Nutrient Response to Land Management Alterations in the Miombo Woodlands Region

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Abstract

South-central Africa is undergoing increased agricultural intensification, however, the long term ecological response is unknown. Through fieldwork and modeling, the short to long term impact on nutrient stocks of crop-fallow agriculture and selective logging are examined in the Miombo Woodlands of south-central Africa. Based on field measurements, initial crop production does not result in significant soil carbon, nitrogen, or phosphorus reductions in rural Tanzania and Mozambique. In rural Tanzania only surface level carbon stocks were reduced in areas with short cultivation periods followed by equal or longer fallow periods. In Malawi, areas under crop production for many years had significantly lower soil nutrient levels than Miombo Woodland areas.

The CENTURY model was parameterized and accurately modeled the Miombo system. When agricultural intensity is increased, modeled system nutrient levels decline over the short and long term. Commonly practiced fallow lengths are not long enough to allow complete soil nutrient recovery. Based on modeled results, selective logging for charcoal production with a rotation cycle greater than ten years is sustainable in the long term. It is recommended that only larger wood and branches be removed from woodland areas and smaller branches and leaves left in place to decompose.

There is an escalating demand for climate change mitigation measures, creating an international market for greenhouse gas emission reductions. Communities in the Miombo region can participate in this market by working together to alter the land management in a way that results in quantifiable carbon emission reductions or carbon sequestration. The carbon and economic impact of increasing fallow periods and logging rotations was examined. Assuming the current average carbon price, at the community scale it will be economically advantageous to elevate the fallow period from five to fifteen years and sell resulting carbon credits. A minimum price of US$28 t CO_2e^{-1} would be needed before it would become more profitable to increase logging rotations to 30 years. These preliminary results suggest potential for the region to participate in the carbon market. It is recommended that this type of analysis be expanded to include a greater number of activity types and encompass a larger area.

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Chapter 1 Introduction and background

1.1 Introduction

The Miombo woodlands are the dominant ecological community within the south-central region of Africa, covering around 2.8 million km^2 and can be found in parts of Angola, Democratic Republic of Congo, Zambia, Zimbabwe, Tanzania, Malawi and Mozambique (Desanker *et al* 1997) (Figure 1.1). Although the woodlands have lower productivity and biomass compared to moister tropical forests, owing to their geographical extent they are a major terrestrial carbon pool for the continent of Africa and worldwide. This region is undergoing rapid land use conversion due to high population growth rates (~2.3%) (UN Statistics 2005), resettlements, expanding agricultural production, and deforestation for wood fuel. In 1996, Campbell *et al* estimated that over 55 million people depend on the woodland resources, including for building material, firewood, thatching grass, honey, fruits, mushrooms, and medicinal plants. The Miombo countries are among the world's poorest with agriculture (cropping and animal husbandry) as the main foreign currency earner for economic and social development (Desanker *et al* 1997).

The Miombo Woodlands region has to the potential to be either a net carbon sink or source, depending on how it is managed. In rural south-central Africa human actions have caused changes in the carbon cycling and many landscapes have become carbon 'sources' through high levels of woodland conversion to agriculture and forest degradation resulting from charcoal production. Alterations to the carbon cycle will also impact the levels of other nutrients such as nitrogen and phosphorus in the landscape and the potential productivity of the system.

Rural populations rely almost exclusively on agriculture and woodland resources for their livelihoods (Malimbwi 2001; Monela *et al* 2000). As human manipulated landscapes come to dominant the land surface there is greater reliance on continuous cropping and shorter fallow periods. Crop yields are poor as carbon and nutrient levels of originally infertile land decline further after years of use. Much of the newly cropped land is unsuitable for agriculture and degrades quickly forcing the farmer to convert even more land to agriculture. It has been estimated that half the land converted to agriculture in tropical areas is only being used to replace previously converted land degraded by agriculture (Houghton 1994). The future productivity of the region's agricultural land and the health of the ecosystem will depend greatly on how agricultural practices alter nutrient levels and on the ability of the ecosystem to recover nutrient stocks following abandonment. Carbons stocks and in particular soil organic carbon can be used as an easily measurable proxy for soil quality and the sustainability of the current land cover.

Therefore there is a basic need to understand the carbon content of natural systems, how carbon content differs within these human induced landscapes, and what effect land management will have on ecosystem health over the long term. Previously conducted studies in the Miombo Woodlands have indicated soil nutrient levels decline significantly when the woodlands are converted to agriculture (Walker 2003; King and Campbell 1994). The increase in land use intensity is relatively recent in the region and therefore it is difficult to directly measure how changing land management will modify nutrient stocks over the long term. The existing field studies both took place in countries with high population density and great land scarcity leading to long cultivation periods followed by very short if any fallow periods. Many farmers in the Miombo Region still live in areas with lower land use pressures, allowing for less intense use of the land. The sustainability of the more traditional practice of short cropping period followed by long fallows has not been adequately examined.

Charcoal production is a significant source of land use change in the Miombo region and even as woodland resources decline the demand for charcoal is still very high (CHAPOSA 2001). Selective logging for charcoal production is an important component to rural farmers' livelihoods (Malimbwi *et al* 2001), therefore, it is imperative for communities to use this resource in a way that is sustainable. Over cutting or logging rotations that are too short will not allow the woodland to recover, however, the long term biomass of the system must be balanced with the need for charcoal production. Understanding the long term impact of various management choices will allow for greater confidence in potentially recommended management practices.

The land use change that has occurred across Africa has also made a significant contribution in the increase in greenhouse gases and resultant climate change (Achard *et al* 2004; DeFries *et al* 2002; Houghton 2003; Houghton and Hackler 2006). As the consequences of climate change become increasingly realized worldwide, there is a rapidly escalating demand for mitigation measures. This has created an international market for greenhouse gas emission reductions. The Miombo Woodlands region has a great potential to become a part of this market by altering the land management in a specific area of land in a way that results in quantifiable carbon emission reductions or carbon sequestration. Projects can be developed by communities to implement these activities, providing an additional strategy for income creation. There are a range of activities with varying possible credit creation and economic consequences that could potentially be initiated by a community. Owing to the nascent nature of this market, resource limited rural communities do not currently have the capability to understand the carbon and economic consequences of initiating such activities or how to take advantage of this newly created commodity.

1.2 Dissertation Objectives and Overview

After a number of years of living among rural farmers in Africa and witnessing the highly tenuous livelihood security experienced by these communities, the main questions that presented themselves were the basis of my dissertation. These farmers are living in a time of great changes. Agriculture is moving from long-term shifting cultivation to high intensity cultivation, but without the added benefit of any technological advances or fertilizer inputs. Little research has been done on how this new land management compares with more traditional practices. Additionally, the long term consequences of such intensification are suspected, but not well examined. Finally, market-based attempts to mitigate human induced climate change, resulting in part from the activities just discussed, possibly presents rural farmers with one strategy to temper or even reverse the degradation that is occurring by participating in the newly created carbon market.

In my masters thesis (Walker 2003) I examined the changes in soil carbon and nitrogen resulting from high land use intensity agriculture. In the following dissertation the nutrient response in an intermediate and lower level agricultural areas are compared to this higher intensity land use. However, most of the region is moving away from the more traditional practices and towards a more aggressive use of the land. Since this move is still relatively recent, modeling was employed to study how this amplification in farming intensity would impact nutrient levels over the long term. The other major land degradation driver, selective logging for charcoal production, was also examined through modeling. I then looked at the possibility of reversing or stopping this trend of degradation through carbon financing. The economic consequences of lengthening rotation cycles was examined and compared to potential carbon income creation.

1.2.1 Overall Project Questions

1. How does carbon cycling change in response to land cover change?
2. Using carbon as a proxy, what is the long-term sustainability of the dominant land use systems in the Miombo Region

1.2.2 Specific Research Questions, Null Hypotheses, and Expected Results

1. How are the nutrients C, N, and P altered by dominant land use conversion found in the Miombo Region?

H_o: Land use conversion will not impact carbon stocks.

H_1: Conversion of forests to agriculture will reduce nutrient (C, N, P) stocks both above- and belowground. Soil C, N, P stocks will be negatively correlated to time since original land use conversion.

H2: In secondary growth, C, N, P stocks will be positively correlated to time since abandonment.

2. How do changes in land management practices alter long-term biomass and nutrient stocks?

Ho: All land management practices result in similar long-term biomass stocks.

H_1: Longer fallow periods will result in less long-term reductions in soil nutrient levels.

H_2: Reducing frequency of woody biomass cutting will result in greater woody biomass and nutrient stocks

3. How does lengthening rotations alter the carbon budget at a larger scale?

Ho: Lengthening rotations does not impact community scale carbon budgets.

H_1: Community scale carbon levels can be increased through rotation lengthening.

1.2.3 Composition of Dissertation

The results from the research questions addressed are treated in turn in three distinct chapters. These chapters are written in journal manuscript style. An overview of each of the chapters is presented here.

Chapter 2. The influence of agriculture on nutrient levels in rural Tanzania and Mozambique

This chapter compares nutrient levels between Miombo woodland areas and areas used for agricultural production in locations along a low, intermediate, and high land use intensity gradient. Soil and vegetation samples were taken in each of these land use types and analyzed for nutrient content. Statistical analyses were then employed to determine the factors influencing soil nutrient levels. The main objective of this analysis is to heighten our understanding of how agricultural production influences soil fertility.

Chapter 3. Carbon response to land management alterations in the Miombo system

As noted, in the Miombo Woodlands region, highly intensive land use is relatively recent and therefore its long term impact is difficult to examine directly. However, models present us with the opportunity to look at various land managements over a longer time scale. The CENTURY model was parameterized for the Miombo Woodlands ecosystem using a combination of published literature and data collected in the field. Crop-fallow periods of a variety of lengths were then modeled and the resulting carbon, nitrogen, and phosphorus changes examined. Additionally, a variety of potential selective logging management practices were also modeled and nutrient responses compared.

Chapter 4. Potential for carbon sequestration through land management alterations in the Miombo woodlands of Tanzania

The potential for the Miombo Woodlands to participate in climate change mitigation is examined. Current crop production and the costs and income from production were surveyed. The CENTURY model was then used to model a variety of crop and logging rotations. Using results from this modeling, the amount of wood produced for charcoal creation was then estimated for each rotation cycle. Additionally, the changes in carbon stocks from a shorter rotation to longer rotations were calculated. These results were then scaled up to the community scale to estimate the overall change in crop production, charcoal production, and carbon stocks. An economic analysis was performed allowing for an economic comparison between various land management options. This analysis presents a first estimation of the carbon and economic potential of developing a carbon project for the Miombo Woodlands without having to institute costly and risky technological improvements to management.

1.3 Background

1.3.1 Overview of Miombo Woodlands

Miombo Woodland is the dominant ecosystem across the majority of south central Africa (Figure 1.1). A precipitation gradient from about 800-1500 mm exists southwest to northeast (Desanker *et al* 1997). Ninety-five percent of annual precipitation occurs during the hot wet season. Fires burn the understory on average every 3 years across the Miombo and savannas and therefore greatly impact the vegetation dynamics of the system (Boaler 1966).

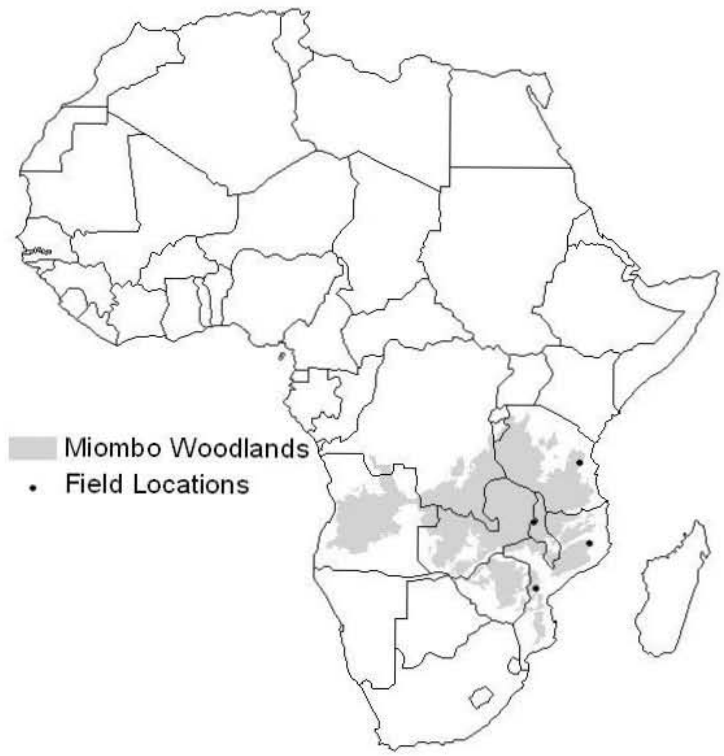

Figure 1.1 Extent of Miombo Woodlands and location of field sites in Malawi, Tanzania, and Mozambique.

Floristic diversity in the Miombo woodlands is very high with an estimated 8500 species, 54% of which are endemic (White 1983). All of the dominant tree species are in the family Fabacaea, within the genera *Brachystegia, Julbernardia,* or *Isoberlinia* (Campbell 1996). These genera are rarely found outside this region. Some plant genera: *Bolusanthus, Cleistochlamys, Colophospermum, Diplorhynchus, Pseudolachnostylis, and Viridivia* are endemic (White 1983). These deciduous, umbrella-shaped trees create an upper canopy at 10-16 m covering 20-60% of the area (Rodgers 1996). Below this canopy is another layer of subcanopy trees at 4-10 m, patches of shrubs at 1-5 m, and well-established tall grasses up to 1.5 m (Rodgers 1996; Trapnell 1959). Of the 98 species of subcanopy trees in Africa listed by White (1976), 86 are found in this region.

Campbell (1996) estimated woody plants contain 95% of the aboveground biomass, with grasses making up the remainder. The dominant trees have very deep roots, between 1.5-4 m in length. Most trees are thick-barked, and many species of trees and shrubs are able to resprout from deep rootstocks. Through this coppicing, tree genera have adapted to tolerate frequent damage from fire, megaherbivory, drought, and frost and this allows the above ground structures to be burned or cut without killing the actual individual (Campbell 1996; Rodgers 1996). The major tree genera are ectomycorrhizal, which is rare in other tropical forests and is thought to be an adaptation to the low phosphorus levels of the soils (Hogberg 1986). Termites are generally pervasive within the woodland region and, along with fire, consume the majority of litter (Goffinet 1976). Invertebrate herbivores are only active during the wet season, eating about 2% of the available foliage (Desanker *et al* 1997). Many of the trees are honeybee pollinated and local populations in the region traditionally practiced beekeeping. Due to low soil nutrient levels, Miombo vegetation also contains small nutrients concentrations and therefore the dominant herbivores are large mammals living at low densities and requiring large areas over which to graze (Campbell 1996). As intact woodland becomes more fragmented due to deforestation, contiguous habitat suitable for these mammals is dwindling, threatening these populations.

The Guinea savannahs of West Africa are ecologically similar *Isoberlinia* woodlands that lack *Brachystegia* and *Julbernardia* (White 1983). While on the Kalahari sands that lie next to the miombo region, sit woodlands containing related genera (Desanker *et al* 1997) Globally, the Miombo Woodlands are ecological similar to South America's *cerrado*, northern Australia's monsoonal tall grass eucalypt woodlands, and south-east Asia's dipterocarp woodlands (Desanker *et al* 1997).

1.3.2 Miombo Woodlands Biomass

Miombo aboveground biomass stocks are between those of the wetter rainforests to the north (121 Mg ha^{-1} in DRC (Bartholomew *et al* 1953)) and the drier savanna and scrubland to the south (11 Mg ha^{-1} in RSA (Scholes and Walker 1993)) (Table 1.1). Published estimates of AG biomass within Miombo range from about 20 to 96 Mg ha^{-1} with woody plant (taller than 2 m) densities ranging from 380-1400 stems ha^{-1} (Trapnell 1959; Mallaise 1978) (Table 1.2; Figure 1.2).

Table 1.1 AG and root biomass estimates from various ecosystems

Country	Vegetation Type	Above-ground Biomass Mg ha^{-1}	Root Biomass Mg ha^{-1}
Ivory Coast	Grassland	4.8	
Brazil	Savanna	5 -100	
R. South Africa	Broadleaf Savanna	11.3	1.2
United States	Subalpine Forest	12	3
Ivory Coast	Wooded Grassland	62.8	
Colorado (to 75 cm)	Shortgrass Steppe		18.9
Mexico	Dry Tropical Deciduous Forest	74	31
United States	Oak-hickory, pine, chestnut, oak, yellow poplar forest	109 - 138	33
DRC	Moist Rainforest	121	32
Belgium	Mixed Oak Forest	121	35
United States	Mesic Deciduous Hardwood	130	36
Puerto Rico	Lower Montane Rainforest	223	69
Ghana	Moist Semideciduous Forest	233	54
France	Mediterranean Evergreen Oak Forest	262	50
Japan	Beech Forest	292	44
Malaysia	Lowland Rainforest	431	43
Ivory Coast	Lowland Rainforest	513	51
Mexico (to 80 cm)	Subtropical Deciduous Forest	51	30

(respectively from: Pomeroy *et al* 1986, Tiessen 1998, Scholes and Walker 1993, Arthur and Fahey 1992[a,] Malaisse 1975; Pomeroy *et al* 1986, Gill *et al* 1999, Castellanos *et al* 1991, DeAngelis 1981[a], Bartholomew *et al* 1953[a], DeAngelis 1981a, Bartholomew *et al* 1953[a], DeAngelis 198[1a], Cox *et al* 1978[a], Frangi and Lugo 1985[a], Greenland and Kowal 1960[a], DeAngelis 1981[a], DeAngelis 1981[a], Bandhu 1973a & Kira 1990[a], Huttel 1975[a] & DeAngelis 1981[a], Castellanos *et al* 1991 (a = taken from Cairns *et al* 1997))

Table 2 Estimates of above and below ground biomass throughout Miombo Woodlands region

Country	Woodland Type	AG t C ha^{-1}	BG t C ha^{-1}	Source
Tanzania	Woodland	9	2.2	Malimbwi 1992
Tanzania	Woodland	39.3		Ek 1994
Tanzania	Woodland	30.2		Zahabu 2001
Tanzania	Woodland	20.2		FRIM unpubl
Tanzania	Woodland	30.2		Jean 1997
Tanzania	Woodland	27.2		Malimbwi 2001
Zambia	Woodland	32.2		Chidumayo 1994
Zambia	Woodland	46.3		Chidumayo 1990
Zambia	Woodland	35	19.5	Chidumayo 1993
Zambia	Woodland	36.5		Chidumayo 1994
Zimbabwe	Woodland	19	8.4	Campbel *et al* 1998
Zambia	Woodland	27.9		Chidumayo 1994
Tanzania	Woodland	18.3		Luoga 2002
Tanzania	Woodland	33.5		Malimbwi 2005
Tanzania	Public land - Degraded Woodland	19.6		Malimbwi 2005
Tanzania	Public land - Degraded Woodland	6.9		Luoga 2002
Tanzania	Public land - Degraded Woodland	19.4		Malimbwi 2001
Tanzania	Degraded - Heavily used Miombo	10.5		Ek 1994
Tanzania	Degraded - Used Miombo	16.2		Ek 1994
Zambia	9 yr old regrowth - no agri	13.6		Chidumayo 1993
Tanzania	10 yr old regrowth	11.7		Ek 1994
Zambia	10 yr old regrowth	12.8		Chidumayo 1990
Zambia	10 yr old regrowth - no agri	12.6	11.8	Chidumayo 1993
Zambia	15 yr old regrowth - no agri	13.4	11.9	Chidumayo 1993
Zimbabwe	16 yr old regrowth - no agri	24.1		Stromgaard 1985
Zambia	18 yr old regrowth - no agri	16	14.4	Chidumayo 1993
Zambia	20 yr old regrowth	38		Chidumayo 1990

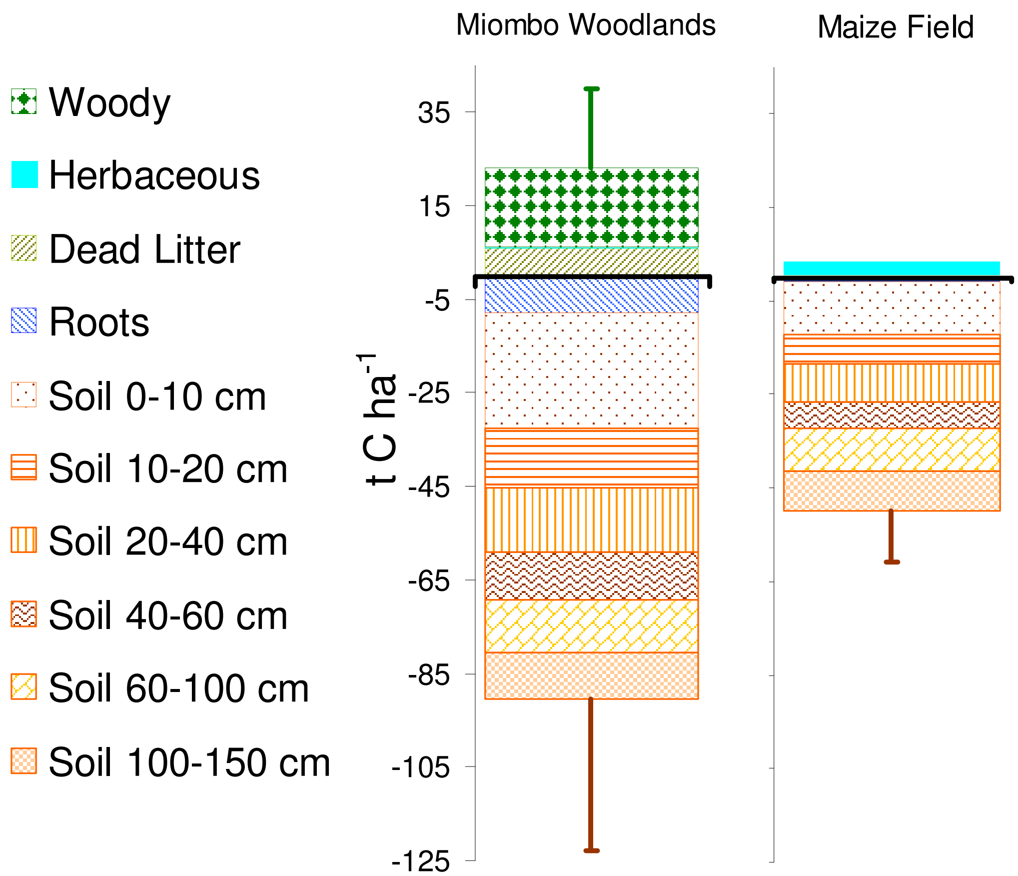

Figure 1.2 Average carbon stocks within Miombo woodland and agricultural area based on published literature

(taken from Campbell 1996; Campbell et al 1998; King and Campbell 1995; Chidumayo 1993; Malimbwi et al 1992; Stromgaard 1992; Walker and Desanker 2004)

At Marondera Zimbabwe, a dry miombo region, Campbell *et al* (1998a) estimated woody biomass and root biomass by destructively sampling *J. globiflora* and *B. spiciformis* trees and also sampled herbaceous plants in 1 m plots. Allometric equations were then developed from these measurements. A break down of organic matter by type was then constructed and an estimate made of 155.9 Mg ha^{-1} total organic matter within

Miombo. Total root biomass was projected to be 31% of total live biomass, 16.7 Mg ha^{-1} of woody roots and 0.722 Mg ha^{-1} of herbaceous roots. Trees roots alone contributed 24% of tree biomass. SOM contains more than 55% of the total organic matter within the system.

Chidumayo (1993) has also developed aboveground biomass equations for old growth Miombo by destructive sampling. To sample roots a one meter radius by one meter deep pit was excavated around trees, and roots removed and weighed. Dry root biomass was estimated at 1.3 kg m^{-2}. 1 m^2 x 1.5 m deep pits were dug to excavate diffuse lateral roots in order to measure diffuse lateral roots and found lateral root biomass to be 2.0 kg m^{-2}. Total root biomass is therefore estimated at 33 Mg ha^{-1}. Chidumayo believed this is an underestimate since fine roots and roots below 1 m were not sampled. One year later coppiced stumps were enumerated (Chidumayo 1993). Chidumayo found an increase in plant density in each regrowth area, with a second clear-cut area having an even higher plant density. Chidumayo attributes this to the fact that both coppicing and seedling growth takes place and plants are not shaded. Stump mortality decreased as tree density in the regrowth increased. Chidumayo concludes that successive clearing of regrowing Miombo after 10 years or older does not reduce the productivity and has little effect on soil and herbaceous properties (Chidumayo 1993).

Malimbwi *et al* (1992; 1994) felled and excavated 17 trees irrespective of species near Morogoro, Tanzania. Stems, branches, and roots were measured and from this sampling biomass and volume equations were developed. Using these equations the researchers found the Miombo area to have a total tree biomass of 33 Mg ha^{-1}, which is much lower than estimates by Campbell (1998a). Root biomass was estimated to contain 17% of total biomass or 6.6 Mg ha^{-1} which is about half the estimate by Campbell (1998a). Exactly how the root sampling took place is not explicitly stated. The researchers simply state that the 'roots were excavated' (Malimbwi *et al* 1992; 1994).

Although root biomass was not measured, Tuite and Gardiner (1994) examined the persistence of Miombo trees under a field continuously cultivated for 15 years. They found 40 tree species within the selected plots that had coppiced throughout this cultivated time. This exemplifies the ability of Miombo tree species, and therefore their root structure, to maintain themselves over long numbers of years under cultivation.

Chidumayo (1997) and Campbell *et al* (1998a) have also examined the contribution of the herbaceous root biomass to the carbon budget. In Zambia herbaceous roots were sampled in 1 m^2 x 50 cm deep pits (Chidumayo 1997) while at the Marondera Zimbabwe soil cores were used to sample herbaceous roots (Campbell *et al* 1998a). Root biomass varied throughout the year, but averaged 2.100 Mg ha^{-1} at the Zambian location (Chidumayo 1997) and a third that (0.722 Mg ha^{-1}) at Marondera (Campbell *et al* 1998a). Herbaceous root biomass makes a minimal contribution to the entire carbon budget, but because of the superior turnover rate of herbaceous roots, the herbaceous root contribution to soil carbon may be substantial.

1.3.3 Miombo Woodlands Soil Carbon

Soil carbon levels in the Miombo Woodlands span the range of carbon levels (0.7%-4% in top 10 cm) found within other dry forests worldwide (Figure 1.3). Comparing measurements around the world, one would not expect soil carbon levels in

Miombo to rise above 3-4% in the top ten centimeters. Values are highest at the surface and quickly decline with depth in a log carbon-log depth regression. This regression type also significantly characterized 76% of the soil profiles examined in the study by Jobbagy and Jackson (2000). Measurements at the surface show more variability with estimates ranging from 0.23-3.8%. By a depth of 10 cm, carbon levels rarely exceed 1%. Profiles with higher carbon levels at the surface usually have slightly elevated carbon levels in the subsurface. Carbon in the top ten centimeters ranges from 7 Mg ha^{-1} to 24 Mg ha^{-1} with an average of about 14 Mg ha^{-1} while estimates of the top 50 cm of soil range from about 30 Mg ha^{-1} to more than 80 Mg ha^{-1} (Figure 1.3).

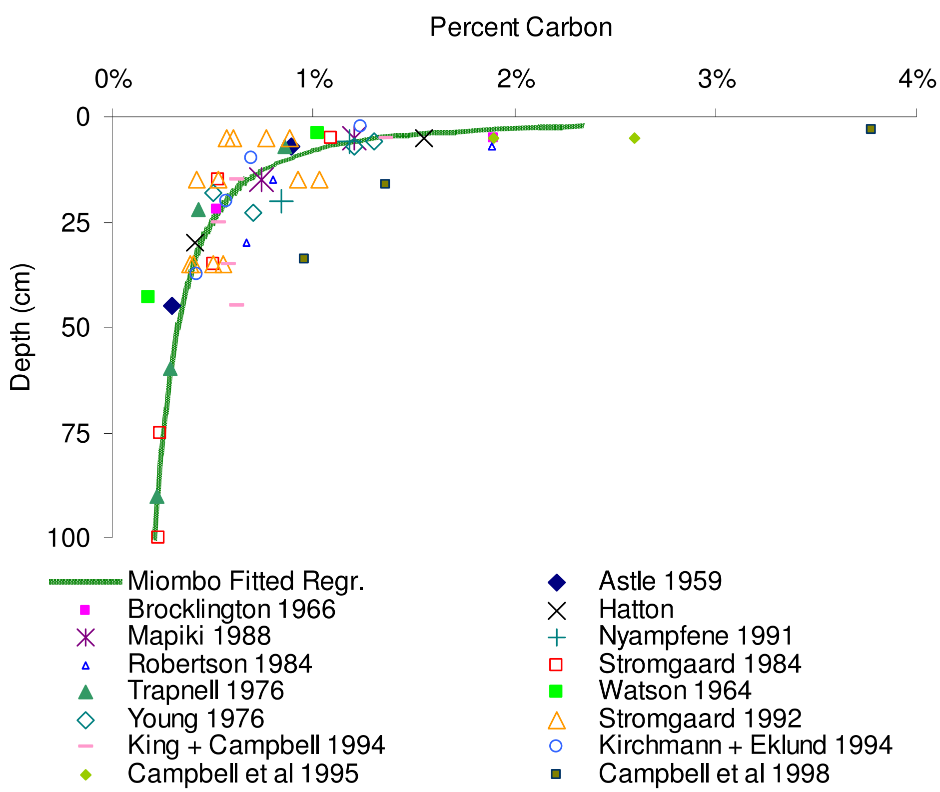

Figure 1.3 Published estimates of soil carbon content in the Miombo Woodlands with regression line fitted to data.

Although low everywhere, surface carbon values can vary considerably within small spatial scales, for example, soil carbon measurements in the top ten cm of natural Miombo sites within the Tropical Soil Biology and Fertility Programme (TSBF) site at Marondera in Zimbabwe vary between 1.18% and 3.78%. Microbial biomass, also examined at TSBF, contributed roughly 6% to the total soil organic matter (Kirchmann and Eklund 1994). The soil carbon component of the system, although seemingly small, is proportionally larger in the Miombo system than in systems with more rainfall (Woomer *et al* 1997). Depending on the estimates used, the first 0.5 m of soil alone contributes 45-65% of the total carbon found within the system.

1.3.3.1 Variables influencing soil carbon levels

Based on published carbon estimates there does not appear to be any overall regional gradient. In fact, the lowest surface estimate and one of the higher estimates are both located extremely close to one another (Stromgaard 1992; Campbell 1998b). Generally the measurements taken near Kasama in Zambia (1000-1400 mm precip) are slightly lower at the surface than the drier and increased clay soil at the TSBF site in Zimbabwe (880 mm precip). However, measurements at a ferrasol site at Chingola, Zambia are relatively high while a luvisol site at Harare had lower carbon levels. Because of the low number of data points, no definite trend due to precipitation or soil type can be established however a distinct trend may be found when data is increased.

The density of the canopy cover in the woodlands varies from almost complete cover to less than 30%. Because an increase in litter inputs will generally increase soil carbon levels, soil under denser canopy cover would be expected to have elevated carbon concentrations. At the TSBF site in Zimbabwe, when examining small scale patterns in miombo structure across transects, Campbell *et al* (1995) found distinct subtypes of structure and soil carbon, grouped loosely into open woodland and closed woodland depending on canopy cover. The closed *Julbernardia* dominant and *Brachystegia* dominant subtypes both had very similar soil carbon values, around 1.5%. Clay concentrated termitaria soils of the closed *Albizia* dominant subtype averaged carbon concentrations of 3.77%. However, the open woodland areas, dominated again by *Brachystegia* and capped with microfloral crusts had distinctly lower soil carbon values with a mean of 1.1% and reduced infiltration rates (Campbell *et al* 1995). The researchers propose that this soil compaction and lowered carbon rates are the result of past human land use and that a positive-feedback is preventing the open woodland areas from developing a denser canopy. The microfloral crust and lower infiltration rates result in higher runoff, removing litter and seeds which then hinder seedling establishment (Campbell *et al* 1995).

In line with other sub-humid and arid systems in Africa, carbon levels decline with increasing distance from the base of miombo trees, conversely this affect was not seen in reference to grass bases (Campbell *et al* 1988). Within the same study transects at TSBF as above, Campbell *et al* (1988) found soil within five meters of a tree trunk averaged 2.12% C while soil greater than three meters from a tree trunk averaged 1.75% (Campbell *et al* 1988). The researchers attribute this difference to larger inputs of litter around trees, especially lichen next to the trunks. Kirchmann and Eklund (1994) at the TSBF site also found canopy cover differences in microbial biomass. Soil at a distance of 0.5 m from a tree contained 632 kg ha^{-1} of microbial biomass in the top 5 cm while soil 3 m from a tree contained 561 kg ha^{-1} (Kirchmann and Eklund 1994). In the Miombo Woodlands, the density of canopy cover also changes at a regional scale, generally increasing along with precipitation. Therefore, average carbon levels influenced by litter inputs, will vary at the tree level, at the stand level, and at a regional spatial scale.

Fire is extremely important in the Miombo Woodlands system, with its intensity and frequency influencing the species composition and density. By oxidizing both alive biomass and litter, fire removes carbon from the system before it even becomes incorporated into the soil, thus reducing carbon inputs. When fires occur, soil organic carbon levels are not altered greatly since most carbon is oxidized and a portion deposited as ash and charcoal. In Zambia, Stromgaard (1992) studied the way in which fire and ash-fertilization altered soils, both immediately after burning and 9 years later. A large area was cut and wood material piled in a small area and burned in the traditional agricultural practice called *chitemene*. Crops are then grown over the burned area or *ash garden*. In most plots soil carbon in the topsoil increased following burning due to organic particles from the ash, but the subsoil was not modified (Stromgaard 1992). In the years following the burning soil carbon levels generally declined, although results were very variable.

A prescribed burning experiment was carried out between 1934 and 1956 by the Northern Rhodesian Forest Department (Trapnell 1959). Three types of plots were maintained: fire exclusion, yearly burning early in the dry season, and yearly burning late in the dry season. Fire exclusion led to greater plant density, especially in the undergrowth, with an increase in evergreen lianes. Early burning did not damage most trees, and the number of individuals declined only slightly. Late burning repeated over many years had a cumulative effect and resulted in a severe tree canopy reduction and an increase in a tall grass layer (Trapnell *et al* 1976). Soil sampling conducted at the end of the experiment in 1956 surprisingly reveals no significant changes in soil carbon or nitrogen levels, with fire exclusion, early burning, and late burning averaging 0.85% C, 0.96% C, and 0.97% C respectively (Trapnell *et al* 1976). The 23 years of increased litter inputs in the protected plot did not result in any elevation of soil carbon or any increased litter accumulation. Furthermore, no significant differences in decomposition rates existed between plot types (Trapnell *et al* 1976). Trapnell *et al* (1976) attributed this lack of enhancement to the high density of termites found throughout the Miombo Woodlands.

The contribution of the herbaceous grass and root layer to the soil carbon pool has not been directly analyzed. Although woody biomass makes up 98% of the live biomass in Miombo (Campbell *et al* 1998a), litter production from trees has been estimated to be 4,300 kg ha^{-1} yr^{-1} by Malaisse *et al* (1975) and 2,000 kg ha^{-1} yr^{-1} by Campbell *et al* (1988), while herbaceous litter was estimated at 1,500 kg ha^{-1} yr^{-1} (Chidumayo 1997; Campbell *et al* 1998a). This high turnover of herbaceous biomass may add a substantial proportion of carbon into the soil pool.

1.3.3.2 Impact of land use on soil carbon levels

As in all systems, conversion to agriculture leads to a decline in the carbon stocks. When the Miombo woodlands is converted to agriculture there is about a 90% reduction in aboveground biomass inputs into the soil (Campbell 1996). A number of studies have also found a reduction in soil carbon values when land is converted to agriculture (Campbell 1996; Mugwira and Nyamangara 1998) The reduction in soil organic matter caused by land use change is most prominent at the surface, where the highest density of carbon is located.

