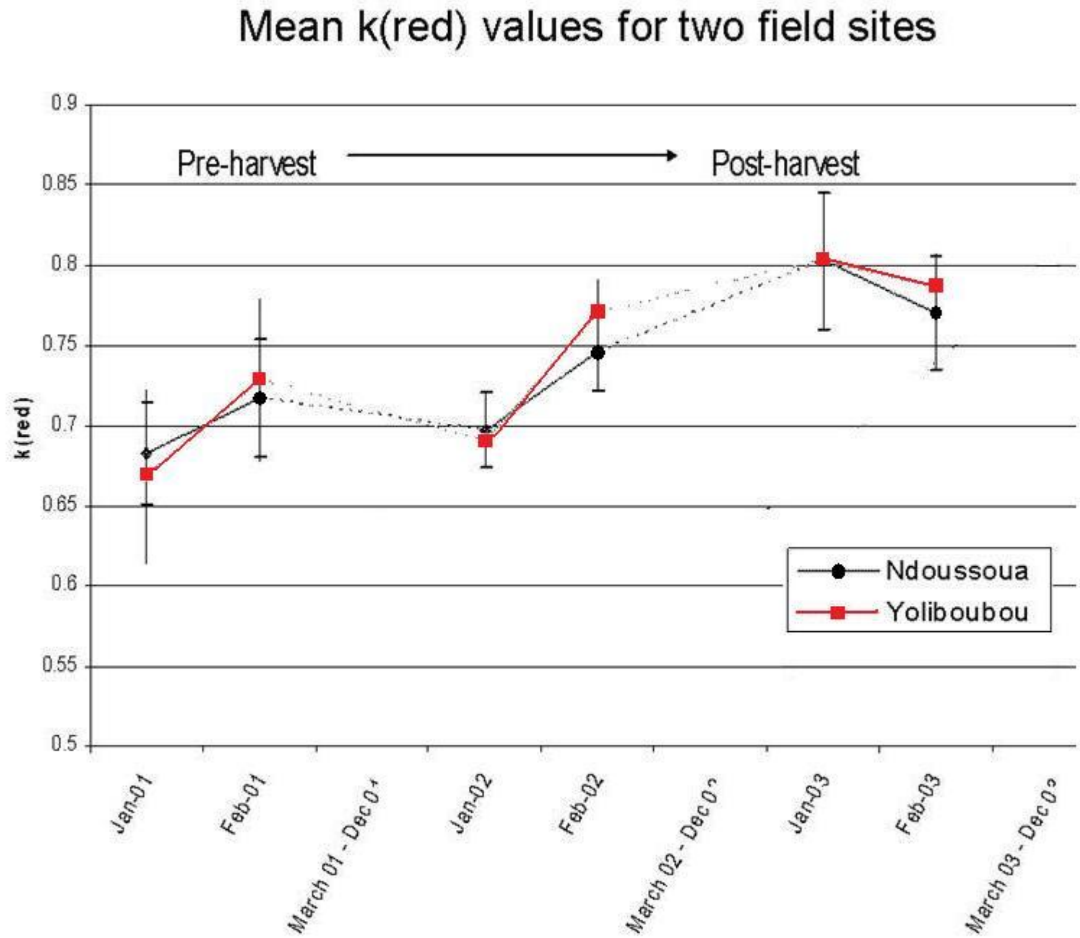

Figure 4-2 - Pre- and post-harvest mean k(red) values for two sites within the Tambacounda study area. Mean k(red) values were calculated from 25 and 32 unique charcoal sites identified in 2002 for Ndoussou and Yoliboubou villages, respectively. Vertical error bars indicate standard deviation from each mean k(red) value at that point in time. The dashed lines between data points are interpolated k(red) values from March to December. Data were not collected during these months because of cloud and aerosol contamination. ANOVA tests demonstrate that pre- and post-harvest conditions are independent datasets ($p < 0.01$).

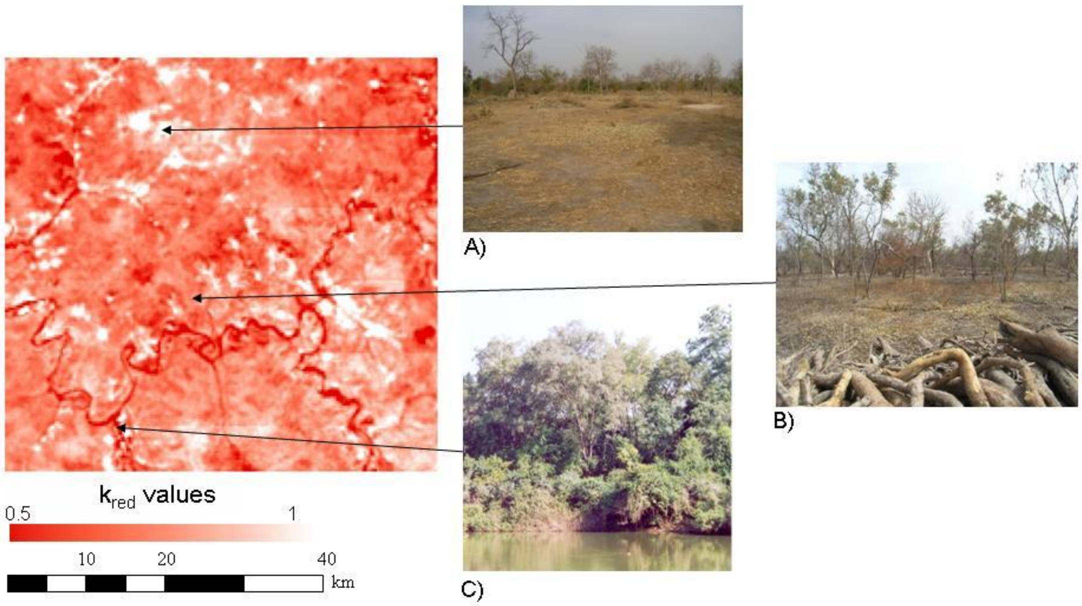

Figure 4-3 - Map of k(red) values derived from inversion of RPV model collected in the red band of MISR instrument over Tambacounda region of Senegal on 9 January 2001. The color code goes from grey tones (k(red) near 0.5) to white colours indicating pixels that exhibit k(red) values near to 1. (a) Bare land with 'low' vegetative structure; (b) a typical woodland environment with relatively 'medium' levels of vegetative structure; (c) a typical gallery forest with relatively 'high' levels of vegetative structure.

Discussion

The relationship between k(red) value and land type appears to be inversely related to vegetation structure. Vegetation structure levels are highest when k(red) is approximately 0.5; areas of forest cover where structural variation and canopy homogeneity are highest. As k(red) approaches 1, the canopy becomes less continuous and vegetation structure decreases resulting in land cover types moving towards bare land (Figure 4-3).

The woodland areas of Senegal consist of large trees dominating the segmented canopy (canopy cover of 10%-60%) and understory trees and shrubs over laterite soil (Wood et al. 2004, Manga 2005). The inverse relationship demonstrated in this study could be due to the incomplete canopy cover found in the woodland environment or a lack of significant contrast between the vegetation and soil background to create the bell-shaped anisotropy patterns seen in previous studies (Pinty et al. 2002, Armston et al. 2007).

Charcoal production sites displayed k(red) values in the pre-harvest stage most closely related to woodland environments (mean=0.69). After harvesting, values moved away from that of the woodland towards the bare land classification (mean=0.78). The increasing k(red) value after harvest is consistent over time and the differences in k(red) values from pre- and post-harvest time periods is highly significant across all plots with known charcoal production ($P<0.0001$). These results suggest that there has been a loss of sub-pixel heterogeneity and therefore an increase in vegetative structural homogeneity.

Recent studies have shown that multi-angle observations are useful for extraction of disturbance related to change in canopy and understory reflectance caused by fire and insects (Pocewicz et al. 2007, Hilker et al. 2009). Fire and timber harvesting occur frequently in the study area (Manga 2005) and could potentially cause a shift in k(red) values over a short period of time. These relationships between k(red) parameters, vegetation structure, and disturbance patterns will be further explored in future remote sensing analysis and field work campaigns.

Conclusion

This study has successfully characterized the relationship between MISR-derived land surface values and forest change in the Tambacounda region. It is evident from the results that the RPV model k(red) parameter can consistently classify land cover types based on vegetation structure and display spatial and temporal patterns corresponding to known variation in vegetation structure caused by charcoal extraction. The results also suggest that an inverse relationship exists between k(red) values and vegetation structure.

The RPV model appears to be appropriate for linking MISR data to land cover type and change in the Tambacounda study area. Analysis of k(red) values around known charcoal production sites suggest that MISR can be used to differentiate between pre- and post- harvest woodland conditions. Although specific locations of charcoal production cannot be derived from this MISR product, it does show significant potential for monitoring vegetation change over time. Future research will expand on this to test the k(red) parameter's capability to detect woodland regeneration over time. It is hypothesized that if woodland is being left to fully regenerate k(red) values should return to pre-harvest values. If land conversion is taking place after charcoal production then k(red) values should remain at post-production levels or even increase to match that of bare land. These results could then be used by forest managers to assess the sustainability of forest extraction practices in the woodland environment.