At the Grasslands Research Station in Zimbabwe, King and Campbell (1994) directly compared a Miombo woodland site to an agricultural field, a Eucalypt plantation, a Pine plantation and a grassland site. The soil carbon at Miombo woodland site (total 48 t C ha^{-1} to 50 cm) declined more drastically with depth than the other cover types. The agricultural field had the lowest total carbon levels in the first 50 cm, 45 t C ha^{-1}. Carbon levels were actually lower at the surface than at 20 cm, presumably due to the higher decomposition rates caused by tillage. The largest soil carbon pool was the Eucalypt plantation, 57 t C ha^{-1} in top 50 cm. Annual leaf litter levels of Miombo (2.72 t C ha^{-1}), eucalyptus (3.27 t C ha^{-1}), and pine (5.08 t ha^{-1}) sites do not account for the high eucalyptus soil carbon levels found nor does the C:N ratio of the litter. Rather, turnover of eucalyptus material (9.9 t C $ha^{-1}yr^{-1}$) through decomposition was much slower than either the Miombo (15.9 t C $ha^{-1}yr^{-1}$) or pine (28.5 t C $ha^{-1}yr^{-1}$) and the researchers suggest high polyphenol levels as the cause (King and Campbell 1994). Microbial biomass within Miombo Woodlands and an agricultural field was investigated by Kirchmann and Eklund (1994). Although microbial biomass at the surface was higher in the woodland site, total microbial biomass to a depth of 50 cm did not differ significantly.

In Zambia under the chitemene ash garden system, fields close to villages tend to have a shorter fallow period of about 10 years while fields away from villages are left fallow for roughly 50 years (Araki 1993). Araki (1993) found ash garden soil within distant fields had greater carbon levels when agriculture was reinitiated than fields near the village (1.3% C, 1.09% C respectively). Unlike Stromgaard's results, burning the vegetation did not significantly alter soil carbon levels. Generally, soil within ash gardens had lower carbon levels and higher bulk densities than the surrounding area which was only cut. Following cutting in the surrounding cut area, carbon levels fell to 1.1% C a few years after clearing due to the reduction in litter fall but then recovered to 1.7% C after more than 20 years while soil within the ash garden did not reach 1.4%C after 50 years (Araki 1993).

Root biomass in agricultural fields is basically unknown at this time. Although root biomass was not measured, Tuite and Gardiner (1994) examined the persistence of miombo trees under a field continuously cultivated for 15 years. They found 40 tree species within the selected plots that had coppiced throughout this cultivated time. This exemplifies the ability of Miombo tree species, and therefore their root structure, to sustain themselves over long numbers of years under cultivation. The existence of these live tree roots may be helping to maintain soil carbon levels. The recovery of belowground carbon in fallow fields is another area where more data is needed.

1.4 Overview of Methods

To examine the current impact of cultivation on nutrient levels, field measurements were taken and soil and vegetation analyzed for nutrient content. The

CENTURY model was then employed to better understand how the system responds to land management over a longer time frame. A combination of field surveyed economic data and CENTURY modeling was utilized to estimate the potential carbon and economic consequences of raising rotation periods.

1.4.1 Field measurements

Field sampling took place at four study locations (Table 1.3; Figure 1.1). The four locations span the range of land use intensity found in the region. Results from the first location in Malawi are presented in greater detail in my masters thesis (Walker 2003) and Walker and Desanker (2004). At all sampling locations, the only land use types sampled were: Miombo Woodlands, agricultural fields, and fallow fields. The Miombo Woodland areas contain a mixed-age stand of Miombo trees with no significant deforestation. At most sites all valuable timber trees have been removed. These areas are used by the community for thatch collection and other non-timber forest products. In the agricultural areas the majority of the indigenous trees had been cut down, the field maintained by burning before planting, and the field plowed using hand hoes. Fallow areas were used for crop production in the past. No trees were actively planted to improve the fallow period. Indigenous trees grow from root stocks, trunks, and seeds. These areas may be used by local people for thatch collection, non-timber forest products, and in Malawi for grazing. There are no grazing animals kept at the Tanzania or Mozambique study areas due to tsetse fly.

Table 1.3 Summary of sites sampled at various locations

Current Land Use	Number of sites
Chimaliro, Malawi	
Miombo Woodlands	5
Agric 1-2 yr	2
Agric 5 yr	2
Agric 10 yr continuously	1
Agric 15 yr continuously	2
Agric 20 yr continuously	1
Agric 30 yr continuously	2
Agric 40 yr continuously	1
Fallow 10 yr	3
Fallow 20 yr	2
Fallow 40 yr	1
Kitulanghalo, Tanzania	
Miombo Woodlands	7
Converted to agric <8 yrs ago	
Agric 1-2 yrs, first cropping cycle	4
Agric 1 yrs, first cropping cycle	1
Agric 5 yrs, first cropping cycle	1
Fallow 5 yr, prev. Agric 5 yr	1
Converted to agric ~30 yrs ago	
Currently Agric - Crop-fallow cycle ~30 yrs (Generally: Agric 2-5yr, Fallow 3-5yr)	4
Currently Fallow - Crop-fallow cycle ~30 yrs (Generally: Agric 2-5yr, Fallow 3-5yr)	4
Mecuburi, Mozambique	
Miombo Woodlands	1
Agric 3 yr, first cropping cycle	1
Fallow 5 yr, prev. Agric 3 yr	1
Fallow 15 yr, prev. Agric 3 yr	1
Fallow 19 yr, prev. Agric 3 yr	1
Pindanyanda, Mozambique	
Miombo Woodlands	3
Agric 1-2 yr, first cropping cycle	2
Fallow 1 yr, prev. Agric 2 yr	1
Fallow 4 yr, prev. Agric 2 yr	1
Fallow 20 yr, prev. Agric 2-4 yr	2
Fallow 4 yr, prev. Agric 3 yr, Fallow 4 yr, Agric 3 yr	1

1.4.1.1 Chimaliro, Malawi

The site (33.51E, -12.48S) is in central Malawi and about 70 km north of Kasungu on the main north road to Mzuzu and has an average annual precipitation of 1000 mm. Field sampling took place within the Chimaliro Forest Reserve and surrounding villages. The Chief in each area has allocated most land surrounding the forest reserve to a particular farmer. Most farmers rotate the use of their allocated land although the crop-fallow cycle is very variable. Research was conducted in conjunction with the Forest Research Institute of Malawi (FRIM) which maintains permanent sample plots within the reserve. Samples collected during this field campaign were originally used for my Master's thesis.

A general survey of the area was conducted with FRIM employees and local farmers to identify the dominant land use types and meetings held with chiefs to receive permission to carry out the study. Within each land use type (Miombo, agriculture, fallow), random sites were then located within and surrounding the forest reserve. The land use history of each site was documented by interviewing the forester, the farmer, and other long term residents. Sampling took place in four 1 m^2 subplots at each site. All non-tree aboveground vegetation was sampled by clipping at the base all vegetation originating from within the subplot and weighing it. A representative subsample was taken and weighed. Downed litter was also removed, weighed, and a representative subsample collected and weighed. Aboveground tree biomass was not estimated. Soil and roots samples were also collected from within a 1 m^2 soil pit. Composited soil samples were taken at the following depths: 0-10 cm, 10-20 cm, 20-40 cm, 40-60 cm, 60-

100 cm, 100-150 cm. Bulk density samples were also taken at each depth using a known volume metal container.

1.4.1.2 Mecuburi, Mozambique

This sampling area is located in northern Mozambique (39.10E, -14.6S) and has annual precipitation of 1000 mm. About 90 km from Nampula is the Mecuburi Forest Reserve. Although this area is a forest reserve, during the civil war the people began to move within the borders of the forest reserve, along the roads creating the perimeter of the reserve. The area is very rural and the population density is low. Although the chief of each village officially has control over the land, because there is not a land shortage people create and abandon fields without consulting the chief. Charcoal production is not occurring in this region because it is too far way from any markets. Fields are generally only cropped for 3 or less years. Sampling for this project took place in conjunction with the Ministry of Forestry and an UN-FAO project. The area was first surveyed with the forestry extension worker and the local farmers by comparing areas with a printed land cover map. Discussions of the history of the area were conducted with various farmers and the village chief. A list of potential sites was created and stratified and then sites were chosen randomly within each classification. Sampling at this location took place within another study estimating the regrowth rate of the Miombo woodlands. At each site a composite soil sample was taken by mixing soil from 12 augered cores. Soil samples were taken at the following depths: 0-5 cm, 5-10 cm, 10-30 cm, and 30-50 cm. A soil sample of a known volume was taken at each depth in one subplot for use in estimating bulk density. Herbaceous above-ground biomass and litter samples could not be taken due to a ground fire that had moved through the area a month previously. Aboveground tree biomass was not estimated.

1.4.1.3 Pindanyanga, Mozambique

Sampling took place in central Mozambique in Pindanyanga village (33.51E, -12.48S) about 35 km from Chimoio. The precipitation averages 1300 mm per year. Within the village was a community based natural resources management (CBNRM) project jointly funded by FAO and the government of Mozambique. This area is at the 'frontier' of deforestation. Villages near the main road have been deforested for several years. Selective logging for charcoal production is slowly degrading the forests farther from the main road. At distances of more than 20 km from the road few farmers live and there is intact unlogged Miombo Woodlands. Although the villages next to the main road are experiencing higher land use pressure, soil samples were taken in areas more than 10 km from the main road. Sampling for this project was undertaken in conjunction with the CBNRM project and members of the project hired as workers and guides. The area was first surveyed with the forestry extension worker and the local farmers by comparing areas with a printed land cover map. Discussions of the history of the area were conducted with various farmers and the village chief. Potential sites were listed and stratified and then sites were chosen randomly within each classification. At each site a composite soil sample was taken by mixing soil from 12 augered cores. Soil samples were taken at the following depths: 0-5 cm, 5-10 cm, 10-20 cm, 20-30 cm, and 30-50 cm. A soil sample of a known volume was taken at each depth in one subplot for use in estimating bulk density. Herbaceous above-ground biomass and litter samples could not be taken due to a ground fire that had moved through the area a month previously. Aboveground tree biomass was not estimated.

1.4.1.4 Kitulanghalo, Tanzania

Sampling in Tanzania occurred in eastern Tanzania (37.95E, -6.70S) in an area with an annual precipitation of 850 mm. Along the road from Dar es Salaam to Morogoro is the Kitulanghalo Forest Reserve, about 50 km east of Morogoro. The Department of Forest Mensuration and Management of Sokoine University of Agriculture has been allocated a section of this forest reserve for scientific study. The current research was conducted in conjunction with Sokoine University.

The area was first surveyed with the forest guard and the local farmers. Meetings were held with the local chiefs on the overall land use history of the area and on the common agricultural practices. A list of potential sites was made and stratified and then sites were chosen randomly within each classification. At each site non-woody vegetation and litter was sampled in 4 1 m^2 subplots. The sample was weighed, and a weighed representative subsample taken. At each site a composite soil sample was taken by mixing soil from 12 augered cores. Soil samples were taken at the following depths: 0-5 cm, 5-10 cm, 10-20 cm, 20-50 cm. A soil sample of a known volume was taken at each depth in one subplot for use in estimating bulk density. Additionally, within each plot in the Miombo Woodland areas, samples of the leaves, branches, and boles of dominant species were collected for nutrient concentration. Aboveground tree biomass was estimated by measuring the diameters of all trees greater than 5 cm at breast height in 20 x 40 m plots. Tree nutrient concentrations and tree biomass estimations were used for CENTURY model parameterization and validation.

A separate survey was conducted in the Morogoro area of Tanzania to estimate the current agricultural practices and the economic returns from agriculture and charcoal collection. Questionnaires were used to elicit information on crop production and sales, patterns of crop production including types of crops, fallow cycles and periods, crop rotation, and costs of production, crop prices, charcoal production and prices. The questionnaires were administered to selected respondents through focus group discussions in 3 villages near Morogoro. The three villages included Maseyu around Kitulanghalo about 50 km from Morogoro towards Dar es Salaam, Gairo about 100 km from Morogoro towards Dodoma and Melela about 100 km from Morogoro towards Mikumi. The focus group composed of members from the village government, Ward/Village agricultural extension officers, forest extension officers, representative from community based organizations in the areas and selected members from the faming community. In addition District and Regional Agricultural Officers from the respective districts and relevant national statistics on agriculture were consulted to verify information obtained from the focus groups.

1.4.2 Laboratory Analysis

Plant and root subsamples were dried at 55º C until a constant weight and then weighed. The ratio of wet weight to dry weight was used to estimate the total dry weight. For Malawi and Mozambique soils, soil texture measurements were performed at the University of Virginia using the hydrometer method. For Malawi soils, soil texture measurements were done on soil from one pit per site, and for depths 0-10 cm, 20-40 cm, 60-100 cm. For Mozambique soils, all samples were measured. For Malawi and Mozambique soils, bulk density estimates were made at the Univ. of Virginia by drying a known volume of soil at 105º C until a constant weight and reweighing. Unfortunately bulk density samples for 5 Malawi sites were lost in shipping samples to the USA and at these sites bulk density measurements from a site with similar land use were used as estimations in data analysis. For the Tanzanian soils, at the Sokoine Univ. of Agriculture soil laboratory all Tanzanian samples were examined for bulk density, pH using KCI, soil texture, iron content, phosphorus using Bray P1 extraction method, Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}.

In preparation for carbon and nitrogen determination, soil samples were first soaked in 10% HCl to remove any carbonates from the soil and then oven dried at 55º C until all moisture was removed (about one week). Soils were ground using a mortar and pestle. Vegetation samples were dried and ground using a Wiley mill. Samples were then analyzed for carbon and nitrogen using the Carlo Erba elemental analyzer. Three replicates were done on each of the samples and the average value of these replicates used in the analysis. Soil carbon and nitrogen densities were calculated by multiplying the soil concentrations found by the elemental analyzer by the bulk density (%C*BD). Soil stocks of carbon and nitrogen were calculated by multiplying the carbon/nitrogen density by the depth of soil sampled (%C*BD*Depth). Total phosphorus content was found using a Kjeldahl digestion and then analyzed for phosphorus using an Alpkem. Total phosphorus and Bray 1 extractable phosphorus were analyzed for the 0-10 cm, 10-

20, and 20-40 cm for Malawi sites, and the 0-5, 5-10, and 10-20 cm depths for Mozambique and Tanzania sites

1.4.3 Use of the CENTURY model

1.4.3.1 Overview of the CENTURY model

The CENTURY model simulates the plant-soil interplay within ecosystems including grasslands, agricultural fields, forests, and savannas. CENTURY predicts long term C, N, P, and S cycling using a monthly time step (Metherell 1993). The major inputs needed by the model include (Metherell 1993; Parton *et al* 1993):

- Latitude/Longitude coordinates
- Monthly average maximum and minimum air temperature
- Monthly precipitation
- Growing season
- Soil texture
- Soil pH
- Soil depth for modeling water budget
- Atmospheric and soil nitrogen inputs
- Initial soil carbon, nitrogen, and phosphorus levels
- Percentage of crop harvested and transfer of dead stover to other pools
- Fire parameters such as percent of plant components removed by fire, % return of nutrients in burned material to soil

- Lignin content of plant material
- Plant type (C3, C4)
- Plant nitrogen, phosphorous, and lignin content of different plant components
- Plant growth characteristics
- Leaf monthly death rates
- Only the top 20 cm of the soil are simulated

Focusing on the Carbon submodel, the soil is divided into three fractions based on decomposition times: the active C pool with a turnover time of 1-5 years, a slow C pool, turnover time 20-40 years, and a passive C pool, turnover time 200-1500 years (Jenkinson *et al* 1999). Plant residues are split into a structural pool, turnover time 1-5 years, and a metabolic pool, 0.1-1 year turnover time, depending on the lignin: N ratio (Motavalli *et al* 1994). The turn over times of each of these fractions is dependent on the abiotic decomposition factor (DECO). This value is a function of precipitation, water storage, soil temperature, and soil texture (Parton *et al* 1994). The other nutrient submodels, N, S, and P, are similar to the carbon submodel. Microbial decomposition is responsible for carbon flows in the soil. Carbon flows out of the active pool are due to leaching, microbial respiration, or movement into the slow or passive pool. Carbon leaving the slow pool is divided between material quickly decomposed in the active pool and with a slow turnover in the passive pool. (Parton *et al* 1993) Because the definition of the organic pools is functional rather than based on physical analytic fractions, experimentally determining the pools sizes is difficult (Paustian and Cole 1998). To get around this problem, initial levels are often assumed to be at a steady state by running the model for 2000 years.

A simple water budget is incorporated into the model, simulating transpiration, evaporation, soil water content, and saturated flow within the soil. These fluxes will be based on biomass, rainfall, and potential evapotranspiration (Parton *et al* 1993).

Plant performance is based on factors such as the amount of water available, the soil water content, and nutrient concentrations. A minimum carbon:element ratio is necessary to sustain plant growth (Parton *et al* 1993). The ecological effect of fire is modeled by returning inorganic nutrients to the soil from the plants, removing the above ground biomass, and increasing the root:shoot ratio. Grazing increases the root:shoot ratio, removes aboveground biomass, returns nutrients to the soil, and increases the nitrogen content of roots and shoots (Parton *et al* 1993).

The CENTURY model has been used to successfully model grasslands (Parton *et al* 1993) worldwide and to model various agricultural management techniques (Parton and Rasmussen 1994). Forested systems have also been well represented by the model, although CENTURY did not model the leaf litter layer as well (Kelly *et al* 1997). More recently, changes have been made to the CENTURY to better represent woodland and savannas systems in which trees and grasses compete with each other (CENTURY 4.5 unpublished).

1.4.3.2 Parameterization of the CENTURY model

In the CENTURY model, the system was modeled as the savanna ecosystem type (trees and grass). Therefore, data on the dominant grass, dominant tree species, and soil parameters were used. Published data required for the CENTURY model were cataloged from the Miombo Woodland literature. Additionally, field data was collected in Malawi and Tanzania. Nutrient analysis of soil and grass and tree vegetation samples collected in Malawi was used as inputs into the model. With this combination of collected data and data from the literature, model parameterization for the Miombo Woodlands was completed. Century model parameters were altered in order to properly represent the Miombo woodland ecosystem including: growth rates, biomass distribution (branches, roots etc), nutrient levels, soil nutrient content, decomposition rates, response to disturbances (ex. growth after fire, agric), interaction between trees and grass, and crop production. Monthly precipitation data was extracted for the Morogoro weather station from the FAO data base (Station 63866) for the years 1922 to 1996 (station is approximately 50 km from the study area). Precipitation data from 1991-2000 was obtained from the Sokoine University weather station, approximately 40 km away from the study area. The standard deviation and skewness of the precipitation was then calculated. Monthly minimum and maximum temperature values for the Morogoro weather station were combined with data from the Sokoine University weather station data. Because these weather stations are so close to each other, the values were very similar.

For all modeling conducted in this analysis, the parameterized model was run for a specific location by using the climate data and soil analysis for the area surrounding the Kitulanghalo Forest Reserve in Tanzania (37.95E, -6.70S). Low intensity understory fires were modeled to occur every 3-5 years during the dry season months. Model results were then compared with vegetation nutrient concentrations analyzed from vegetation in Tanzania, soil nutrient measurements, and aboveground biomass estimates from field measurements and published data collected in the Kitulanghalo area.

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Picture 1.1 Miombo Woodlands - Mozambique

Picture 1.2 Miombo Woodlands after ground fire - Mozambique

Picture 1.3 Miombo Woodlands - Tanzania

Picture 1.4 Miombo Woodlands - Tanzania

Picture 1.5 Three year old regrowth Miombo Woodlands after ground fire - Mozambique

Picture 1.6 Fifteen year old regrowth Miombo Woodlands after ground fire - Mozambique

Picture 1.7 Wood cut for charcoal production in public lands, Tanzania

Picture 1.8 Charcoal kiln

Picture 1.9 Charcoal for sale

Picture 1.10 House, field, and communal lands – Tanzania

Picture 1.11 Agricultural field – Communal lands in background – Tanzania

Picture 1.12 Agricultural field, House, forest reserve – Malawi

Chapter 2 The influence of agricultural production on nutrient levels in the Miombo Woodlands

Abstract

Although in much of the world advances in crop production have led to great increases in productivity, rural agriculturalists in much of Africa still practice subsistence level shifting cultivation. Soil organic carbon can be used as an easily measurable proxy for soil quality and the sustainability of the current land use. In nutrient poor soils, soil carbon can also play a strong role in maintaining soil fertility. The Miombo Woodlands ecosystem covers a wide area of Africa, containing different countries with varying regulations and human population densities. In many areas of the region populations are increasing, leading to greater land use intensity with longer cropping periods and a shorter number of years of fallow. However, in some locations, population densities are still relatively low and land availability allows for less intense agricultural use. The following study examines nutrient levels at locations along a gradient of land use intensity. Two rural location in central and northern Mozambique served as the low land use intensity areas while for intermediate land use intensity sampling took place near Morogoro, Tanzania. An area of central Malawi served as the highest land use intensity area. Soil, herbaceous, and tree samples were collected in Miombo areas, agricultural fields, and fallow fields and analyzed for carbon, nitrogen, and phosphorus content. Soil nutrient levels were similar to those found in previous studies and were very low at all locations with soil carbon levels in the top ten centimeters averaging 1.9% and soil

nitrogen levels averaging 0.12%. Other soil nutrients were highly correlated with soil carbon levels. Soil texture greatly influences soil carbon levels, with high clay soils having greater levels of carbon. In Mozambique and Tanzania when land was under crop production for less than five years, there was no significant reduction in soil nutrient stocks. In areas in Tanzania that had undergone several short crop-fallow cycles soil carbon concentrations were reduced, but only significantly at the surface. In contrast, in Malawi, soil carbon stocks in agricultural and fallow areas were on average 60% lower than Miombo Woodland sites in the top 50 cm of soil. In Malawi, both agricultural and fallow fields had also been through several crop-fallow cycles, but the crop production portion of the cycle was on average many years longer than practiced in Tanzania because of the land scarcity. Fallow fields did not have significantly different soil carbon stocks than the agricultural areas and older fallow areas did not have elevated carbon stocks. Based on this analysis, it appears that in the Miombo system which naturally has very low soil nutrient stocks, conversion to a crop production may not significantly reduce nutrient levels in the short term. In Tanzania crop-fallow agriculture has lead to some nutrient loss but in Malawi many years of agriculture have resulted in more substantial land degradation.

2.1 Introduction

The Miombo Woodlands are the dominant ecological community within the south-central region of Africa, covering around 2.8 million km^2. Human activity in the region is dominated by subsistence agriculturalists practicing shifting cultivation or crop fallow agriculture, depending on the population density. The future productivity of the region's agricultural land and the health of the ecosystem will depend greatly on whether the current agricultural practices reduce nutrient levels through time and therefore whether the repeated crop-fallow cycle common in this region is a sustainable agricultural practice. Although aboveground carbon stocks can be altered quickly, soil nutrient stocks have much slower turnover rates and therefore soil carbon levels measured over time can be used as an indicator for soil quality and the possible sustainability of the current land use. The soils underlying the Miombo Woodlands region are geologically ancient and naturally nutrient poor with soil carbon levels spanning the range (0.7%-4%) found within other dry forests worldwide (Campbell 1996; Walker and Desanker 2004). In such systems, soil organic carbon can play an important role in the stability, quality, and fertility of the soil and therefore is integral toward maintaining soil health and long term sustainability.

In undisturbed ecosystems, the soil carbon pool is generally in equilibrium, with inputs such as deadwood and litter being balanced by outputs such as erosion, leaching, and decomposition (Tate 1987). Conversion of land to agriculture generally reduces the amount of inputs into the soil carbon pool and increases the rate of carbon leaving the pool (Nye and Greenland 1965). Depending on the original vegetation type, the amount of dead woody and herbaceous litter deposited is reduced substantially especially when crop residues are removed. An increase in erosion and the oxidation of organic compounds, rising the rate of output, is caused by tillage breaking up soil aggregates and the alteration of soil temperature and water levels. Studies worldwide have found reductions of soil carbon when land is converted to agriculture up to 75% (Lal 2004). Several studies have examined soil carbon levels under different land use types within areas covered by the Miombo Woodlands ecosystem type and found a reduction in carbon and nitrogen levels within agricultural areas (King and Campbell 1994; Kirchmann and Eklund 1994; Araki 1993). The following study expands this examination of soil nutrient stocks by comparing locations across the Miombo woodlands at different population densities. Sampling took place in rural Mozambique, Tanzania, and Malawi where subsistence agriculture is practiced. In Mozambique a brief agricultural cycle is followed by long fallow periods. In Tanzania, the length of cropping period is similar to Mozambique, but the fallow period is shortened. At the Malawi sampling locations the common agricultural period is substantially longer followed by a fallow period of varying lengths.

This study examines how these various cropping systems will influence soil nutrient stocks. Soil carbon, nitrogen, and phosphorus levels are examined in Miombo woodland areas and agricultural fields both currently under crops and during the fallow periods. Nutrient levels in aboveground vegetation are also compared between woodland and fallow areas at the Tanzania location. It is expected that a low number of years of agricultural production, followed by many years of biomass inputs during the fallow periods will result in less significant impacts in comparison to higher intensity agriculture.

2.2 Methods

Sampling took place at four locations across the Miombo Region: central Malawi (33.51E, -12.48S), annual precipitation of 1000 mm; eastern Tanzania (37.95E, -6.70S), annual precipitation of 850 mm; northern Mozambique (39.10E, -14.6S) with annual precipitation of 1000 mm; and central Mozambique (33.51E, -12.48S) with precipitation averaging 1300 mm per year.

2.2.1 Land use history of sampling locations

The populations currently living in the sampling locations have different histories, and therefore, have used the land in different ways. The area surrounding the Chimaliro forest reserve north of Kasungu in Malawi served as the high land use intensity site during this study. In this area all land outside of the forest reserve had been allocated to a specific farmer by the chief. The only Miombo woodland areas in accessible distance to the farmers are within the guarded Chimaliro forest reserve. Most farmers have the majority of their allocated land under agricultural production and a smaller portion under fallow (personal communication with village chiefs and farmers). The main crops sowed are maize, tobacco and sorghum. The fallow period is used not only as a method to increase soil fertility, but also as a source of wood fuel, pole wood, and grazing since there are not other areas the farmer can access for such products. Therefore, although varying between farmers, some fields had been cropped continuously for more than 30 years. Owing to the cost, nutrient additions such as fertilizers are very minimal and only used when tobacco is planted. The agricultural fields sampled had undergone at least one previous crop-fallow period, however, it was not able to be determined when the fields had originally been converted from Miombo Woodland. The sampling at this location took place within a previous study (Walker 2003) and the research took place in conjunction with the Forestry Research Institute of Malawi.

In the area sampled in Tanzania, the land is used in a less intensive manner and serves as the intermediate land use intensity area in the study. Large areas of communal land covered by Miombo Woodlands still exist and could be converted into crop production, however, these lands are farther from current villages. In the 1970's under a governmental 'villagisation' policy, farmers were concentrated within villages, leading to a large amount of land surrounding the newly developed villages to be deforested for agriculture at this time. More recently, governmental policies have changed and people have begun to move to less populated nearby areas and have cleared new areas for farming. This research took place in conjunction with Sokoine University in Morogoro, Tanzania and sampling took place within the Kitulanghalo Forest Reserve and the surrounding community. Based on interviews with the village chiefs and farmers, the average crop fallow cycle at the time of field data collection was 2-3 years of agriculture followed by about 3-10 years of fallow period. The cycle will vary among farmers dependent on access to additional lands or due to cultural connections to certain areas. The main crops are maize, sorghum, and cassava.

In Mozambique, sampling took place in the two rural communities of Mecuburi and Pindanyanda and the Miombo woodlands surrounding the Mecuburi Forest Reserve and the Gorongosa National Park respectively. These locations serve as the low land use intensity areas in the study. Due to the remote location, human population density was low at in both areas, however since the end of the civil war, many farmers had just recently moved into the area from other parts of the country. Land is generally cropped for 3-5 years and then abandoned. The main crops are maize, sorghum, and cassava. The fallow period has traditionally been more than 20 years (farmer interviews), however at both locations in Mozambique due to influx of new farmers the agricultural land sampled had not previously been cultivated. Large areas of communally held Miombo woodland areas surround both communities.

In all areas sampled, to prepare a field for agriculture production, trees are cut by local farmers and used for either charcoal production, lumber or household construction, or household firewood. Remaining small trees and tree limbs are then burned on the field. Plowing is done with a hand hoe and fertilizers are used very minimally if at all as farmers generally do not have enough resources to properly fertilize. Burning of fields is repeated each year prior to each crop being sown to remove the regrowth of trees in the fields and to kill pests. The form of agricultural production referred to locally in Zambia as *chitemene* was not practiced in any of the areas sampled (Chidumayo 1997).

The current land use types sampled at all locations were Miombo woodlands, agriculture, and fallow. However, at the Tanzania location, agricultural fields pass through successive crop-fallow cycles and therefore analysis on the agricultural fields is also conducted to compare areas recently converted to agricultural lands with areas converted to agricultural land during the villigisation program in the 1970's and 1980's.

2.2.2 Field Sampling

At all sampling locations, the areas were first surveyed with either a forestry extension worker or University technician along with the local farmers by comparing areas with a printed land cover map. The history of the areas were discussed and the dominant land use types in the region were determined with various farmers and the village chiefs. A list of potential sites was created, stratified by land use category, and then sites randomly chosen within each classification. Once at the site, the farmer using the land was interviewed and the land use history recorded included: date of land use conversion, prior land cover type, the use, type, and amount of fertilizer, crops sowed, burning regime, grazing regime, collection of pole or firewood. The location of rivers, roads, footpaths and other influencers were noted. A total of 16 woodland sites were measured along with 24 agriculture and 19 fallow areas (Table 2.1).

Sampling location was determined by randomly choosing a direction and number of steps to walk. Soil sampling took place at the four corners (3 auger cores per location in Tanzania and Mozambique) of a 20 x 20 m area (agricultural areas in Tanzania, all locations in Mozambique and Malawi) or a 20 x 40 m area (Miombo and fallow areas in Tanzania). At each site a composite soil sample was taken for each depth by mixing soil from the 12 augered cores. In Malawi similar sampling took place except 1 x 1 m soil pits were dug. In Tanzania and Mozambique, using a soil auger of a known volume, one bulk density per depth range was also taken at each site. In Malawi a container of known volume was pressed into the side of the soil pit and this sample used to measure bulk density.

In order to estimate the biomass of non-woody standing vegetation and litter, in Tanzania and Malawi all non-woody standing vegetation was sampled by clipping at the base all vegetation originating from within a 1 x 1 m subplot and weighing it. A representative subsample was taken and weighed. Downed litter was also removed from the 1 x 1 m subplot, weighed, and a representative subsample collected and weighed. Roots were sampled in a 25 cm x 25 cm x 10 cm depth area. In Tanzania within a 20 x 20 m area (agricultural areas) or 20 x 40 m area (Miombo and fallow areas) samples of the leaves, branches, and boles of dominant species were collected. For woodland and fallow sites, within six 5 m x 5 m subplots, the grass height was measured 5 times, grass species were found, and the relative cover of each species estimated. Coarse woody debris was collected in each 5 x 5 m subplot, weighed and a subsample taken and weighed. At both the Mozambique sites, above-ground herbaceous biomass and litter samples could not be taken due to ground fires that had moved through the area a month previously.

Table 2.4. Description of sample locations

Current Land Use	Number of sites
Chimaliro, Malawi	
Miombo Woodlands	5
Agric 1-2 yr	2
Agric 5 yr	2
Agric 10 yr continuously	1
Agric 15 yr continuously	2

Current Land Use	Number of sites
Agric 20 yr continuously	1
Agric 30 yr continuously	2
Agric 40 yr continuously	1
Fallow 10 yr	3
Fallow 20 yr	2
Fallow 40 yr	1
Kitulanghalo, Tanzania	
Miombo Woodlands	7
Converted to agric <8 yrs ago	
Agric 1-2 yrs, first cropping cycle	4
Agric 1 yrs, first cropping cycle	1
Agric 5 yrs, first cropping cycle	1
Fallow 5 yr, prev. Agric 5 yr	1
Converted to agric ~30 yrs ago	
Currently Agric - Crop-fallow cycle ~30 yrs	4
(Generally: Agric 2-5 yr, Fallow 3-5 yr)	
Currently Fallow - Crop-fallow cycle ~30 yrs	4
(Generally: Agric 2-5 yr, Fallow 3-5 yr)	
Mecuburi, Mozambique	
Miombo Woodlands	1
Agric 3 yr, first cropping cycle	1
Fallow 5 yr, prev. Agric 3 yr	1
Fallow 15 yr, prev. Agric 3 yr	1
Fallow 19 yr, prev. Agric 3 yr	1
Pindanyanda, Mozambique	
Miombo Woodlands	3
Agric 1-2 yr, first cropping cycle	2
Fallow 1 yr, prev. Agric 2 yr	1

Current Land Use	Number of sites
Fallow 4 yr, prev. Agric 2 yr	1
Fallow 20 yr, prev. Agric 2-4 yr	2
Fallow 4 yr, prev. Agric 3 yr, Fallow 4 yr, Agric 3 yr	1

2.2.3 Laboratory Analysis

Plant, litter, and root subsamples were dried at 55º C for 3 days and then weighed at the University of Virginia. The ratio of wet weight to dry weight was used to estimate the total dry weight of the 1 m^2 sample. The average dry weight of the four subplots per site was then scaled to the hectare level. All soil analysis for the Mozambique and Malawi soils took place at the University of Virginia. Soil texture measurements were performed using the hydrometer method, bulk density measurements were performed by drying the soil at 105º C for two days and then reweighing the samples, and plant available phosphorus analyzed via the Bray P1 extraction method followed by analysis on an Alpkem. For Tanzanian soils, bulk density, soil texture, pH using KCI, soil texture, iron content, phosphorus using Bray P1 extraction method, Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} were all measured at the SUA soil laboratory. For Mozambique, Malawi, and Tanzania samples, total phosphorus content of soil and plant material was found using a Kjeldahl digestion and then analyzed for phosphorus using an Alpkem at Univ. of Virginia. Total phosphorus and Bray 1 extractable phosphorus were analyzed for the 0-10 cm, 10-20, and 20-40 cm depths for Malawi sites, and the 0-5, 5-10, and 10-20 cm depths for Mozambique and Tanzania sites

In preparation for carbon and nitrogen determination, soil samples were first soaked in 10% HCl to remove any carbonates from the soil and then oven dried at 55 º C until all moisture was removed (around 1 week). Soils were ground using a mortar and pestle. Vegetation samples were ground using a Wiley mill. Samples were then analyzed for carbon and nitrogen using a Carlo Erba elemental analyzer at the Univ. of Virginia. Three replicates were done on each of the samples and the average value of these replicates used in the analysis. Soil carbon and nitrogen densities were calculated by multiplying the soil concentrations found by the elemental analyzer by the bulk density (%C*BD). Soil stocks of carbon and nitrogen were calculated by multiplying the carbon/nitrogen density by the depth of soil sampled (%C*BD*Depth).

2.2.4 Statistical Analysis

All statistical measures were completed using SAS (SAS Institute 1989). The variables of the data were first tested for normality. When necessary, variables were log transformed to meet normality conditions. Comparisons of data between land use types and sampling locations were completed using PROC GLM, an analysis of variance procedure in SAS (SAS Institute 1989). For each sampling location, to compare land use types, site was nested within land use (LU) type and depth nested within site and LU type. Land use types compared were: Miombo woodlands, agriculture, and fallow for all sampling locations. For Tanzania sites the analysis was repeated and land use was also divided by: Miombo woodlands, recent agriculture (areas converted <8 yrs previously), and older agriculture (areas converted 28-30 year previously). When appropriate, for the variable being tested (such as for carbon and nitrogen), soil texture or other soil properties were added as covariates. This test was also repeated, separating data by depth, by soil texture, and/or by BD class. Correlations between C, N, P and other variables such as soil texture were made.

A multiple stepwise regression was completed to determine what variables were influencing carbon and nitrogen levels. The variables included were log depth in cm, % clay, % sand, iron content (Tanzania sites only), and dummy variables for each land use type. Multiple regressions were also performed for each land use type separately. For the agriculture and fallow land use type, length of the current land use and number of years since land use conversion were also included in the stepwise multiple regression. Different equation models were fitted to just the carbon/nitrogen and depth measurements to find the model that best represented the relationship of carbon/nitrogen with depth.

2.3 Results

2.3.1 Overview of soil properties and nutrients

There was a wide range of soil textures across the sites with some sites being dominated by clays and others containing more sand. At the Tanzania and Malawi sites, clay content ranges 11%-45% clay in the top 5 cm (Table 2.2). On average, clay content is 22% lower at the surface than at 0.5 m. In Tanzania soil texture did not significantly vary between Miombo woodland sites and older agricultural sites. However, more newly established agricultural sites had significantly greater amounts of clay than both Miombo and older agricultural sites. This difference is true at all depths. At the Mozambique sites, the soil had a high sand content, averaging 82%, with very little clay. No significant differences in soil texture in Mozambique occur between land use classifications, either based on age of field initiation or current land use. In Malawi on average clay content is 30% lower in the top 10 cm than the depths below 20 cm. Soil texture did not differ significantly between land uses for each depth. Bulk density levels in Mozambique and Malawi sites averaged about 1.3 g cm^{-3} while in Tanzania averaged about 1 g cm^{-3} (Table 2.2)

Soil nutrient levels were low at all locations with soil carbon levels at 0-5 cm depth, averaging 1.9% and soil nitrogen levels averaging 0.12% (Table 2.2, Figure 2.1, 2.2). Soil carbon and nitrogen values are in a similar range at all sampling locations. Although one woodland site had very high carbon values of 5.6% at the surface, most sites ranged from 0.45% to 3.5% soil carbon in the top 5 cm (Figure 2.1, 2.2). Nitrogen values followed the pattern of carbon ranging from 0.03-0.41% nitrogen in the top 5 cm. Total phosphorus concentration were highest in Malawi, averaging 460 mg/kg in the top 10 cm (range 230-800 mg/kg), intermediate in Tanzania with a value of 420 mg/kg (range 160-870 mg/kg) and lowest in Mozambique the average was 301 mg/kg (range 150-760 mg/kg) in the top 5 cm. Mean levels of plant available phosphorus levels were about 20 mg/kg in the top 5 cm in Tanzania and Mozambique but on average were higher in Malawi, with an average about 45 mg/kg in the top 10 cm.

Table 2.5. Mean soil properties and nutrient levels at Tanzania, Mozambique, and Malawi sites (standard deviations in parentheses) (Recent agriculture= areas converted <8 yrs previously, Older agriculture=areas converted 28-30 year previously)

	Depth	% C	% N	C:N	Total P (mg/kg)	Plant Avail. Phosphorus (mg/kg)	BD (g/cm3)	%Clay+Silt
Tanzania:								
Recent Agric	0-5 cm	2.05% (0.25%)	0.16% (0.02%)	13 (0.9)	462 (128)	20 (14.3)	0.98 (0.21)	36% (12%)
	5-10 cm	1.95% (0.22%)	0.15% (0.02%)	12.7 (0.8)	576 (250)			
	10-20 cm	1.68% (0.35%)	0.14% (0.04%)	12.4 (1.3)	352 (42)	8.5 (6.7)	1.11 (0.13)	41% (16%)
	20-50 cm	1.21% (0.28%)	0.10% (0.02%)	11.9 (1.2)	274 (113)	7.3 (7.2)	1.05 (0.06)	46% (16%)
Older Agric	0-5 cm	1.67% (0.33%)	0.12% (0.03%)	14.2 (1.2)	278 (105)	18.3 (15.4)	0.89 (0.09)	26% (4%)
	5-10 cm	1.50% (0.34%)	0.10% (0.02%)	14.4 (1.7)	302 (122)			
	10-20 cm	1.21% (0.36%)	0.09% (0.03%)	14.4 (1.2)	331 (107)	9.2 (6.5)	0.97 (0.09)	29% (6%)
	20-50 cm	0.89% (0.24%)	0.07% (0.02%)	13.9 (1.6)	391 (137)	5.7 (3.1)	1.03 (0.08)	31% (5%)
Woodland	0-5 cm	2.08% (0.40%)	0.13% (0.03%)	16 (1.5)	279 (55)	21 (15.2)	0.88 (0.11)	24% (6%)
	5-10 cm	1.91% (0.57%)	0.12% (0.03%)	15.4 (1.6)	297 (89)			
	10-20 cm	1.41% (0.43%)	0.10% (0.03%)	14.8 (1.4)	242 (88)	12.9 (13.3)	0.93 (0.09)	27% (7%)
	20-50 cm	1.00% (0.21%)	0.07% (0.02%)	14.1 (1.7)	474	10.3 (12.5)	0.9 (0.05)	29% (9%)
Mozambique:								
Agric	0-5 cm	1.44% (0.94%)	0.10% (0.07%)	15.3 (0.9)	289 (150)	34.6 (19.5)	1.4 (0.22)	18% (9%)
	5-10 cm	1.39% (0.72%)	0.10% (0.05%)	14.8 (3.3)	211 (90)	16.8 (13.7)	1.29 (0.12)	19% (10%)
	10-20 cm	1.25% (0.90%)	0.09% (0.06%)	14.2 (0.9)	339 (145)	8.4 (3.3)	1.46 (0.04)	16% (15%)
	20-30 cm	0.82% (0.52%)	0.06% (0.04%)	14.9 (1.9)	212 (94)	9.5 (7.3)	1.43 (0.07)	18% (7%)
	30-50 cm	0.46% (0.20%)	0.03% (0.01%)	14 (1.6)	165 (58)	3.4 (1.3)	1.35 (0.15)	19% (2%)
Fallow	0-5 cm	1.60% (1.12%)	0.10% (0.06%)	14.6 (2.1)	314 (205)	16.6 (5)	1.28 (0.13)	15% (9%)
	5-10 cm	1.23% (0.66%)	0.08% (0.04%)	14.9 (1.7)	242 (155)	11.3 (6.4	1.21 (0.18)	19% (11%)

	Depth	% C		% N		C:N		Total P (mg/kg)		Plant Avail. Phosphorus (mg/kg)		BD (g/cm3)		%Clay+Silt	
	10-20 cm	1.42%	(0.74%)	0.10%	(0.04%)	14.5	(3.4)	301	(132)	7.1	(4.8)	1.42	(0.21)	24%	(15%)
	20-30 cm	0.78%	(0.58%)	0.05%	(0.03%)	15.2	(1.1)	201	(70)	5.7	(3.6)	1.41	(0.15)	19%	(10%)
	30-50 cm	0.50%	(0.34%)	0.04%	(0.03%)	17.2	(6.5)	171	(89)	3.8	(1.1)	1.4	(0.12)	21%	(13%)
Woodland	0-5 cm	2.72%	(2.04%)	0.17%	(0.16%)	17.5	(4.9)	294	(88)	17.8	(8.2)	1.36	(0.14)	12%	(6%)
	5-10 cm	1.88%	(1.31%)	0.12%	(0.11%)	17.1	(6.4)	168	(55)	11.2	(9.4)	1.45	(0.08)	14%	(6%)
	10-20 cm	1.07%	(0.57%)	0.07%	(0.03%)	16.4	(5.5)	223	(109)	4.5	(0.9)	1.46	(0.11)	16%	(4%)
	20-30 cm	0.58%	(0.30%)	0.03%	(0.01%)	16.5	(3.7)	121	(59)	4.2	(1.3)	1.43	(0.08)	13%	(6%)
	30-50 cm	0.41%	(0.19%)	0.02%	(0.01%)	17.7	(4.4)	108	(34)	3.4	(1.2)	1.24	(0.25)	11%	(2%)
Malawi: Agriculture	0-10 cm	0.88%	(0.10%)	0.06%	(0.005%)	13.61	(6.20)	443	(151)			1.21	(0.08)	53%	(9%)
	10-20 cm	0.50%	(0.08%)	0.04%	(0.004%)	11.79	(3.45)	418	126)			1.27	(0.08)	51%	(18%)
	20-40 cm	0.34%	(0.09%)	0.03%	(0.004%)	13.20	(5.01)	377	(73)			1.22	(0.08)	56%	(13%)
	40-60 cm	0.24%	(0.04%)	0.03%	(0.003%)	12.90	(5.23)	372	(122			1.26	(0.12)	51%	(15%)
	60-100 cm	0.18%	(0.09%)	0.02%	(0.004%)	12.94	(5.65)	443	(151)			1.23	(0.10)	52%	(13%)
	100-150 cm	0.16%	(0.05%)	0.02%	(0.006%)	11.48	(3.16)					1.23	(0.09)	54%	(18%)
Fallow	0-10 cm	1.04%	(0.13%)	0.06%	(0.008%)	11.36	(7.59)	456	(145)	21.3	(17.4)	1.26	(0.08)	61%	(15%)
	10-20 cm	0.66%	(0.08%)	0.04%	(0.010%)	8.67	(2.37)	452	(138)	38.4	(30.0)	1.28	(0.06)	44%	(21%)
	20-40 cm	0.38%	(0.08%)	0.02%	(0.004%)	12.57	(13.66)	411	(162)	42.3	(21.6)	1.21	(0.06)	54%	(15%)
	40-60 cm	0.25%	(0.19%)	0.02%	(0.011%)	8.47	(3.92)	431				1.30	(0.09)	53%	(23%)
	60-100 cm	0.14%	(0.01%)	0.01%	(0.001%)	8.88	(2.87)	286				1.23	(0.06)	55%	(18%)
	100-150 cm	0.11%	(0.03%)	0.01%	(0.011%)	8.50	(2.16)	304				1.30	(0.11)	50%	(14%)
Woodland	0-10 cm	2.14%	(0.18%)	0.13%	(0.011%)	14.76	(1.56)	582	(38)	46.4	(21.5)	1.32	(0.12)	42%	(6%)
	10-20 cm	1.08%	(0.14%)	0.07%	(0.009%)	14.89	(2.20)	395	(87)	49.7	(29.9)	1.33	(0.16)	39%	(14%)
	20-40 cm	0.58%	(0.03%)	0.05%	(0.003%)	16.97	(1.39)	543	(132)	40.3	(33.9)	1.24	(0.08)	52%	(9%)
	40-60 cm	0.40%	(0.05%)	0.04%	(0.004%)	13.88	(1.63)					1.25	(0.05)	38%	(11%)

Depth	% C		% N		C:N		Total P (mg/kg)	Plant Avail. Phosphorus (mg/kg)	BD (g/cm3)		%Clay+Silt	
60-100 cm	0.23%	(0.01%)	0.03%	(0.004%)	15.17	(4.18)			1.26	(0.14)	48%	(10%)
100-150 cm	0.15%	(0.09%)	0.05%	(0.098%)	15.01	(4.70)			1.31	(0.18)	39%	(17%)

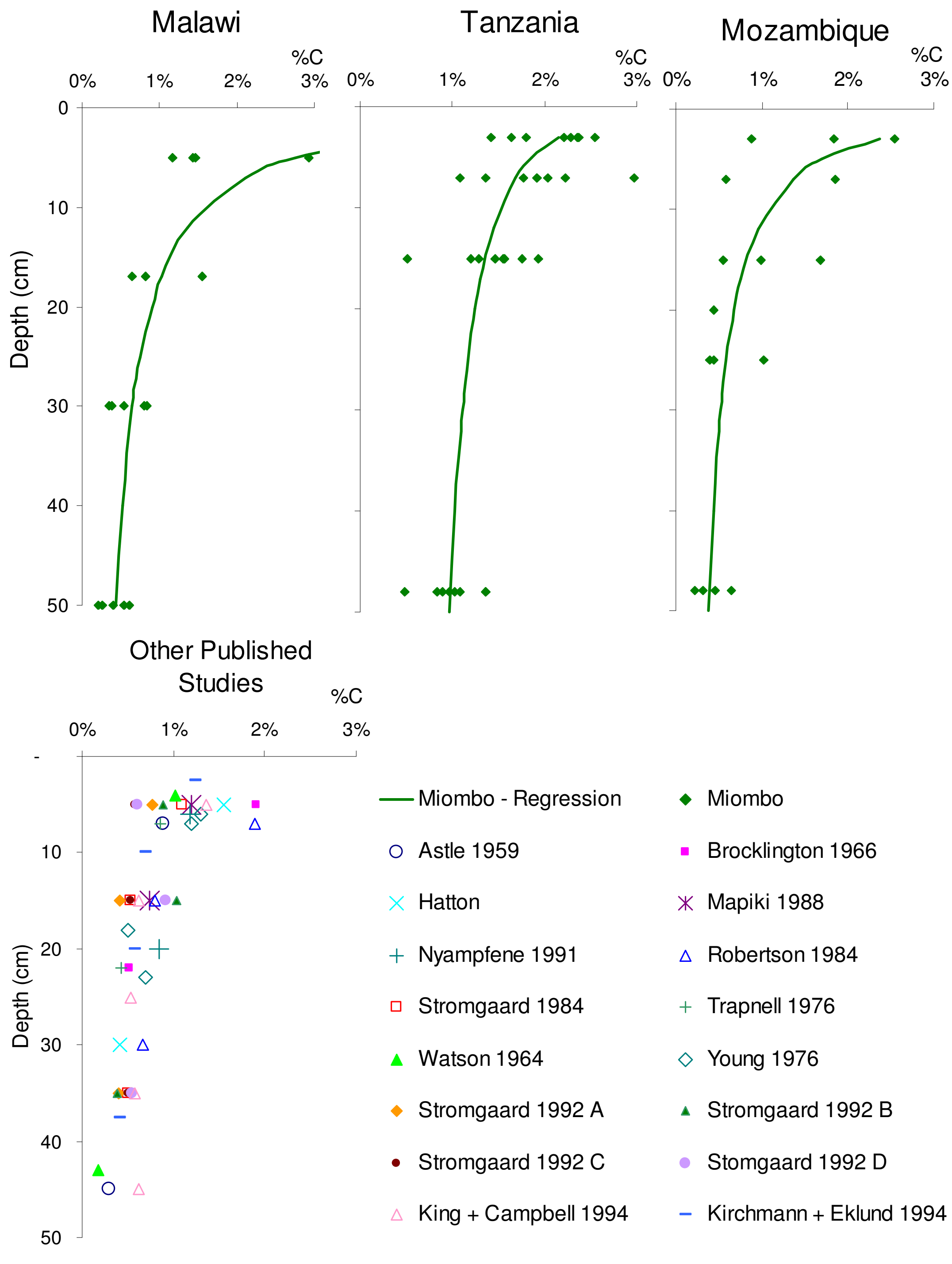


Figure 2.4 Soil Carbon levels in Miombo Woodland sites in Malawi, Tanzania, and Mozambique in comparison to previously published soil carbon levels across the Miombo Woodlands. Log carbon – log centimeter regression line fitted to data.

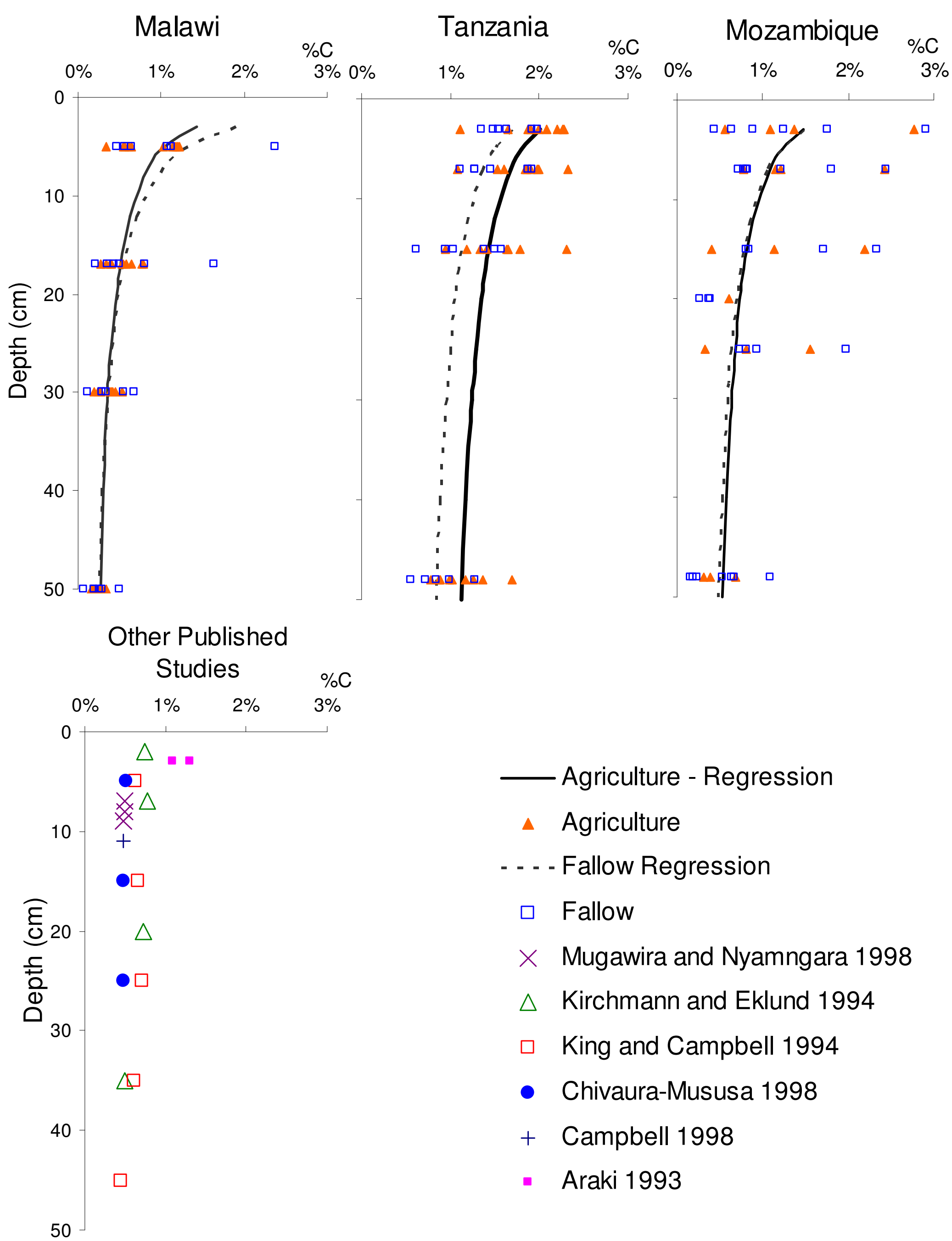


Figure 2.5 Soil carbon levels in areas under crop production at the time of sampling and areas in a fallow state at the time of sampling in Malawi, Tanzania, and Mozambique in comparison to previously published soil carbon levels in areas of Miombo woodlands also converted to agriculture. Log carbon – log centimeter regression line fitted to data.

The C:N ratio averaged about 15 in the top 10 cm at all locations (Table 2.2). The C:N ratio is relatively similar throughout the soil profile in Tanzania and Mozambique but in Malawi declines to about 12 at 50 cm. The C:N ratio is lower in the more recent agricultural sites in Tanzania and the agricultural sites in Mozambique and Malawi. Low C:N ratios are found in sites with high nitrogen levels.

Following a thorough investigation of models, log carbon–log depth regression equations were found to significantly best represent soil carbon and soil nitrogen with depth (Figure 2.1, 2.1). Soil carbon, nitrogen, and phosphorus are greatest at the surface and then decline with depth. The variance between sites and within a site is highest at the surface and values become more similar with depth. In the top 50 cm of soil, roughly 35 to 45% of the soil carbon is stored in the top 10 cm in all sampling locations, however in Tanzania almost 60% of the nitrogen is in the top 10 cm while in Mozambique and Malawi nitrogen follows carbon with an average of 42% in the top 10 cm. In Tanzania about 70% of the total phosphorus to a depth of 20 cm is found in the top 10 cm while in Mozambique and Malawi about 30% of phosphorus is in the top 10 in the first 50 cm of the soil profile. For carbon, nitrogen, and phosphorus no significant differences in proportional storage are found between either land use categories or current land use types in all sampling locations.

All nutrients examined except plant available phosphorus were highly correlated with carbon content at all depths, including: total phosphorus, nitrogen at all locations and calcium, magnesium, potassium, and sodium in Tanzania (Figure 2.3). Plant available phosphorus levels decline with depth and become less variable. At the

Tanzanian sites, total phosphorus and plant available phosphorus are correlated, although not strongly within the 10-20 cm depth and no measurements of total phosphorus were made for the 20-50 cm depth (Figure 2.3). In Tanzania the CEC level of the soils is highly significantly positively correlated with total phosphorus levels. Plant available phosphorus is not correlated with any nutrients or soil attributes examined for the Mozambique sites.

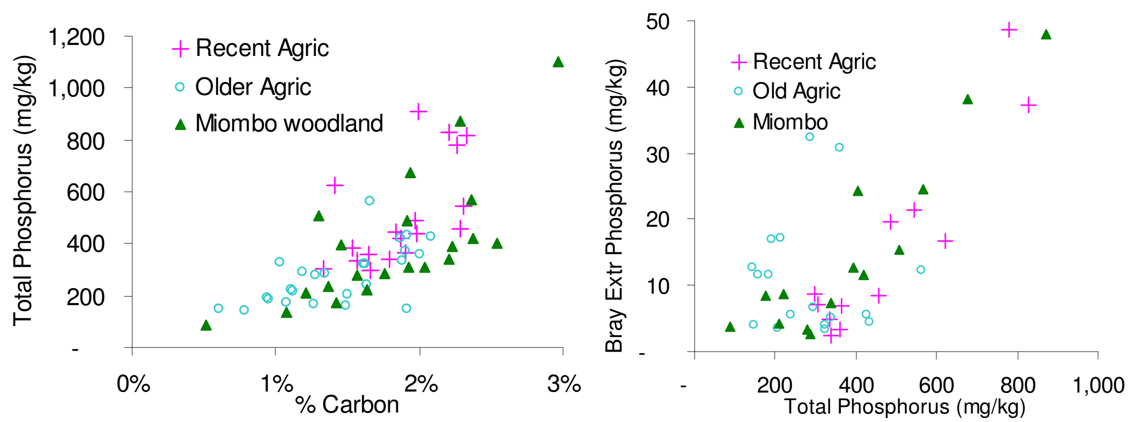


Figure 2.6 Correlation between total phosphorus and carbon content and total phosphorus and available phosphorus in Tanzania (Recent agriculture= areas converted <8 yrs previously, Older agriculture=areas converted 28-30 year previously)

2.3.2 Factors influencing soil nutrient levels

Soil texture is correlated with carbon content, especially at the surface. Clay dominated soils have the greatest carbon levels. The influence of clay on carbon content decreases deeper in the soil profile. Carbon levels are positively correlated with pH, with higher organic matter levels resulting in higher pH. A stepwise regression performed on all data points was able to explain a large portion of the variation (Tanzania: R^2=0.648, Mozambique: R^2= 0.736, Malawi: R^2= 0.79). Depth accounted for the majority of the variation in Tanzania (partial R^2=0.405) and Malawi (partial R^2=0.61) with %clay+silt (partial R^2=0.1 in both locations) being the second largest contributor while in Mozambique, depth and soil texture had a more similar influence. Land use type was also significantly included in the regression at all locations. In Malawi the length of time under agriculture was a significant contributor but not the length of time in fallow. In Tanzania both the length of time since conversion from woodlands and the length of time within fallow significantly contributed to explaining the variation in areas currently in fallow and that had been passing through successive crop-fallow periods for 30 years however were not significant contributors to areas currently under agriculture, regardless of the length since conversion.

In Tanzania, since soil texture is highly correlated with carbon and the agricultural fields recently established have significantly higher clay+silt content than the agricultural fields initiated during villagisation in the 1970's, soil texture was added as a covariate in an analysis of variance. Areas under cropland and fallow at the time of sampling had significantly less percent soil carbon levels in the top 10 cm than Miombo woodland areas but were not significantly different from each other. In only the top 5 cm nitrogen levels in agricultural areas and Miombo woodlands were significantly different. More recently established agricultural fields (areas converted <8 yrs previously) in Tanzania have significantly less soil carbon concentrations than Miombo woodlands in the top 5 cm, but do not have significantly different levels of carbon, nitrogen, or phosphorus than Miombo woodland sites at other depths depth (Appendix 2.2). Areas under crop-fallow production for about 30 years contain significantly less percent carbon and nitrogen than Miombo woodlands in the top 10 cm but levels are not significantly different from more recently established fields.

In Mozambique, the analysis of variance found that nutrient levels in land use types were not significantly different from each other, both when examined at each sampling location separately and when combined (Appendix 2.3). In Malawi, carbon, nitrogen, and phosphorus levels in agricultural and fallow fields are not significantly different from each other, but nutrient levels in Miombo sites areas are significantly higher. This is true both when soil texture is included as a covariate and when it its not.

The Miombo Woodland areas span the range of nutrient and soil textures sampled, although on average have greater C, N, P, and CEC content than older agricultural sites even though mean clay content is similar (Figure 2.4, 2.5). The carbon content of the older agricultural fields do not vary as greatly as the more recently deforested sites or the Miombo sites. However, there is no strong overall trend of carbon stock change since the date of deforestation. Additionally, as the length of the fallow period increases there is no evidence of increasing nutrient levels at all sampling locations.

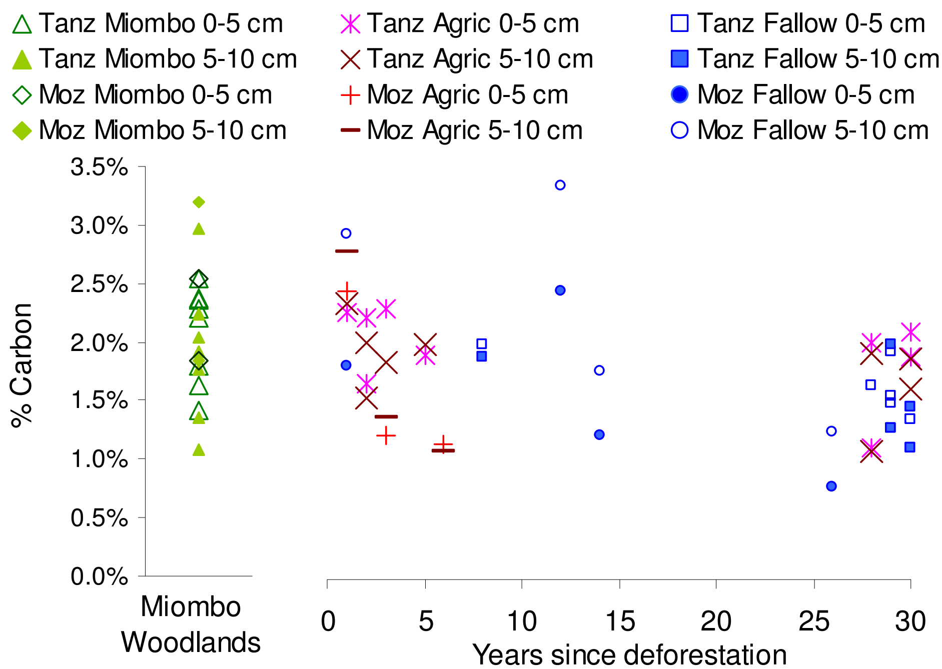


Figure 2.7 Impact of age on soil carbon levels at sampling locations in Tanzania (Tanz) and Mozambique (Moz) (one site with 5.6% soil carbon level at surface excluded from figure)

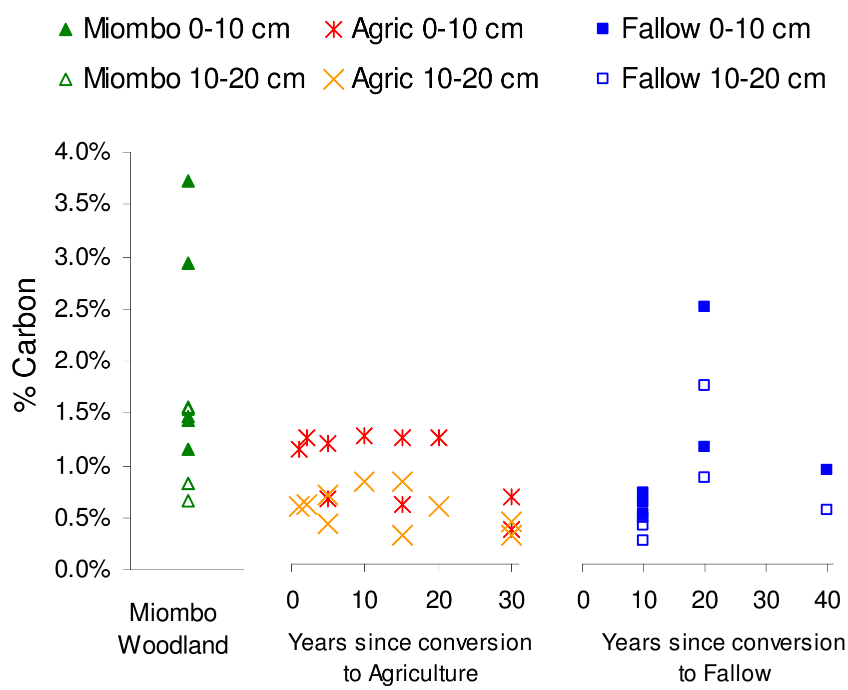
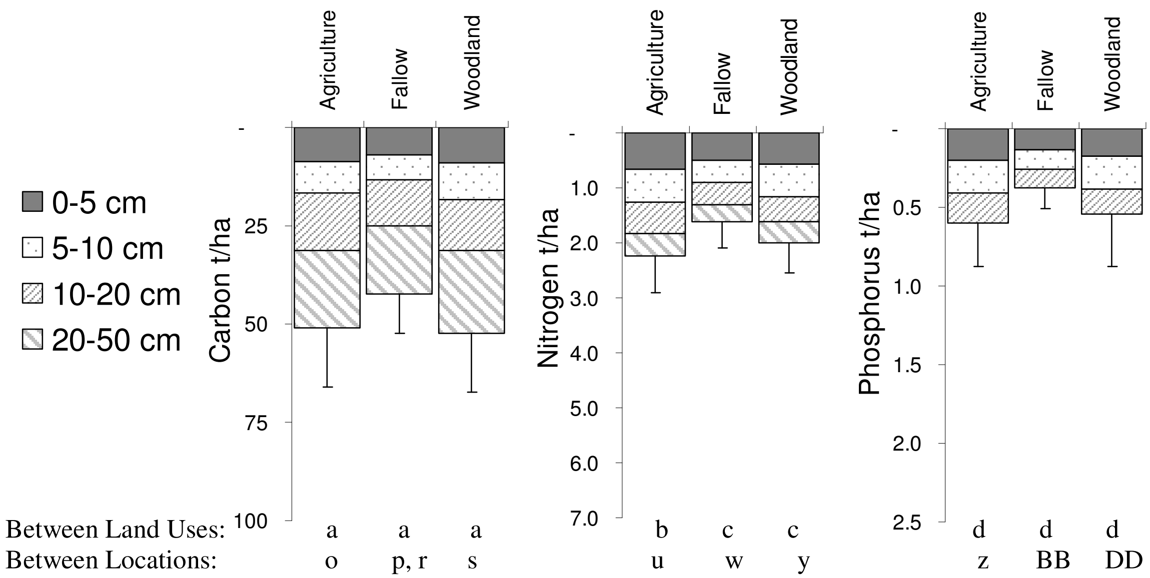
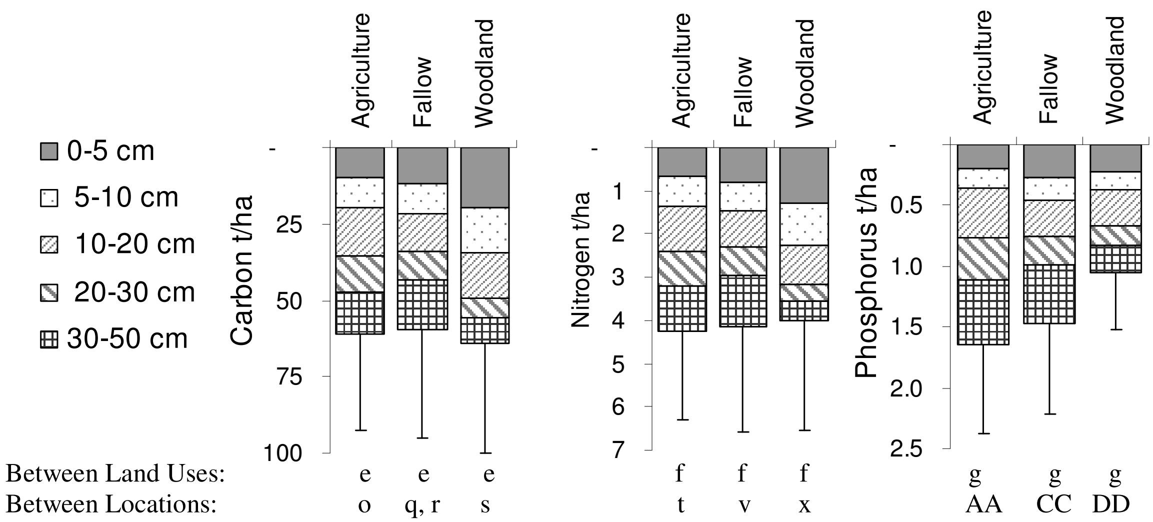


Figure 2.8 Soil carbon levels at sampling locations in Malawi

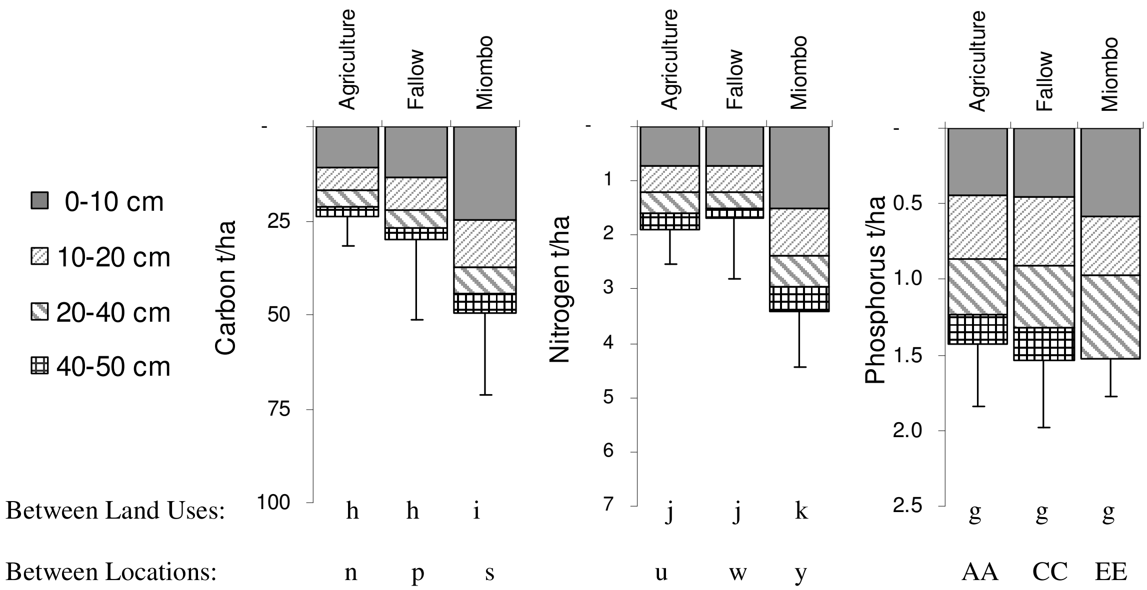
If the total soil carbon stock to 50 cm is examined in the Tanzanian sites, more recently developed agricultural fields have the largest nutrient levels, followed by Miombo sites and older agricultural sites have the lowest nutrient levels. However these differences are not significant and are influenced by the higher clay content in the more recently developed agricultural fields. There is significantly greater stocks of nitrogen in the more recent agricultural areas than in areas converted to agriculture in the 1970's and there is significantly greater nitrogen stocks in land under crop production when sampling than lands in fallow use or Miombo during sampling (Figure 2.6a). Total stocks of carbon and phosphorus to 50 cm are not significantly different between land uses within Tanzania and C, N, and P stocks are all statistically equivalent in the Mozambique sites (Figure 2.6a, b). Carbon and nitrogen stocks are significantly lower in the agricultural and fallow areas in Malawi than Miombo Woodland stocks, however soil phosphorus stocks are not significantly different (Figure 2.6c). Looking across sampling locations, Miombo woodland total carbon stocks were not significantly different from each other. Soil nitrogen stocks in Malawi and Tanzania were significantly lower from those in Mozambique, however soil phosphorus Malawi and Mozambique stocks were significantly higher than in Tanzania.



a) Tanzania



b) Mozambique



c) Malawi

Figure 2.9 Average mass of Carbon, Nitrogen, and Phosphorus in top 50 cm of soil in areas under agriculture, fallow, or Miombo woodland at the time of sampling. Total stocks statistically compared between land uses at the same location, and between locations for the same land use. (same letter = no significant difference in total stocks, different letter=significantly different total stocks)

2.3.3 Nutrients within aboveground biomass

Vegetation and litter data were analyzed only for the Tanzania sites. Tall grass, about 1.5 m high, dominated the understory cover of all woodland and fallow sites. Sampled grass biomass was about 1.5-2.5 t C ha^{-1} in the woodland and fallow areas while litter levels were around 0.7 t C ha^{-1} (Table 2.3). In woodland and fallow areas biomass, mean nutrient content, height, and canopy cover of grass vegetation did not differ significantly (Figure 2.4). Nitrogen levels of the grass averaged about 0.45% and measured phosphorus levels averaged 0.2%. Average nitrogen levels in the agricultural areas are higher, at 1.37% N, because this vegetation contained both grass and a large proportion of herbs (Table 2.3). As expected, average nitrogen levels of tree leaves were greatest at 1.6% followed by small branches (0.68% N) and large wood had lowest nitrogen levels (0.53% N) (Table 2.3; Appendix 2.4). Mean phosphorus levels were similar in all vegetation types, but varied from 0.04% to 0.3% P. For all in tree components, mean nitrogen and phosphorus levels of trees in woodland areas were not significantly different from trees growing in fallow areas (Figure 2.7).