Chapter 5 - Using MISR to Monitor the Effects of the Harvesting of Wood for Charcoal Production on Forest Structure and Regeneration in Senegal

Abstract

Harvesting of wood for charcoal production has led to conclusions that charcoal production leads to widespread forest degradation across Africa, but the effect of charcoal production on vegetation structure is not well understood. This chapter tests the MISR derived k(red) parameter to 1) detect differences between harvested and undisturbed sites and 2) detect subtle changes in structure in relation to the known time since last harvest. A total of 77 field sites with known forest structure were used to validate 1x1 and 3x3 pixel k(red) kernel values from March 2008. Twenty-six sites of known years since last harvest were used to test MISR's ability to detect subtle changes in forest structure. Results suggest that k(red) is not capable of consistently differentiating structural differences between harvested and undisturbed sites and does not detect structural changes as plots regenerate after being cut. A weak significant relationship exists between k(red) values and harvested site plot height. Although no other significant relationships are shown, this demonstrates the potential of multi-angle sensors to detect change in forest structure due to charcoal harvesting or other disturbances that change the forest canopy height.

Introduction

Harvesting of wood for charcoal production has led to conclusions that charcoal production leads to widespread forest degradation across Africa (Post and Snel 2003, Tappan et al. 2004, Mwampamba 2007), but the effect of charcoal production on vegetation structure is not well understood. Vegetation structure, as defined in chapter 4, is the 'the horizontal and vertical distribution of components within a plant community' (Jupp and Walker 1996). Local and regional quantification of forest structure and regeneration is needed to fully understand the impact charcoal has on the forest environment and assist the development of appropriate forest management practices throughout sub-Saharan Africa.

Remote sensing technology offers the ability to accurately and efficiently monitor forest resources (Justice et al. 1998, DeFries et al. 2002, Coppin et al. 2004). To assess changes in vegetation structure after disturbances like the harvesting of wood for charcoal production, sub-pixel variation in canopy heterogeneity must be detected. Multi-angle remote sensing sensors like the National Aeronautics & Space Administration (NASA)'s Multiangle Imaging SpectroRadiometer (MISR) satellite collects data across four spectral bands and nine view angles at a spatial resolution of 275m. Research since MISR's launched in 2000, has demonstrated its capabilities in detecting changes in canopy heterogeneity (Widlowski et al. 2001, Gobron et al. 2002, Pinty et al. 2002, Armston et al. 2007, Su et al. 2007a, Chopping et al. 2008, Sedano et al. 2008, Chopping et al. 2009).

The previous chapter demonstrated the MISR k(red) parameter's ability to differentiate between landcover classes and between pre and post-harvest forest conditions. This chapter tests the capability of the MISR derived k(red) parameter in detecting changes in forest cover due to extraction of wood for charcoal production.

Field data, collected from January-April 2008 and discussed in Chapter 3, was used to validate MISR derived k(red) values across the Tambacounda landscape. Analysis of the field data concluded that significant differences existed between harvested and undisturbed plot percent canopy cover (PCC), average tree plot height and plot density (chapter 3). Validation points were categorized by harvested and non-harvested sites and the number of years since the last known harvest. MISR k(red) values within classes were tested against field information to test the instruments capability in detecting local changes in forest structure.

Goals and Objectives

The goal of this chapter is to assess the relationship between the bidirectional reflectance factor (BRF) land surface values and forest change resulting from the harvesting of wood for charcoal production and subsequent forest regrowth. This chapter provides validation of the previous MISR k(red) results discussed in Chapter 4 by (1) assessing the utility of the MISR k(red) parameter for monitoring the impact of charcoal production undisturbed and harvested sites; and (2) detect subtle changes in forest structure due to tree regeneration after the cutting of wood for charcoal production.

Data and Methodology

MISR Level 1B2 Terrain Projected Radiance (Version F03_0022, Version F03_0024), Level 1B Geometric Parameters (Version F03_0012, Version F03_0013, Version F03_0014), and Level 2 Land Surface Products (Version F04_0015, Version F04_0017) covering the study area were acquired through the Earth Observing System (EOS) Data Gateway at the National Aeronautics and Space Administration (NASA) Langley Research Center Atmospheric Science Data Centre. The Level 1B2 Terrain Projected Radiance data was acquired in Global mode.

Data used for this study were from March 18, 2008. This date was selected to match field survey dates. During this time period, there is also a lack of cloud cover, smoke, and other atmospheric contaminants. Minimal cloud and smoke contamination was present in this scene allowing for the acquisition of pixel values for each of the 77 field validation plots.

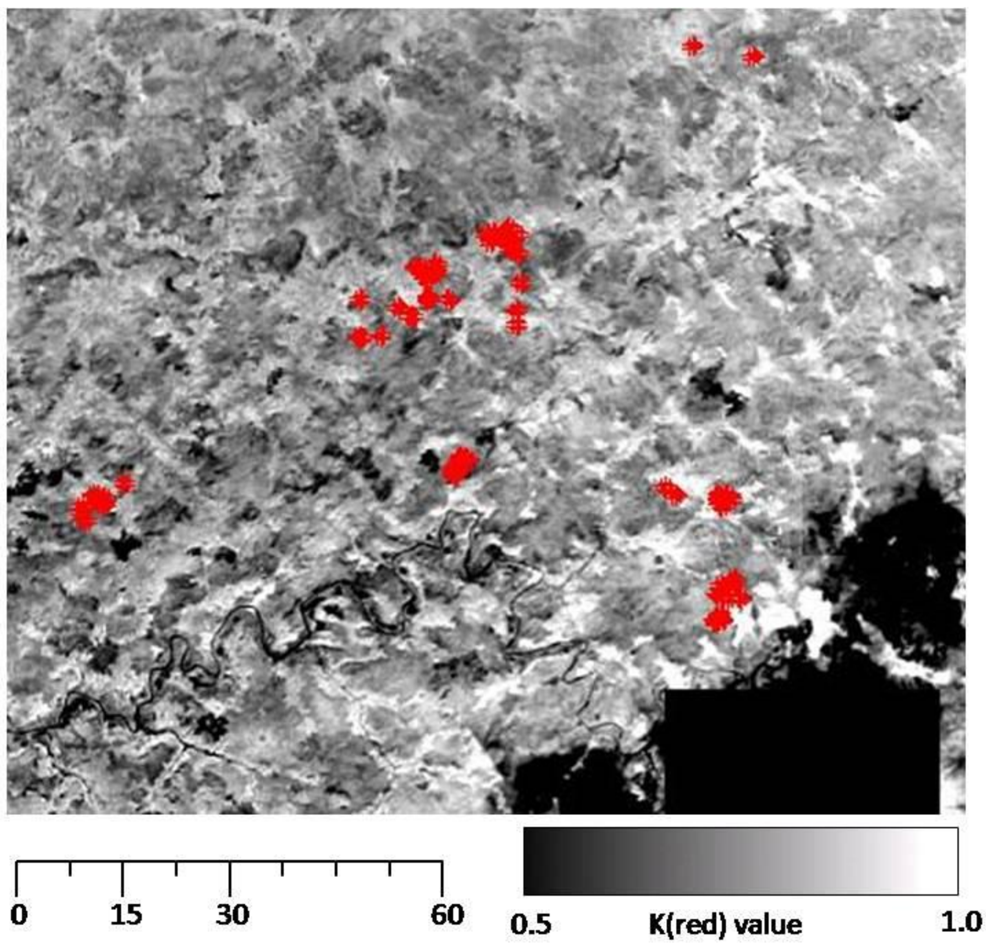

Figure 5-1 - MISR k(red) output of study area. Red dots indicate field plots where forest structure variables (Percent Tree Cover (PCC), plot tree height and plot density (trees/hectare) were collected from January through April 2008. Low k(red) values, darker colors, are areas of more dense vegetative structure (forests and dense woodlands) while lighter colors are less dense woodlands, agriculture and bare lands. The large dark portions in the bottom right of the scene were omitted from the calcuation of k(red) due to cloud or other atmospheric contamination.

Vegetation structure was estimated using the Armston method of MISR Rahman Pinty Verstraete (RPV) inversion (Armston et al. 2007). This process uses MISR "at sensor" radiance values to calculate surface bidirectional factor (BRF) followed by an analysis of the nine MISR view angles fitted with the RPV model to obtain the best set(s) of data. Detailed descriptions of the RPV model are available (Rahman et al. 1993, Widlowski et al. 2001, Pinty et al. 2002). Further explanation of the models k(red) parameter output is found in Chapter 4.

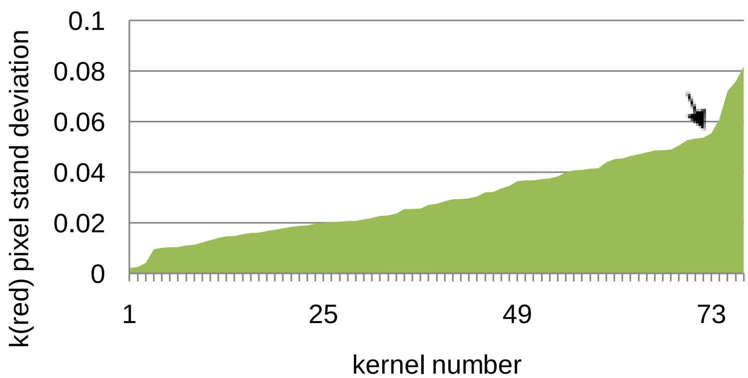

Figure 5-2– Variability in units of standard deviation for a 3x3 kernel. A standard deviation threshold of 0.055 (marked with and arrow) was selected based on the natural break at this point. 60 of the 77 original plots where within this threshold.

Field data were collected in 77 plots in January through April 2008 (Figure 5-1). 52 plots were surveyed that had previous charcoal activity and 15 plots were surveyed as undisturbed sites (no known charcoal extraction based on visual assessment and/or local knowledge). Based on local knowledge or previous field work conducted by Dr. Alla Manga (University Cheikh Anta Diop, Dakar) in 2003, 27 of the sites were classified as either being harvested in the past year, within the last 1-2 years, within the previous 2-4 years, or within the previous 4-6 years.