Table 2.6 Mean biomass and nutrient levels in aboveground vegetation in different land uses (standard deviations in parentheses)

Nutrient		Grass/ Herbs	Litter	Tree - Large Wood	Tree - Small Wood	Tree - Leaves
Biomass (t C ha^{-1})	Woodland	2.16 (0.88)	0.67 (0.41)			
	Agriculture	0.64 (0.56)	1.26 (0.68)			
	Fallow	1.43 (0.59)	0.75 (0.41)			
% Grass Cover	Woodland	85% (7%)				
	Fallow	70% (18%)				
Grass Height (m)	Woodland	1.54 (0.36)				
	Agric	1.30 (0.78)				
	Fallow	1.56 (0.58)				
% Nitrogen	Woodland	0.45% (0.15%)	0.70% (0.20%)	0.48% (0.18%)	0.68% (0.41%)	1.58% (0.38%)
	Agric	1.37% (0.54%)	0.49% (0.11%)			
	Fallow	0.42% (0.09%)	0.50% (0.05%)	0.63% (0.33%)	0.75%	1.51% (0.76%)
% Phosphorus	Woodland	0.192% (0.058%)	0.095% (0.024%)	0.110% (0.052%)	0.149% (0.081%)	0.165% (0.098%)
	Agric	0.206 % (0.101%)	0.125% (0.082%)			
	Fallow	0.217% (0.066%)	0.092% (0.039%)	0.147% (0.076%)		0.122% (0.056%)

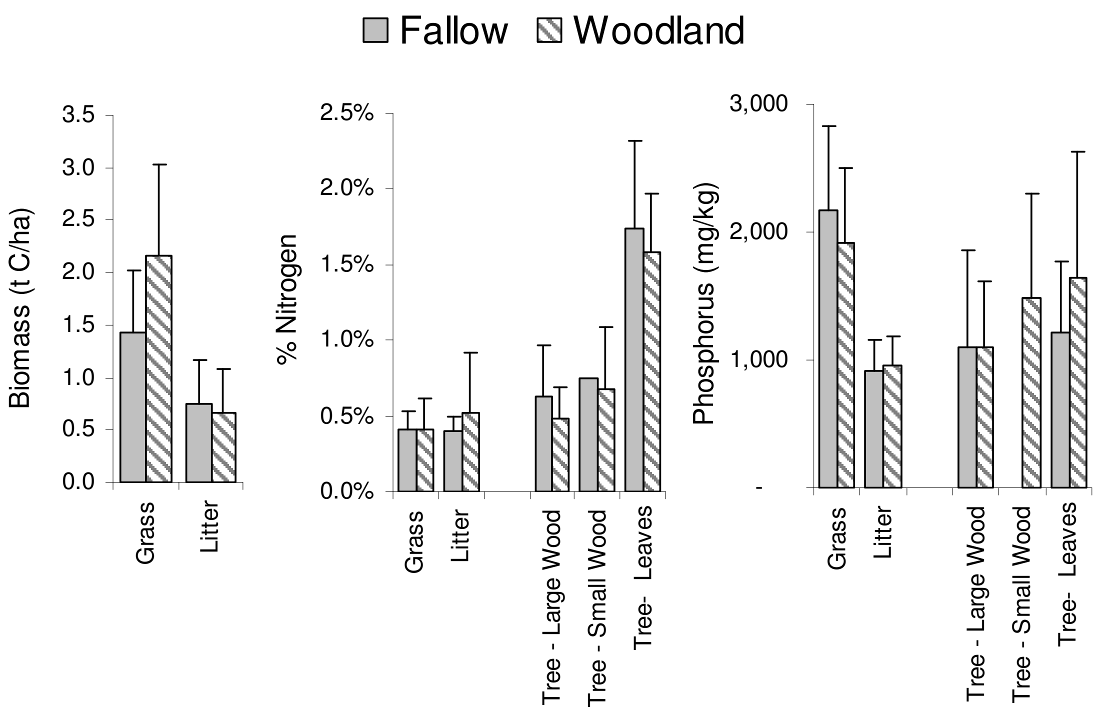


Figure 2.10 Biomass and nutrient levels of vegetation in Woodland and Fallow areas (no significant differences between fallow and woodland)

A shift in the prevalence of grass species exists, with one species, commonly known as Mafundo being the dominant grass species in woodland areas and two other species, commonly known as Nyoyi and Sanze, being more dominant in fallow areas. Non-woody aboveground standing biomass, phosphorus content, and nitrogen content were all significantly positively correlated with each sites' soil nitrogen, total phosphorus, plant available phosphorus (Figure 2.8).

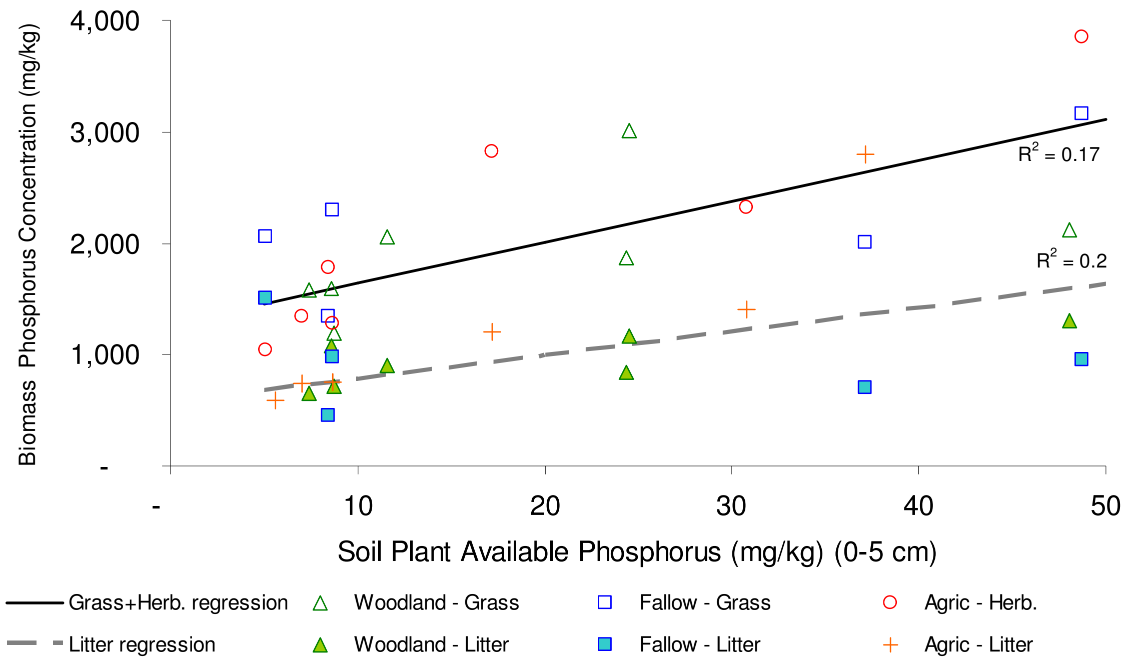


Figure 2.11 Correlation between non-woody vegetation and litter phosphorus and soil plant available phosphorus (0-5 cm) in Tanzania. Regression lines significantly different than the mean.

2.4 Discussion

2.4.1 Soil differences due to land use type

Worldwide many other studies have found levels of SOC to decline by between 15%-50% following conversion to agriculture, although very little of this change takes place at depth (Nye and Greenland 1964; Detwiler 1985; Scholes and Hall 1996; Solomon et al 2000; Guo and Gifford 2002). In the current study the impact of agriculture varied between the low land use intensity areas of Mozambique, the intermediate intensity in Tanzania, and the higher land use intensity seen in Malawi.

In the lower agricultural intensity areas sampled in Mozambique there were no significant differences in the soil nutrients examined across all land use types. All agricultural and fallow fields sampled had been under crop production for less than five years thus, differences may not have yet been apparent. Older agricultural fields at these locations could not be found. Since the population density is relatively low in both of the locations, farmers shift to another area within five years of cultivation, limiting the soil nutrient impacts of agriculture. Many researchers have found that reductions in soil carbon to occur within the first years of conversion (Houghton et al 1983; Schlesinger 1986; Davidson and Ackerman 1993; and Solomon *et al* 2000), however in many of these studies the type of agricultural production involved mechanical plowing perhaps leading to more of a break up of soil aggregates than hand plowing. For example, in Nigeria plow-tillage systems were found to more greatly reduce carbon levels when compared to no-till farming (Lal 1998).

In the area of sampling in Tanzania, agriculture generally takes place in a crop-fallow cycle and currently nearby Miombo woodlands still exist that farmers convert to agriculture. The number of years of agriculture and fallow varies, but ranges from about 2-5 yrs agriculture, then 3-10 yrs of fallow. During a villagisation program about thirty years ago a large number of areas were converted from Miombo woodlands to this crop-fallow land use pattern. These areas contain significantly less soil carbon and nitrogen than Miombo woodland areas in the top 10 cm, both with and without the inclusion of soil texture as a covariate. On average these areas, which have gone through about 3-5 crop-fallow periods since conversion to agriculture, contain about 15% less carbon stocks in the top 50 cm than Miombo Woodland areas. More recently, regulations have changed allowing farmers to open up new agricultural areas. Similarly to the results in

Mozambique, these agricultural areas, which have all been cropped for less than five years, do not contain significantly less soil carbon and nitrogen levels than Miombo Woodland areas. As expected, other soil nutrient levels were highly influenced by the soil carbon levels, with N, total P, and the CEC level all being highly positively correlated with carbon (Brady and Weil 1999). Although plant available phosphorus levels were slightly higher within woodland areas in Tanzania than other land use types, the range of plant available phosphorus found in the soil was quite large. Also as is expected, declining soil pH resulted in a reduction in plant available phosphorus. Within the Tanzania study area, agricultural sites converted during the time of villigisation in the 1970's share more soil attributes with the Miombo woodland sites. More recent agricultural conversion has taken place in areas with higher clay content and nutrient content. Therefore, now that farmers are free to farm in a larger area, it appears farmers are using existing local knowledge of soil fertility when choosing lands to convert to agriculture.

In Malawi agriculture is practiced at a more intense level as very little new areas exist for farmers to convert from Miombo Woodlands, and due to this land scarcity, land is often cropped for upwards of 30 years before being converted to fallow. Additionally, unlike in Tanzania and Mozambique, the fallows continue to be used for grazing, thatch, and/or firewood. Compared to Miombo woodland sites, the agricultural and fallow fields sampled on average both contained about 50% less carbon stocks and 60% less nitrogen stocks to a depth of 50 cm. Soil phosphorus stocks in the agricultural and fallow areas were about 25% lower than Miombo Woodland sites in the top 10 cm. Soil carbon levels were similar in young and medium aged agricultural fields, and therefore may indicate that soil carbon levels declined quickly after conversion to agriculture. The length of time since the agricultural areas were first converted from Miombo Woodlands is not known, however, the areas had undergone at least one previous crop-fallow period prior to the current agricultural use. Soil nutrient levels were not elevated during the fallow period, but instead were statistically the same as the agricultural sites, thus pointing to the land degradation that has taken place in this area.

A study in Zimbabwe on soil nutrient changes under agriculture have found a 6% mean reductions in soil carbon stocks under agriculture over the entire soil profile and 54% lower carbon stocks in the top 10 cm (King and Campbell 1994). Kirchmann and Eklund found soil carbon levels to be 40% lower in the top 5 cm in similar locations in Zimbabwe (1994) (Figure 7). Farming by rural subsistence farmers in Zimbabwe, as in Malawi, is also very intensive and results are similar to those seen at the Malawi location. A study in the Miombo woodlands region of Zambia also found agricultural intensity to alter agricultural impacts. Agricultural fields with a shorter fallow period of 10 years had lower soil carbon levels (mean 1.09% C) than fields far away from villages with a fallow period of 50 years (mean 1.3% C) (Araki 1993). A study in Burkino Faso with similar precipitation levels found a significant reduction in soil carbon levels as land use moved from fallow periods of 30 years to continuous cultivation thus showing that lower levels of land use intensity have less impact on soil quality (Outtara *et al* 2006).

In the Sahel region of West Africa, annual rates of SOC loss when land was converted to cultivation ranged from 1.5-7% loss depending on soil texture and management style (Pieri 1989). Conversion to crops from Acacia woodland in Tanzania resulted in a 56% decline in soil carbon stocks in the top 10 cm (Solomon et al 2000). SOC decline in the coarse and fine sand fractions was most rapid, pointing to a greater proportion of the reduction in labile SOC. Lal reports a 20% decline in soil carbon in Nigeria after six years of cultivation (1985). Results from an agricultural study in Kenya (Moshi et al 1974) are similar to those seen worldwide. Declines in soil carbon are greatest within the top layers, especially the plow layer, which is disproportionately depressed (Figure 2.2). Woomer et al. (1997) report losses of SOC of 0.69 t C ha^{-1} yr^{-1} for Eastern Africa, associated with losses in N and, thus, decreased soil fertility.

2.4.2 Overall soil nutrient levels

Soil carbon levels were similar to those found in previous studies in the Miombo Woodland Region (Figure 2.1), however in the Tanzania sites, on average carbon levels were greater than published figures at lower depths. Soil carbon stocks in the Miombo Woodland sites were not statistically different across all sampling locations even though the precipitation varied from 800-1300 mm per year. Based on these results in combination with previously collected data from across the region the precipitation gradient does not appear to result in significantly different soil carbon stocks. Soil carbon values are similar to other dry forested areas in Africa (Table 2.4). Soil carbon with depth was most accurately represented with a log carbon – log cm equation. This equation type was also found to be the most accurate equation type within a Jobbagy and Jackson (2000) study which compared soil carbon across many ecosystem types. At most sites soil carbon is highest at the surface and then declines slowly with depth. However, in both the Tanzania and Mozambique sites, the decline of soil nutrients with depth was not as strong as in the Malawi study area. African systems with very low soil carbon levels, such as below 1% C at the surface, also have been found to have very little reduction with depth (Scholes and Walker 1993; Stromgaard 1990; Ringrose et al 1998; Chivaura-Mususa and Campbell 1998). As seen in the logarithmic nature of the soil nutrient distribution, the majority of the nutrients are found within the surface layers of the profile. An average of more than 65% of the soil carbon to a depth of 50 cm is found in the top 20 cm at all sampling locations. Nitrogen is even more strongly concentrated at the surface in Tanzania with 82% of the nitrogen to a depth of 50 cm found in the top 20 cm, while in Mozambique and Malawi nitrogen follows the pattern more closely with that of carbon. More labile nutrient sources are usually found within the upper depths of the soil and more recent changes in land use history will more greatly affect the surface layers (Sombroek et al 1993). These differences decline deeper in the soil profile where soil carbon is dominated by relative stable and inert organic complexes not easily altered by land cover changes.

C:N ratios ranged from 11 to 24 at the surface and averaged at about 15. This average C:N ratio is similar to that found in other studies of soils in the Miombo region. King and Campbell (1994) found an average C:N of 15 at Miombo sites while Stromgaard (1992) found C:N values to vary from 12 to 25 and a lower value of 8 was found by Murwira (1993). In most systems, the C:N ratio ranges from 8-12, emulating that of most soil microbes (Waksman 1924). It was expected that as the age of the agricultural field increased, the C:N ratio would decrease due to the reduction of labile sources of carbon, reduced carbon inputs, and possible fertilizer additions. Although, agricultural sites tend to have lower C:N ratios, the C:N ratio is not correlated with the number of years under current cropping or time since land was first converted from Miombo woodlands. Additionally, the C:N ratio of fallow areas, likewise, does not increase with age of the fallow. However, these trends may be more apparent if the number of locations sampled was increased.

As found in a large number of studies worldwide (Jobbagy and Jackson 2000) and in east and southern Africa (Birch and Friend 1956; Foster 1981; Paul 1984; Bird 2000), soil carbon was significantly positively correlated with clay content. Jones (1973) found clay content to describe 57% of the variability of SOC in savannah soils of West Africa. In an analysis of 700 carbon profiles across the Congo, Schwartz and Namri (2002) found soil texture to be the main determinant of SOC. Carbon can be captured within clay particles that are not easily accessible to microbial action or become bound within the interlayers of silicate clays (Paul 1984; Lepsch et al 1994; Lilienfein et al 1998).

Table 2.7 Soil carbon levels within natural and human disturbed regions in Africa

Country	Natural Land Cover	Natural % C	Natural t C/ha top 10 cm	Human disturbed % C	Human disturbed t C/ha top 10 cm	Annual Precip (mm)	Soil Type	Source
Nigeria	Shrub Grassland	1.10%	14.7	0.70%	9	500	Luvisol-Sandy	Gbadegesin and Sadiq 1995
Kenya	Grassland	1.60%	20.8			600		Ogutu 1999
Zimbabwe	Acacia grassland	0.70%	9.9	0.51%	7.7	750	Luvisol-Sandy	Chivaura-Mususa and Campbell 1998
Zimbabwe	Terminalia Tree Savanna	1.00%	13			586	Loamy Sand	Campbell et al 1994
Zimbabwe	Acacia Tree Savanna	3.00%	39			586	Sandy Loam	Campbell et al 1994
RSA	Broadleaf Savanna	0.40%	5.2			620	Ferrasols and Lithosols	Scholes and Walker 1993
Kenya	Shrubland	1.30%	16.9			800		Ogutu 1999
Nigeria	Guinea savanna	2.00%	25.4			1000-1200	Sandy	Isichei and Muoghalu 1992
Botswana	Kalahari	0.25%	3.3			200-650	Arenosols	Ringrose et al 1998
Senegal	Savanna	0.70%	9.1	0.30%	3.9	500-600	Arenosols/ Luvisols	Tiessen et al 1998
Kenya	Bushland	2.80%	36.4			1000		Ogutu 1999
Niger	Tiger Bush	0.80%	9			560	Luvisol	Guillaume et al 1999
Sudan	Acacia woodland	0.08%	1			104	Sandy	Alstad and Vetaas 1994

Country	Natural Land Cover	Natural % C	Natural t C/ha top 10 cm	Human disturbed % C	Human disturbed t C/ha top 10 cm	Annual Precip (mm)	Soil Type	Source
Malawi	Agric. field w/ Acacia	2.40%	30.9	2.38%	30.9	635		Saka et al 1994
Zimbabwe	Mopane woodland	1.00%		0.58%		650	Sandy Clay	Tafangenyasha and Campbell 1998
Zimbabwe	Acacia woodland	1.40%	18.2			757	SCL	Dunham 1989
Zimbabwe	Miombo Woodlands	1.40%	18.2	0.60%	7.8	850	CSC Luvisol	King and Campbell 1994
Kenya	Woodland	4.70%	61.1			1200		Ogutu 1999
Mozambique	Dune evergreen forest	1.20%	15			800	Sandy	Campbell et al 1990
Kenya	Evergreen forest	6.80%	72.1	3.80%	40.3	980	Oxisol-Clay	Moshi 1974
Kenya	Tropical Forest	5.10%	65.7			1300		Ogutu 1999
Nigeria	sub-humid forest	2.20%	28.6	1.50%	19.5	1335	Alfisol	Salako 1999
Nigeria	Moist evergreen forest	5.40%	69.8	2.18%	28.3	1300-1600	Ferrasols	Aweto 1981
Cameroon	Humid tropical forest	~ 6%	76		69	~1500	Ferrasols	Woomer et al 1998
Cameroon	Lowland rainforest	3.00%	39			5460		Gartlan et al 1986

2.4.3 Aboveground vegetation

A tall grass understory layer is a standard characteristic of the Miombo Woodlands ecosystem type. Grass quickly returns following agriculture and grass biomass was not significantly different in fallow areas than woodland sites. However, this contradicts measurements by Chidumayo and Kwibisa (2003) who found grass biomass levels to be significantly higher in areas cut than areas not cut. Nutrient values of the grass and woody biomass were similar in both woodland and fallow areas, including areas only recently under fallow and therefore the agriculture taking place has not led to a decline in nutrient quality of the vegetation. However, the dominant grass species that grew in the understory changed from mostly Mafundo grass to a mix of Sanzi and Nyoyi. Herbaceous standing biomass estimates (1.5-2.5 t C ha^{-1}) were higher than the levels reported by other researchers (0.5-1.2 t C ha^{-1}) working in drier Zambia and Zimbabwe (Chidumayo 1993; Chidumayo 1997; Campbell 1998; Chidumayo and Kwibisa 2003). Chidumayo (1997) estimated Miombo understory grass %N in Zambia to average 0.6% and phosphorus 0.8%. These values are greater than the average (0.45% N, 0.2% P) values found in this study but within the range measured. Average litter nitrogen levels measured (0.7%) in this study were significantly lower than the 1.94% and 1.82% N that was reported in mixed litter by Mtambanengwe and Kirchmann (1995) and Musvoto et al (2000), respectively, both in a drier Miombo area of Zimbabwe. But were very similar to the average estimate reported by Chidumayo (1994) (0.66% N) in Zambia. Litter phosphorus content (0.9%) was also similar to that reported by Chidumayo (0.14%) (1994). Tree leaf nitrogen levels (1.58% N) were similar but phosphorus levels much lower (0.16% P) than foliage measurements in Zambia (1.65% N, 0.65% P) (Chidumayo 1994). Campbell (1994) states average mature leaf nitrogen levels for Miombo trees to be 1.89% and phosphorus levels to be 0.19%. However, he notes that the range is large both within and among species even in the same location and depending on the season (Ernst 1975; Lawton 1980; Jachmann and Bell1985; Hogberg 1986).

2.5 Conclusions

The areas sampled across the Miombo Woodlands contain rural communities practicing subsistence level agricultural production with little to no nutrient inputs. In the past human populations practiced shifting cultivation, with long periods of Miombo regrowth between cropping periods. Based on the analysis conducted, within the lower population density areas sampled in Mozambique the practice of farming for three to five years before moving to a new location did not significantly change soil carbon, nitrogen, or phosphorus levels. This result was also seen in Tanzania for areas that had been converted from Miombo woodlands to agriculture less than five years earlier. In a more intermediate use of the land in Tanzania where sampled areas had passed through several crop-fallow cycles, soil nutrient levels were only significantly reduced within the top ten centimeters of depth. This points to the possible sustainability of repeated, consecutive crop-fallow agricultural land use in the Miombo region. This positive finding of sustainability should be read with caution as this study was of limited scope and pressures in this entire region are leading to increased areas of land use conversion and reductions in fallow periods. This has already taken place in land-scarce Malawi where soil nutrient levels were dramatically lower in agricultural areas. Additionally, based on the results of this study it appears that in Malawi the dominant fallow field land management technique is not allowing for nutrient recovery. The soil nutrient dynamics of fallow fields are in need of further study. As the area of land converted to agriculture across the Miombo Region increases, land in this regrowth state may become the more dominant form Miombo Woodlands. Therefore studies of the nutrient dynamics in this type of land cover will be essential.

2.6 References

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2.7 Appendices

Appendix 2.1 Additional soil properties of land use types in Tanzanian samples

	Depth		pH KCI	Fe (ppm)	CEC	Ca2+	Mg2+	K+	Na+
						(meq/100 g soil)			
Tanz Woodland	0-5 cm	Mean	5.7	29.61	13.55	10.57	2.17	0.49	0.32
		Std Dev	0.13	12.64	8.84	8.55	0.5	0.18	0.14
	5-10 cm	Mean							
		Std Dev							
	10-20 cm	Mean	5.36	30.68	8.17	5.74	1.72	0.38	0.34
		Std Dev	0.24	14.79	4.04	3.36	0.72	0.15	0.25
	20-50 cm	Mean	4.99	22.47	6.99	4.55	1.94	0.27	0.24
		Std Dev	0.28	15.34	1.48	1.25	0.65	0.13	0.05
Tanz Recent Agric	0-5 cm	Mean	5.96	17.18	13.75	9.45	3.05	0.61	0.64
		Std Dev	0.27	4.32	9.05	7.02	1.81	0.26	0.29
	5-10 cm	Mean							
		Std Dev							
	10-20 cm	Mean	5.42	20.07	9.12	5.66	2.44	0.52	0.5
		Std Dev	0.31	8.03	2	1.36	0.56	0.15	0.24
	20-50 cm	Mean	5.24	18.6	8.57	5.28	2.45	0.46	0.38
		Std Dev	0.31	7.02	3.46	2.58	0.94	0.18	0.22
Tanz Older Agric	0-5 cm	Mean	6.05	22.22	8.84	6.13	1.75	0.56	0.4
		Std Dev	0.66	8.81	4.92	3.96	0.75	0.24	0.17
	5-10 cm	Mean							
		Std Dev							
	10-20 cm	Mean	5.53	17.26	6.85	4.62	1.52	0.42	0.3
		Std Dev	0.36	4.52	3.23	2.63	0.68	0.1	0.04
	20-50 cm	Mean	5.4	12.84	5.92	3.76	1.54	0.37	0.26
		Std Dev	0.59	3.15	4.03	3.74	0.56	0.06	0.08

Appendix 2.2 Proc GLM ANOVA p-values comparing land use types in Tanzania. Analysis of variance for carbon and nitrogen also completed with clay+silt as covariate. For the analysis of all depths together, depth was nested within site and land use category.

	% C	%C w/ covariate	% N	%N w/ covariate	Total P	Plant Avail P	%Clay+Silt	BD
woodland vs. recent agric								
All Depths	0.65	0.13	**0.00**	**0.02**	0.06	0.60	**<.0001**	0.31
0-5 cm depth	0.86	**0.03**	0.10	0.30	**0.00**	0.93	**0.00**	0.48
5-10 cm depth	0.87	0.15	0.06	0.64	**0.01**	0.93	**0.00**	0.35
10-20 cm depth	0.21	0.61	0.05	0.92	0.17	0.36	**0.00**	0.25
20-50 cm depth	0.17	0.51	**0.03**	0.68		0.23	**0.00**	0.00
woodland vs. older agric								
All Depths	**<.0001**	**0.01**	0.07	0.11	0.55	**<.0001**	**0.01**	0.61
0-5 cm depth	**0.02**	**0.00**	0.33	**0.02**	1.00	0.14	0.44	0.80
5-10 cm depth	0.05	**0.01**	0.17	**0.01**	0.96	0.14	0.44	0.17
10-20 cm depth	0.29	0.36	0.51	0.31	0.21	0.16	0.39	0.09
20-50 cm depth	0.44	0.25	0.59	0.22		0.09	0.28	**0.04**
recent agric vs. older agric								
All Depths	**<.0001**	**<.0001**	**<.0001**	**<.0001**	0.02	**<.0001**	**<.0001**	0.58
0-5 cm depth	**0.05**	0.78	**0.01**	0.38	**0.00**	0.20	**0.00**	0.64
5-10 cm depth	0.05	0.47	**0.00**	**0.05**	**0.01**	0.20	**0.00**	0.75
10-20 cm depth	**0.03**	0.80	**0.01**	0.46	0.75	0.72	**0.01**	**0.01**
20-50 cm depth	**0.04**	0.90	**0.01**	0.67		0.73	**0.01**	**0.03**

	pH	Fe	CEC	Ca	Mg	K	Na
woodland vs. recent agric							
All Depths	**0.00**	**<.0001**	**0.00**	0.10	**<.0001**	**<.0001**	**<.0001**
0-5 cm depth	**0.04**	**0.00**	0.21	0.49	**0.00**	0.12	**<.0001**
5-10 cm depth	**0.04**	**0.00**	0.21	0.49	**0.00**	0.12	**<.0001**
10-20 cm depth	0.68	0.08	0.43	0.97	0.12	**0.03**	**0.00**

20-50 cm depth	0.38	0.27	0.09	0.38	**0.01**	**0.00**	**0.00**
woodland vs. older agric							
All Depths	0.15	**<.0001**	**0.00**	**0.00**	0.08	0.17	0.58
0-5 cm depth	0.30	**0.00**	0.22	0.19	0.46	0.54	0.58
5-10 cm depth	0.30	**0.00**	0.22	0.19	0.46	0.54	0.58
10-20 cm depth	0.94	0.02	0.18	0.18	0.27	0.40	0.62
20-50 cm depth	0.27	**0.02**	0.33	0.36	0.13	0.02	0.51
recent agric vs. older agric							
All Depths	**<.0001**	0.38	**<.0001**	**<.0001**	**<.0001**	**0.00**	**<.0001**
0-5 cm depth	0.25	0.82	**0.02**	0.07	**0.00**	0.31	**<.0001**
5-10 cm depth	0.25	0.82	**0.02**	0.07	**0.00**	0.31	**<.0001**
10-20 cm depth	0.73	0.58	**0.05**	0.21	**0.02**	0.13	**0.00**
20-50 cm depth	0.91	0.24	**0.01**	0.09	**0.00**	0.43	**0.01**

Appendix 2.3 Proc GLM ANOVA p-values comparing land use types in Mozambique

	% C	%N	Total P	Plant Avail. P	%Clay +Silt	BD
woodland vs. agric						
All Depths	**0.02**	0.12	0.54			0.86
0-5 cm depth	0.21	0.30	0.96	**0.05**	0.42	0.73
5-10 cm depth	0.46	0.64	0.62	0.41	0.46	0.17
10-20 cm depth	0.78	0.55	0.27	0.29	0.98	0.96
20-30 cm depth	0.52	0.33	0.11	0.09	0.51	0.91
30-50 cm depth	0.83	0.51	0.32	0.96	0.51	0.33
woodland vs. fallow						
All Depths	**0.01**	**0.05**	0.17	0.35	0.07	**0.00**
0-5 cm depth	0.22	0.31	0.84	0.85	0.58	0.42
5-10 cm depth	0.28	0.37	0.35	0.98	0.40	**0.02**
10-20 cm depth	0.56	0.35	0.41	0.40	0.41	0.73

20-30 cm depth	0.54	0.41	0.11	0.54	0.25	0.78
30-50 cm depth	0.60	0.21	0.20	0.58	0.31	0.14
agric vs. fallow						
All Depths	0.93	0.83	0.50			**0.04**
0-5 cm depth	0.86	0.89	0.81	**0.02**	0.69	0.30
5-10 cm depth	0.76	0.66	0.69	0.39	0.95	0.44
10-20 cm depth	0.77	0.75	0.70	0.69	0.48	0.74
20-30 cm depth	0.91	0.77	0.82	0.19	0.75	0.70
30-50 cm depth	0.81	0.64	0.90	0.61	0.82	0.69

Appendix 2.4 Nitrogen and Phosphorus content of various tree species

				Large Wood		Small Branches		Leaves	
Family	Species	Local Name		% N	Phos (mg/g)	% N	Phos (mg/g)	% N	Phos (mg/g)
Apocynacae	Diplorhynchus condylocarpon	Mtogo	mean	0.65%	2.10	0.35%	0.67	1.30%	1.26
			stdev	0.01%	0.32			0.16%	0.69
Caesalponioideae	Jublernarida globiflora	Mhnodolo	mean	0.50%	1.76	0.48%	1.49	2.09%	1.84
			stdev		0.62	0.17%	0.41		0.45
Caesalponioideae	Brachystegia boehmii	Myombo	mean	0.51%	1.60	0.51%	0.90	1.67%	1.39
			stdev	0.09%	1.22			0.02%	0.20
Combreteaceae	Combretum collinum	Mlama(doli	mean						3.60
			stdev						
Combreteaceae	Combretum molle	Mlama(mweusi	mean			0.85%	1.60	1.18%	2.46
			stdev			0.45%	0.81		1.37
Combreteaceae	Combretum adenogonium	Mlama(ng'ombe	mean	0.46%	0.99	0.44%	1.75	1.37%	1.74
			stdev		0.53	0.04%	0.92	0.12%	0.99
Combreteaceae	Terminalia sericea	Mtanga Mfumba	mean			0.28%	1.28		2.50
			stdev				1.23		0.22
Euphorbiaceae	Flueggea virosa	Mkwambe	mean	0.75%		0.43%	2.17		1.10
			stdev						
Euphorbiaceae	Bridelia cathartica	Msinzila	mean	0.29%	1.89	0.29%	0.82	1.41%	2.40
			stdev	0.01%	1.30	0.05%	0.39	0.11%	1.38
Mimosoideae	Dichrostachys cinerea	Kikulagembe	mean	0.78%	1.14	0.53%		1.21%	0.63
			stdev			0.21%		0.13%	0.06
Mimosoideae	Acacia goetzei	Kisasa	mean					1.65%	0.78
			stdev						
Mimosoideae	Acacia nigrescens	Mkambala	mean	0.59%	0.75	0.62%	0.48	1.72%	0.95
			stdev						

				Large Wood		Small Branches		Leaves	
Family	Species	Local Name		% N	Phos (mg/g)	% N	Phos (mg/g)	% N	Phos (mg/g)
Mimosoideae	Acacia robusta	Mkongowe	mean						
			stdev						
Mimosoideae	Albizia harveyi	Msisimisi	mean			0.52%		1.52%	0.81
			stdev						
Papilionoideae	Ormocarpum kirkii	Kilumbulumbu	mean	1.22%	1.01			1.74%	1.01
			stdev						
Papilionoideae	Lonchocarbpus capassa	Mfumbili	mean	0.55%	0.99	0.90%	1.22	2.20%	1.29
			stdev					0.19%	0.07
Papilionoideae	Dalbergia melanoxylon	Mpingo /Mhingo	mean	1.78%	1.28	1.03%	0.52	2.25%	1.06
			stdev					0.16%	0.00
Sterculiaceae	Dombeya rotundifolia	Msosowana /Mlwati	mean			0.42%	1.71	1.20%	2.31
			stdev			0.03%		0.10%	1.78
Other			mean		1.15		0.96		1.34
			stdev		0.73		0.35		0.51
Average for all species listed			mean	0.68%	1.41	0.53%	1.20	1.57%	1.58
			stdev	0.39%	0.77	0.24%	0.63	0.38%	0.91

Chapter 3 Carbon response to land management alterations in the Miombo system

Abstract

In the Miombo Woodlands region of south-central Africa human actions have caused the region to become a carbon source through deforestation, forest degradation and agricultural production leading to ecosystem degradation. Conversion of the Miombo woodlands to agriculture reduces aboveground biomass. Soil carbon levels also decline over time but owing to the slower turnover rates of carbon pools this decline happens more slowly. In many areas in the Miombo woodlands the intensity of agriculture has increased with farmers moving to longer agricultural periods and shorter fallows in contrast to the long term shifting cultivation cycle practiced traditionally. Since this change is relatively recent how this will impact soil nutrient levels is not well known. The production of charcoal through selective logging is a dominant source of cash income for rural farmers and therefore the sustainable use of the Miombo woodlands area is integral to maintaining livelihoods. The use of modeling allows the long term impact of various land management options to be compared. The CENTURY model was parameterized for the Miombo Woodland system and was able to accurately model growth and biomass levels. Various cropping and selective logging rotations were then modeled. Soil carbon stocks are reduced rapidly during the first years of agriculture. When land is converted to agriculture soil carbon stocks are reduced by 15% after five years and 25% after ten years. If crop production is performed continuously on the land, after about 60 years of

continuous agriculture soil carbon stocks persistently decline by about 1% per year. When agricultural activity ceases, soil nutrient levels recover, however this increase is only 1-2% per year and therefore unless the fallow period is very long, over successive crop-fallow periods, soil nutrient levels continue decline. To examine the impact of selective logging for charcoal production the time of year, the rotation cycle, and the type of wood removed from the system were modeled over time. Selective logging during the dry season had a slightly lower impact on nutrient stocks than logging during the wet season, however, the difference was minimal. During charcoal production, only the large wood is generally used. Removing the large wood from the system but leaving the small branches and leaves in place has a significantly lower impact on nutrient stocks, thus reducing 'nutrient mining'. For example, over 200 years 24% of soil phosphorus is removed if all the wood is removed using a 5 year selective logging rotation, but by only removing the large wood from the system the reduction changes to only 15%. Based on model results, a selective logging of 30% of the wood every 8-10 years would reduce tree biomass on average by about 20%, but that reduction would be sustainable overtime and not result in a progressive reduction in tree carbon stocks. It is recommended that communities develop some type of participatory forest management agreements and actively manage the public lands by instituting selective logging practices and agreed upon rotation cycles of 8-10 years.