Plots were classified as harvested or undisturbed and years since last known harvest. Variables related to plot vegetation structure (average plot tree height, percent canopy cover (PCC), and plot density) were calculated and regressed against k(red) values.

To maintain high geometric data quality, MISR image geolocation and camera co-registration errors have been carefully monitored and refined (Jovanovic 2007). Geolocation errors still exist ranging from 115m at nadir to up to 165m at the most oblique angles (MISR 2001). In many instances, plot location was not in the center of the pixel therefore making it susceptible to pixel value error based on geolocation error. To correct for this, a 3x3 pixel kernel with the plot pixel in the center was sampled. Further refinement of the sample was made to select only the most accurate 3x3 kernels. A standard deviation threshold of 0.055 was calculated (Figure 5-2). Applying this threshold reduced the number of 3x3 kernels to 60 (540 pixels).

Table 5-1 - Plot characteristics within all undisturbed and harvested plots

Plot characteristics	Undisturbed		Harvested		
	Mean	SD	Mean	SD	P-value
k(red)	0.81	0.05	0.81	0.05	NS
k(red) - select 3x3 kernels	0.81	0.04	0.81	0.04	NS
Estimated Canopy Cover (%)	48.13	15.71	19.17	12.45	***
Height (m)	7.78	1.24	4.17	1.48	***
Plot density (trees/hectare)	246.67	69.73	270.77	134.92	NS

Plot density and estimated tree height values were calculated from trees and coppiced trees.
*** $P<0.001$, NS not significant based on one-way ANOVA

Table 5-2 - Regression results for k(red) values

	1x1 harvested	3x3 harvested	1x1 undisturbed	3x3 undisturbed
PCC	-0.002	0.001	-0.000	0.000
	(0.001)	(0.000)	(0.001)	(0.000)
Height	0.003	-0.001	0.027	0.005
	(0.006)	(-0.001)	(0.013)	(0.006)
Density (trees/ha)	0.000	-0.000	0.000	0.000
	(0.001)	(0.000)	(0.000)	(0.000)
Adjusted R-squared	0.032	-0.001	0.162	0.025
No. observations	61	432	14	90
p-value	NS	NS	NS	NS

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

Results

Values for 1x1 k(red) (77 pixels) and 3x3 kernel k(red) (693 pixels) were recorded over the study area. K(red) parameter values for 1x1 pixels had a minimum of 0.69, maximum of 0.93, mean of 0.82 and standard deviation of 0.05. K(red) parameter values for 3x3 pixel kernels were a minimum of 0.69, maximum of 1.0, mean of 0.82 and standard deviation of 0.06. When thresholding was applied, 3x3 k(red) kernels were reduced to 60 plots (540 pixels) with a minimum of 0.69, maximum of 0.92, mean of 0.81 and standard deviation of 0.04.

Field surveys discussed in Chapter 3 demonstrated significant differences between vegetation structural characteristics of harvested and undisturbed sites (Table 5-1). Field results also suggest that plot level regeneration is occurring after trees are harvested for charcoal production. Significant changes in plot vegetation structure (average plot height and average plot dbh) were recorded over time.

All k(red) values for 1x1 and 3x3 threshold kernels were classified as harvested or undisturbed to assess MISR's ability to differentiate between harvested and undisturbed plots. No significant statistical differences were found between the two classes for both 1x1 and 3x3 threshold kernels (Table 5-1). Figures 5-3, 5-4 and 5-5 show scatterplots of 1x1 and 3x3 kernels plotted against plot structural variables (PCC, average plot height and plot density) collected during field work. The only statistically significant result was between undisturbed 1x1 pixel k(red) values and average undisturbed plot height. Although this result was statistically significant at $p<0.05$, the relationship between the two is very weak.

The harvested and undisturbed data were further analyzed by multiple regression, using PCC, plot tree height and plot tree density as explanatory variables. To ensure collinearity between explanatory variables does not introduce bias, variance inflationary factor (VIF) statistics were calculated. Results from these diagnostics procedures demonstrated VIF statistics ranging from 1.04 to 1.9 for harvested and undisturbed plots, suggesting that the study was not confounded by collinearity. Harvested and undisturbed k(red) values for 1x1 pixel and 3x3 pixels kernels were used as the dependent variable (Table 5-2). Results demonstrate that no significant relationships are found suggesting that harvested and undisturbed k(red) values have no relationship with the explanatory variable field data.

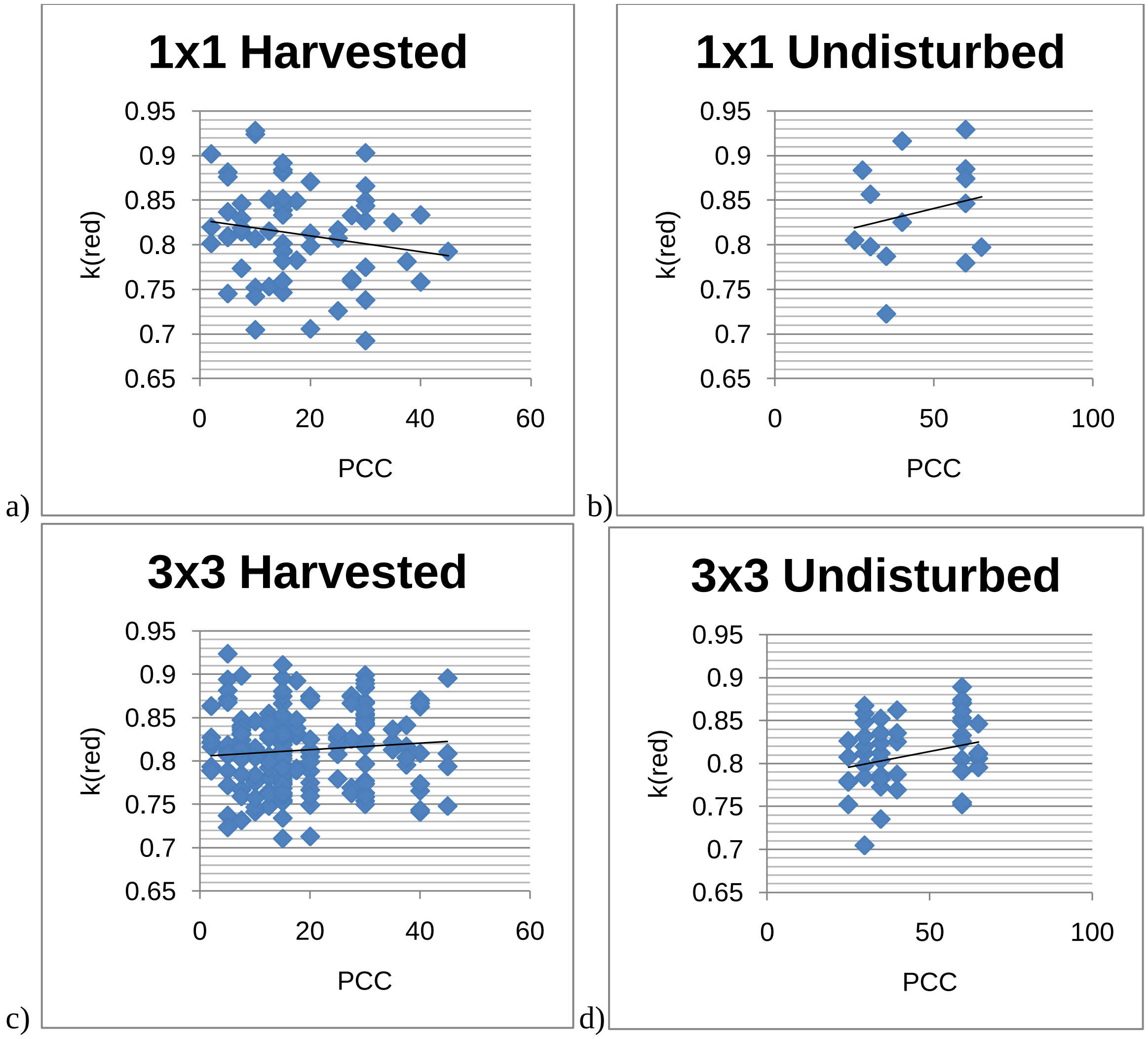

Figure 5-3– Scatter plots of Tambacounda study area 1x1 and 3x3 MISR k(red) values plotted against a) harvested plots PCC (1x1 pixel) ($y = -0.0009x + 0.8279$, $R^2 = 0.0309$), b) undisturbed plots PCC (1x1 pixel) ($y = 0.0009x + 0.7968$, $R^2 = 0.0508$), c) harvested plot PCC (3x3 pixel) ($y = 0.0004x + 0.8055$, $R^2 = 0.0092$), and d) undisturbed plot PCC ($y = 0.0007x + 0.7768$, $R^2 = 0.0658$). No significant relationships exist.

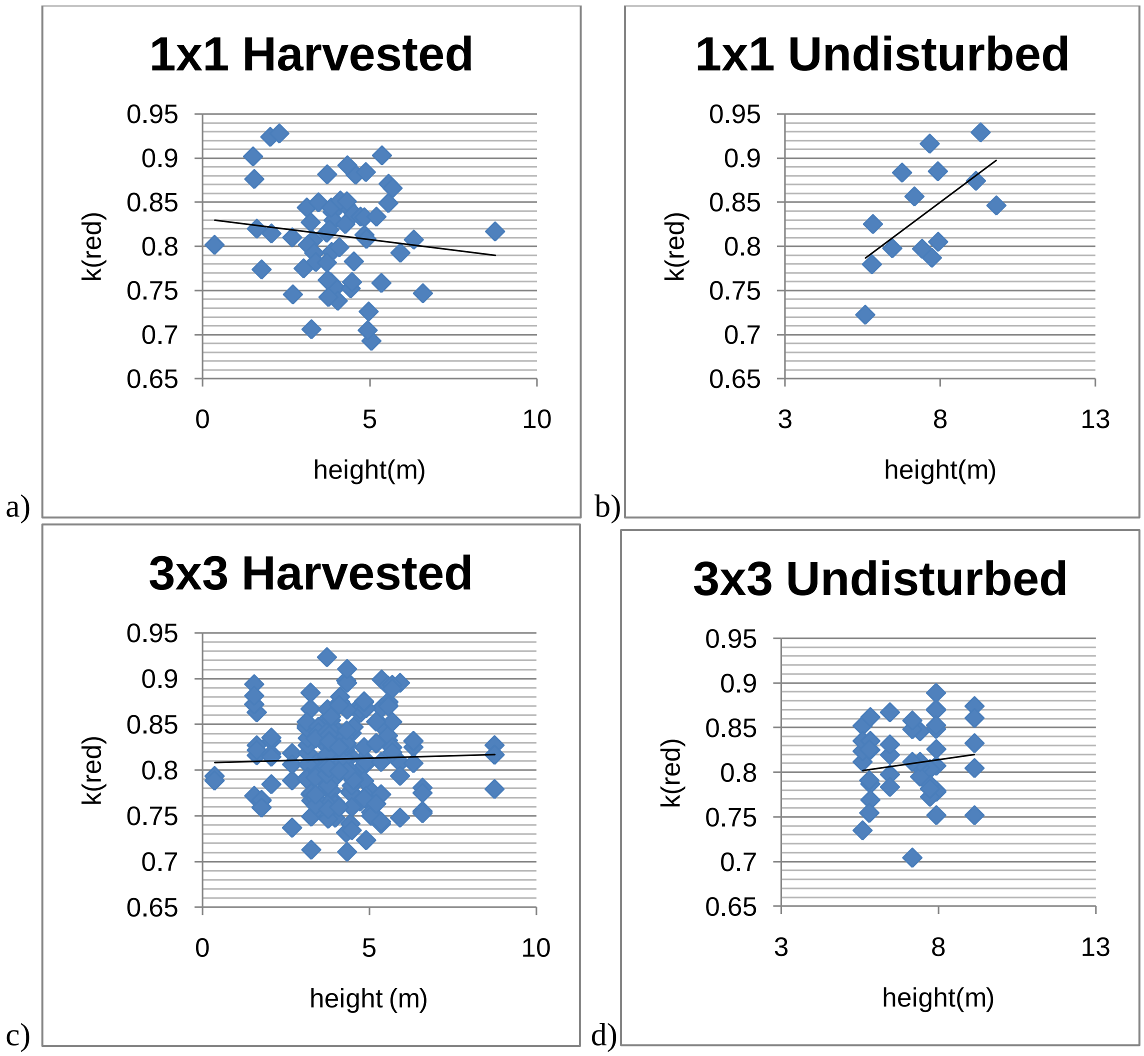

Figure 5-4 – Scatter plots of Tambacounda study area 1x1 and 3x3 MISR k(red) values plotted against a) harvested plots height (1x1 pixel) ($y = -0.0047x + 0.8312$, $R^2 = 0.0146$), b) undisturbed plots height (1x1 pixel) ($y = 0.0262x + 0.6403$, $R^2 = 0.3528$)**, c) harvested plot height (3x3 pixel) ($y = 0.001x + 0.8081$, $R^2 = 0.0012$), and d) undisturbed plot height ($y = 0.0051x + 0.7734$, $R^2 = 0.0173$). P-value, **$p<0.05$.

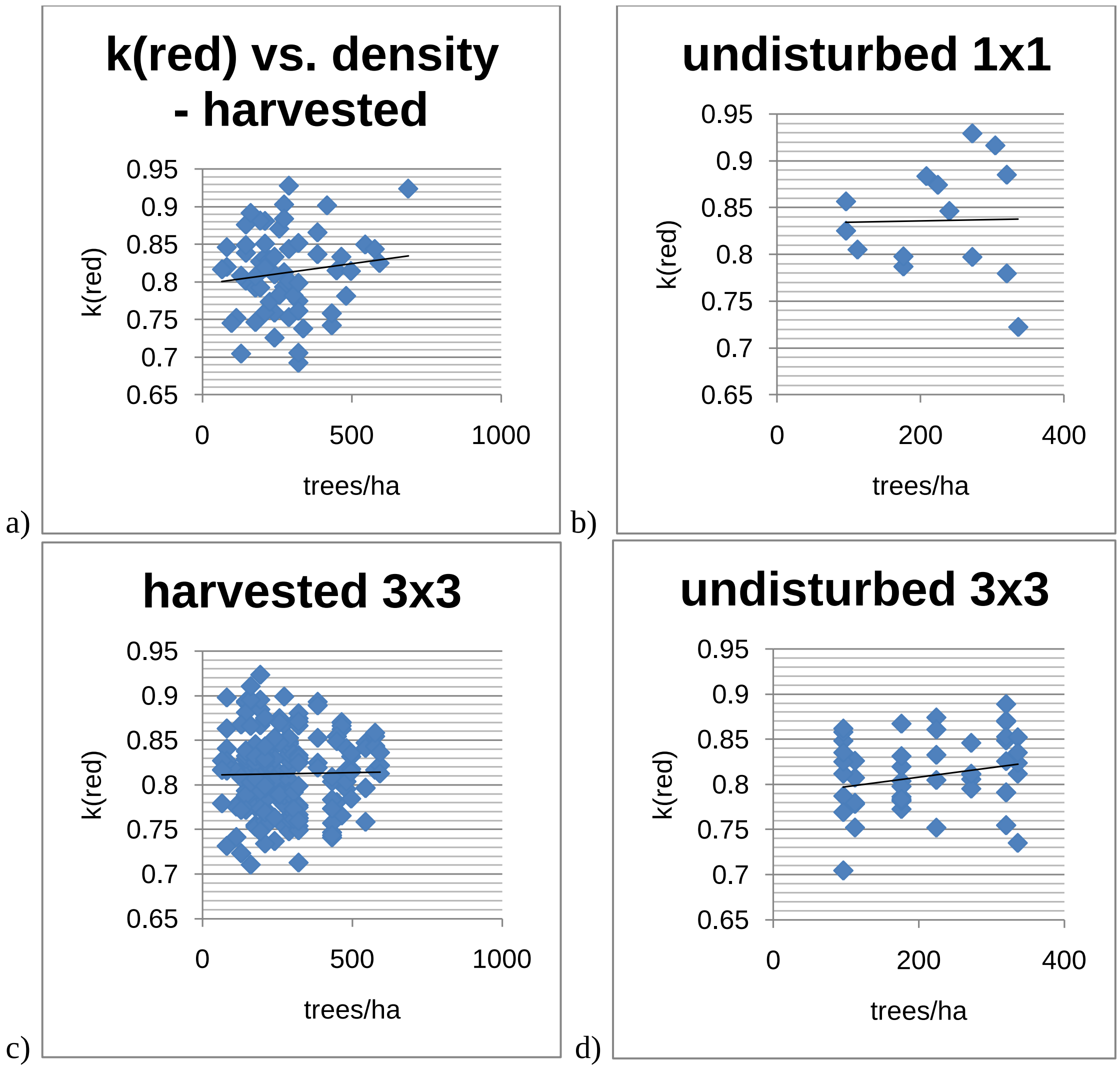

Figure 5-5– Scatter plots of Tambacounda study area 1x1 and 3x3 MISR k(red) values plotted against a) harvested plots density (1x1 pixel) (y = 6E-05x + 0.7971, R^2 = 0.0191), b) undisturbed plots density (1x1 pixel) (y = 2E-05x + 0.8327, R^2 = 0.0005), c) harvested plot density (3x3 pixel) (y = 6E-06x + 0.8107, R^2 = 0.0004), and d) undisturbed plot density (y = 0.0001x + 0.787, R^2 = 0.051). No significant relationships exist.

K(red) values from plots with known harvest dates were analyzed to test the k(red) parameters ability to detect regeneration after harvesting for charcoal production (Figure 5-5). As demonstrated by the field data, changes in vegetation structure are relatively slow and subtle after harvest. Average coppiced tree heights increase during the first two time-steps, then take a small drop during the third time-step before increases again, but do not return to undisturbed levels. Additionally, PCC increases at each time step after cutting occurs. The increases in plot PCC and average plot height suggest that vegetation structure is increasing.

Analysis for the k(red) values within the plots of known harvest date shows no statistical difference between k(red) values of different time steps (Fig 5.5). K(red) values change at each time-step, but no changes are statistically significant. Additionally, k(red) values fluctuate in spite of the steady increase in tree height demonstrated within the plots.

Discussion

The results discussed in chapter 4 were encouraging. The MISR derived k(red) parameter was able to differentiate between bare, woodland and forest landcover types and display spatial and temporal patterns corresponding to known variation in vegetation structure caused by charcoal extraction.