3.1 Introduction

Over the last several centuries anthropogenic activities have dramatically altered the natural carbon cycle and the carbon stocks found in different landscapes. Carbon stocks accumulate through photosynthesis and assimilation of carbon into biomass. Carbon then cycles into various carbon pools through death and decomposition. Actions that alter the rate of carbon cycling can lead to net carbon sequestration, thus carbon accumulation, or net carbon emissions. In rural south-central Africa human actions have caused many landscapes to become carbon 'sources' through deforestation, forest degradation and agricultural production leading to ecosystem degradation. Altering the management style implemented in a region can change the net emissions over time. Additionally, alterations to the carbon cycle will also impact the levels of other nutrients such as nitrogen and phosphorus in the landscape and thus the potential productivity of the system.

The Miombo Woodlands region of south-central Africa have become a net source of emissions. Carbon stocks across the landscape have been reduced resulting from high levels of conversion from woodlands to agriculture and of forest degradation due to charcoal production (Abbot and Homewood 1999; Mlotha 2001; Hudak and Wessman 2000; Jansen *et al* 2008). Rural populations rely almost exclusively on agriculture and woodland resources for their livelihoods (Malimbwi 2001; Monela *et al* 2000). Subsistence shifting cultivation and low intensity crop-fallow agriculture has been practiced throughout the region, however, as populations increase and more land has been converted, agricultural intensity is increasing resulting in longer cropping periods and shorter fallow times (Chirwa 1997; Ajayi *et al* 2007). However, this move to shorter fallow periods has generally not been accompanied by higher technology or adequate fertilizer supplements (Chirwa 2003; Ajayi *et al* 2007).

Conversion of a woodland ecosystem to agriculture dramatically reduces the aboveground biomass, but may also result in a decline soil carbon and other nutrients. Clearing removes most organic inputs into the soil and the increase in soil temperature, reduced transpiration rates, and breaking up of soil aggregates from tillage will raise the rate organic matter loss (Allen 1985; Tate 1987; Blank and Fosberg 1989). Recently conducted studies in the Miombo Woodlands have indicated that while low intensity agriculture with long fallow periods does not seem to have a significant impact on soil carbon and nitrogen levels in the short term (Walker 2008; Araki 1993), when cropping becomes more intense, soil nutrient levels decline by almost 40% (Walker 2008; Walker and Desanker 2004; King and Campbell 1994). Since this increase in intensity is relatively recent in the region, it is not possible to directly measure how changing land management will change nutrient stocks over the long term. Representation of nutrient cycling through models, such as the CENTURY model, allows examination of how land management practices may impact various nutrient pools at longer time scales.

Charcoal production is a significant source of land use change in the Miombo region and even as woodland resources across the region decline the demand for charcoal is still very high (CHAPOSA 2001) The production of charcoal is a dominant source of income for rural families. In the dar es Salaam area of Tanzania, more than 50% of the cash income rural households receive is derived from forest products such as charcoal, honey, wild fruits, and firewood (Malimbwi *et al* 2001). Because selective logging for charcoal production is such an important component to rural farmers livelihoods, it is imperative for communities to use this resource in a way that is sustainable. Over cutting or logging rotations that are too short will not allow the woodland to recover, however, the long term biomass of the system must be balanced with the need for charcoal production. Although the production and sale of charcoal is regulated by governments in the region, enforcement and collection of taxes is inadequate (CHAPOSA 2001). Owing to limited resources, the policies and recommendations made to rural populations should maximize the sustainability of the woodlands as a charcoal resource but should not include regulations that have little long term impact. By modeling various possible management policies, insight can be gained into the long term impact of such management on woodland nutrient levels.

Through the CENTURY model, the main land use drivers in the Miombo region are examined: agriculture, fires, and forest degradation for charcoal production. Various crop-fallow lengths are modeled and the impact at the short, medium and long term evaluated. Fire and logging frequency and time of year are also modeled in the short to long term. Through this modeling greater understanding of the long term impacts of the dominant land use management can be achieved. Additionally, alternative management recommendations can be evaluated.

3.2 Background

3.2.1 Miombo Woodlands

The Miombo woodlands are the dominant ecological community within the south-central region of Africa, covering around 2.8 million km^2 and can be found in parts of Angola, Democratic Republic of Congo, Zambia, Zimbabwe, Tanzania, Malawi and Mozambique (Desanker *et al* 1997). This region is undergoing rapid land use conversion due to high population growth rates (~2.3%) (UN Statistics 2005), resettlements, expanding agricultural production, and deforestation for wood fuel. In 1996, Campbell *et al* estimated that over 55 million people depend on the woodland resources, including for building material, firewood, thatching grass, honey, fruits, mushrooms, and medicinal plants (Campbell *et al* 1996). The Miombo countries are among the world's poorest with agriculture (cropping and animal husbandry) as the main foreign currency earner for economic and social development (Desanker *et al* 1997).

These open woodlands lie between the wetter, denser rainforests of West Africa to the north-west and the drier savanna and scrubland to the south. A precipitation gradient from about 800-1500 mm exists southwest to northeast (Desanker *et al* 1997). 95% of annual precipitation occurs during the hot wet season. Fires burn the understory on average every 3 years across the Miombo and savannas and therefore greatly impact the vegetation dynamics of the system (Boaler 1966). Fires generally occur during the dry season. The majority of fires are caused by human activity such as hunting, charcoal production, grazing management, honey collection, and cropland preparation (Chidumayo 1997). Fire has been a component of the Miombo ecosystem for thousands of years and there is evidence of human-induced fires for at least 55,000 years (Rodgers 1996).

Deciduous, umbrella-shaped trees create an upper canopy at 10-16 m covering 20-60% of the area (Rodgers 1996). Below this canopy is another layer of subcanopy trees at 4-10 m, patches of shrubs at 1-5 m, and well-established tall grasses up to 1.5 m (Rodgers 1996; Trapnell 1959). The dominant trees have very deep roots, between 1.5-4 m in length. Campbell (1996) estimated woody plants contain 95% of the aboveground biomass, with grasses making up the remainder. Many species of trees and shrubs are able to resprout from roots or the stem, allowing above ground structures to be burned or cut without killing the actual individual (Campbell 1996; Rodgers 1996). Globally, the Miombo Woodlands are ecological similar to West African Guinea Isoberlinia woodlands, South America's cerrado, northern Australia's monsoonal tall grass eucalypt woodlands, and south-east Asia's dipterocarp woodlands (White 1983; Desanker *et al* 1997). Termites occur at high densities throughout most of the Miombo Woodlands and, along with fire, consume a large proportion of the litter (Goffinet 1976; Campbell 1996).

Miombo aboveground biomass stocks are between those of the wetter rainforests to the north (121 Mg ha^{-1} in DRC (Bartholomew *et al* 1953)) and the drier savanna and scrubland to the south (11 Mg ha^{-1} in RSA (Scholes and Walker 1993)). Published estimates of aboveground biomass within Miombo range from about 42 to 96 Mg ha^{-1} (Malaisse 1975, Chidumayo 1990, Chidumayo 1995, Tietema 1993, Chidumayo 1995, Ward and Cleghorn 1964, Endean 1968 Campbell *et al* 1998).

3.2.2 CENTURY Model

The CENTURY model simulates the plant-soil interplay within ecosystems including grasslands, agricultural fields, forests, and savannas. The CENTURY model has been used to successfully model grasslands (Parton *et al* 1993) worldwide and to model various agricultural management techniques (Parton and Rasmussen 1994). Forested systems have also been well represented by the model, although CENTURY did not model the leaf litter layer as well (Kelly *et al* 1997). More recently, changes have been made to the CENTURY to better represent woodland and savannas systems in which trees and grasses compete with each other (CENTURY 4.5 unpublished).

CENTURY predicts long term C, N, P, and S cycling using a monthly time step (Metherell 1993). The major inputs needed by the model include: Latitude/Longitude coordinates, climate data, growing season, soil texture and pH, fire parameters, plant nutrient levels, plant growth rates, and tree leaf monthly death rates (Metherell 1993; Parton *et al* 1993). The top 20 cm of the soil are simulated. Focusing on the Carbon submodel, the soil is divided into three fractions based on decomposition times: the active C pool with a turnover time of 1-5 years, a slow C pool, turnover time 20-40 years, and a passive C pool, turnover time 200-1500 years (Jenkinson *et al* 1999). Plant residues are split into a structural pool, turnover time 1-5 years, and a metabolic pool, 0.1-1 year turnover time, depending on the lignin: N ratio (Motavalli *et al* 1994). The turn over times of each of these fractions is dependent on the abiotic decomposition factor (DECO). This value is a function of precipitation, water storage, soil temperature, and soil texture (Parton *et al* 1994). The live tree carbon is distributed across the pools: large wood, small branches, leaves, coarse roots, and fine roots. The other nutrient submodels, N, S, and P, are similar to the carbon submodel.

In the CENTURY model, microbial decomposition is responsible for carbon flows in the soil. Carbon flows out of the active pool are due to leaching, microbial respiration, or movement into the slow or passive pool. Carbon leaving the slow pool is divided between material quickly decomposed in the active pool and with a slow turnover in the passive pool. (Parton *et al* 1993) Because the definition of the organic pools is functional rather than based on physical analytic fractions, experimentally determining the pools sizes is difficult (Paustian and Cole 1998). To get around this problem, initial levels are often assumed to be at a steady state by running the model for 1000's of years. A simple water budget is incorporated into the model, simulating transpiration, evaporation, soil water content, and saturated flow within the soil. These fluxes are based on biomass, rainfall, and potential evapotranspiration (Parton *et al* 1993). Plant performance is based on factors such as the amount of water available, the soil water content, and nutrient concentrations. A minimum carbon:element ratio is necessary to sustain plant growth (Parton *et al* 1993). The ecological effect of fire is modeled by returning inorganic nutrients to the soil from the plants, removing the above ground biomass, and increasing the root:shoot ratio. To mimic the consumption of grass and litter by termites, low levels of grazing are modeled. Grazing increases the root:shoot ratio, removes aboveground biomass, returns nutrients to the soil, and increases the nitrogen content of roots and shoots (Parton *et al* 1993).

3.3 Methods

3.3.1 Field location

Data for CENTURY model parameterization was collected from two locations: near Morogoro, Tanzania, and near Kasungu, Malawi. (Table 3.1) At both locations tree, grass, and soil data were collected from natural Miombo woodland areas, agricultural fields, and fallow areas. Both areas contained rural populations of farmers growing predominantly maize in a crop-fallow cycle. Cropping cycles in Tanzania lasted 3-5 years of cropping, followed by 3-10 years of fallow, depending on the particular field. At the Malawi site, population density was higher and therefore fallow periods shorter. Throughout the Miombo region, conversion of woodland to crop production starts with the cutting down of trees. A portion of this dead wood is used to make charcoal and some used for household firewood. The field is then burned, and thus the remaining wood and grass biomass is burned. Crops are then planted. Every year, prior to planting, the field is burned again. This serves two purposes: to remove any trees or grass that have started to regrow, and, more importantly, in order to try and prevent a common crop pathogen, the corn weevil.

Table 3.8 Site characteristics for two field study sites

	Malawi	Tanzania
Latitude/Longitude	12.5 S, 33.55 E	6.7 S, 38.0 E
Climate		
Minimum mean monthly temperature	15.3 ºC	18.6 ºC
Maximum mean monthly temperature	26.4 ºC	30 ºC
Annual Precipitation	1000 mm	850 mm

Soil characteristics		
Sand	54%	68%
Clay	16%	5%
Silt	30%	27%
pH	5.5	5.7
Bulk density	1.19 g cm^{-3}	1 g cm^{-3}

At both sites, Miombo woodland data was collected within a forest reserve that was adjacent to the farmland. At the Tanzania site, there also existed a large area of communally held lands covered by woodlands that are controlled by the community but are not being actively farmed by a specific individual. It is this type of land where charcoal producers cut wood for charcoal production. At the Malawi location, this type of land cover has been completely deforested. Further descriptions of field data collected is presented in Walker (2003) for Malawi, and Walker (2008) for Tanzania and Malawi.

3.3.2 CENTURY Model Parameterization

In the CENTURY model, the system was modeled as the savanna ecosystem type (trees and grass). Therefore, data on the dominant grass, dominant tree species, and soil parameters were used. Published data required for the CENTURY model were cataloged from the Miombo Woodland literature. Additionally, field data was collected in Malawi and Tanzania. Nutrient analysis of soil and grass and tree vegetation samples collected in Malawi was used as inputs into the model (Walker and Desanker 2004; Walker *et al* 2008). With this combination of collected data and data from the literature, model parameterization for the Miombo Woodlands was completed. Century model parameters were altered in order to properly represent the Miombo woodland ecosystem including: growth rates, biomass distribution (branches, roots etc), nutrient levels, soil nutrient content, decomposition rates, response to disturbances (ex. growth after fire, agric), interaction between trees and grass, and crop production.

Monthly precipitation data was extracted for the Morogoro weather station from the FAO data base (Station 63866) for the years 1922 to 1996 (station is approximately 50 km from the study area). Precipitation data from 1991-2000 was obtained from the Sokoine University weather station, approximately 40 km away from the study area. The standard deviation and skewness of the precipitation was then calculated. Monthly minimum and maximum temperature values for the Morogoro weather station were combined with data from the Sokoine University weather station data. Because these weather stations are so close to each other, the values were very similar.

For all modeling conducted in this analysis, the parameterized model was run for a specific location by using the climate data and soil analysis for the area surrounding the Kitulanghalo Forest Reserve in Tanzania (37.95E, -6.70S). Low intensity understory fires were modeled to occur every 3-5 years during the dry season months. Model results were then compared to vegetation and soil nutrient concentrations from field measurements and aboveground biomass estimates from field measurements and previously published data collect in the Kitulanghalo area.

3.3.3 Modeling land management

The long term impact of various land management practices common in the region were modeled using CENTURY. Three human-induced land management types were modeled: Miombo areas converted into crop production, Miombo woodland areas selectively logged for charcoal production but not cropped, and Miombo woodland areas where the only modeled human disturbance is fire. Prior to any land management alterations, the model is run for 200,000 years for the system to reach equilibrium.

3.3.3.1 Agricultural production

Agriculture is commonly practiced in a crop-fallow cycle. Various crop and fallow lengths were modeled and soil nutrient levels and crop yields compared. As maize is the dominant crop produced in the area, this crop was modeled. The following agricultural cycles were simulated:

Continuous agriculture	10 yrs cropping – 5 yrs fallow
5 yrs cropping – 5 yrs fallow	10 yrs cropping – 10 yrs fallow
5 yrs cropping – 10 yrs fallow	10 yrs cropping – 15 yrs fallow
5 yrs cropping – 20 yrs fallow	10 yrs cropping – 50 yrs fallow
5 yrs cropping – 70 yrs fallow	10 yrs cropping – 65 yrs fallow

The impact on soil nutrient levels was examined, along with the average aboveground biomass levels resulting from each cycling period. For site preparation, 90% of the aboveground tree pools were cut. The entire large wood pool was removed, and then all remaining vegetation was burned. As is common practice, a low intensity fire took place prior to planting every year and no fertilizer additions were modeled. During the fallow period, the area was modeled to have an understory burn every 3-5 years.

3.3.3.2 Charcoal production initiated woodland degradation

A study of biomass levels conducted in the Kitulanghalo Forest Reserve area of Tanzania by Ek (1994) found that following cutting for charcoal production in communal lands, aboveground tree biomass was reduced by on average 30%. Therefore, this cutting level was assumed to be the lowest percentage cut in the modeling of lands that are assumed to stay in the woodland land use. During charcoal production, only larger wood is used in the charcoal kilns (Malimbwi *et al* 2001). This means that the smaller branches and leaves are cut off the main stem and usually left in the woodland. It is common practice in this region for the men to be involved with all stages of charcoal production and women to be in charge of firewood collection for household use. Often, although the men have left the smaller branches in the woodland, women follow behind the men at a later date and collect these branches for household use. To mimic this woodland management, the following parameters were altered and simulations run: a) frequency of wood cutting; b) month of the year during which cutting and removal takes place; c) percentage and type tree wood pool (large wood, small branches, and leaves) removed from woodland.

3.3.3.3 Fire frequency and seasonality

In the baseline Miombo woodland case, fires were simulated to occur during the dry season from June-Sept. every 3-5 years. Different levels of understory fires were simulated during which the grass biomass, a portion of deadwood, the litter, and a small portion of the leaves and branches were assumed to burn. The Miombo system response to which months the fires occur was simulated since there have been policy deliberations on this issue. Fires were simulated to occur either: at the very start of the dry season, throughout the dry season, or only at the end of the dry season. The frequency of fire recurrence was also simulated: every year, every 3-5 years, every 10 years, and every 30 years. During these simulations, the season of fires was kept to the same months as the baseline case. The results of differing fire intensities were not modeled. In all simulations the same combination of understory fires were used as was used in the baseline woodland case.

3.4 Results

3.4.1 Parameterization for Tanzania site

The Century model was able to accurately model the natural Miombo system (Figure 3.1 and 2, Table 3.2) at the Kitulanghalo, Tanzania site. Modeled soil carbon levels (46 t C ha^{-1}) are above the Miombo average of 26 t C ha^{-1} and above the average from field measurements in the Kitulanghalo area, but are within the range found in this system. Modeled above and below ground tree biomass ranges from 50 to 70 t C ha^{-1}. Modeled tree biomass levels vary over time due to modeled fires and simulated weather changes (Figure 3.1). Published estimates of aboveground tree biomass only average about 28 t C ha^{-1} but range from about 8 to 55 t C ha^{-1} (Chidumayo 1990; Malimbwi 1992; Ek 1994; Chidumayo 1994a; Jean 1997; Campbell *et al* 1998; Zahabu 2001; Malimbwi and Mugasha 2001; Luoga 2002; Malimbwi 1992; FRIM unpublished;).

However, the belowground tree carbon levels are proportionally higher than found in the published literature. Other studies have found roots to be about 20% of aboveground biomass estimates (Malimbwi 1994, Campbell 1998, Chidumayo 1993), while the modeling estimates the coarse roots to be around 50% of the total aboveground biomass. The growth of trees overtime was parameterized to mimic published mean annual growth rates of Miombo woodland tree species, this includes trees regrowing from root or shoots. Therefore biomass levels over time are similar to reported estimates of regrowth aboveground biomass with 15-20 yr old regrowth averaging 18 t C ha^{-1} in the published literature (Stromgaard 1983; Chidumayo 1990; Chidumayo 1993) and model results averaging 21 t C ha^{-1}.

The more labile portions of the soil organic matter have faster turnover rates, reacting quickly to the changes in nutrient inputs versus decomposition rates over the year. However, proportionally, these pools contain only 7% of the total soil carbon pool. The slow and passive soil pools change more slowly, but contain 52 and 41% of the carbon in the soil, respectively. The passive pool is very stable overtime when the land stays in the Miombo Woodland system. The slow pool changes slightly in response to various fires and changes in precipitation between years.

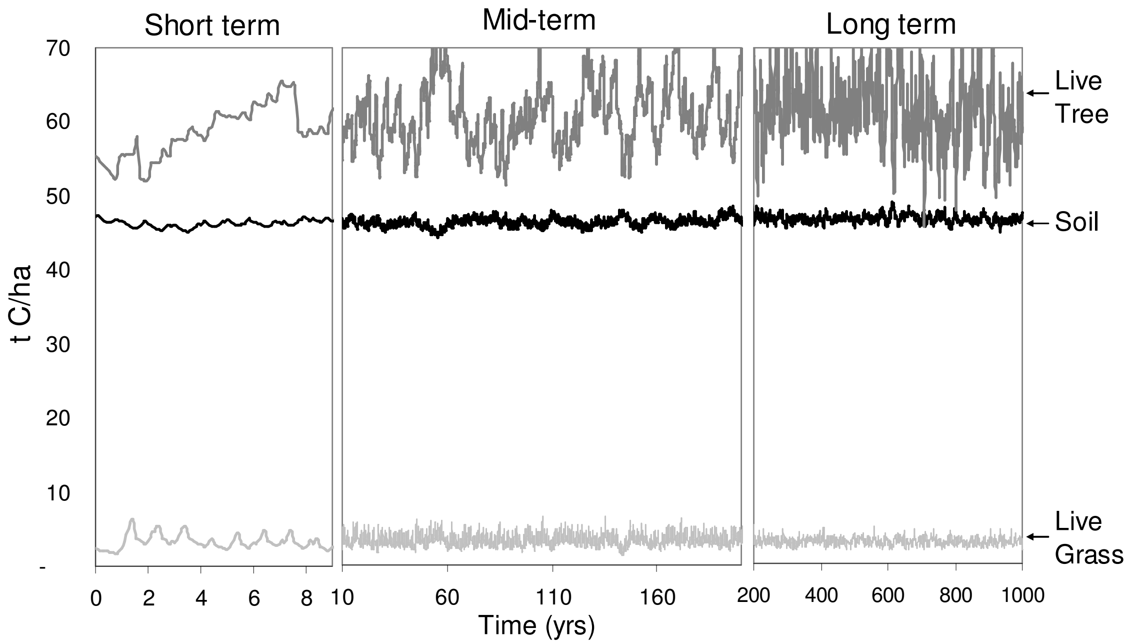


Figure 3.12 Carbon levels of live above and below ground tree carbon, AG and BG grass carbon, and total soil carbon in the Miombo Woodland system modeled with CENTURY.

Output for the years 0-200 presented on a monthly basis. Output for the years 200-1000 presented yearly.

Table 3.9 Estimates of carbon stocks from field data, published literature, and CENTURY model results (t C ha^{-1})

	Field data Tanzania sites (Walker 2008)	Range of published estimates from Kitulanghalo Area[1]	Average of published estimates throughout Miombo Region[2]			Century Model Results		
			Miombo Woodland	10-15 yr regrowth	16-20 yr regrowth	Tanzania Baseline	10 yr regrowth	20 yr regrowth
	C t ha^{-1}							
Soil (to 20 cm)	31		26			46	29.6	31.4
Trees								
Aboveground	25	10-40	28	13	18	33.1	15.1	21.3
Belowground		3.2	12			22	10.2	11.7
Grass								

	Field data Tanzania sites (Walker 2008)	Range of published estimates from Kitulanghalo Area[1]	Average of published estimates throughout Miombo Region[2]			Century Model Results		
			Miombo Woodland	10-15 yr regrowth	16-20 yr regrowth	Tanzania Baseline	10 yr regrowth	20 yr regrowth
	C t ha^{-1}							
Aboveground	2.15*		0.529			0.46**		0.63**
Belowground			0.722			2.4**		2.97**

*maximum, includes standing alive and dead

**ave stock over year

1. Malimbwi 1992; Ek 1994; Zahabu 2001;
2. Campbell *et al* 1998; Chidumayo 1990; Chidumayo 1993; Chidumayo 1994a; Ek 1994; FRIM unpublished; Jean 1997; Luoga 2002; Malimbwi 2005; Malimbwi and Mugasha 2001; Malimbwi 1992; Stromgaard 1985; Zahabu 2001

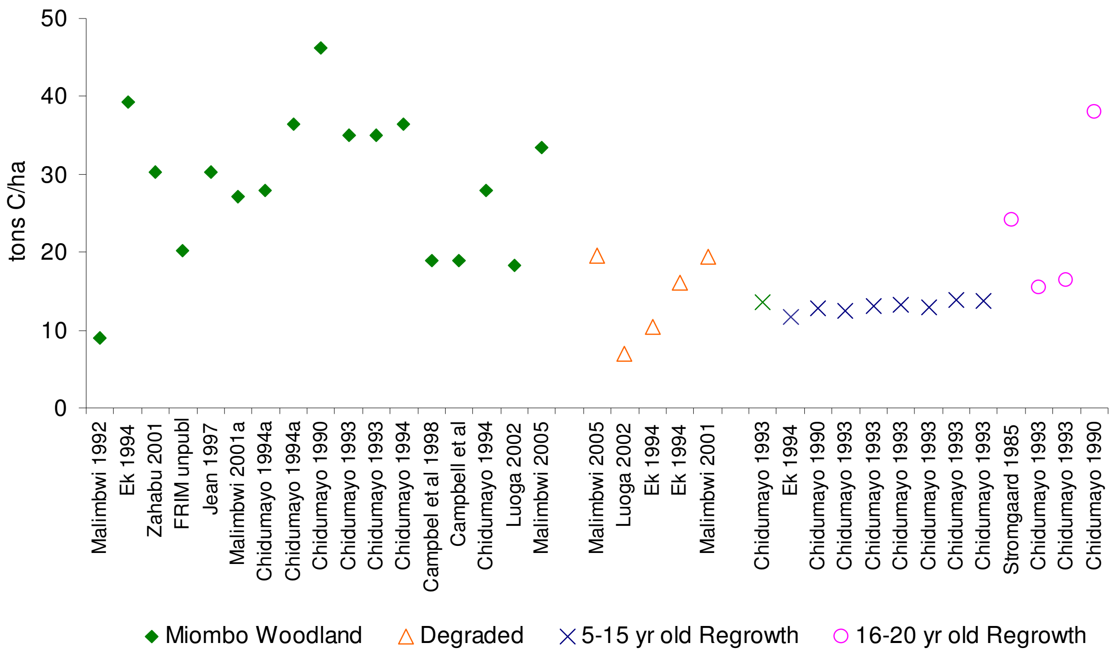
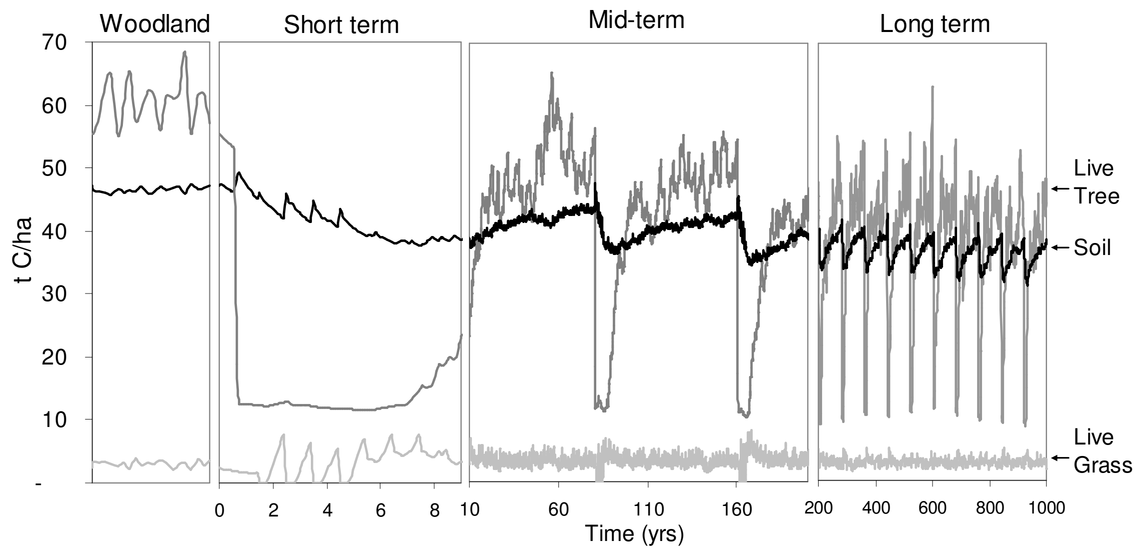


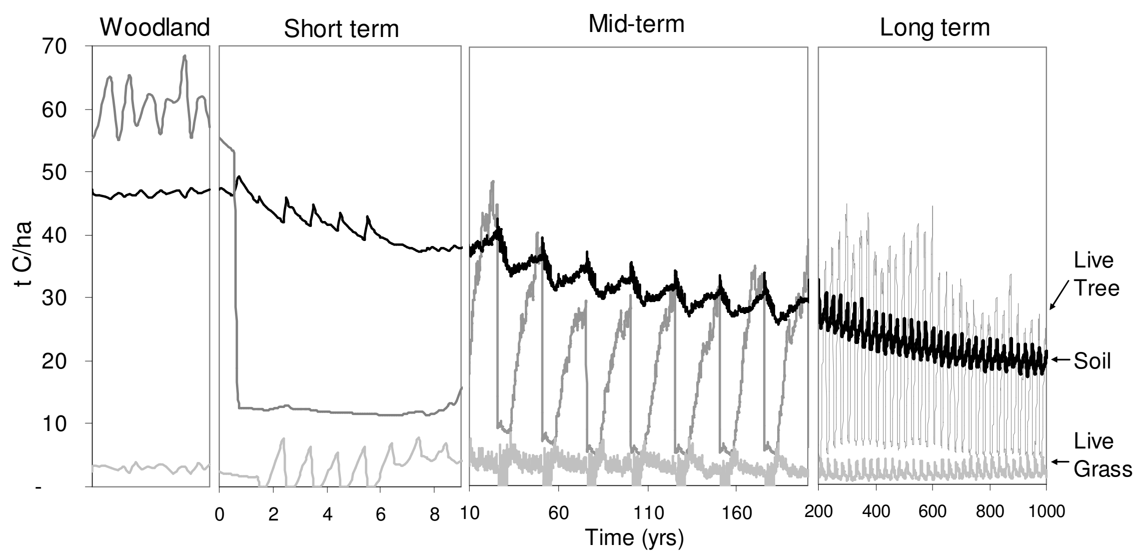
Figure 3.13 Range of published AG tree biomass levels in Miombo Region. Degraded forest is areas where cutting for charcoal production has taken place.

3.4.2 Agricultural management

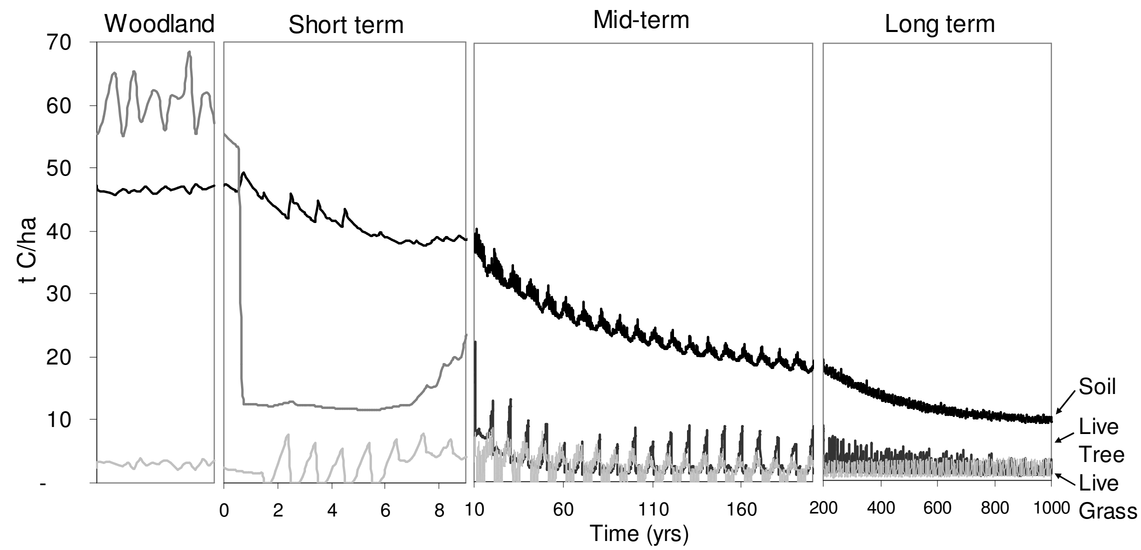
Various crop-fallow cycles were examined. Aboveground tree biomass is cut, the large wood portion removed, and the rest is burned and therefore this pool is reduced almost to zero. Modeled soil carbon levels begin to decline immediately following the conversion of the woodland to agriculture. Modeled soil carbon levels were reduced by 15% following five years of cropping and by about 25% after 10 consecutive years of cropping (Figure 3.3). In the years immediately after crop production ceases, soil carbon levels continue to decline slightly and then increase very slowly. In the year of field preparation in which the trees are cut and large amounts of small branches are burned, there is a slight increase in soil carbon stocks followed by a slow reduction during cropping. In subsequent crop-fallow cycles, over the years of agriculture soil carbon levels decline, however, by a smaller amount (~8-15%) than the first crop cycle. The soil carbon stock over time when land is converted to agriculture is logarithmic in shape, although the change over time in the first few years is not as rapid. However as in a logarithmic function, the rate of change in soil carbon does decline over time and after about 60 years of continuous agriculture reduced by less than 1% a year.



a. CENTURY model results from 5 years agric followed by 70 years of fallow



b. CENTURY model results from 5 years of agric followed by 20 years of fallow



c. CENTURY model results from 5 years of agric followed by 5 years of fallow

Figure 3.14 Average CENTURY model estimates of carbon stocks over the short, medium, and long term under various crop-fallow lengths.

Soil nutrient levels do recover during the fallow period, but that recovery is protracted and even after 70 years of a fallow period soil carbon levels are still ten percent less than prior to cropping. The longer the fallow period, the greater recovery in soil nutrient stocks (Figure 3.4). As fallow periods are shortened, the impact on soil nutrient levels amplifies. A crop-fallow cycle of 5 years agriculture followed by 20 years fallow reduces soil carbon stocks by 30% over the first 200 years (Figure 3.4). Moving to continuous agriculture reduces modeled soil carbon by about 55% over 200 years. Reductions in soil nitrogen are not as great as soil carbon but are still reduced by almost 40% if land is under continuous cultivation (Figure 3.4 and 3.5). With a longer fallow period of 20 years soil nitrogen levels are reduced by only 20%. Based on model results, when fallow periods are short, such as 5 years, cropping for ten years continuously has the same impact on soil nutrient levels as farming for only five years before returning to a five year fallow period (Figure 3.4. 3.5).

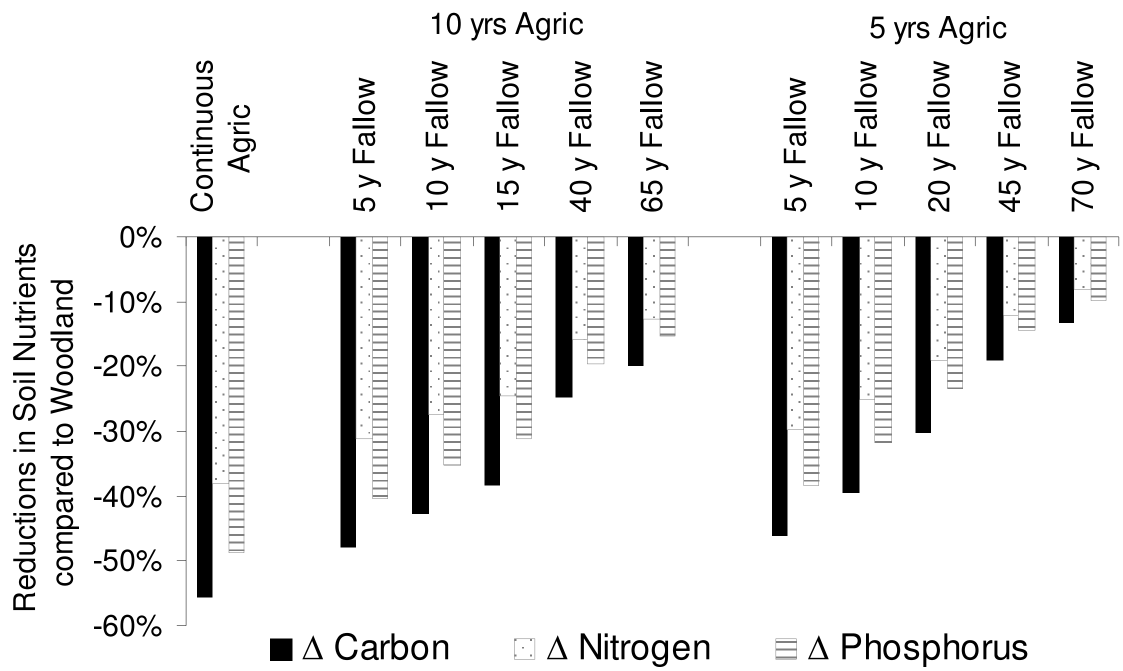


Figure 3.15 Average reductions in soil nutrient stocks over 200 years in comparison to nutrient stocks in Miombo Woodlands resulting from various crop-fallow cycles.