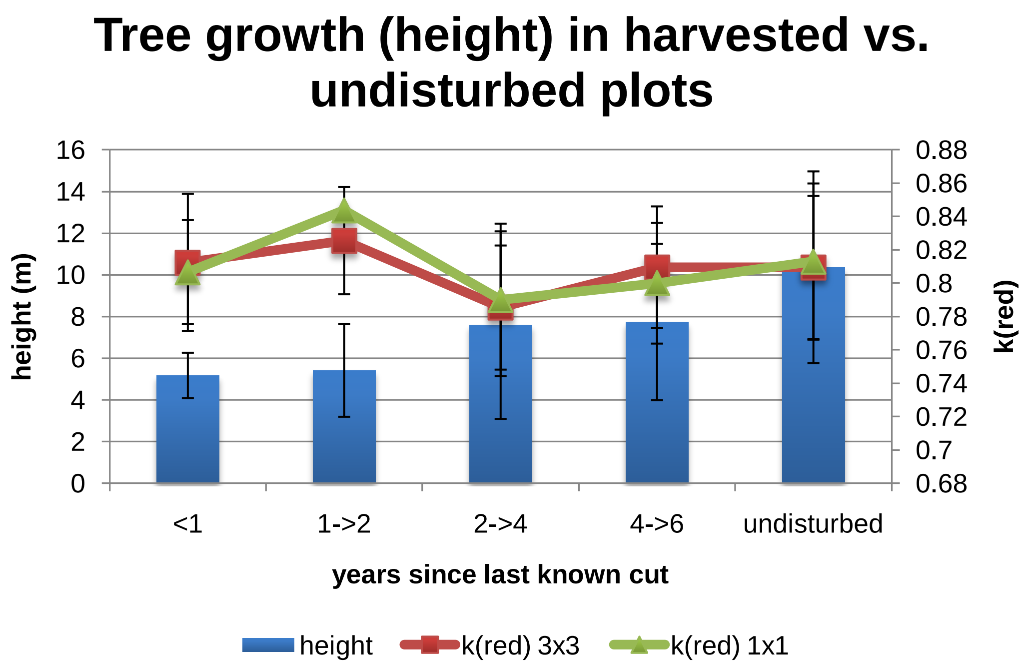

Figure 5-6 – Bar figures show average plot height values over time since last known harvest. K(red) values over time are shown in the line graph.

Based on the results of the current chapter, MISR k(red) did not consistently detect differences in tree plot height, PCC or tree plot density in harvested and undisturbed plots. A weak relationship was discovered between 1x1 pixel k(red) values and plot tree height. Similar relationships have been found between additional MISR derived alorigthms and canopy height (Chopping 2009). These results, although weak, demonstrate the potential of multi-angle sensors to detect variations in canopy height. Within all harvested sites of known time since last cutting, MISR k(red) could not accurately detect subtle changes in forest structure due to plot regrowth.

A number of factors could have led to these results. First, the spatial scale of MISR of 275m is not optimal to detect the changes in this environment. Information gathered from field work demonstrated that the forests in the study area are highly variable. Wood is cut for charcoal production, local fuelwood consumption and timber harvesting throughout. Sometimes these activities are localized, but in many cases they are spread out over a large area.

Harvested locations from the study (chapter 4) were most clustered; with five to seven kilns located very near to each other helping to create a large degradation footprint sufficient for detection by a 275m pixel. Harvested sites visited during field work often did not cluster, but instead were spread across the landscape. Although many of the trees are cut adjacent to a kiln, the forest tree density is such that severe cutting will take place adjacent to the kiln with intensities inversely related to distance from the kiln.

Frequently kiln locations are used to stack wood and produce charcoal that is not cut in the immediate vicinity of the kiln. Charcoal producers may cut the wood up to 500 meters from the kiln. This not only spreads the impact of degradation across the landscape, but limits the dependability of the physical location to act as a marker of the assumed area of degradation.

Spreading the impact of degradation across the landscape also widely distributes regrowth across the landscape. While cutting is an individual event at a particular location, regrowth is collection of a subtle changes in forest structure over time. Thus adding to the difficultly of a 275m pixel instrument detecting changes that are happening.

Frequent fires throughout the study area might also have a negative impact on the detection of forest structure in the study area. Previous research has shown that 60 to 90 percent of the woodlands in the study area burn annually (Mbow et al. 2000, Mbow et al. 2008). The frequent burning of the landscape not only hinders tree regeneration, but also scars the soil. Changes in background characteristics significantly impact BRF reflectance values (Pinty et al. 2002, Widlowski et al. 2004). Therefore the changes in soil characteristics (from a pre-fire bright, lightly colored laterite surface to a post-fire black surface) creates less than optimal surface conditions for assessment of BRF derived values.

Conclusion

The previous study (Chapter 4) demonstrated that MISR k(red) could differentiate between land cover categories and pre- and post-harvest conditions. Based on the results of the current study, it is concluded that the MISR derived k(red) parameter does not consistently and accurately classify harvested and undisturbed plots or detect subtle changes in forest structure occurring during forest regeneration after the cutting of wood for charcoal production. These results were not surprising given the spatial resolution of MISR and the subtle changes in forest structure that were analyzed.

In other environments, MISR was able to assess forest structure by incorporating multi-angle BRF values into models for deriving forest characteristics (Chopping et al. 2008, Sedano et al. 2008, Chopping et al. 2009), but the nature and scale of forest degradation and regeneration in the study area calls for analysis at a finer scale. The weak relationships detected between k(red) value and tree plot height should be explored. A smaller scale, multi-angle sensor such as Compact High Resolution Imaging Spectrometer (CHRIS), on board the European Space Agency's Project for On Board Autonomy (PROBA) might perform well with recent work demonstrating the utility of finer-scaled multi-angle sensors in detecting subtle changes in forest structure (Rautiainen et al. 2008, Galvao et al. 2009). Further analysis of the impacts of wood harvesting on forest structure by a finer-scaled sensor could result in an accurate assessment of forest degradation and regeneration for the region.

Chapter 6 - Conclusions

The objective of this research was to assess the effects of forest management type on forest structure, tree species composition and forest regeneration around charcoal production sites in Senegal. To accomplish this, a combination of ecological and local ecological knowledge was collected through field surveys and semi-structured interviews. This information was then used to test remote sensing data to analyze patterns of forest degradation around harvested and undisturbed and across forest management types.

How does charcoal production affect forest structure and species composition?

Hypothesis 1: Forest structure and tree species composition and richness will be less in areas of charcoal production when compared to areas of no production.

Analysis in all phases of the research provided strong evidence for the acceptance of hypothesis one; significant differences exist between harvested and undisturbed forest plots. Harvesting of wood for the production of charcoal does significantly change the structure and species composition of the forest. Tree size, diameter at breast height (dbh) and height, were smaller in harvested areas. Species diversity was significantly lower in harvested than undisturbed plots. Information derived from size class distribution (SCD) analysis of the each species concluded that few species are regenerating in both harvested and undisturbed areas. Only common species are regenerating at rates to rates capable of replacing the existing population. Uncommon species, specifically large hard wood and fruit trees lack sufficient numbers of seedlings and saplings to replace current populations. For many of these species no seedlings or saplings were sampled over the entire study area in harvested or undisturbed plots.

Local people interviewed described changes that have been occurring in the forest in recent memory. In some people's opinions the forest, or bush, had changed to such a degree that it could no longer be called by the same name. A forest full of wildlife and diverse tree species was gone, replaced by a space without animals, few large or fruiting trees and only a handful of dominant tree species. Many believed that the harvesting of wood for charcoal production was part of this change. Charcoal workers cut the forest, and even though the forest regrows, they still negatively altered the landscape by cutting trees.

Remote sensing analysis of the MISR k(red) parameter also showed variations in signal values between pre- and post-harvest conditions. A significant increase in k(red) values from pre- to post-harvest conditions suggested a decrease in forest structure after wood was harvested for charcoal production over a three year time period. This analysis was not able to be applied to the regional level, but does demonstrate the potential of multi-angle sensors to detect changes in forest conditions.

What are the factors that influence forest composition and structure after charcoal production?

Hypothesis 2: Forest composition and structure are positively correlated with proximity to villages, roads and park edges.

In other regions deforestation can be associated with proximity to roads, villages (Serneels and Lambin 2001, Overmars and Verburg 2005) or park edges (Skole and Tucker 1993, Laurance et al. 2002). The results of the ecological analyses and semi-structured interviews allow hypothesis two to be rejected. Proximity to villages, roads and park edges had little relationship with plot structure and species diversity. When relationships were found using regression analysis, they were very weak and inconsistent.

These conclusions verified what interviewees had suggested; people use the entire forest. When charcoal is legally produced it could be near to a village or road, but was frequently dependent on the previous location of an old kiln and the areas with the best wood. If illegal charcoal activity occurred in an areas it often took place just far enough out of sight to avoid being caught by infrequently patrolling Forest Service employees. Transporting charcoal from these more isolated locations was not a problem because horse or donkey carts could easily access most of the forest via small footpaths connected villages and cutting through the forest.

In addition to the proximity to villages, roads or park edges other disturbances were noted throughout the study area. Livestock were seen grazing in nearly every portion of land, the impacts of fire were apparent and frequently observed across the study area and large stumps from the harvesting of mature trees for timber were frequently recorded.

These observations were confirmed during semi-structured interviews. Fire, cutting of trees for timber and grazing were cited by local interviewees as drivers of forest change. Interviewees said that charcoal workers did cut trees in the forest, but a majority of those trees were known to regrow. Many interviews believed that the loss in species diversity was due to the harvesting of wood for timber and the frequent fires that burn the region. Combinations of these two activities were thought to cause the decline of the large trees in the forest. Timber harvests cut large trees that grow slowly; before seedlings or saplings are established enough to resist fire, fires would burn the area killing nearly all of the saplings, significantly decreasing the ability of large, hard wood trees to naturally regenerate. The species of trees harvested for charcoal production were not as affected by frequent fires because of their ability to regrow quickly after being cut and resilience to quick-burning grass fires.

Do regeneration rates around charcoal production areas differ depending on forest management type?

Hypothesis 3: Land management type will result in no significant variation in regeneration rates near charcoal production sites.