When fallow periods are short, soil nutrient levels do not stabilize at a lower level, but continue to decline over successive rotations (Figure 3.5). Soil nutrients start to recover during the fallow period, but then that recovery is stopped when land is converted back to agriculture and soil nutrients start to lower again (Appendix 3.1). The labile pools change rapidly over the year, but with each successive crop cycle the minimum level over the year is reduced. After 50 to 100 years, this minimum level in the labile pools stabilizes. The slow soil carbon pool also declines quickly under agriculture and starts to recover under the fallow. When fields are cropped for 5 years followed by 5 yrs of fallow, the slow soil carbon pool changes by about 1 t C ha^{-1} over the cycle. But over every successive cycle, the highest point the pool reaches during the fallow period is successively lowered by about 0.3 t C ha^{-1}. Thus, the stock progressively declines overtime and does not stabilize at a lower level for 300 years. A similar pattern occurs in the passive soil carbon pool, but with a lesser amount of change in each rotation and continues to very gradually decline even after 500 years. A similar pattern takes place in nitrogen and phosphorus pools. This reduction in the maximum and minimum level also occurs in the tree biomass, however, these levels stabilize only after about 60 years when under a 5 yr crop – 5 yr fallow cycle.

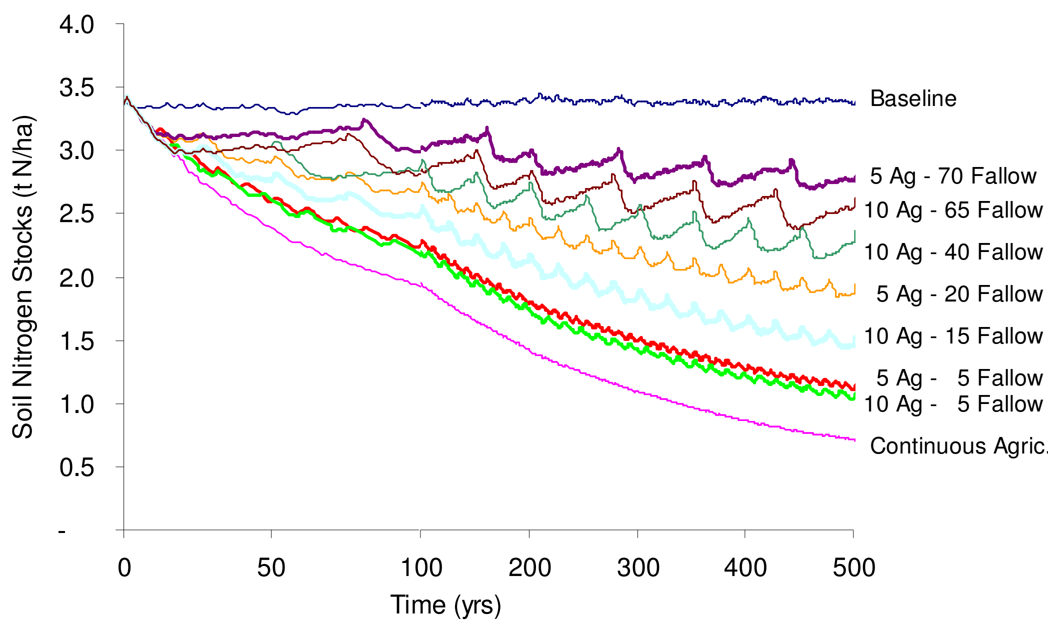


Figure 3.16 Total soil nitrogen stocks over time under various crop-fallow cycles. Number refers to number of years under agriculture (Ag) or fallow. Note change in scale at year 100.

3.4.3 Fire timing and frequency

Various fire periodicities were modeled: at the very start of the dry season, throughout the dry season, and only at the end of the dry season. When fires occur only at the very start of the dry season (April-June) overall tree biomass levels are reduced by 16% in comparison to fires occurring through the dry season (June-Sept) (Table 3.3). While when fires were modeled to only occur at the end of the dry season (Sept-Oct), the carbon stocks were highest. Changes in grass biomass were minimal. Soil nutrient level changes mimicked changes in tree biomass. Carbon:nutrient ratios were not significantly altered in the soil by changes in the month of fires.

Table 3.10 Differences in nutrient stocks under varying fire seasonality. Average value after 200 years of fire times. Fire ranging from June-Sept is used as the baseline. For all simulations fire was simulated to occur every 3-5 years

	June-Sept	April-June	May-July	Sept-Oct
	kg ha^{-1}			
Tree				
Live				
Carbon	61,542	51,637	59,484	63,191
Nitrogen	287	245	278	295
Phosphorus	73	62	71	75
Dead				
Carbon	12,781	10,631	12,329	13,130
Nitrogen	44.47	36.62	42.79	45.75
Phosphorus	13.76	11.46	13.27	14.16
Live Grass				
Live				
Carbon	3,028	2,965	2,992	3,059
Nitrogen	64	63	64	65
Phosphorus	14	14	14	13
Dead				
Carbon	1,100	1,039	1,078	1,125
Nitrogen	15.54	14.59	15.21	15.95
Phosphorus	4.23	4.11	4.21	4.20

	June-Sept	April-June	May-July	Sept-Oct
	kg ha^{-1}			
Soil				
Carbon	46,807	42,422	45,719	47,946
Nitrogen	3,357	3,044	3,270	3,450
Phosphorus	219	199	214	225

The frequency of fire recurrence was modeled. In the base case, fires occurred at some point between June and September every 3-5 years (Table 3.4). In each subsequent case, the season of fires was not altered, only the frequency. When fires are excluded, tree carbon stocks increase rapidly over time and reach a new equilibrium after several hundred years (Appendix 3.2). Reducing the fire frequency leads to an increase in alive and dead biomass with fire exclusion leading to more than three times the tree live biomass. Repeated fires yearly reduces tree stocks, however a new equilibrium point is reached after only about 150 years (Appendix 3.2). Average live grass biomass in the long run does not significantly change under various fire regimes.

Table 3.11 Nutrient stocks under varying fire frequencies. Average stocks over 200 years of fire regime (kg of nutrient ha^{-1}). Fire frequency of every 3-5 years is used as baseline.

	30 yrs	10 yrs	1 yr	3-5 yrs
	ave after 200 years (kg ha^{-1})			
Tree				
Live				
Carbon	142,627	101,933	11,907	61,474
Nitrogen	611	450	76	286
Phosphorus	164	117	16	73
Dead				
Carbon	28,948	22,551	2,004	12,752

	30 yrs	10 yrs	1 yr	3-5 yrs
	ave after 200 years (kg ha^{-1})			
Nitrogen	106	81	7	44
Phosphorus	30	24	2	14
Live Grass				
AG and BG Live				
Carbon	2,644	2,781	2,431	3,010
Nitrogen	63	63	48	64
Phosphorus	12	13	12	13
Standing Dead				
Carbon	1,309	1,270	72	1,088
Nitrogen	22	20	1	15
Phosphorus	5	5	0.33	4
Soil				
Carbon	73,068	62,834	22,049	22,049
Nitrogen	5,264	4,515	1,539	1,539
Phosphorus	326	287	101	101

3.4.4 Woodland degradation

The frequency of logging, the time of year, and the type of wood removed were the various land management scenarios modeled. In all scenarios, 30% of the aboveground tree biomass was cut. To examine the impact of frequency, the cutting and removal of all aboveground tree biomass pools was modeled to take place every 30 years, every 10 years, and every 5 years. For each of these cutting cycles, the model was also repeatedly run with cutting taking place at various months of the year (e.g. 30% cut in January, every 10 years, then run again with 30% cut in February every 10 years). The type of wood pool removed was also varied.

In general, the Miombo system is able to recover quickly from such selective cutting. Modeling cuttings every 30 years produced only a 5% decline in soil nutrient stocks and a 15% reduction in tree biomass over 200 years in comparison to the baseline. If cutting is repeated every 10 years, soil carbon stocks decline by 13% and tree alive and dead biomass by about 30% over 200 years (Table 3.5). Nitrogen and phosphorus levels change by similar amounts, although phosphorus levels were reduced proportionally more in the live tree pool than the other nutrients. Reductions on carbon, nitrogen, and phosphorus were the smallest when cutting was modeled to take place during the month of August, when vegetation is dormant. However, the differences in stock reductions between months are very minimal (Table 3.5). Between August and January, the difference in soil carbon stocks is only 1.3 t C ha^{-1} and in tree biomass is only 4.1 t C ha^{-1}. In the soil pool, percentage changes are greatest in the soil active pool, however, in terms of stock quantities, reductions in the 'slow' soil nutrient pools were largest.

Table 3.12 Reductions in various nutrient stocks resulting from the removal of 30% of above ground tree biomass (large, small, leaves) every ten years during various months. Average change over first 200 years presented

	Baseline	Jan	May	July	Aug	Oct	Nov
	kg ha^{-1}	Average Δ kg ha^{-1} from baseline levels in 200 years					
Tree - Live							
Carbon	61,411	-21,675	-21,005	-20,845	-17,550	-20,599	-21,199
Nitrogen	286	-88	-84	-83	-70	-82	-85
Phosphorus	73	-32	-32	-32	-29	-30	-31
Soil							
Carbon	46,590	-9,124	-8,961	-8,765	-7,853	-8,432	-8,702

	Baseline	Jan	May	July	Aug	Oct	Nov
	kg ha^{-1}	Average Δ kg ha^{-1} from baseline levels in 200 years					
Nitrogen	3,339	-599	-587	-573	-513	-549	-568
Phosphorus	218	-36	-36	-35	-31	-33	-34

Alterations on the type of wood removed from the system following cutting significantly changes the modeled reductions of nutrients from the system (Table 3.6, Figure 3.6, Appendix 3.3). For example, if wood was cut every 5 years for 200 years, but only the woody biomass removed, soil carbon stocks are reduced by only 6% instead of 13%. The reductions resulting from removing both the large wood and branches are larger than if only the large wood is removed, however, with a wood removal rotation cycle of 10 years, only about 150 kg ha^{-1} more nitrogen is lost from the system if both the branches and the leaves are taken than if the branches taken but the leaves are left. Over successive cycles, differences in reductions become more pronounced (Figure 3.6).

By removing only the large wood from the system, even at a rotation cycle of every 5 years, over the long term (1000 years) tree biomass levels are on average only reduced by the amount cut and thus although biomass levels are lower, this level of cutting is sustainable and does not slowly reduce tree carbon stocks overtime (Appendix 3.3).

Table 3.13 Average percent change from baseline levels over 200 years resulting from the cutting of 30% of above ground tree biomass (large, small, leaves) every 30, 10, or 5 years during the month of January.

After cutting occurs, either all cut biomass (large wood, branches, and leaves) is removed, only the large wood and branches, or just the large wood is removed. The remaining cut pools decompose on site or burn during subsequent fires.

	All cut biomass removed			Large wood and branches removed			Large wood only removed		
	every 30 yrs	every 10 yrs	every 5 yrs	every 30 yrs	every 10 yrs	every 5 yrs	every 30 yrs	every 10 yrs	every 5 yrs
				System Total					
ΔCarbon	-12.5%	-21.9%	-28.7%	-10.7%	-18.0%	-23.2%	-9.8%	-16.2%	-20.5%
ΔNitrogen	-3.6%	-7.5%	-10.5%	-2.6%	-5.4%	-7.3%	-2.0%	-4.1%	-5.4%
ΔPhosphorus	-6.2%	-12.1%	-16.5%	-4.9%	-9.2%	-12.4%	-3.9%	-6.9%	-8.8%
				Total Soil					
ΔCarbon	-4.1%	-9.1%	-12.8%	-3.0%	-6.5%	-9.1%	-2.1%	-4.6%	-6.2%
ΔNitrogen	-2.4%	-5.7%	-8.1%	-1.6%	-3.8%	-5.3%	-1.1%	-2.6%	-3.5%
ΔPhosphorus	-2.3%	-5.9%	-8.5%	-1.4%	-3.7%	-5.3%	-0.8%	-2.3%	-3.2%
				Live Wood Total					
ΔCarbon	-18.3%	-30.4%	-39.0%	-16.1%	-25.7%	-32.4%	-15.4%	-24.6%	-30.9%
ΔNitrogen	-14.5%	-25.2%	-33.0%	-12.4%	-20.6%	-26.5%	-11.8%	-19.5%	-24.9%
ΔPhosphorus	-16.0%	-27.6%	-36.0%	-13.8%	-23.0%	-29.8%	-12.5%	-19.8%	-24.9%

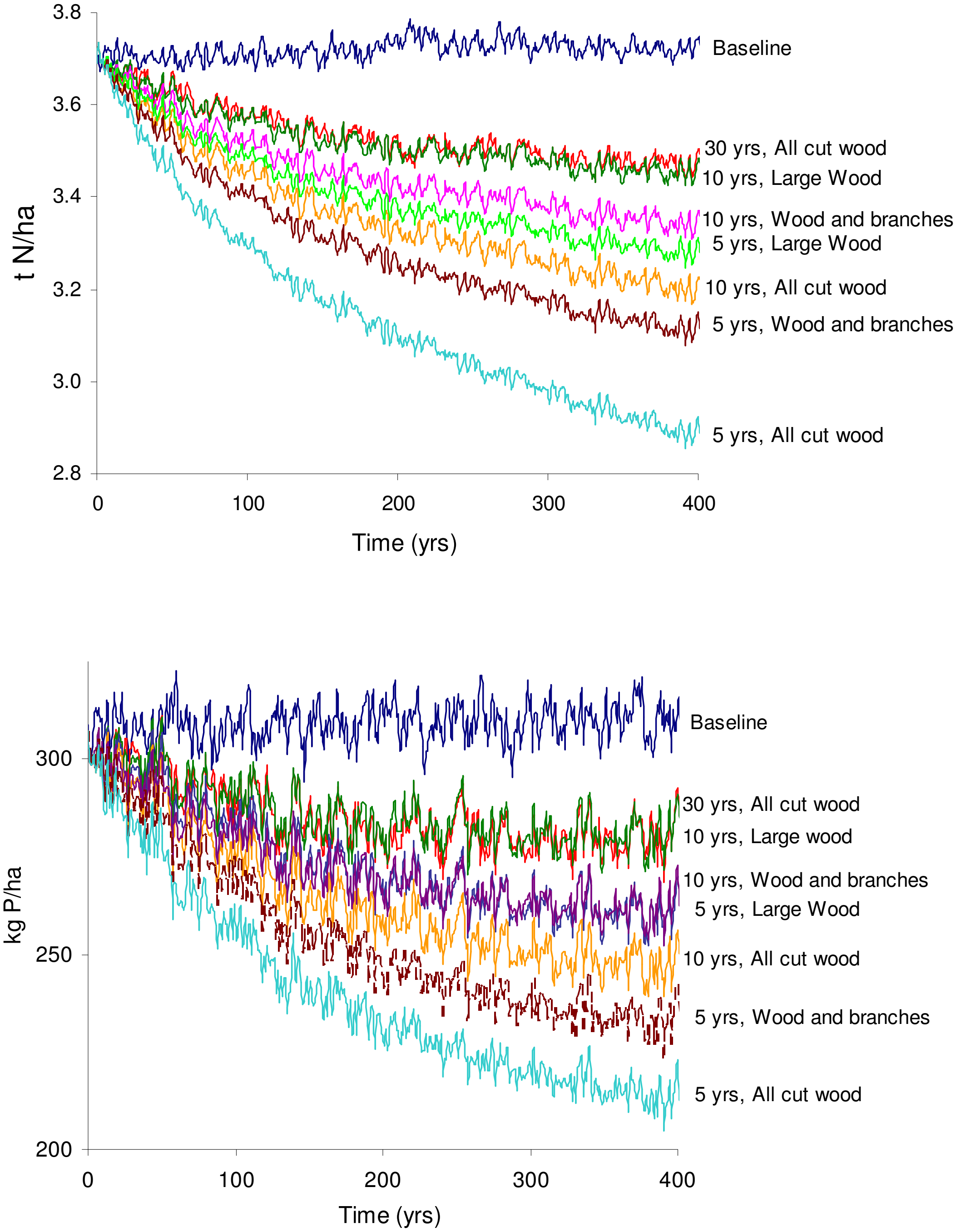


Figure 3.17 Simulated reductions in total system nitrogen and phosphorus stocks resulting from the cutting of 30% of above ground tree biomass (large, small, leaves) during the month of August every 30, 10, or 5 years.

All cut wood = all tree biomass cut is removed, Wood and branches = All woody material cut (large and small) is removed but leaves remain, Large wood = Large wood is cut, but small branches and leaves remain to decompose.

3.5 Discussion

3.5.1 Agricultural cycles

Conversion of the land to agriculture reduces nutrient levels, including soil nutrient stocks. Soil carbon stocks decline from both an increase in decomposition due to a change in the soil temperature and moisture levels and from a decrease in biomass inputs. When agricultural activity ceases, soil nutrient levels recover, however this increase is only 1-2% per year and therefore unless the fallow period is very long, over successive crop-fallow periods, soil nutrient levels will continue decline.

In recent studies on soil nutrient levels under agriculture in the Miombo region (Walker 2008; Walker and Desanker 2004), the impact of soil nutrient reduction was dependent on the length of the crop and fallow cycle. In areas with many years of cropping (10-30 years) in Malawi, soil carbon stocks were 40% lower than in Miombo areas (Walker and Desanker 2004). While in areas in Mozambique and Tanzania with short agriculture periods (3-5 years), soil carbon levels were not significantly reduced by cropping in the first five years and only reduced in the top 10 cm over several successive crop-fallow periods (Walker 2008). Soil carbon stocks were reduced by 53% within ten years when land was converted to agriculture in a dry sandy location in Zimbabwe (Zingore *et al* 2005). The CENTURY modeling results are very similar to field measurements in the higher intensity agricultural area. Continuous agriculture for 10-30 years resulted in a 25-40% reduction in modeled soil carbon levels. Conversion to agriculture for less than five years was found to have no significant impact on soil carbon levels in field studies (Walker 2008) while model results show a 15% reduction in soil carbon levels after five years of agriculture.

Many previous studies throughout the world have found soil carbon loss to be very rapid in the years immediately after conversion to agriculture, as the labile carbon from the previous land use is decomposed, but then the rate diminishes through time and may reach a new equilibrium (Houghton 1983; Schlesinger 1986; Davidson and Ackerman 1993; Feller and Beare 1997; Zingore *et al* 2005). In the sandy soils of Zimbabwe, Zingore *et al* (2005) found soil carbon levels declined quickly from about 20 t C ha^{-1} to about 10 t ha^{-1} and then stabilize within ten years. Although levels vary between fields, on average soil carbon levels display no overall downward trend as the age of fields reach even 40 years. Zingore *et al* (2005) attribute this long lasting carbon to the charcoal found in the soil. The model results also show a decline in soil carbon levels with the onset of agriculture; however, in the model soil carbon levels continue to decline over time and do not stabilize for hundreds of years. When land is converted to agriculture, CENTURY models the loss in soil carbon to take place at a slower rate than found by Zingore *et al* (2005). After ten years, 23% of modeled soil carbon had been lost, however, after 40 years, the model also shows a 52% decline in soil carbon stocks, the same proportion lost in the study by Zingore *et al* (2005). Modeled carbon stocks only change by about 1% per year after about 40 years of cropping, and with the natural variability that exists between fields this type of change may not be detected in field measurements. Very few studies have examined the longer term impact of such cropping in the Miombo region, pointing to one advantage of modeling. In areas where it is difficult to find and document areas where agriculture has been taking place for more than 50 years, the longer term results of the current land management practices are unknown. Modeling allows us to predict the outcome of various land management practices on the long term. These model results present a warning that if the current trend of increased cropping and shorter fallows continues without complementary increase in fertilizer use or other management change, then soil nutrient levels will continue to decline through time.

Ceasing of agriculture often results in an improvement of carbon stocks, although this recovery is often seen to be slow (Post and Kwon 2000; Szott *et al* 1999; Guo and Gifford 2002). One of the significant conclusions of the Walker and Desanker (2004) study and Williams *et al* (2008) was the continued depression of soil carbon and nitrogen levels in the fallow fields. Successively older abandoned agricultural fields in a study in the Miombo woodlands area of Mozambique did not increase in soil carbon levels over time, although soil carbon stocks were in the range found within previously uncultivated Miombo woodlands (Williams *et al* 2008). Fallow fields in the lower land use intensity locations by Walker (2008) did not have elevated carbon stocks compared to agricultural fields, but were again in the same range as Miombo woodland areas. Model results support this finding with twenty years of fallow period only increasing soil carbon stocks by about 4.5% or less than an average of 0.1 t $ha^{-1}yr^{-1}$. To increase modeled soil carbon levels more than 10% from the level at cessation of cropping takes over 50 years. Field studies have relied on a space-for-time comparison. This will lead to a greater variability in nutrient stocks then following a specific location due to differences in soil type and conditions between locations. This may account for some of the differences between field and modeled results.

Although crop yields were not examined in this analysis, the continued decline of soil nutrient levels indicate that crop yields would most likely also decline with time as soils become more degraded. Levels of soil carbon and nitrogen have been found to be significantly correlated to maize yields in Malawi and Zimbabwe (Chirwa *et al* 2004; Mtambanengwe and Mapfumo 2008). The recent trend in the region of shorter fallow periods will most likely lead to greater soil degradation and reduced crop yields. Tiessen *et al* (1998) felt that carbon levels will not generally fall below 50% of the original values because productivity would be too low and the fields would be abandoned, however in highly populated regions this may not be an option.

3.5.2 Fire timing and frequency

In the Miombo system, fires are most common in the dry season, particularly in the months of August – October. The majority of these fires are anthropogenic. During this drier period, most of the grass has senesced and is therefore drier, and burns more easily. By modeling fire frequency rates, it is seen that the current biomass levels found in the Miombo system is maintained by recurrent fires. Excluding fires allows tree biomass levels to increase overtime. A similar result of increased tree biomass was also found in the experimental burn plots described by Trapnell (1959). If fires reoccurred yearly, tree biomass levels would be reduced to a much lower level.

The management of fire in the Miombo system has varied significantly over time. In colonial times fire suppression was promoted, while more recently fire has not been as actively managed and has resulted in more frequent fires (Eriksen 2007). At various times, government policies and scientists have promoted early dry season ‘prescribed burns’ as a method to reduce the amount of biomass damaged by fires (Chidumayo 1988; Rodgers 1996). An experimental fire study found that early season burning retained plant community similar to that found in surrounding woodlands while late season burning reduced regeneration and total stocking (Rodgers 1996; Trapnell 1959). Although neither the rate of fire expansion nor the impact of fires on seedling survival can be modeled within the Century model, some insights may still be gained. Altering the timing of fires had an insignificant impact on average grass aboveground, belowground, and standing dead biomass, except in the particular years when fires occurred. Contrary to the fire studies conducted (Trapnell 1959), earlier fires led to less modeled tree biomass because earlier in the year the tree is still growing and therefore the portion of the tree biomass that was burned was not able to grow, thus reducing overall biomass levels. However, fires occurring May-July only reduced tree stocks by 3%, and therefore if these earlier burns are thought to have other benefits not able to be modeled, this will not have major impacts on nutrient stocks.

3.5.3 Woodland Degradation

Century model results show that a rotation cycle of 30 years reduces average wood carbon stocks by only about 15% and that extending that rotation cycle to 60 years reduces wood carbon stocks by about 11%. These modeled results are similar to conclusions from field measurements. Zahabu (2001) suggests a rotation length of 15 years based on estimated mean annual increment, current volumes on public lands, and the volume of wood found in the forest reserve, however, for the same region Malimbwi and Mugasha (2001) suggest a rotation age of 60 years and Malimbwi *et al* (2005) recommend a 8-15 year cycle. Chidumayo (1993) recommends a rotation period of 34-65 years. Similar to field studies, modeled soil carbon levels are not reduced greatly by charcoal production (Chidumayo 1993; Luoga 2002). Model results also find that selective cutting of 30% of the biomass every five years, although reduces overall tree biomass stocks, does not lead to progressive reduction in tree biomass over time.

A study of charcoal production found that logging and charcoal making takes place throughout the year and therefore there is not a season during which the majority of wood is cut (Malimbwi *et al* 2001). Modeled results show that the time of year cutting takes place does not have a large impact on nutrient levels, and therefore no recommendations need to be made to alter the time of wood cutting. However, the type of wood removed does significantly change the impact of logging on nutrient stocks. Because a greater concentration of nitrogen and phosphorus in a tree is found in the leaves and smaller branches, leaving these wood pools in place and allowing them decompose or burn significantly reduces the impact of logging on nutrient stocks. It is recommended that only large wood should be removed and small branches and leaves left in place. If the community requires the small branches to be used, then branches should be left in the woodlands and only collected for firewood after all the leaves have fallen off. This simple policy recommendation will reduce the ‘nutrient mining’ resulting from charcoal production.

3.6 Conclusions

Changes in population and current land management are leading to greater deforestation and land degradation. When agricultural intensity is increased, modeled system nutrient levels cannot be maintained and nutrient stocks continue to decline over long time periods. Natural fallow periods allow some recovery of soil nutrient levels; however, the modeled recover is slow and takes more years than is the current land management practice in many parts of the region. Such soil degradation will lead to reductions in crop yields.

Selective cutting for charcoal production will continue to be a dominant activity for rural households until the demand for charcoal in peri-urban and urban areas declines. Except in the small number of communities that have implemented participatory forest management plans, the selective cutting of the woodlands is not actively managed. In many areas repeated cutting leads to degradation over time. However, this woodland system does have the capacity to supply wood on a long term basis provided the cutting remains selective. Therefore it is recommended that communities create management plans for their public lands and institute a rotation length of at least 8-10 years at a selective logging level of 30%. To reduce 'nutrient mining', only the large wood and branches should be removed from the woodland area. Smaller branches and leaves should be left in place to decompose. Based on model results, there is no need for policies to recommend or regulate the time of year in which cutting takes place.

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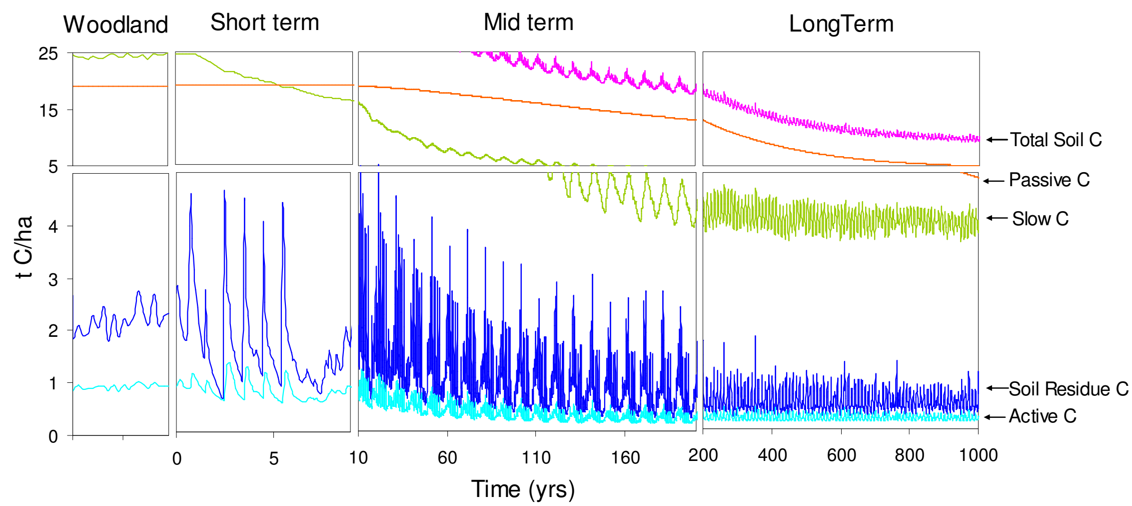
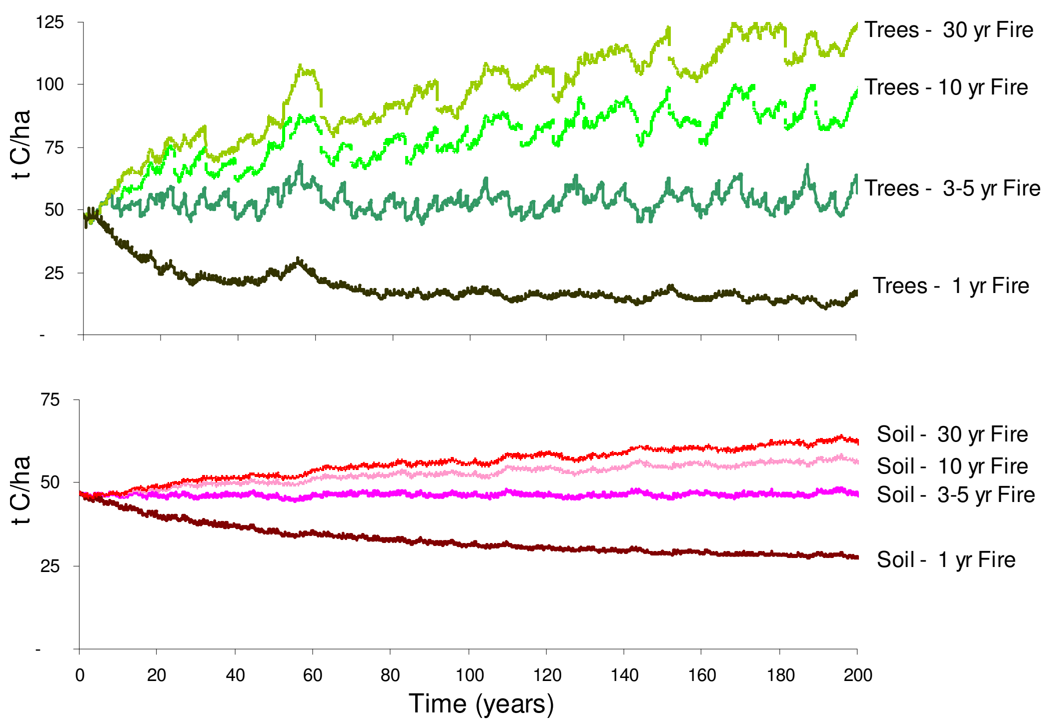
3.8 Appendix



Appendix 3.5 Modeled soil carbon pools when land is cropped for five years followed by 5 years of fallow (note the changes in scale)



Appendix 3.6 Changes in tree and soil carbon levels under varying fire frequencies

Appendix 3.7 Changes from baseline levels resulting from the cutting of 30% of above ground tree biomass (large, small, leaves) every 30, 10, or 5 years during the month of January and August.

Average change in nutrient levels over 200 and 1000 years of successive cuttings presented. After cutting occurs, either all cut biomass (large wood, branches, and leaves) is removed, only the large wood and branches, or just the large wood is removed. The remaining cut pools decompose on site

Month Cut		Time Period	All pools removed			Large wood and branches removed		Large wood only removed	
			every 30 yrs	every 10 yrs	every 5 yrs	every 10 yrs	every 5 yrs	every 10 yrs	every 5 yrs
			System Total						
January	ΔC	ave over 200 yrs	-12.5%	-21.9%	-28.7%	-18.0%	-23.2%	-16.2%	-20.5%
	ΔN	ave over 200 yrs	-3.6%	-7.5%	-10.5%	-5.4%	-7.3%	-4.1%	-5.4%
	ΔP	ave over 200 yrs	-6.2%	-12.1%	-16.5%	-9.2%	-12.4%	-6.9%	-8.8%
August	ΔC	ave over 200 yrs	-12.1%	-19.0%	-28.4%	-15.9%	-23.4%	-14.0%	-20.7%
	ΔN	ave over 200 yrs	-3.3%	-6.5%	-10.4%	-4.8%	-7.7%	-3.6%	-5.6%
	ΔP	ave over 200 yrs	-5.8%	-10.3%	-16.2%	-8.1%	-12.7%	-5.7%	-8.8%
January	ΔC	ave over 1000 yrs	-12.5%	-23.7%	-30.2%	-19.0%	-24.0%	-16.7%	-20.9%
	ΔN	ave over 1000 yrs	-4.8%	-10.4%	-13.7%	-7.4%	-9.6%	-5.6%	-7.1%
	ΔP	ave over 1000 yrs	-7.2%	-15.2%	-19.8%	-11.6%	-15.0%	-8.2%	-10.3%
August	ΔC	ave over 1000 yrs	-12.1%	-20.3%	-31.0%	-16.5%	-25.1%	-14.2%	-21.7%
	ΔN	ave over 1000 yrs	-4.4%	-8.9%	-14.2%	-6.6%	-10.5%	-4.8%	-7.7%
	ΔP	ave over 1000 yrs	-6.8%	-13.2%	-20.5%	-10.4%	-16.2%	-6.8%	-10.8%

			Total Soil						
January	ΔC	ave over 200 yrs	-4.1%	-9.1%	-12.8%	-6.5%	-9.1%	-4.6%	-6.2%
	ΔN	ave over 200 yrs	-2.4%	-5.7%	-8.1%	-3.8%	-5.3%	-2.6%	-3.5%
	ΔP	ave over 200 yrs	-2.3%	-5.9%	-8.5%	-3.7%	-5.3%	-2.3%	-3.2%
August	ΔC	ave over 200 yrs	-3.7%	-7.9%	-12.8%	-6.0%	-9.7%	-4.0%	-6.6%
	ΔN	ave over 200 yrs	-2.2%	-4.9%	-8.0%	-3.5%	-5.7%	-2.3%	-3.7%
	ΔP	ave over 200 yrs	-2.0%	-4.9%	-8.4%	-3.3%	-5.7%	-2.0%	-3.4%
January	ΔC	ave over 1000 yrs	-5.2%	-11.7%	-15.6%	-8.4%	-11.1%	-6.0%	-7.8%
	ΔN	ave over 1000 yrs	-3.8%	-8.7%	-11.5%	-5.9%	-7.8%	-4.2%	-5.4%
	ΔP	ave over 1000 yrs	-3.6%	-8.6%	-11.5%	-5.6%	-7.5%	-3.8%	-4.9%
August	ΔC	ave over 1000 yrs	-4.8%	-10.1%	-16.3%	-7.7%	-12.3%	-5.2%	-8.5%
	ΔN	ave over 1000 yrs	-3.5%	-7.5%	-12.0%	-5.4%	-8.7%	-3.7%	-5.9%
	ΔP	ave over 1000 yrs	-3.2%	-7.3%	-12.0%	-5.1%	-8.4%	-3.3%	-5.4%

			Total Live Wood						
January	ΔC	ave over 200 yrs	-18.3%	-30.4%	-39.0%	-25.7%	-32.4%	-24.6%	-30.9%
	ΔN	ave over 200 yrs	-14.5%	-25.2%	-33.0%	-20.6%	-26.5%	-19.5%	-24.9%
	ΔP	ave over 200 yrs	-16.0%	-27.6%	-36.0%	-23.0%	-29.8%	-19.8%	-24.9%
August	ΔC	ave over 200 yrs	-17.8%	-26.0%	-38.2%	-22.1%	-31.9%	-21.0%	-30.6%
	ΔN	ave over 200 yrs	-14.0%	-21.2%	-32.1%	-17.4%	-26.0%	-16.3%	-24.5%
	ΔP	ave over 200 yrs	-15.5%	-23.3%	-35.0%	-19.6%	-29.3%	-16.1%	-23.7%
January	ΔC	ave over 1000 yrs	-17.5%	-31.5%	-39.7%	-26.0%	-32.4%	-24.4%	-30.3%
	ΔN	ave over 1000 yrs	-14.1%	-26.5%	-34.0%	-21.2%	-26.8%	-19.6%	-24.8%
	ΔP	ave over 1000 yrs	-16.4%	-31.6%	-40.1%	-26.3%	-33.4%	-20.6%	-25.7%
August	ΔC	ave over 1000 yrs	-17.0%	-26.5%	-40.0%	-22.0%	-32.9%	-20.3%	-30.9%
	ΔN	ave over 1000 yrs	-13.6%	-22.0%	-34.0%	-17.6%	-27.1%	-16.0%	-25.0%
	ΔP	ave over 1000 yrs	-15.9%	-27.3%	-41.0%	-22.9%	-34.9%	-16.4%	-25.6%

Chapter 4 Potential carbon sequestration through land management alterations in the Miombo woodlands of Tanzania

Abstract

Climate change mitigation is becoming one of the largest challenges facing the world today. Implementing activities that increase net sequestration or reduce emissions in the agriculture, forestry, and other land use sectors (AFOLU) have the potential to play a significant role in emission mitigation. The recently amplified demand for voluntary carbon market credits has greatly widened the amount of land and the types of activities in which AFOLU type carbon projects can generate marketable carbon credits. Although there have been great advances in agricultural productivity worldwide, rural farmers in Tanzania are still mainly practicing subsistence level agriculture with low crop yields. Rural communities require innovative strategies for poverty alleviation and environmental conservation. Community initiatives aimed at increasing the carbon stocks on their land for carbon credit sale may supply additional revenue to rural farmers while acting as incentive for carbon emission mitigation. However, prior to the implementation of a carbon project, the impact of changing land management on carbon stocks and on revenues should be understood. The following study takes a first step on this path by examining the potential for creating carbon credits through increasing fallow lengths and selective logging rotations in the Miombo woodlands. The landscape average changes in

carbon stocks resulting from an increase from 3 years of fallow to 5, 10, 25, and 45 years of fallow and extending selective logging rotations for charcoal production from 5 and 8 years to 10, 30, and 60 year rotations are estimated using the CENTURY model. The changes in revenues resulting from a permanent change in land management are also estimated over the long term. Raising the fallow period from 3 to 10 years increases live wood carbon stocks at the landscape level by 22 t CO_2e ha^{-1} while an increase to 45 years changes live wood carbon stocks by 94 t CO_2e ha^{-1}. Bringing selective logging rotations from 8 years to 30 years results in a positive change of 39 t CO_2e ha^{-1} in live wood while ceasing logging raises that to 47 t CO_2e ha^{-1}. Field surveys were used to estimate crop yields and costs of production. Based on reported average crop yields and costs, crop production only produced an average profit of \$121 ha^{-1}. Increasing the fallow period will reduce the proportion of fields producing crops at any given time, thus reducing revenues. However, some of this revenue can be offset through the increased amount of wood and hence charcoal which can be produced at a longer fallow period. A permanent change in management to a 15 year fallow period would result in an estimated discounted net revenue loss of \$107 ha^{-1} at the community scale. Given the current average price of carbon in the AFOLU sector of about \$6 t CO_2e^{-1}, the potential revenue from the change in the live tree biomass alone is estimated at \$270 ha^{-1}. At this price carbon credit sale would allow a net profit from the switch to a 15 year fallow period. Selective logging for charcoal production, on the other hand, produces a higher profit and a permanent change from a selective logging rotation of 8 years to 30 years results in an estimated discounted reduction in profit of US\$830 ha^{-1}. The price of carbon would need to be a minimum of about US$28 t CO_2e^{-1} before it would become more profitable to increase logging rotations to 30 years and sell the resulting carbon credits. It is recommended that this type of analysis be repeated for additional activity types such as agroforestry and improved agricultural management. This analysis could be repeated at the regional or national scale, informing policymakers what activities and what locations would produce the greatest benefits at the lowest costs. If a carbon project were to be implemented by a community, more site-specific research would be required on existing land management practices and carbon stocks. Revenue resulting from the carbon project could be used to implement improved agricultural management to increase crop yields and thus ensure changes in management do not threaten the food security of communities.

4.1 Introduction

Climate change is garnishing increasing amounts of attention by the public, governments, and private enterprises. In order to stem this climate change a very wide variety of activities aimed at climate mitigation must and are being initiated. The need for climate change mitigation has created a market for greenhouse gas (GHG) emission reductions. According to the Intergovernmental Panel on Climate Change (IPCC), implementing activities in the agriculture, forestry, and other land use (AFOLU) sector should be considered as a major strategy for climate mitigation. By altering the land cover and management practices, it is possible to avoid emissions and create net sequestration. In many areas of Africa increased population and other drivers have led to increased land degradation and reductions in landscape carbon stocks. The newly created climate change mitigation market may have the potential to provide the necessary financial incentive for communities to alter current land management with the aim of increasing carbon stocks and at the same time moderate land degradation.

In the most recent IPCC report, the global scientific community stated that the warming of the climate is 'unequivocal' and that this observed increase is due to anthropogenic GHG emissions (Metz *et al* 2007). According to the IPCC, global emissions of greenhouse gases have increased by 70% between 1970 and 2004. While the largest growth in global GHG emissions has come from the energy supply sector, land use, emissions from agriculture, forestry and other land uses (AFOLU) have grown by 40%. Although studies differ, over the continent of Africa, around 4 million ha yr^{-1} of forest are estimated to have been lost during the 1990's, with annual carbon flux estimates resulting from forest and other vegetation ranging from 440 to over 1200 Mt CO_2 yr^{-1} for sub-Saharan Africa (Achard *et al* 2004; DeFries *et al* 2002; Houghton 2003; Houghton and Hackler 2006).

In response to the growing evidence of climate change, the United Nations Framework Convention on Climate Change (UNFCCC) was formed and entered into force in 1994 and is currently ratified by 192 countries. At the third annual meeting of the UNFCCC, referred to as the "Conferences of the Parties" (COP), the Kyoto Protocol was agreed upon. This protocol established binding greenhouse gas emission reductions for industrialized countries (Annex 1 countries) and countries with economies in transition. Annex 1 countries committed to reduce their emissions by an average of 5 % below 1990 levels in the period between 2008 and 2012. To date, 174 members have ratified or acceded to the Kyoto Protocol, including 37 Annex 1 members representing 64% of

Annex 1 parties' emissions. Within the Kyoto Protocol three market-based mechanisms were created to allow Annex I countries to reduce emissions beyond their national boundaries yet include the reductions in their national level target: International Emissions Trading (Article 17), Joint Implementation (JI; Article 6), and the Clean Development Mechanism (CDM; Article 12). The CDM allows for the sponsorship and implementation of project activities in non-Annex 1 Parties, countries with no binding emission reduction targets. The greenhouse gas emissions reductions resulting from the CDM projects may be used by an Annex 1 country to meet their target.

These market based mechanisms have created the new tradable commodity GHG emission reduction credits. Additionally, there is a rapidly growing market for GHG emission reductions outside the protocol. Worldwide many companies are voluntarily seeking to reduce greenhouse gas emissions by changing internal practices or through investing financial resources in projects that are reducing greenhouse gas emissions, thus creating a voluntary market for GHG emission credits. The lower levels of bureaucracy and regulations found in the voluntary market have grabbed the attention of many investors.

The AFOLU sector has the potential to become a part of this market by altering the land management in a specific area of land in a way that results in quantifiable carbon emission reductions or carbon sequestration. Projects can be developed to implement these activities using the financial funding resulting from the sale of GHG emission credits created. Under the CDM the only allowable AFOLU project type is afforestation/reforestation (A/R) of areas that have not been forested since 1990.

However, in the voluntary market there is no such limit on the types of activities that can generate emission credits allowing for much greater potential for the types of projects that can be implemented.

The carbon market is growing extremely rapidly. The World Bank recently estimated the regulatory carbon market to be worth US$64 billion dollars in 2007, a more than doubling of size for the second year in a row (Capoor and Ambrosi 2008). Although much smaller than the regulatory market, in 2007 the voluntary market reached a value of US$331 million and transacted 65 Mt CO_2e, thus more than tripling both in value and volume since 2006 (Hamilton *et al* 2008).

Despite the large size of the markets, Africa and the AFOLU have remained among the smallest sectors in the CDM market with only 5% of all CDM volumes originating from Africa and less than 1% of volumes coming from land use, land use change and forestry (LULUCF) projects worldwide (Hamilton *et al* 2008). Under the EU ETS, credits generated from A/R projects are excluded, limiting the market value of A/R credits. The AFOLU sector has more dominance in the voluntary market, with AFOLU projects accounting for 36% of the volumes transacted in 2006, but only 18% in 2007 due to reduction in credits originating from afforestation with native species. Over all project types, transactions originating from Africa in the OTC market actually declined from about 6% to 2% of market share between 2006 and 2007. Reasons for the low African involvement in climate mitigation have been attributed to low internal capacity, the investment climate in Africa, the limited potential of energy CERs that can be created in Africa, and methodological issues (Walker *et al* 2008).

Interest in AFOLU projects and Africa is growing. Recent surveys show that there are almost sixty AFOLU projects across Africa either in place or at some stage of development (Jindel 2006; Walker *et al* 2008). Most projects involved multiple project activities, with the majority including some type of afforestation/reforestation. The majority of AFOLU projects initiated in Africa have been implemented with the goal of assisting local communities. The addition of carbon finance allows the creation of activities that have multiple benefits to communities.

Large areas of Africa have experienced land cover change that has resulted in a reduction in carbon stocks. One recent continent-wide analysis estimated that in Tanzania alone there are over 28 million hectares of land that could potentially sustain woody plant cover but are currently either cultivated or are classified as covered by other non-woody vegetation (Walker *et al* 2008). Tanzania lost an additional 27 thousand hectares of woody cover between 2001 and 2004 (FAO Tanzania country profile).

In the Miombo Woodlands area of Tanzania, the cause of this loss of woody cover is primarily due to charcoal production, agricultural expansion, and timber cutting (Malimbwi *et al* 2001; Misana 2001; Olsen *et al* 2004). However, the relative contribution of these drivers differs between the area studied. While in the Morogoro area of Tanzania, Malimbwi *et al* (2001) found 75% of the woodland degradation to be attributed to charcoal making, Olsen *et al* (2004) found that 40% of woody area conversion isto caused by agricultural expansion in the area surrounding Mt. Kilimanjaro.

The majority of the 17 million hectares of cropland (GLC 2000) in Tanzania are managed by rural subsistence agricultural farmers (Tanzania Ministry of Agriculture 2008). Generally rural farmers rely on low-input shifting cultivation. In the past, long fallow periods were common between cropping cycles. However, more recently fallow periods have shortened due to population increases and various government policies. The level of technology and improved practices are limited with over 70% of cropland being hand ploughed without any nutrient additions or advanced technological practices (Tanzania Ministry of Agriculture 2008). Although worldwide crop yields have increased through greater investments in technology and nutrient additions, this has not taken place in Tanzania. For example while the worldwide average maize yield has increased by more than a third since the 1980's, average maize crop yields in Tanzania have shown only slight if any positive growth and Africa wide have increased by only about 18% (FAO Statistics). In farming communities in rural areas of Tanzania, crop yields are less than a third of the worldwide average (FAO Statistics). A recent modeling study found that reductions in the number of fallow years results in long term further degradation (Walker 2008b) and long term land degradation may result in even lower crop yields.

For decades both donor groups and African governments have attempted to address this rural poverty using a wide range of approaches. A number of studies have found that in countries such as Tanzania where the majority of the population is dependent on the land for their income, successful sustainable poverty reduction is dependent on improving land productivity (Jayne *et al* 2003). The type of approach to tackle poverty has varied significantly over the years and more recently has focused on direct participatory poverty reduction strategies (Staatz and Eicher 1998). This approach has also taken place to address land degradation and has coincided with a transfer of forest land ownership and management responsibilities from the Tanzanian national government level to local communities (URT 1998; URT 2002; Environmental Management Act No. 20 of 2004). Local communities now have the authority to develop different forms of participatory forest management (PFM) agreements (Topp-Jørgensen *et al* 2005) and therefore have direct control of the land and its resources.

With the development of the carbon credit market, participatory community initiatives may be created to include the management of landscape carbon stocks. One of the first steps needed is to formulate a greater understanding of what the carbon credit potential is for various land management activities, and importantly, the financial implication of altering current practices. Although preventing deforestation and reforesting areas with the aim of conservation may result in the highest carbon credits, for most African populations, removing land completely from economic production may not be a realistic option. Therefore, innovative methods of land management that combine both economic productivity and the additional commodity of carbon credit sale may provide farmers with a more pragmatic approach towards involvement in climate change mitigation.

This study provides a first estimation of the potential magnitude of carbon credit creation and economic consequences resulting from changing existing land management practices. Many existing carbon projects have focused on implementing new activities such as agroforestry, plantation development, improved fallows, and other improved farming techniques along with land conservation. Instead, this study looked at maintaining current land activities but extending rotation periods. The current main land uses in rural Miombo woodland areas are agricultural production in a crop-fallow cycle that is repeated over time and selective logging for charcoal production in areas of Miombo Woodlands that are communally held.

The field and community level average changes in carbon stocks from increasing the length of agricultural fallows and extending selective logging rotations in communal Miombo Woodland are modeled. The carbon credit potential from these changes is estimated and compared to the economic consequences resulting from this changed land management. Finally a theoretical case study is presented to illustrate how the implementation of such land management changes could alter the economic production of a community in the Morogoro area of Tanzania.

4.2 Methods

4.2.1 Estimation of Carbon Stocks

Estimated carbon stocks under various land management systems were modeled using the CENTURY model. CENTURY models carbon, nitrogen, and phosphorus cycling (Parton 1994). The model divides the aboveground tree biomass into three components: large wood, small branches, and leaves. In a previous study, this model was parameterized for the dominant forest type in Tanzania, the Miombo Woodlands, and was found to adequately represent the system (Walker 2008b). The model was able to accurately match field measurements of carbon stocks of mature and regrowing Miombo woodland.

The model was run using the average soil texture and climate found in the Morogoro area of Tanzania. Monthly precipitation data was extracted for the Morogoro weather station from the FAO data base (Station 63866) for the years 1922 to 1996. Precipitation data from 1991-2000 was obtained from the Sokoine University weather station also in Morogoro, Tanzania. The standard deviation and skewness of the precipitation was then calculated. Monthly minimum and maximum temperature values for the Morogoro weather station were combined with data from the Sokoine University weather station data. Because these weather stations are so close to each other, the values were very similar. Soil texture data was extracted from the Soil and Terrain Database (SOTER 2004) and a weighted average created. This soil texture was found to be similar to field measured soil texture estimates from the same area (Walker 2008a). Low intensity fires were modeled to occur every 3-5 years during the dry season months. Prior to any land management alterations, the model is run for 200,000 years for the system to reach equilibrium.

4.2.1.1 Field-level carbon stocks

The three dominant land uses found in rural Tanzania were modeled: unmanaged Miombo woodlands with low levels of human caused degradation, communally held Miombo woodlands that are selectively cut for charcoal production, and crop-fallow agriculture.

Previous field studies have found that in communally held Miombo woodland lands, following cutting for charcoal production the aboveground tree biomass was reduced by an average 30% (Ek 1994). Therefore, thirty percent of the aboveground biomass was modeled to be cut during each selective logging event. All large wood cut was removed from the system and was assumed to be used in charcoal production. The smaller branches and leaves, although cut, remain in place to decompose or burn. Fire periodicity and intensity remain the same as in uncut woodlands. The following logging rotations were modeled: 5 yr, 8 yr, 10 yr, 30 yr, 60 yr, and ceasing logging completely.

The common practices of land use conversion for cropland production were modeled. At the start of agricultural production, all trees within the field were modeled to be cut down. The large wood is then removed for charcoal production but smaller branches, leaves, and herbaceous biomass remain and are burned. The field is burned each year prior to cropping. At the end of the fallow period, all wood is cut down. Large wood is removed and assumed to be used for charcoal production. Cut smaller branches, tree leaves, and herbaceous vegetation remain and are burned. A survey of local village government officials, agricultural extension workers, and local farmers reported the common farming practice is currently five years of crop production followed by three years of fallow. In this study this will be assumed to be the dominant existing land use practiced over time in the area or the ‘baseline’ land use. Various fallow cycles were modeled: 5 years of agriculture followed by 3 years of fallow then return to the cycle, 5 years of agriculture followed by 10 years of fallow then return to the same cycle, 5 years of agriculture followed by 25 years of fallow then return to the same cycle, and 5 years of agriculture followed by 45 years of fallow then a return to the same cycle. Since the study is modeling a change from one management style to the next, the area is modeled to go through one cycle of five years of agriculture and three years of fallow before changing to the new management cycle.

4.2.1.2 Landscape-scale changes in carbon stocks

Across a landscape, different locations are at different stages in the land use cycle. In this analysis it is assumed that at a given scale there is an equal distribution of each stage in the cycles present across the landscape. For example, if the land use cycle is 5 years of crop production followed by 3 years fallow (5A-3F), the baseline case, it is assumed that there are eight different years a given hectare could be in and there is an equal number of hectares at each year in the cycle.

Using this assumption, the baseline carbon stocks were calculated for the landscape scale on a per hectare basis. The alteration of land use to each new land management system was also modeled at the landscape scale. In the agricultural areas, it was assumed that a given hectare would continue its current crop cycle until it reached the fallow period and then the land use switched to the new land use system. In areas only cut for charcoal production but not cropped, it was assumed the land would immediately change to the new land management state.

Since the market traded commodity of carbon is universally expressed in terms of tons of carbon dioxide equivalency (t CO_2e), the changes in carbon stocks are presented in t CO_2e. To convert from the mass of carbon to the mass of CO_2e, values are multiplied by 44/12.

4.2.2 Economic Analysis

A combination of Food and Agriculture Organization (UN FAO) reported country level statistics, government published data, and local surveys were used to estimate the various economic costs and incomes resulting from the land use activities.

Questionnaires were used to elicit information on crop production and sales, patterns of crop production including types of crops, fallow cycles and periods, crop rotation, and costs of production, crop prices, charcoal production and prices. The questionnaires were administered to selected respondents through focus group discussions in 3 villages near Morogoro, Tanzania. The three villages included Maseyu around Kitulanghalo about 50 km from Morogoro towards Dar es Salaam, Gairo about 100 km from Morogoro towards Dodoma and Melela about 100 km from Morogoro towards Mikumi. The focus group composed of members from the village government, Ward/Village agricultural extension officers, forest extension officers, representative from community based organizations in the areas and selected members from the farming community. In addition District and Regional Agricultural Officers from the respective districts and relevant national statistics on agriculture were consulted to verify information obtained from the focus groups.

Using CENTURY modeling results and the economic data from the local surveys, revenues resulting from crop production and charcoal creation were then calculated at the field and landscape level for a range of land management practices: 5 years of agriculture followed by 3, 10, 25, or 45 years of fallow and selective logging rotations of 5, 8, 10, 30, and 60 years. It was assumed that the modeled large wood pool cut would be used for charcoal creation both at the end of the fallow period within the agricultural lands and in Miombo woodland areas selectively logged. It is expected that crop yields would differ depending on the degree of land degradation and the length of the previous fallow period. Soil nutrient stocks have been found to be significantly correlated to maize yields in the Miombo region (Chirwa *et al* 2004; Mtambanengwe and Mapfumo 2008) and previous modeling results have found that longer fallow periods result in less soil nutrient loss (Walker 2008b). Therefore, it is likely that lengthening the fallow period beyond the common practice may increase crop yields or at least not decrease yields. Hence, crop yields were conservatively assumed to be constant regardless of the length of the fallow.

The landscape scale differences in revenues resulting from a switch from the dominant existing land management to an alternate land management were then calculated. The annual revenue was then discounted over various time periods (5, 10, 20, 40, and 200 years). A 200 year time period was used to equal a permanent change in the revenue. Discounting is used to account for the time-value of money as well as the uncertainty of future events related to future production. A real (adjusted for 2% inflation) discount rate of four percent was used.

$$NPV = \sum^{t} \frac{\mathrm{Re}\,venue_t - Costs_t}{(1 + dicount\_rate)^t}$$

Where *NPV* is the net present value and *t* is the number of years.

4.2.3 Case study

A specific area near Morogoro, Tanzania was chosen to represent a hypothetical participatory forest management (PFM) project with carbon management as one of the management goals. The area chosen contains a mix of agricultural lands, communal lands, and the Kitulanghalo Forest Reserve.

To create a land cover map of the Kitulanghalo area, the region was clipped from a 2000 Landsat image. Using a combination of supervised and manual classification this area was then classified into the classes: woodland, degraded woodland, agriculture and other.

A subset of data from the Soil and Terrain Database (SOTER) (World Soil Information 2004) was extracted for the area surrounding the Kitulanghalo Forest Reserve area. This database includes the soil classification along with an estimate of the percent clay, silt and sand. The average soil texture for the area was determined using an area weighted average.

The CENTURY model was run using the average soil texture found in the Kitulanghalo area. In this analysis it was assumed that the following land management practices are the practices that normally occur in the region:

- Degraded woodland areas: 30% of wood biomass is cut every 5 years
- Agricultural areas: 5 years of agriculture – 3 years of fallow followed by a return to the same cycle.

The following land use practices were then examined as the practices the community would change to:

- Degraded woodland areas: 30% of wood biomass is cut every 15 years
- Degraded woodland areas: all selective logging is ceased

- Agricultural areas: 5 years of agriculture – 15 years of fallow followed by a return to the same cycle.

The field level and landscape scale carbon stocks were then estimated for each of these cases. These carbon stocks were then mapped for each land cover type in the hypothetical project area.

The carbon stocks in the region resulting from the activities that would have taken place in the area normally are considered the ‘baseline’ carbon stocks. In this case study, carbon stocks resulting from the new management practices will be referred to as the ‘project’ carbon stocks. Using the economic data collected, the costs and income for the ‘baseline’ and ‘project’ land uses were calculated, including the potential income from the sale of carbon credits.

4.3 Results

4.3.1 Carbon stocks

4.3.1.1 Miombo woodland areas selectively logged

Woodland areas selectively cut for charcoal production will change in carbon stocks depending on when the last logging took place. If land management moves from a shorter logging rotation to an extended one, the trees will have a greater length of time to grow and therefore increase carbon stocks. At the landscape scale, extending the logging rotation will increase overall carbon stocks. The longer the rotation in comparison with the original cycle, the larger the tree growth and change in landscape carbon stocks

(Figure 4.1; Table 4.1). Although soil carbon and deadwood stocks will increase some, the majority of the change is in the tree biomass stocks. Increasing the rotation from 5 to 10 years allows for a modeled tree stock increase by 26 t CO_2e ha^{-1} at the landscape scale while a sixty year rotation increases modeled tree stocks by 57 t CO_2e ha^{-1}.

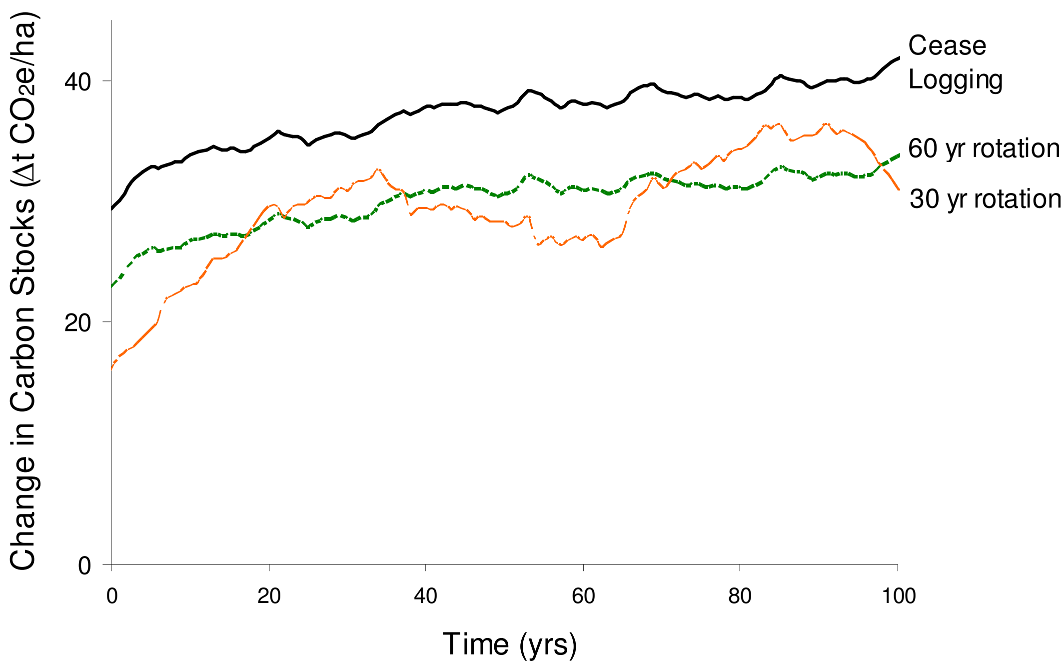


Figure 4.18 The change in landscape level live tree carbon stocks when an area changes woodland anagement from selective cutting every 8 yrs to longer rotation lengths (Δt CO_2e ha^{-1})

Table 4.14 Average change in carbon stocks over one hundred years when selective logging rotations are increased (Δt CO_2e ha^{-1})

a) Landscape scale average carbon stock increase from 5 year logging rotation to a longer rotation (Δ t CO_2e ha^{-1}):

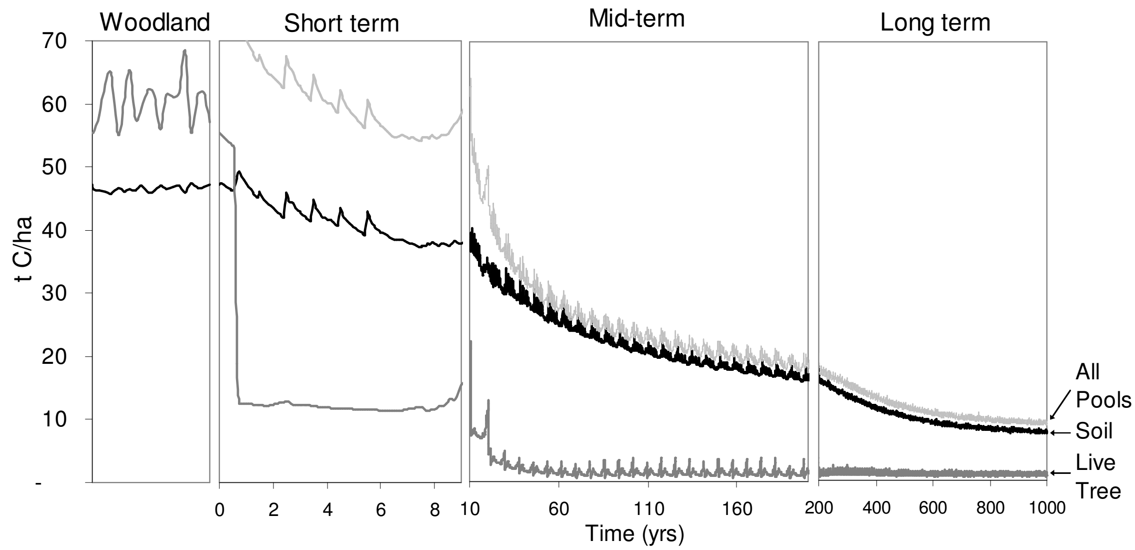
	cease logging	60 yr rotation	30 yr rotation	10 yr rotation	8 yr rotation
			Δ t CO_2e ha^{-1}		
Total system	67	57	46	26	14
Live tree	47	40	39	19	9

b) Landscape scale average carbon stock increase from 8 year logging rotation to a longer rotation (Δ t CO_2e ha^{-1}):

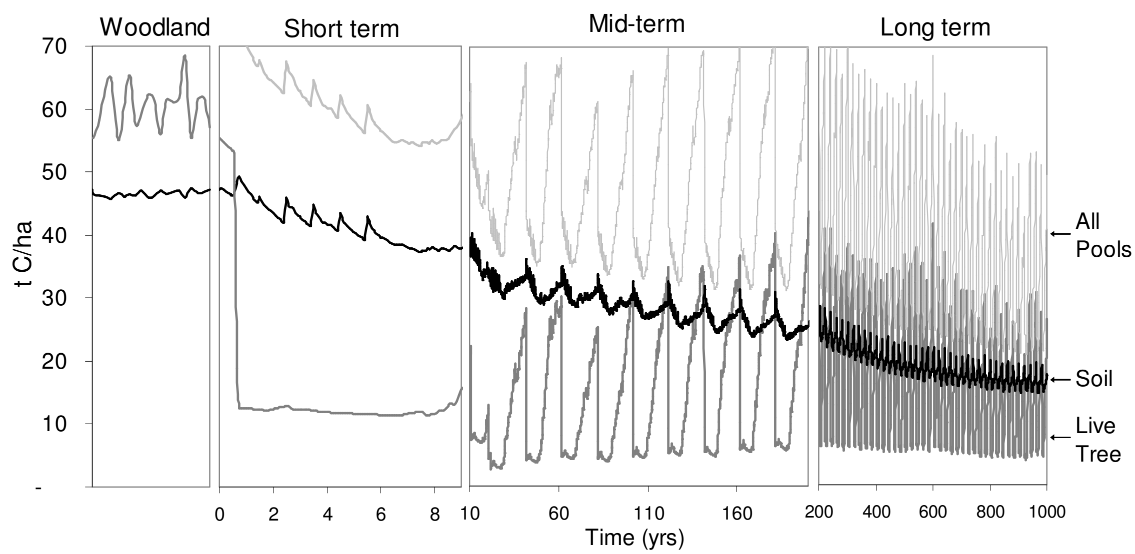
	Cease logging	60 yr rotation	30 yr rotation	10 yr rotation
		Δ t CO_2e ha^{-1}		
Total system	51	41	31	12
Live tree	37	30	29	10

4.3.1.2 Cropland production

At the field level, the modeled carbon stocks will vary depending on which year it is in the agricultural cycle. Aboveground carbon stocks decline when the field is cut and then trees slowly regrow during the fallow period thus increasing the C stock. Soil carbon stocks decline during agriculture and recover during the fallow period, but at a much slower rate (Figure 4.2). Over successive cycles, soil degradation takes place. Longer fallow periods allow for a greater recovery in carbon stocks. Trees have a longer time period in which to regrow and biomass additions to the soil slowly raise carbon and other soil nutrient stocks.



a) Conversion from woodland to 5 years of agriculture - 3 years of fallow



b) Conversion from woodland to 5 years of agriculture - 3 years of fallow and then every subsequent cycle moves to 5 years agriculture – 15 years fallow

Figure 4.19 Carbon levels in Miombo Woodland system modeled with CENTURY following the conversion of woodland to a crop-fallow cycle. Note changes in scale.

Based on modeled results, the land degradation can be halted and reversed by instituting longer fallow periods. Since different fields are at different stages of the crop-fallow cycle, as fields convert to the new land management style, the average carbon stocks at the landscape scale increase (Figure 4.3). The greater the length of the fallow period, the greater the increase in carbon stocks (Table 4.2). Lengthening the fallow from 3 to ten years increases tree stocks by an average of 22 t CO_2e ha^{-1} and an increase in fallow length to 45 years raises tree carbon stocks by 94 t CO_2e ha^{-1} on average. Soil stocks do accumulate, however, this increase is slower and only reaches a stable level at the landscape level after more than 30 years of changed management. In the first ten years after management changes there is only about a 10% increase in soil carbon levels on the landscape scale.

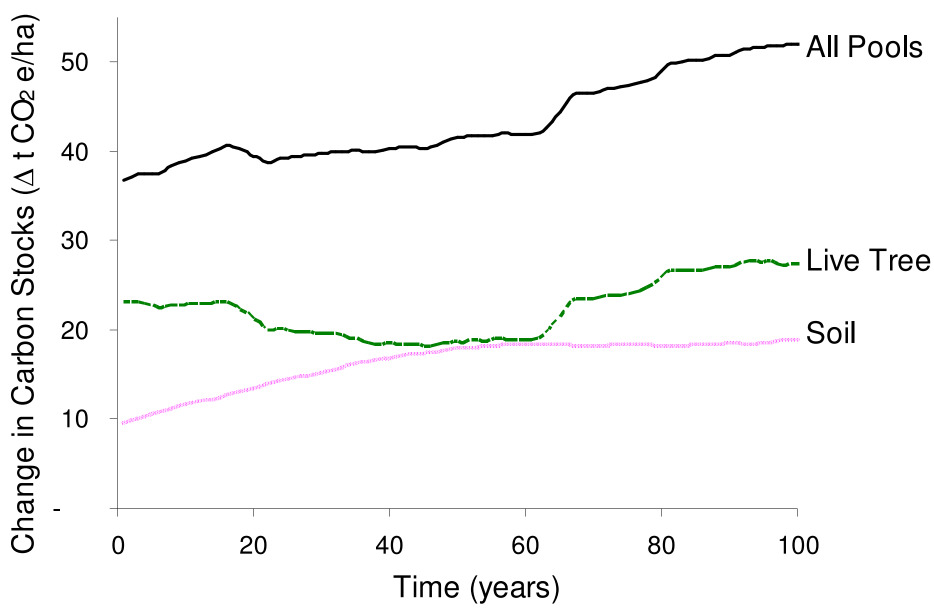


Figure 4.20 The change in landscape level carbon stocks when an area changes agricultural management from 5 yrs agric-3 yrs fallow to 5 yrs agric-10 yrs fallow (Δt CO_2e ha^{-1})

Table 4.15 Average change in carbon stocks over one hundred years when land management is changed from 5 yrs agric – 3 yrs fallow to a greater number of fallow years (Δt CO_2e ha^{-1})

	5 yr Agric –10 yr Fallow	5 yr Agric - 15 yr Fallow	5 yr Agric - 25 yr Fallow	5 yr Agric - 45 yr Fallow
System Total	43	78	110	164
Soil	16	25	34	49
Live Wood	22	44	62	94

4.3.2 Economic analysis

4.3.2.1 Charcoal production in Miombo Woodland areas and croplands

Wood for charcoal production originates from community woodland areas specifically cut for charcoal and from agricultural fields. In agricultural fields at the end of the fallow period, all trees are cut and the large wood may potentially be used in charcoal production. After cutting an area, the large wood is piled up into stacks, thatched with grass, and plastered with earth on the outside, thus creating a kiln. The wood is then partially combusted to form charcoal. Malimbwi *et al* (2001) examined the efficiency of the kilns used to create the charcoal. The average efficiency was 19%, meaning that of the total wood biomass weight burned, the amount of charcoal produced is equal to 19% of the original weight. The charcoal is sold in large bags, estimated to weigh an average of 53 kg and sold for about US$9.00 per bag (Malimbwi *et al* 2001, field survey).

Using the model estimates of large wood biomass cut and removal and the kiln efficiency level, the average amount of charcoal produced under the various land management styles was calculated (Table 4.3). At a five year selective logging rotation about 6 bags of charcoal, with a market value of almost US$60, are produced per hectare per year at the landscape scale. During longer rotation cycles, since the proportion of the area that is being selectively logged is smaller, the amount of charcoal produced per hectare at the landscape scale actually declines, for example a thirty year rotation only produces about 2 bags of charcoal (US$18 market value) per hectare per year at the landscape scale. Because all of the large wood at the end of the fallow period is cut, the amount of charcoal produced in agricultural areas with longer fallow periods can be comparable to charcoal production in the selective logging areas. After three years of fallow the model shows a small amount of wood can be cut for charcoal, however, it is unlikely that in actuality any charcoal would be made and sold since the supply of wood is so minimal. Instead it is more likely the wood would be cut, a portion used by the household, and the rest burned. Therefore, the income derived from this crop-fallow management is overestimated. Model results show that under ten year fallow management, almost 4 bags of charcoal (US$35) are able to be produced per hectare at the landscape scale. However, raising the fallow period to 25 years actually produces a comparable quantity of charcoal since the proportion of land being cut at any given year is reduced.

Table 4.16 The landscape level production of charcoal produced per unit area per year under various land management styles (ha^{-1} yr^{-1})

	Large Wood (kg)	Charcoal (kg)	# bags	Price US$
5 yr Agric - 3 yr Fallow	26	10	0.18	1.72
5 yr Agric - 10 yr Fallow	542	206	3.89	36.43
5 yr Agric - 15 yr Fallow	694	264	4.98	46.69
5 yr Agric - 25 yr Fallow	507	192	3.63	34.05
5 yr Agric - 45 yr Fallow	389	148	2.79	26.18
5 yr Logging rotation	886	337	6.35	59.55
8 yr Logging rotation	767	291	5.50	51.57
10 yr Logging rotation	676	257	4.85	45.43
30 yr Logging rotation	273	104	1.96	18.34
60 yr Logging rotation	187	71	1.34	12.60

The production of charcoal requires very little capital outlays to initiate. The only expenditure required are tools which include an ax, a hoe, a shovel and machete (Luoga *et al* 2000). Because these tools last for many years, these fixed costs contribute very little costs. Charcoal production is very labor intensive. Luoga *et al* (2000) estimated that an average of 100 person days were spent creating a single charcoal kiln. Luoga *et al* (2000) found an average of 44 bags per kiln created while Malimbwi *et al* (2001) reported a mean of 26 bags per kiln, but with a wide range of 16-77. Depending on the estimate used, this equates to 2.25 or 3.85 person days of labor per bag. Based on field surveys the average wages are \$1.68 day^{-1}. Therefore, if labor were to be incorporated, this would add a cost of \$4.10 per bag of charcoal, reducing profits to US\$4.90 bag^{-1}. Labor is carried out mostly by the men in households. Labor sharing is common, however, people are seldom hired by one farmer and therefore direct labor costs are not paid (Luoga *et al* 2000; Malimbwi *et al* 2001). The costs of labor are not included in the analysis because persistent unemployment results in very little opportunity costs and this would underestimate the profits realized by the farmers.