Based on the results of the ecological data, hypothesis three is accepted. Forest management types do not affect the rate of regeneration near charcoal production sites. Forests are regenerating after harvesting. In all management types, regenerating tree species increase in dbh and height over time. In many Classified Forests and Rural Community Forests, charcoal workers said they returned to cut areas after four to six years. Trees in the study area are not regenerating quick enough to support this rotation cycle. The eight year rotation period proposed in co-managed areas will allow for two additional years of growth, but trees still will not reach undisturbed levels.

Additionally, forest management types have little impact on forest composition and structure after harvesting. Significant differences were shown between co-managed (Wula Nafaa and PROGEDE) harvested and undisturbed species diversity and government managed (Classified Forests and Rural Community Forests) tree species diversity, but these higher levels of species diversity might be short-term. Species diversity was reduced by over 50% in harvested Wula Nafaa and PROGEDE sites after was harvested for charcoal production. Although species diversity values were higher in these management types, regeneration patterns observed through SCD and time-since harvest analysis was low in all types. Small trees capable of natural regeneration after cutting had high regenerative properties while large, hard wood trees were present as mature trees, but very rarely encountered as seedlings or saplings.

Many co-managed areas were new to charcoal production. A severe decline in tree species diversity could be due to fewer historical disturbances (Chidumayo 2002, Jansen et al. 2008, Kindt et al. 2008). This might explain the higher levels initial levels of diversity. A wider variety of species were harvested for charcoal production in co-managed areas, some of them with poor regenerative potential in frequently disturbed environments. The severe decline in species diversity could be a result of inexperienced charcoal workers selectively cutting all trees in the area, not just those with strong regenerative potential. If these activities continue, the forest will probably continue to degrade until only the species with the highest levels of regenerative capacity, such as those in the Combrateceae family, remain.

A Management Matter?

In the forests of southeastern Senegal, from an ecological perspective, the ways in which the current forest management types are implemented do not matter. The cutting of trees for the production of charcoal has a significant negative effect on the structure and trees species composition of the forest, regardless of management type. After the harvesting of wood for charcoal production, forests are naturally regenerating, regardless of management type. The same dominant species have the same or similar regenerative capabilities, regardless of management type. Species diversity is higher in co-managed areas. Despite this, co-managed forests are decreasing in tree species diversity and the large, hard wood trees that are more numerous here, thus giving higher species diversity values, showed little capacity to regenerate naturally.

The consistency of forest structure, tree species composition and tree regeneration across management types is due to the even distribution of disturbances across the landscape. People all over the study area heavily depend on the forest for fuel, income, and food for livestock. Fires burn frequently, livestock graze and timber is cut throughout. These activities are relatively consistent. Illegal charcoal production and timber extraction are done far-enough out of the site of Forest Service employees to avoid being caught. In co-managed areas, disturbances such as illegal timber harvesting and fires still frequently occur.

The central hypothesis behind co-management is when people have the opportunity to manage the forest and benefit financially from the forest; they will regulate access and therefore limit ecological degradation. If this hypothesis is true, then why are co-managed forests losing tree species diversity as quickly as government managed forests? After two, three or four rotations might these forests be at the same level of degradation as the government managed forests?

Tree species preferred for charcoal production are the most abundant and resilient of all the trees in the forest. After harvesting and even in spite of frequent fire people said these species naturally regenerate and are re-harvested. Forest management had the potential to play an important role, but under current government or co-managed types a lack of consistent action and forestry law enforcement exists. The question still remains if management type would result in increased regeneration and species diversity if forestry laws were enforced, by government officials and/or local communities.

In rural community forests, most interviewees believed the government was in control of the forest despite forest decentralization laws that were supposed to designate decision making power to local authorities. On paper, communities may have the authority to manage the land, but many people in the villages still believe the real authority and power to manage is held by the government. The reality is a majority of the indirect and direct decision making power is still held by government officials. The current relationship between Forest Service and local groups results in local populations having little power to control and/or manage legal or illegal forest activities. Local people felt they didn't have the responsibility or authority to tell another community member to stop cutting timber. Because of this, many illegal activities occurring in the forest, particularly timber harvesting, are left untouched and unenforced.

Management could matter if responsibilities are shared jointly amongst all acting parties. Local communities involved in co-management were pleased with the increased the income they can gain from charcoal production and forest management, but frustrated by the lack real decision making authority they are given. Local people in the study area also displayed concern for the degrading conditions within the forests and want to do something about it. If real management power and resources are given to these communities a domino effect of improved enforcement and decreased illegal activity might follow.

Policy Recommendations

Based on this research three policy recommendations are proposed to help ensure sustainable forest extraction practices in the study area:

1. The production of charcoal should not be limited to specialized parks or forests, but should be allowed in any forest (classified, co-managed or community rural forest) were local communities agree to grant access.

2. Increased monitoring and enforcement of illegal timber extraction should be conducted by both local and government stakeholders.
3. Payment systems for the monitoring of forest extractions activities should be continued and expanded in the study area.

Recommendations are not intended to be exhaustive, but are only the most salient points that can be directly drawn from the research. These recommendations along with strengthened laws transferring increased decision-making and law enforcement authority to local communities could result the further decentralization of decision making power and monitoring responsibility to local communities by granting them the authority to decide who can access forests surrounding local communities, what forest products are allowed to be harvested, when it is allowed and by whom and how local communities are compensated for their efforts in ensuring sustainable forest extraction practices.

1. **The production of charcoal should not be limited to specialized parks or forests, but should be allowed in any forest (classified, co-managed or community rural forest) were local communities agree to grant access.**

The resilience of a site to disturbance and its natural regenerative capacity are determined by the species composition of the site. The Tambacounda study area is dominated by trees from the Combrataceae family, most notably the *Combretum glutinosum* species (53% of the all individuals sampled). The resistance of this species to change is highly important because of the frequent natural and human driven changes in the study area including, frequent burning, harvesting for fuelwood (charcoal and firewood) and timber collection. This species is also preferred for the production of charcoal by local producers because of the known regenerative capacity and higher quality of charcoal (longer burning and lower amounts of smoke) it produces.

This research also demonstrated that the effects of harvesting of wood for the production of charcoal are distributed throughout the study area independent of management type and proximity to roads, villages and park boundaries. Sites that were harvested for the production of charcoal were reduced in forest structure, but regeneration did occur in all sites, again regardless of management type and proximities. These results strongly suggest that the natural ecology of the forests in the study area can support charcoal production without significant forest management efforts.

The development of co-managed forests in the study area by coordination between international donor agencies (World Bank and USAID) and the Senegalese forest service has resulted in proposals that would restrict production of charcoal to these zones (PROGEDE 2007, Heermans 2008). The concentration of harvesting zones would further restrict the land that is legally open to the harvesting of wood for charcoal production and could potentially create greater tension between communities that are "allowed" to produce charcoal and those who are not.

Evidence for allowing charcoal to be produced across the landscape was also demonstrated by the changes in species composition in newly harvested co-managed areas. Greater than 50 percent declines in species diversity were observed in some co-managed plots. Selective harvesting of most tree species was practiced in these plots (generally cutting two-thirds of all trees on the plot desired for charcoal). Although a wider variety of species were initially present in these sites, the decline in species diversity suggests that a wider variety of species are being cut for charcoal or other practices around the same time. Many of these species lack the ability to regenerate naturally or are incapable of regenerating because of frequent disturbance via fire, grazing or other human and/or natural disturbances.

The opening of the entire study area to charcoal production is also supported by the knowledge and high level of dependence people throughout the study area have on the forest. Local people in all management types depend heavily on the forest for energy, income, graze land and food. Over many generations, local communities have developed a rich understanding of the forest and have observed changes in the diversity of flora and fauna in recent memory. They feel that government management has had little ecological benefit for the forest and few social benefits for the local population.

Currently, local communities are not fully involved in discussions pertaining to management, extraction and enforcement of forest laws. Local leaders and community members expressed the desire for increased responsibility and power to determine how the forest is managed. The opening up of extraction to all areas could increase the decision making power of local communities; allowing them to determine extent and timing of forest access for charcoal production.

2. **Increased monitoring and enforcement of illegal timber extraction should be conducted by both local and government stakeholders.**

The removal of hardwood and fruit trees decreases tree species diversity and negatively impacts local communities by permanently removing sources of fruit, traditional medicine and other non-timber forest products. The illegal removal of these trees must be closely monitored by local populations and supported by Forest Service and donor agency activities to ensure that sustainable practices of hardwood trees are created.

As previously stated the forests in the study area are dominated by a handful of resilient species capable of regeneration after being harvested for charcoal production, but species diversity is greatly increased by the presence of slower growing hardwood or fruiting trees such as *Cordyla pinnata, Pterocarpus erinaceus, Sclerocarya birrea, Ficus dicranostyla, Terminalia macroptera, Bombax costatum* and *Cassia sieberiana.* Although theses species are less abundant, they are still depended upon by the local population as sources of fruit, natural medicine and other non-timber forest products, construction materials such as support beams for building roofs and as income through timber sales for the construction of furniture, drums or construction materials.

Local populations believe that unsustainable timber extraction has contributed to the decreasing tree species diversity in the study area. This was validated during ecological surveys when no large, hardwood species demonstrated the proper size-class distribution required for natural regeneration. Large, hardwood trees were sampled as mature individuals and very infrequently as seedlings or saplings. Often they were observed as stumps or recently felled trees. None of these species regenerate via coppicing like the highly resilient and abundant species in the Combretaceae family, increasing the probability of seedlings and saplings dying after fire or other disturbances.

The act of cutting of hardwood trees for timber extraction was observed throughout management types, with little to no enforcement conducted by local monitors, Forest Service or donor agency officials. This was stated to occur because local monitors felt that management plans placed an emphasis on charcoal production, not on timber extraction and therefore they did not have the power, authority or responsibility to stop someone from harvesting timber. Forest Service or donor agency officials were said to visit sites infrequently and when they visited did not go deep enough into the forest to detect illegal timber harvesting.

3. **Payment systems for the compensating local populations for the monitoring of forest extractions activities should be strengthened and expanded.**

Although the forest is naturally regenerating after most harvesting of wood for charcoal production, monitoring by local populations must continue to ensure that extraction is being conducted in areas agreed upon by the community and charcoal producer, the sustainable extraction of large hardwood trees for timber production is in place and the impact of fire is being minimized by reducing fuel loads (cutting grass) and maintaining firebreaks. These monitoring responsibilities should be shared between local community members, Forest Service officials and donor agency partners. Individuals interviewed strongly believed that dependable employment and payment for services is necessary for local enforcement to succeed. Payment for local monitoring services could be a shared cost of the Forest Service, donor agencies and local communities.

Results and conclusions from semi-structured interviews and field observations demonstrate that local populations are frustrated and often feel powerless in respect to management practices and implementation. In co-managed areas people were relatively content with management, but still felt they lacked the authority to enforce forestry laws. In these communities, individuals and groups are theoretically rewarded for participation in co-management of forests by gaining a return from taxes and/or fees paid by charcoal workers. This money is then divided up amongst all participating communities and to individuals who assist with forest monitoring and enforcement of forest rules and regulations regarding the legal and illegal harvesting of wood and timber.

In many instances people knew of these regulations and profit sharing mechanisms, but felt like profits were not properly distributed to individuals and the community. Additionally, because most co-management project emphasized the regulation of charcoal production, other illegal activities, particularly timber extraction went unregulated.

Continued payment of local monitors is necessary for the effective management and regulation of the forest environment in the study area. Monitoring must be consistently and frequently conducted across large areas. Therefore, local monitors must be provided with sufficient monetary compensation (i.e. – full-time employment). They should also be provided with well-maintained bicycles that would allow them to more efficiently monitor areas (foot monitoring would also be necessary in much of the area).

A Multidisciplinary Research Approach

This research demonstrated the utility of incorporating social, ecological and remote sensing methods to assess the ecological impacts of the harvesting of wood for charcoal production and the effect of different forest management types on forest properties at local and regional scales. Each method provided a unique perspective. Together they complemented each other and created a comprehensive understanding of the present state of the forest.

Information gathered during the semi-structured interviews added depth to the research by informing and helping guide the collection of ecological data and the analysis of remotely sensed data. Forest ecological data quantified what many interviewees suggested, that the forests were changing, large species were disappearing and only the most resilient species remained. Ecological data demonstrated the similarities and differences between management types while the information from the semi-structured interview helped explain why they exist. Data gathered from semi-structured interviews and ecological surveys were used to validate, test and complement remote sensing data which showed the potential to assess the effects of charcoal production on the entire landscape.

Each aspect of research also added unique perspectives and information that contributed to a deeper understanding of how the harvesting of wood for charcoal production and forest management types influences forest composition and regeneration.

Information collected through semi-structured interviews brought forward the fine-scale local ecological knowledge people in the communities have of the surrounding forest (Chapter 2). Interviewees spoke at length of the changes occurring to forests, government and co-managed, in recent years. Local people also emphasized that forest products are important supplemental income in years of poor agricultural production; collecting and selling deadwood or producing charcoal to sell to local merchants. The effects of intensive harvesting are seen and acknowledged by charcoal workers and others alike, but equally recognized is the regenerative capacity of the forest. Interviewees also expressed frustration with forest management types stating they have little authority to manage the forest and therefore no responsibility to enforce laws.

Ecological research provided a detailed assessment of the current state of the forest and its capacity to regenerate over time (Chapter 3). This aspect of the research showed that harvesting of wood for the production of charcoal does significantly change the structure and species composition of the forest, trees are significantly smaller and plots are less diverse with only a few trees showing strong regenerative capacity. The species that are regenerating are common, small trees most in the Combretaceae family of trees (preferred family for charcoal and firewood). Large, hard wood and fruit trees are sparse and are not regenerating at sufficient levels to replace current populations.

The data gathered and analyzed in the social and ecological portions of the research were also valuable to the remote sensing component. Forest plot structure and time since harvest data was used to validate the MISR k(red) parameter capabilities in detecting changes in forest structure. Satellite data was able to detect differences between the different land classifications in the region and showed the ability to detect pre- and post-harvest conditions (Chapter 4). Further analysis of the forests stretched the intended capabilities of MISR by using it to detect subtle changes in forest structure due to harvesting of wood for charcoal production. A consistent assessment of forest regeneration was not accomplished (Chapter 5), but he satellite did demonstrate the potential of using multi-angle remote sensing technology to measure forest structure.

Next Steps – Future Research

The increasing demand for charcoal throughout Africa has the potential to greatly alter the state of the environment if it is not done in a sustainable manner. The combination of local community forest dependence, urban demand and the implementation and debate of different forest management types is apparent throughout Sub-Saharan Africa (Arnold et al. 2006, Mugo and Ong 2006, Mwampamba 2007, Reed 2008). There is a wealth of research analyzing the growing charcoal demand by urban markets (Hosier and Milukas 1992, Brouwer and Falcao 2004, Maconachie et al. 2009), the need for local communities to produce large quantities of charcoal (Naughton-Treves et al. 2007, Namaalwa, Hofstad and Sankhayan 2009), the ecological degradation caused by the harvesting of wood for charcoal production (Malimbwi 2001, Chidumayo 2002, Oguntunde et al. 2008, Ayodele et al. 2009, Stromquist and Backeus 2009) and debating the best management techniques (Chidumayo 2002, Mugo and Ong 2006). Many of these studies concentrate on the miombo woodlands and forests of Eastern and Southern Africa and look at questions from an ecological, economic or social perspective. A multidisciplinary methodology, particularly one using the complementary methods and information elicited from local ecological knowledge, ecological surveys and remote sensing data would add breadth and depth to the discussion; helping better understand how ecological, social and economic processes interweave.

Additionally, each component of the approach should be independently developed. Remote sensing research should continue to explore the most effective and accurate ways to detect the subtle changes caused by wood harvesting and regrowth. Although MISR was not able to detect the subtle changes in forest structure it could differentiate between cover types and demonstrated the ability over a three-year time period to differentiate between pre- and post-harvest conditions. These successes should be built upon in the future. Recent research using the MISR satellite has shown its ability to detect changes in tree canopy height over large areas (Chopping et al. 2009) along with the ability to detect large-scale changes in the woodland environments of southern Africa (Sedano et al. 2008). These methods show promise and could be tested in this environment. Additionally, other finer spatial resolution multi-angle satellites such as CHRIS have demonstrated the capability to detect subtle changes in forest structure (Rautiainen et al. 2008, Galvao et al. 2009) might be ideally suited to detect changes due to disturbance.

Understanding the rate of regeneration after disturbance is vital information when government and communities are developing ways to sustainably use the forest. Additional research assessing tree growth rates and species diversity should be conducted to further understand what species are regenerating and what variables influence regeneration rates. This information will then allow managers to determine optimal harvesting methods and rotations for the production of charcoal.

Finally, semi-structured interviews should be continued in the area to collect additional local ecological knowledge related to forest composition and change, gauge local communities' levels of interest and satisfaction with forest management types. The local communities who use and depend on the forest are the key components in sustainable forest management. If they do not believe that are empowered to control their local environment, management plans developed by the government and donor agencies will have little impact on the local community and therefore, little will change in the forest. Continuing communication and information must be gathered by all invested parties to understand what local communities need to take more active roles in forest management.

Future research in all disciplines should also focus on the role of fire in the ecosystem. Local populations identified fire as a major forest disturbance and fire was apparent in most forests during field surveys. Fire should be further explored to understand its ecological impacts on soils, forest regeneration and species composition. The social factors that drive or mitigate fire should also be further explored; why fires are started, who starts them, how are they fought are all questions that should be thoroughly understood by managers. Remote sensing could also add a wealth of data to this area of future research (Justice et al. 2002) by detecting and quantifying fire frequency and intensity over the region.

A better comprehension of timber harvesting and the timber industry would also help understand how forests are changing in the region. This research indicated that timber harvesting could have severe negative impacts on the long-term composition of the forests. The continued removal of the less densely populated large, hard-wood and fruiting species will quickly transition the forest from one punctuated with large trees, but dominated by the Combretaceae family to forests that are made up only of Combretaceae trees. An increased understanding of large tree species use and age-class population patterns would inform managers on how to maintain or increase large tree populations.

In most cases, this research established a baseline that future research can be measured against. This is an important step in understanding the ecology of the area and how management and policy changes impact the forest. A multidisciplinary methodology combining remote sensing, local ecological knowledge and ecological data provides an approach that can increase the breadth and depth of understanding to all participants. Future research should build on baseline information from this study to help all participants in forest management, the Senegalese Forest Service, donor agencies (World Bank and USAID) and local communities understand the multitude of forces that add to the complexity of managing Senegalese forests. Current management types are not producing the promised results. Alternative methods must be developed to facilitate government management and co-management types to obtain their ultimate objective; an empowered local community sustainably managing their forests.