4.3.2.2 Cropland production

Based on average survey results, the common crop rotation is relatively intensive with five years of cropland followed by three years of fallow (Table 4.4). The main costs of production are seeds which need to be purchased annually and tools which will last many years. Farmers reported purchasing no fertilizers (Table 4.5). The survey reported average maize yields were very low at 790 kg ha^{-1} yr^{-1} and based on reported crop prices only allow for an income of US$199 ha^{-1} yr^{-1} (Table 4.6). These yields are similar to the crop yields reported to the FAO by Tanzania in the late 1990's but are about half the currently reported national average (FAO Stat) (Table 4.6). Average crop prices from the survey are very similar to those reported by the Tanzania Ministry of Agriculture, Food, and Cooperatives (http://www.agriculture.go.tz). Once the costs of production are subtracted from the income, the profits per hectare of maize production are only US$67 ha^{-1} yr^{-1} using the survey reported yields and US$200 ha^{-1} yr^{-1} using the Tanzania average yield (Table 4.7). Although labor costs were estimated (Table 4.5), very few if any farmers hire any additional assistance, and therefore cost of labor is not included in the revenue resulting from crop production.

Table 4.17 General Agricultural Information

Average crop rotation	5 years cropland, 3 years fallow
Crops grown	Corn, cassava, sorghum
Fertilizer use	no fertilizers used
Average area per farmer	1.5 ha
Area used to produce food for household consumption	1 ha
Cost of buying food instead of producing crops	USD$285 family^{-1} yr^{-1}

Table 4.18 Costs of Production

Type	USD$ ha^{-1} yr^{-1}
Fertilizer	0
Seeds	126
Tools	43
Labor	427

Table 4.19 Average yield and income from crop production

Crop	Average Yield	Country Average* (range for 1980-2006)	Price (US$)	Income (US$)
Corn	790 kg ha^{-1}	1326 kg ha^{-1} (range: 617- 2100 kg ha^{-1})	$0.25 kg^{-1}	$199 ha^{-1}
Cassava	20 bags ha^{-1}	10000 kg/ha (range: 8,000-13,000 kg ha^{-1})	$16.76 bag^{-1}	$335 ha^{-1}
Sorghum	600 kg ha^{-1}	1012 kg/ha (range: 600-1700 kg ha^{-1})	$0.13 kg^{-1}	$75 ha^{-1}

* from FAO Stat

Table 4.20 Average profits from crop production per hectare, assuming no labor costs are paid.

Crop	USD\$ ha^{-1} using survey reported yields	US\$ ha^{-1} using countrywide average yield
Corn	67	202
Cassava	203	
Sorghum	-56	-5

At the landscape scale, increasing the length of the fallow period reduces the proportion of the landscape under crop production and thus potential income from crop production. However, with increased fallow periods, trees grow for a longer time period before being cut and therefore the potential quantity of charcoal produced is greater. The combined impact on revenue of reducing the proportion of fields under crop production and the increase in charcoal production was then calculated at the landscape scale (Table 4.8). Because survey reported yields are substantially lower than the countrywide average, the revenue from crop production was estimated using both crop yields. When using survey reported crop yields it was assumed that lands were cropped for three years with maize followed by two years of cassava. Since sorghum is grown at a net cost, by not including sorghum production in the crop rotation, the calculated average income from crop production is over estimated. Owing to the increase in potential charcoal production and sale, increasing the fallow period from 3 to 10 years only results in a landscape scale average revenue loss of US\$2 ha^{-1}yr^{-1}. It is estimated that about US\$25 ha^{-1}yr^{-1} would be lost on average across the landscape if the fallow period were elevated to 25 years. If fields produced yields at the national average, a loss of US\$62 $ha^{-1}yr^{-1}$ is estimated at the landscape scale if the community increased the fallow period to 25 years.

Table 4.21 Landscape level change in revenue from increasing the fallow period from three years to longer periods.

a) Using survey reported crop yields:

	Crop Revenue Lost	Charcoal Revenue Gained Δ \$ ha^{-1} yr^{-1}	Total Revenue Lost
5 yrs Fallow	-\$14	\$16	\$2
10 yrs Fallow	-\$36	\$35	-\$2
15 yrs Fallow	-\$49	\$45	-\$4
25 yrs Fallow	-\$57	\$32	-\$25
45 yrs Fallow	-\$65	\$24	-\$40

b) Using Tanzania national average crop yield for Maize:

	Crop Revenue Lost	Charcoal Revenue Gained Δ \$ ha^{-1} yr^{-1}	Total Revenue Lost
5 yrs Fallow	-\$23	\$16	-\$7
10 yrs Fallow	-\$60	\$35	-\$26
15 yrs Fallow	-\$82	\$45	-\$37
25 yrs Fallow	-\$95	\$32	-\$62
45 yrs Fallow	-\$107	\$24	-\$83

4.3.2.3 Change in revenue from extending logging rotations in communally held Miombo Woodland areas

Extending the length of time between selective logging events across the landscape will reduce overall income resulting from charcoal production. The annual revenue was then discounted over various time periods to estimate this change in income over the long term (Table 4.9). The longer the rotation, the greater the loss in charcoal production income. Communities who permanently change the selective logging rotation from 5 to ten years would incur a net loss of over US$350 ha^{-1}. Ceasing all logging would reduce revenues by almost US$1500 ha^{-1}. This analysis does not include either labor costs in production nor the fact that the reduced labor would allow workers to conduct other alternative activities.

Table 4.22 Discounted change in income ($ ha^{-1}) resulting from a change in logging rotation across the landscape over various lengths of time.

	Over 5 years	Over 10 years	Over 20 years	Over 40 years	Permanent Change
Switch from 5 yr logging rotation to:					
8 yr rotation	-$36	-$65	-$109	-$158	-$200
10 yr rotation	-$63	-$115	-$192	-$279	-$353
30 yr rotation	-$183	-$334	-$560	-$816	-$1,030
60 yr rotation	-$209	-$381	-$638	-$929	-$1,173
Cease logging	-$265	-$483	-$809	-$1,179	-$1,488
Switch from 8 yr logging rotation to:					
10 yr rotation	-$27	-$50	-$83	-$121	-$153

	Over 5 years	Over 10 years	Over 20 years	Over 40 years	Permanent Change
30 yr rotation	-$148	-$270	-$452	-$658	-$830
60 yr rotation	-$173	-$316	-$530	-$771	-$974
Cease logging	-$230	-$418	-$701	-$1,021	-$1,289

With the addition of carbon as a new potential commodity to be sold, some of this loss in income can be offset from the increase in landscape scale carbon stocks. The most recent estimate of the average price of carbon in the voluntary market is $6.10 t CO_2e^{-1} (Hamilton *et al* 2008). The majority of the change in carbon stocks is in the live tree biomass, therefore, to be conservative, in all estimates it is assumed that carbon credits are sold only for the change in the live tree biomass. The longer the increase in rotation cycle, the larger the average carbon stock per hectare, and therefore the greater amount of carbon able to be sold. Using an average price of 6.10 t CO_2e^{-1}, over US$100 ha^{-1} in income could potentially be received if a community raised logging rotations from 5 to ten years. Ceasing all logging would bring that potential income to US$289 ha^{-1}.

In the voluntary market, carbon credits are often sold under the assumption that the change in carbon sequestered is permanent, and therefore the increase in income from carbon must be compared with a permanent change in logging rotation. Given the current average price of carbon the income from carbon alone does not offset the reduction in income from reduced logging (Table 4.10). Any increases in carbon stocks resulting from a change in management can be lost if the rotations are again reduced in the future or if the land is deforested. Therefore there is a risk of non-permanence. To act as a buffer against this risk of non-permanence it is likely that a certain percentage of the credits created within a project would not be sold. The amount required for this buffer is dependent on the contractual arrangement made with the buyer, but may be as large as 50%.

Assuming all carbon credits created were sold, the price of carbon would need to increase to above \$20 t CO_2e^{-1} before carbon credits would offset charcoal revenue losses (Table 4.10). If all logging were ceased the price of carbon would need to be greater than US\$30 t CO_2e^{-1}. If only 60% of the credits were sold and the rest kept as a buffer, the price of carbon would need to be above \$30 t CO_2e^{-1} for the sale of carbon to make up for the lost charcoal revenue when logging rotations were increased to 10 years and to US\$52 t CO_2e^{-1} if all logging were ceased.

Table 4.23 Minimum carbon price needed for altering management to be more profitable than baseline management (\$ t CO_2e^{-1}) . Assuming no buffer and 40% of credits withheld from market as a buffer.

	No buffer	40% Buffer
	\$ t CO_2e^{-1}	
Switch from 5 yr logging rotation to:		
8 yr rotation	\$22.15	\$36.92
10 yr rotation	\$18.41	\$30.68
30 yr rotation	\$26.42	\$44.03
60 yr rotation	\$29.12	\$48.54
Cease logging	\$31.37	\$52.28
Switch from 8 yr logging rotation to:		
10 yr rotation	\$15.09	\$25.15

	No buffer	40% Buffer
	$ t CO_2e^{-1}	
30 yr rotation	$28.30	$47.17
60 yr rotation	$32.42	$54.03
Cease logging	$34.64	$57.74

4.3.2.4 Change in revenue from lengthening fallow periods in agricultural lands

Although increasing the length of the fallow period may reduce land degradation, income will also be reduced. In order to examine how lengthening would impact income over the long term, the annual revenue was discounted over various time periods (Table 4.11). This analysis does not include the cost of labor or the freeing of labor now available for alternative activities. Again, because of the potential increase in the sale of charcoal, permanently increasing the fallow period from 3 to 10 years would only reduce income by about US$40 ha^{-1}, assuming the current crop yield. At higher crop yields, the opportunity costs are substantially higher. Increasing the fallow period to 10 years would reduce income by over US$600 ha^{-1}.

Table 4.24 Net present value change in income (ΔUS$ ha^{-1}) resulting from increasing the fallow period from three years to various longer periods.

a) Using survey reported crop yields:

	Over 5 years	Over 10 years	Over 20 years	Over 40 years	Permanent Change
			ΔUS$ ha^{-1}		
10 yrs Fallow	-$7	-$13	-$22	-$32	-$40
15 yrs Fallow	-$19	-$35	-$58	-$84	-$107
25 yrs Fallow	-$110	-$201	-$336	-$490	-$619
45 yrs Fallow	-$179	-$327	-$547	-$797	-$1,006

b) Using Tanzania national average crop yield for Maize:

	Over 5 years	Over 10 years	Over 20 years	Over 40 years	Permanent Change
			Δ $ ha^{-1}		
10 yrs Fallow	-$114	-$208	-$348	-$507	-$640
15 yrs Fallow	-$164	-$298	-$500	-$727	-$919
25 yrs Fallow	-$278	-$506	-$848	-$1,236	-$1,560
45 yrs Fallow	-$369	-$673	-$1,128	-$1,642	-$2,074

The reduction in income from increasing the fallow period can be somewhat offset through the sale of the additional commodity of carbon credits. Using the current average price of carbon for AFOLU project types of US$6.10 t CO_2e^{-1} (Hamilton *et al* 2008) and the estimated landscape scale increase in carbon stocks resulting from lengthening the fallow period, the potential income from carbon credit sale is $135 ha^{-1}

when the fallow cycle is lengthened to 10 years and over US$375 ha^{-1} with a 25 yr fallow management cycle.

Assuming a permanent change in land management and the resulting carbon credits sold at current average carbon price, the fallow period can be increased to 15 years and the net revenue received will be larger than during the original crop production system (Table 4.12). This would remain true even if only 60% of the credits were sold to buffer against the risk of non-permanence. If crop yields are actually closer to the national country average yields, the price of carbon would need to be over US$20 t CO_2e^{-1} without a buffer or US$35 t CO_2e^{-1} with a 40% buffer in order for it to be more profitable to alter land management to a 15 year fallow period (Table 4.12).

Table 4.25 Minimum price that carbon would need to be in order for the losses from the long term discounted revenue loss to equal the sale of carbon credits ($ t CO_2e^{-1}). Assuming no buffer is required and 40% of credits withheld from sale.

	No buffer		40% buffer	
	Using survey crop yields	Using Tanz country ave yields	Using survey crop yields	Using Tanz country ave yields
	$ t CO_2e^{-1}			
5 yrs Fallow	$0	$10.22	$0	$17.04
10 yrs Fallow	$1.83	$28.90	$3.04	$48.16
15 yrs Fallow	$2.41	$20.77	$4.02	$34.61
25 yrs Fallow	$9.99	$25.18	$16.64	$41.97
45 yrs Fallow	$10.69	$22.03	$17.81	$36.72

4.3.3 Case study

To better understand how the proposed changes in land management would impact a community, a theoretical case study area was developed. The villages surrounding the Kitulanghalo Forest Reserve outside of Morogoro, Tanzania were chosen since previous research had been conducted there, including agricultural management, the impact of selective logging (Malimbwi *et al* 2001), and CENTURY model parameterization (Walker 2008b) (Figure 4.4a). This area contains an existing forest reserve and is surrounded by agricultural fields, and communally held Miombo woodland areas. This agricultural community is included in the area covered by the economic surveys and therefore it can be assumed that crop-fallow periods and average crops yields are directly applicable.

In this case study it is assumed the community has decided to implement, enforce, and monitor a Participatory Forest Management (PFM) plan on 23,000 hectares with a focus on restoring the forest reserve, reducing degradation of communal woodland areas, and increasing fallow periods. A direct goal of this PFM project is the sale of the increased carbon stocks resulting from such a change in management.

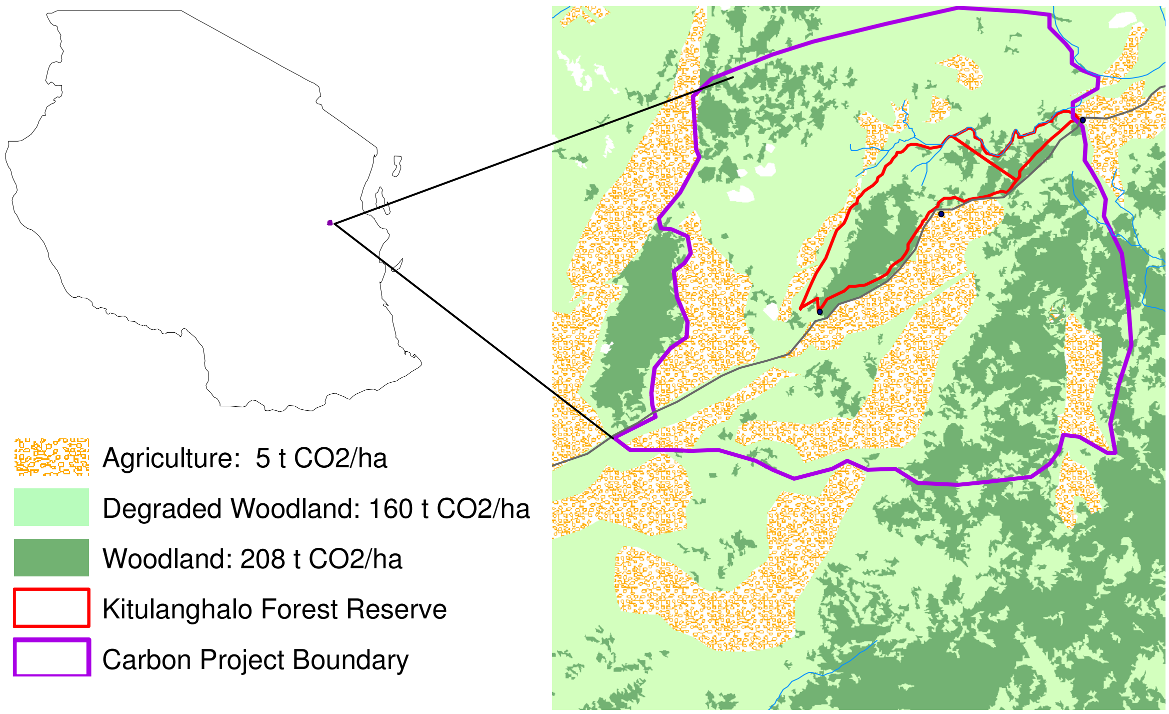


Figure 4.21 Hypothetical project area surrounding the Kitulanghalo Forest Reserve outside of Morogoro, Tanzania. Landscape scale average baseline carbon stocks

4.3.3.1 Baseline conditions

Based on the classification of the Landsat imagery, some areas of the communal lands have been less significantly degraded from charcoal production however, more than half the area of the forest reserve has been selectively logged. Under the current or 'baseline' conditions, it is assumed that the crop-fallow period is 5 years of cropping followed by 3 yrs of fallow and that the previously selectively logged woodland areas are cut on average every five years. In this area, about 25% of the land is under agriculture and about half the area has been previously selectively cut for charcoal production (Table 4.13).

Assuming these conditions are relatively stable, the revenue from 2800 t maize crop and 78,000 bags of charcoal results in more than a million dollars worth of products per year (Table 4.13). It is understood that the majority of the US$427,000 worth of maize would not be sold, but would be used for household consumption, therefore this should be considered the potential revenue. In this baseline case, it is assumed that the remaining area of land currently classified as non-degraded woodland in the immediate future will become a part of the charcoal production area, adding an additional $280,000 in annual revenue. However, to be conservative the unlogged area remaining in the forest reserve is assumed to continue to be unlogged.

Table 4.26 Area of case study and value of products produced.

	Area (ha)	Tree biomass (t CO_2e)	Annual Revenue (US$)	Yearly production
Agriculture	5,637	30,682	$427,796	2783 t maize
Communal Lands				
Degraded	11,304	1,811,564	$673,161	78,300 bags of charcoal
Currently not degraded	4,711	978,539	($280,554)*	30,000 bags of charcoal*
Forest Reserve				
Degraded	1,034	165,667	$61,561	6,570 bags charcoal
Not degraded	966	200,570		

*if land starts to be selectively logged

4.3.3.2 Project estimates

Since a goal of the project is to restore the forest reserve, under the PFM plan any selective logging previously taking place within the forest reserve will be ceased. A selective logging team will create a management plan in which the areas to be logged each year will be planned and selective logging will only occur every 10 years instead of the current 5 year logging rotation. It is assumed that all woodland areas outside forest reserve will be selectively logged (Figure 4.5). During selective logging, on average only 30% of the tree biomass will be cut. This will reduce charcoal production revenue, but will increase the average carbon stocks on the land. Additionally, fallow periods will be increased from 3 years to 15 years. At the end of the fallow period, farmers will cut trees that have regrown for charcoal production. This longer fallow period will also increase the average carbon stocks on the land. Increasing the fallow period to 15 years allows there to be greater than 15 t C ha^{-1} in trees on 45% of the agricultural land at any given time, therefore vastly increasing the area of woodland habitat. The income received was then discounted over time to also estimate the long term impact of a permanent change in the land management (Table 4.14).

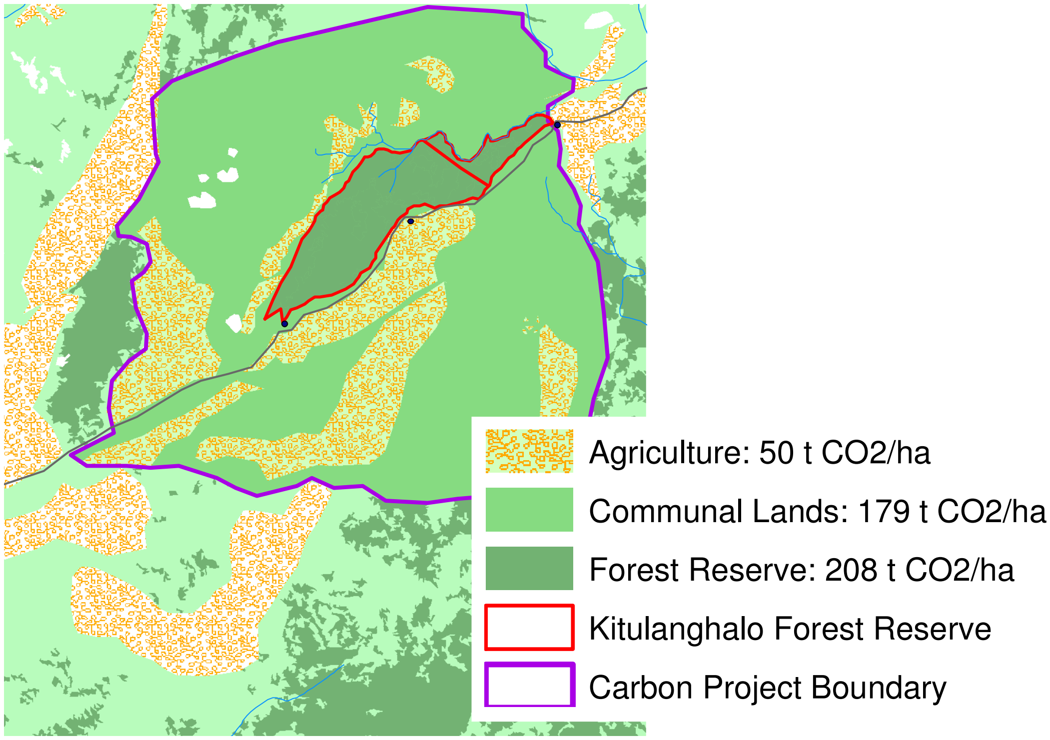


Figure 4.22 Hypothetical project area surrounding the Kitulanghalo Forest Reserve outside of Morogoro, Tanzania. Landscape scale average project carbon stocks

Table 4.27 Project case values of biomass, annual revenue, estimated lost revenue assuming permanent land management changes and potential revenue from carbon credit sale.

	Area (ha)	Tree biomass (t CO_2e)	Annual Revenue	Yearly production	Discounted Revenue lost	Potential Revenue from Carbon
Agriculture	5,637	280,144	$228,158	1484 t maize	-$603,135	$1,521,719
Communal Lands	16,015	2,873,541	$727,576	77,600 bags of charcoal	-$5,653,456	$1,872,519
Forest Reserve	2,000	415,484			-$1,538,250	$299,197

Because of the low crop yields reported, increasing the length of the fallow produces over US$900,000 more revenue from carbon credit sale than the revenue lost from agricultural production (Table 4.14). However, the sale of carbon credits produced by increasing logging rotations will not make up for the loss in charcoal production. Therefore, there would need to be additional benefits seen by the community resulting from this reduction in charcoal production for the community to decide to take this action. The price of carbon would have to reach about \$18.50 t CO_2e^{-1} before it would make up for the loss in charcoal revenue. At a price of \$32 t CO_2e^{-1} it would become more profitable to stop all charcoal production on all woodland areas.

4.4 Discussion

Despite decades of investments by African governments and donors, rural communities still face high levels of poverty. Success in combating poverty will most likely come from a wide variety of measures, each improving different components but must include increasing income derived from land use activities. Past development experiences have found that development initiatives meet greater success when activities are simple to implement, require few financial investments, have multiple benefits, and include a variety of activities (Walker *et al* 2008).

The recent growth of the voluntary carbon market has created the opportunity for communities to come together and as a community alter management practices and sell created carbon credits. Recent changes in many African government regulations, including in Tanzania, have given communities more direct control of the land and its natural resources. Therefore communities have the authority to development management plans and alter land management practices with the direct aim of increasing landscape level carbon stocks. However, communities will only be interested in investing in the development and implementation of a carbon project if it can be shown that there will be direct financial benefits.

There are a variety of land management changes that a community could institute that will result in varying levels of carbon changes and economic revenue changes. This analysis presents a first step towards understanding the potential resulting from increasing the rotation cycles of agriculture and selective logging. These two management styles may be attractive to communities because they do not require new activities or techniques to be implemented. The only inputs required will be the development of a management plan, additional field measurements to better estimate baseline conditions, and commitment by the community to permanently put the plan into practice.

The crop yields in the area surveyed were very low, even compared to the Tanzania average. In areas where crop yields are higher, sale of carbon credits alone may not offset revenue lost from increasing fallow periods. An average crop yield was used but in reality crop yields will vary across an area controlled by a community. Some fields will have higher fertility and higher crop yields while others will be less fertile. It is recommended that the land be stratified based on estimated productivity. The opportunity costs of increasing the fallow period will be lowest on highly degraded and low productivity lands. Based on the analysis conducted, fallow periods of 15 years will produce more revenue from carbon than the current short crop-fallow cycle. Increasing fallow periods on highly productive lands will most likely result in a net loss and therefore could possibly be omitted from this management alteration.

Based on modeled results, a fallow length of between 15 and 20 years will maximize the amount of charcoal that can be produced at the end of the fallow period. A fallow length greater than this will actually reduce the amount of charcoal able to be produced at the landscape scale as the increase in tree carbon stocks overtime ceases to make up for the reduction in the proportion of fields being converted to fallow per year at a fallow period greater than between 15 and 20 years.

Additional benefits from longer fallow periods besides increased carbon stocks will also be realized by the community. The area of woodland habitat will increase since a greater proportion of the land will be covered by trees. This will allow for a possible increase in wild animal populations and non-timber forest products, will reduce soil erosion and degradation, and will improve water quality. Currently, rural communities in the Miombo region derive a substantial quantity of products from the woodlands, both for household use and for sale (Malimbwi *et al* 2001). The resulting increase in area of woodland habitat, therefore, can also be seen as an additional buffer, or climate adaptation strategy, against the potential impact climate changes may have on crop production in the future. A recent study of the expected long term impact of various fallow periods estimates that under a fallow period of five years, soil nitrogen levels would be reduced by over 30% and phosphorus levels by almost 50%. (Walker 2008b). Increasing the fallow period will allow for less soil nutrients reductions. Based on modeled results, soil nutrient levels do recover during the fallow period, however, the rate of increase is only 1-2% per year (Walker 2008b). Although not included in the current analysis, it is expected that an increase in fallow period will most likely also increase crop yields. Elsewhere in the Miombo region maize yields have been found to be significantly positively correlated to soil carbon and nitrogen levels (Chirwa *et al* 2004; Mtambanengwe and Mapfumo 2008). The current revenue changes only include the sale of carbon credits from increased tree carbon, however, within agricultural areas soil carbon stocks will also increase significantly. If credits can be created and sold from this carbon increase, the revenue from carbon credit creation will almost double.

In Tanzania, the use of the woodland resources are currently unsustainable (Malimbwi *et al* 2001; Misana 2001; Olsen *et al* 2004). Luoga *et al* (2002) estimated that the annual wood removed in the Kitulanghalo area of Tanzania exceeds the annual growth rate and thus the current removal rate is not sustainable and will lead to greater woodland degradation. Malimbwi *et al* (2005) recommends that communities take an active role in preventing this degradation by creating management plans for the public forest lands in which the area is divided into sections.

A first step is to examine the impact of different management plans with the goal of maximizing sustainability, charcoal production, and carbon stocks. The current baseline assumption used was set at a conservative level of 30% woodstock removal (Ek 1994). This resulted in an average reduction in tree biomass stocks of about 25%. Other studies have found a greater difference in biomass stocks between areas cut for charcoal and areas with less human impact. Luoga *et al* (2002) found the biomass of community lands to be only 40% of the nearby Kitulanghalo Forest Reserve while Malimbwi *et al* (2005) found community lands to be on average 60% of forest reserve carbon stocks. If this greater level of selective cutting was to be the baseline estimate, increasing the rotation would result in even greater loss in charcoal revenue, but would also result in a larger change in carbon stocks, and therefore potential carbon credits.

The degree of woodland degradation has been found to be highly correlated with the distance to a main road or village, with carbon stocks increasing farther away from the road or village (Ek 1994; Malimbwi *et al* 2005; Luoga *et al* 2002; Malimbwi *et al* 2001; Vermeulen 1996). Therefore, if a project was developed it is recommended that baseline carbon stocks estimates of the area be stratified based on distance to roads.

If selective logging is implemented in which 30% of large wood is cut, at a 30 year felling cycle this would only be an average of a 6% reduction in livewood biomass while a ten year felling cycle would only reduce stocks by about 12% on average (Walker 2008b). Walker (2008b) note that as long as the logging stays at a low 30% percent cut per rotation cycle, a 8-10 year felling cycle is sustainable over the long term. Assuming current reduction levels, Malimbwi *et al* (2005) estimates that in areas near the road a 16-23 year felling cycle is required for tree biomass stocks to reach the stocks found in uncut areas while in areas more than 10 km from the road, a rotation cycle of 8-15 years could be implemented.

Unfortunately, assuming a baseline reduction of tree carbon stocks by 25%, the price of carbon would have to be greater than US$20 t CO_2e^{-1} before it would be financially beneficial to increase rotations. Given the current average price of US$6 t

CO_2e^{-1}, the sale of carbon credits will not offset the loss of charcoal revenue and will not be an attractive management decision for communities to implement.

We are entering into an ever-more ‘carbon-constrained’ world. The market has seen large increases and if demand starts to overtake supply, the price of carbon may increase rapidly. Additionally, in the voluntary market the price of carbon is often determined directly between the buyer and the seller. Prices for afforestation and avoided deforestation type projects ranged widely from about \$2.30 - \$50/t CO_2e (Hamilton *et al* 2007). Therefore, given the additional co-benefits of this type of project such as reduced land degradation and improvements in rural livelihoods, projects may be able to find buyers interested in investing more than the average current price.

In order for the successful implementation of the management alterations examined, a community based management plan would need to be instituted. This would require the organization of a large number of farmers within a community and the long term commitment to such management changes. Therefore, a community based organization would most likely need to be either created or an existing organization would need to initiate and management such a project. The above analysis does not currently include all the costs that would be incurred from the creation of a carbon project. These include costs carbon project management, additional project activities instituted by the project, project verification, and measuring and monitoring costs. The inclusion of these costs would raise the minimum price of carbon needed for project activities to be profitable.

The success of such a project will only take place if both the short, mid, and long term interests and livelihood needs of the community are not compromised. Since the primary goal of instituting such a project will be to improve livelihoods, it must be assured that all activities achieve this need. Given the recent increase in crop prices, any project will not be successful if it reduces a community's food security. If fallow periods are lengthened, and therefore the proportion of land producing crops reduced, it is highly recommended that this be done in concert with an improved agricultural management program. Depending on the techniques implemented, it may be necessary to increase fallow periods in only a portion of cropland controlled by the community, while in another portion of cropland, the carbon revenue can be used to invest in improved agricultural techniques, thus increasing crop yields. It may also be possible to account for any increases in soil carbon credits resulting from the improved land management. Before a community initiates such a project a thorough analysis of the potential risks and gains of such a project should take place.

The analysis conducted should be seen as a first estimation of the potential to manage rural landscapes for carbon credit creation. One of the benefits of the chosen land management activities is that to institute such management does not require the use of technology unknown to the community or the training in new locally unknown farming practices or crops. However, it is recommended that the management practices examined here be further compared with additional activities such as afforestation for plantations or woodlots, agroforestry, and improved fallow systems. This type of analysis could also be repeated at the national scale, providing the government a better understanding of what types of activities should be encouraged and in what locations. Prior to the creation of an actual carbon project in a certain location, site-specific information will need to be collected. This would include detailed community surveys of current management and field measured estimates of baseline carbon stocks for each land use.

4.5 Conclusion

One of the major challenges facing the world today is how climate change can be mitigated. This is a problem that will not be solved with one solution, but will require a large number of solutions, each contributing towards the goal of reducing greenhouse gas emissions. One of the major challenges facing rural communities in Tanzania is reducing poverty and increasing livelihood security. Again, this problem will most likely only be solved with different small solutions working in concert.

Community based initiatives in carbon stock land management offer the potential to combat both of these challenges together. Communities have the opportunity to work together to reduce land degradation and improve crop yields and at the same time receive additional revenue through the sale of carbon credits.

The low crop yields found in the Morogoro area of Tanzania mean that the opportunity costs from reducing the amount of land in crop production are lower than the potential revenue that could be received resulting from the carbon credit formation of increasing crop yields. Given current average prices for carbon, the sale of carbon credits from increasing logging rotations will not make up for the losses in charcoal production. However, prices are rising quickly and the minimum carbon price required for switching management to be economically beneficial is inside the range of prices paid to AFOLU project types in the past. Additionally, given the social and environmental benefits of such a project, buyers may exist that are willing to pay a greater price for the carbon credits.

This analysis covers a limited number of potential activities. It is recommended that this analysis be repeated to include other activity types such as afforestation and agroforestry. This type of analysis done at the regional or national scale would allow governments to provide informed recommendations to communities and focus assistance to activities and locations that will result in the highest benefits and the lowest costs.

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Chapter 5 Dissertation Conclusions

Although in much of the world the standard of living has risen dramatically in the last century, to a large extent the rural populations living in the Miombo Woodlands region still face deep poverty and livelihood insecurity. These populations rely almost exclusively on the ability of the vegetation and land to sustain them. Because of population increases, traditional land management is changing. Agriculture is taking place for longer on the same area of land and much of the woodland areas are degrading from over cutting for charcoal production. Unfortunately, these changes are not taking place along side technological advances, increased inputs, or thorough planned management.

Based on field measurements, soil carbon, nitrogen, and phosphorus levels are not significantly altered by the initial conversion of Miombo woodland areas to agriculture. In both Mozambique and Tanzania areas where crop production had taken place for less than five years did not have significantly different carbon stocks than Miombo woodland areas. Areas in Tanzania that had undergone several crop-fallow cycles in which the cropping period was less than five years, soil nutrient levels were only significantly reduced within the top ten centimeters of depth. It is recommended that further research of traditional farming practices be completed in other areas to reinforce these results. However, in Malawi where agricultural production has taken place for a longer period before being left fallow, soil carbon and nitrogen levels were significantly reduced. Soil carbon and nitrogen levels in older fallow areas were not significantly higher than agricultural areas, indicating that soil nutrient recovery is either only occurring at a very slow rate or not taking place within the current land management.

Across the Miombo Region land use pressure is increasing, even in areas of lower population densities. Over the several years between field sampling in Tanzania and the economic survey conducted, the average crop-fallow period moved from 3-5 years of cropping followed by 3-10 years of fallow to 5 years cropping followed by 3 years of fallow. Although people highly value the woodlands for the multiple resources they provide, people are faced with few options for certain cash income generation besides the creation of charcoal. It is most likely that while the demand for charcoal in peri-urban and urban areas continues, selective cutting for charcoal production will continue to degrade woodland areas.

The use of modeling allowed a more long term examination of how such increased land use could potentially impact ecosystem nutrient stocks. Unfortunately, model results show that under short crop-fallow cycles system nutrient levels cannot be maintained and nutrient stocks continue to decline over long time periods. Natural fallow periods allow some recovery of soil nutrient levels; however, the modeled recover is slow and requires more fallow years than currently practiced in many areas of the region. Although not included in the current analysis, it is expected that such a decline in nutrient stocks will result in lower crop yields.

In many areas of the Miombo region logging for charcoal has lead to successively degraded woodland areas. However, based on modeled results this system does have the capacity to supply wood on a long term basis provided the cutting remains selective and the woodland is allowed sufficient time for recovery. In many countries the communities now have direct authority over the public lands in their region. Instead of passively allowing unsustainable degradation, it is recommended that communities come together to form management plans for their communal lands. Rotation lengths should be at least 8-10 years at a selective logging level of 30%. Model results found that the time of year logging takes place does not need to be regulated. It is recommended that management plans state that only large wood and branches should be removed from the woodland areas and smaller branches with leaves should be left in place to decompose, thus reducing ‘nutrient mining’.

Communities also have to potential to take advantage of the newly forming carbon market by organizing themselves to form a carbon project. Carbon has the potential to provide additional income to communities. Lands within the community with low fertility and crop yields offer low opportunity costs, and thus lengthening the fallow period and quantifying and selling the carbon quantity change will actually provide greater income to the community than the current land practices. Although the average price of carbon is currently too low, the price of carbon needed for it to become economically advantageous to lengthen logging rotations is inside the range of prices paid to land based carbon projects in the past. Given the social and environmental benefits of such a project, buyers may exist that are willing to pay a higher than average price for the carbon credits.

Since the primary goal of any community based management plan will be improving livelihoods over the short and long term, it must be assured that all activities achieve this need. Given the recent increase in crop prices, any project will not be successful if it reduces a community's food security. If fallow periods are lengthened, and therefore the proportion of land producing crops reduced, it is recommended that a portion of the funding received from carbon credits be used to implement improved agricultural techniques that will lead to increased crop yields. The current analysis only covers a limited number of potential activities. This type analysis should be repeated to include other activity types such as afforestation and agroforestry. Additionally, conducting this type of analysis at the regional or national scale would allow governments to provide informed recommendations to communities and focus assistance to activities and locations that will result in the highest benefits and the lowest costs.

The land within the Miombo Region has low agricultural productivity and large areas of land degradation. In much of the region carbon stocks are far below their ecological maximum. Generally, this situation has had negative impacts for the ecosystem and human populations. However, all indications show that we are entering a new era, a new 'carbon-constrained world'. The high potential for carbon stock increases combined with very low opportunity costs, owing to low productivity, means that this region has the potential to play an important role in climate change mitigation, while at the same time bringing needed supplementary financial resources to rural communities. Additionally, the land management practices required to increase carbon stocks have multiple added benefits such as improved habitat, soil fertility, and reduced soil erosion. It is highly recommended that governments and donor organizations take an active role in encouraging and formulating such carbon projects within the region.