Appendix A – Tree Species List with Local Names

Names			Family
Scientific	**Peul Fouta,** *Fula Kunda*	**Manding**	
Acacia macrostachya	***Tandassara**, Ciidi*	*Ngoko*	*Mimosaceae*
Adansonia digitata	***Bohi***	*Sitoo, Fulayo*	*Bombacaceae*
Annona senegalensis	***Dukumi,** Cobbal gaynaako*	*Sung kung*	*Annonaceae*
Anogeissus leiocarpus	*Godioli, **Béydooji***	*Kéréto*	*Combretaceae*
Bombax costatum	*Luukum, **Joohi***	*Bungkung*	*Bombacaceae*
Cadaba farinose	***Béñébbi***		*Capparidaceae*
Cassia sieberiana	***Sindia**, Samba sindia*	*Sindiang*	*Caesalpiniaceae*
Combretum glutinosum	***Dooki gorko***	*Jambakatang*	*Combretaceae*
Combretum lecardii	***Dooki debbo***		*Combretaceae*
Combretum micranthum	*Taddi, **Kankéliba**, Talli*	*Baro*	*Combretaceae*
Combretum molle	***Ngañaka**, Ñakayi*	*Ngaña iro*	*Combretaceae*
Combretum nigricans	*Dooki boyla mawba, **Busti***	*Kouloukalang*	*Combretaceae*
Cordyla pinnata	***Duuki***	*Duuto, Dougouto*	*Caesalpiniaceae*
Crossopteryx febrifuga	***Bélèndé**, Lalooji, Monirdé*		*Rubiaceae*
Ficus dicranostyla	***Cèeké***	*Touro*	*Moraceae*
Grewia bicolor	***Sélékou**, Tintékula*	*Dioung*	*Tiliaceae*
Grewia flavescens	*Mbolémbocé, **Kelleyh***	*Sammbèw*	*Tiliaceae*
Hannoa undulate	*Kolonsso, **Kékuuhi***	*Kého, Kèekoo*	*Simaroubaceae*
Hexalobus monopetalus	*Boylé, **Boileh***	*Kundiéwo*	*Annonaceae*
Khaya senegalensis	***Kahi***	*Dialo*	*Meliaceae*
Lannea acida	***Cuko bale**, Cingôli*	*Bèmbo*	*Anacardiaceae*
Ostryoderris stuhlmannii	***Bani dané***	*Mo iro*	*Papilionaceae*
Piliostigma thonningii	***Barké céwdi***	*Fara musso*	*Caesalpiniaceae*
Pterocarpus erinaceus	***Bani***	*Kéno*	*Papilionaceae*
Sclerocarya birrea	***Eeri***	*Kuntang*	*Anacardiaceae*
Sterculia setigera	***Bobori***	*Kunkusitoo*	*Sterculiaceae*
Strychnos innocua	***Kupaleh,** Patakuhl*	*Fataculèw*	*Loganiaceae*
Terminalia albida	***Puulémé****		*Combretaceae*
Terminalia avicennoides	***Boori,** Boodi*	*Volo koyo*	*Combretaceae*
Terminalia macroptera	*Boori billèl, **Puulémé***	*Volo ba, wolobiso, wolojonga*	*Combretaceae*
Vitex madiensis	***Bummi***	*Simbong*	*Verbenaceae*
Ziziphus mauritiana	***Jaabi***	*Tomborong*	*Rhamnaceae*

Appendix B – Forest Plot Form

FOREST PLOT FORM

Research ID______ Country ID _____Site ID: ______

Date of site visit (mm-dd-yr): __________

Name of Forest <FNAME>: ____________________________

Plot identification number <PPIN>: _____________

Record the area (in square meters) of each plot below.

Name of person filling out this form:

____

A. CONDITIONS OF THE PLOT

A1. Describe the soil within the forest plot. (long text) <PSOIL>

A2. Is there evidence of active soil erosion in the forest plot? <PEROSION>
Mark only one answer.
(1) No
(2) Yes, minor erosion; surface vegetation and humus layer are absent
(3) Yes, major erosion; large gullies are present in barren soil.

A3. Is there evidence of livestock use within the forest plot? <PLIVESTOCK>
Mark only one answer:
(1) No
(2) Yes

A4. Is there evidence of extreme damage by insects/pests within the forest plot? <PINSECTS>
Mark only one answer.
(1) No
(2) Yes

A5. Is this plot located within a section of the forest that is set aside for specific forest management practices?
<PLOCA TION>
The answers to A5-A5b here should correlate to answers for B3-B3g on the Forest Form.
Mark only one answer
(1) No
(2) Yes

A5a. If yes, how many years has it been since this section of the forest was subject to a major harvesting effort?
Please use whole numbers. <PYEARS> ___ years
A5b. If yes, what is the name of this unit as listed on the *Forest Form,* 83g? <I'MGMTNAME>

A6. Plot elevation in meters. <I'ELEVATION>:

A7. What is the steepness of the slope in degrees? <I'STEEP>

Sample Forest Plot Form (P)
A8. If the plot is on a slope, what direction does the plot face? <PORIENT>
Mark only one:
(1) ____ North
(2) ____ Northeast
(3) ____ East
(4) ____ Southeast
(5) ____ South
(6) ____ Southwest
(7) ____ West
(8) ____ Northwest

A9. What is the percentage of crown cover in this plot? <PCROWN COV>
____

A10. Provide any other observations that pertain to plot conditions, e.g., tree falls, evidence of charcoal burning, fire damage, storm damage, etc. *(text)* <PCONDITION>

IF EVIDENCE OF CHARCOAL PRODUCTION PROCEDE TO **A11**.

A11. Charcoal plot information

A11a. Is a kiln still present on this plot? <CKILN_P>
Mark only one answer:
(1) No
(2) Yes

A11b. What is the diameter of the old kiln in meters? <CKILN_D>

A11c. Approximately when was charcoal produced on this plot? <CKILN_AGE>
Mark only one answer:
(1) ____ Within the last year
(2) ____ 1-2 years ago
(3) ____ 3-4 years ago
(4) ____ 5-8 years ago
(5) ____ More than 8 years ago
(6) ____ Unknown

A11d. How was the age of the charcoal harvest estimated? <CKILN_AGEEST>
Mark only one answer:
(1) ____ Local charcoal producer knowledge
(2) ____ Coppicing tree age estimate
(3) ____ Other, explain: ____________________________________

A11e. What percentage of tree appear to have been harvested within the plot? <CKILN_PERC>
Mark only one answer:
(1) ____ one-third
(2) ____ two-thirds
(3) ____ all

B. GEOGRAPHIC AND POSITIONING INFORMATION

If using GPS technology to collect data for this section, all GPS units must be set to the same Datum and Spheroid while collecting data across all plots. Be sure to specify in the *Site Overview Form* (Form 0) which Datum is being used across all plots.

Use decimal degrees or degrees-minutes-seconds for latitude and longitude.

E1. What is the latitude of this plot? <PLATITUDE>
____________ (*decimal degrees)*
or
___ º___ ‘ ____” *(degrees-minutes-seconds)*

E2. What is the longitude of this plot? <PLONGITUDE>
____________ (*decimal degrees)*
or
___ º___ ‘ ____” *(degrees-minutes-seconds)*

E3. What is the Estimated Position Error (EPE) for this position? <PEPE>

____

C. PREVIOUS SURVEY INFORMATION

C1. Has this plot been previously surveyed?
Mark only one answer
(1) No
(2) Yes (cont to C2)

C2. Who conducted the previous survey?

C3. When was the survey conducted?

C4. If available, what is the point ID of this location?

Appendix C – Forest Plot Species Forms

TREE, PALM, AND WOODY CLIMBER INFORMATION

Record the local and botanical names of each tree, palm, and woody climber found in the 25mx25m plot. For each tree, record its DBH and height in metric units. (P_INFO)

Starting at the corner of the plot, create a rectangle that is 25-meters by 25-meters. For each tree, palm, and woody climber species in this area, answer the questions below.

Remember to record only those trees with a DBH greater than or equal 5 cm. If possible, collect a sample of each unknown species.

Forest Name: ________________________________

Plot ID # (PPIN) __________

	Name of Species				
What is the family name of the this plant species	*Botanical*	*Local*	*Is this a tree, palm, or woody climber? Write "T" for tree, "M" for palm, "C" for woody climber <P_TYPE>*	*Maximum stem diameter of the climber, or DBH of the tree (cm) <P_DBH>*	*Estimated height of the tree or palm (not climbers) (m) <P_HEIGHT>*

COPPICING TREE INFORMATION

For coppicing tree, palm, and woody climber species within the 25mx25m plot, answer the questions below.

Forest Name: _________________________________

Plot ID # __________

	Name of Species					
What is the family name of the this plant species	*Botanical*	*Local*	*Number of stumps <P_STUMP>*	*Number of shoots from coppiced tree <P_REG>*	*Maximum stem diameter of shoot <P_DIA>*	*Estimated height of coppiced tree <P_CHEIGHT>*

SHRUB, SAPLING, PALM, AND WOODY/HERBACEOUS CLIMBER INFORMATION

Record the local and botanical names of each shrub, sapling, palm, and woody/herbaceous climber found in the circle of 10-meter radius. For shrubs and climbers, record maximum diameter and height in metric units. For saplings, record DBH and height in metric units. {P_INFO;

For each sapling, shrub, palm, and woody/herbaceous climber species in this area, answer the questions below. Remember that a sapling is defined as a young tree with a DBH greater than 1 cm but less than 5 cm.

Forest Name: ___________________________________ Plot ID # __________

	Name of Species				
What is the family name of the this plant species	*Botanical*	*Local*	*Is this a shrub, sapling, palm, or climber? Write "B" for shrub, "P" for sapling, "L" for palm, "W" for woody climber <P_TYPE>*	*Maximum stem diameter of the shrub or climber, or DBH of the sapling (cm) <P_DBH>*	*Estimated height of the shrub or sapling (not climbers) (m) <P_HEIGHT>*

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